Emre Tokgöz

Total Hip Arthroplasty

Medical and Biomedical Engineering and Science Concepts

Contributions by Alessia Truden

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Preface

A typical phrase that you may read in a peer-reviewed article is the fame of total hip arthroplasty (THA) for being one of the most successful surgeries in the history of surgical procedures. This success of THA procedures makes it valuable for the relevant work done; however, it still leaves some room for improvement with the potential advancements in engineering and technology. In this book, we cover the fundamentals and advancements of THA from a variety of perspectives, including

- Pre-existing conditions
- Surgical procedure types
- Complications
- Patient care
- Biomechanics
- Optimization
- Robotics
- Artificial intelligence (AI), deep learning (DL), and machine learning (ML)
- Psychological therapy and research

There are two sides to this book: medical and engineering. Approximately 1000 peer-reviewed articles related to THA are used, with about 1100 referenced citations. We tried to prevent using the total knee arthroplasty (TKA)–related work unless THA results are reported separately in several articles. We intended to separate THA from TKA due to the differences in the success rates of implantation. This book is appropriate for medical doctors and biomedical engineers, while it may be appropriate for junior or senior undergraduate biology students, particularly those with knowledge of genetics**.** Parts of this book may be appropriate for anyone with a microbiology background. We should note that though biomechanics-, AI–, DL– and ML–related parts may require technical knowledge, these parts may not be appropriate for some of these audiences.

While reading of this book, you will find ideas for advancing THA using computing and engineering. There are articles in the literature that are not shared in this book, but the comprehensiveness of this book may give you more ideas for improvement that you can put into your own work. As much as we intended to keep this work comprehensive with the extensive number of articles cited and used, we could only cover so much; more publications came out while authoring this book. There are new research ideas such as the inclusion of psychological factors in the declining increase of THA occurrences by using technology and additional therapeutical help for patients. Our main intention is to comprehensively the THA-relevant considerations under a single umbrella. Even though we provided the above-mentioned headlines and content coverage in this book, the utilization of the content goes beyond this list.

Alessia Truden was the primary author of the first 6 chapters while Professor Emre Tökgoz was the second author. Professor Tokgöz was the primary author of Chapters 7–11 where Alessia contributed to a lesser degree to these chapters as the second author. Professor Tokgöz was the only author of Advancing Engineering of Total Hip Arthroplasty chapter.

We hope you will enjoy it all!

Hamden, CT, USA Emre Tokgöz

Contents

The original version of the FM was revised. The correction to this book is available at https://doi.org/10.1007/978-3-031-08927-5_13

About the Author

Emre Tokgöz is currently the Rector and Associate Professor of Industrial Engineering at Quinnipiac University. He completed a PhD in mathematics, a PhD in industrial engineering, an MS in computer science, and an MA in mathematics at the University of Oklahoma. He also completed an MS in mathematics and a BA in mathematics at the University of Ankara, Turkey. He completed this book during his applied biomedical engineering master's degree completion at Johns Hopkins University in 2022. His research, publication, and teaching areas included pedagogy, optimization, biomedical engineering, robotics, game theory, network analysis, financial engineering, facility allocation, inventory systems, queueing theory analysis, supply chain—renewable energy sources, STEM education, machine and deep learning, and Riemannian geometry.

Surgical Approaches Used for Total Hip Arthroplasty

Abstract Total hip arthroplasty (THA) is a surgical procedure performed when the patient's hip joint is worn or damaged. The main aim of the surgery is to reduce the pain experienced by the patients while simultaneously increasing their potential range of motion, thus allowing them to return to their daily activities without experiencing severe pain that could potentially interfere with their performance. There are a variety of approaches that could be employed for THA, and the main differences involve the positioning of the patient on the operating table, as well as the methodology used to access the hip joint, which subsequently leads to distinct positive outcomes alongside negative impacts. In this work, we review research literature for each approach and highlight the strengths as well as the weaknesses of each individual approach.

1 Introduction

Total hip replacement, also named total hip arthroplasty (THA), is an orthopedic procedure performed to relieve the hip pain resulting from a wide spectrum of conditions that ultimately provoke the degeneration of the hip joint. The procedure consists of the removal of sections of the affected femoral bone and pelvis and the subsequent replacement with a prosthetic component, to effectively restore the kinematics of the joint [1]. Figure 1 depicts the main anatomical landmarks of the hip joint that substantially aids the surgeon during the performance of the THA surgery.

Based on the information provided by the Agency for Healthcare Research and Quality, as of 2007, the overall number of THA procedures performed annually exceeds 450,000 solely in the United States [2], and the numbers are expected to rise significantly over the next few decades.

THA is particularly recommended in patients affected by osteoarthritis, rheumatoid arthritis, and osteonecrosis, as well as the ones subjected to injuries resulting in the fracture of the pelvis or the femoral head [3].

E. Tokgöz, *Total Hip Arthroplasty*, https://doi.org/10.1007/978-3-031-08927-5_1

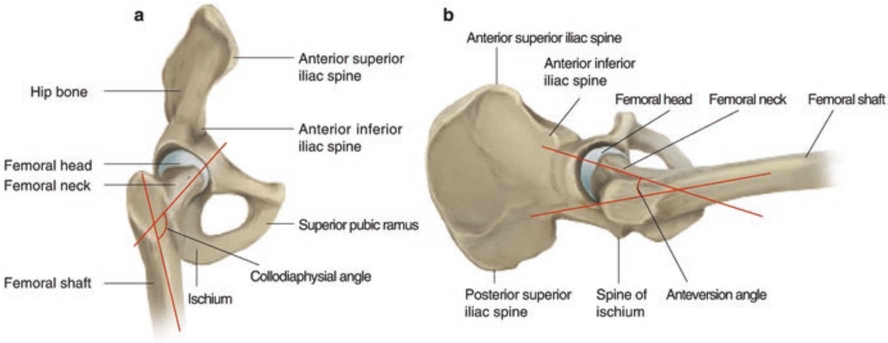

Fig. 1 Anatomical landmarks of the hip joint section [73]

Osteoarthritis is considered as the number one condition leading to the requirement of THA. In osteoarthritic individuals, the thin layer of hyaline cartilage that surrounds the ball-and-socket joint of the hip progressively deteriorates, eventually leading to increased friction between the head of the femur and the acetabulum of the pelvis, thus causing inflammation and the development of chronic pain [4]. Rheumatoid arthritis is, instead, an autoimmune disease that leads to the inflammation of the afflicted body structures. This condition primarily targets the joints, causing deformities that substantially increase the pain experienced by the affected individuals; however, it could also impact other bodily tissues, resulting in damages to organs including the heart and the eyes [5]. Osteonecrosis, or avascular necrosis, is a condition induced by the decreased blood supply to the bones that form the joints, which reduces the amount of nutrients and oxygen transported to the bone connective tissue and leads to its degeneration [6]. Fractures of the pelvis or the head of the femur could result as a consequence of high-impact or low-impact traumatic events. High-impact traumas could be caused by motor vehicle accidents or by falls from a substantial height and occur primarily among the younger population. Instead, low-energy traumas, such as falls from standing height, are particularly common in the elderly, mainly because of the increased fragility of their bones caused by the progressive loss of calcium and phosphate [7].

THA can be performed via a variety of approaches that differ with regard to the position of the patient during the surgery, as well as the site of the incision, subsequently impacting different muscles and structures based on the modality chosen for the surgical procedure. Such approaches include the direct anterior, the anterolateral, the direct lateral, the lateral transtrochanteric, the posterior, and the posterolateral approach. Figure 2 displays the placement and orientation of the superficial incisions to perform THA via the various approaches [74].

2 The Direct Anterior Approach

The direct anterior approach (DAA) was initially described by Carl Hueter in the second half of the nineteenth century; however, it was not used as frequently as other aforementioned approaches because of the several complications associated

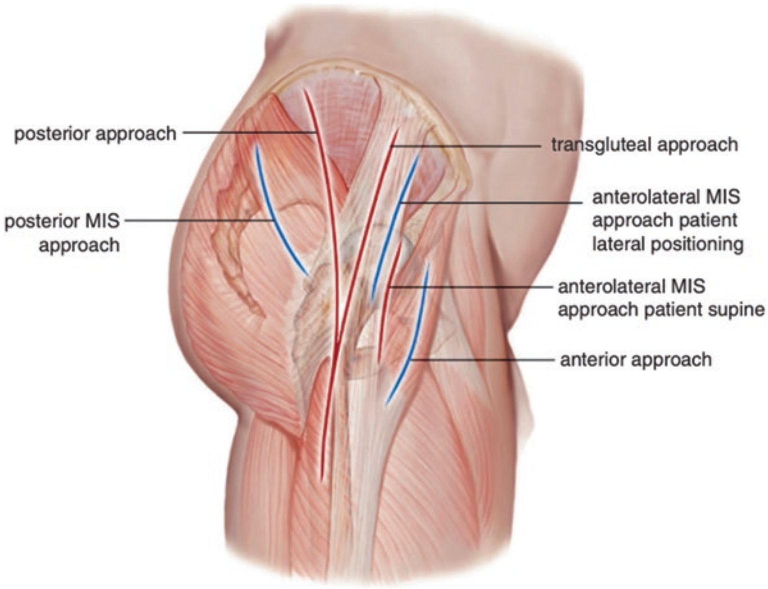

Fig. 2 Superficial incision placement and orientation to perform THA via the various approaches [74]

with it [8]. The DAA has begun to gain popularity over the past decade, in an attempt to satisfy the increasing demand for minimally invasive surgeries that are generally correlated to inferior postoperative pain, shorter hospitalization period, as well as better cosmetic outcomes.

As a matter of fact, the DAA has been described as a minimally invasive approach, mainly due to its muscle-sparing nature that allows for the preservation of the internervous and intermuscular planes during the incision, ultimately achieving a comprehensive exposure of the hip by utilizing the interval between the sartorius and the tensor fasciae latae muscles, and simultaneously preventing damages to the lateral femoral cutaneous nerve [8]. Figure 3 depicts the trajectory followed during THA performed via the direct anterior approach, between the areas innervated laterally by the superior gluteal nerve, and medially by the femoral nerve. Incision of the tensor fasciae latae is performed to enable the visualization of the medial aponeurosis, located laterally to the sartorius muscle. Retraction of the rectus femoris toward the medial side and of the gluteus medius laterally is then performed, to allow the exposure of the anterior capsule of the hip, followed by capsulotomy to achieve complete visualization of the joint [75].

Prior to the beginning of the procedure, the patient is placed in the supine position on the operating table. Subsequently, the incision is initiated about 2–3 cm posteriorly and 1–2 cm distally to the anterior superior iliac spine of the hip, to then extend distally toward the head of the fibula, in line with the belly of the tensor fasciae latae and slightly anterior to the perforating vessels located on the translucent fascia of the tensor. The incision is initiated about 3 cm posteriorly and 2 cm distally to identified anatomical landmark, which is the anterior superior iliac spine of the hip, marked with a red X as displayed in Fig. 4 [75].

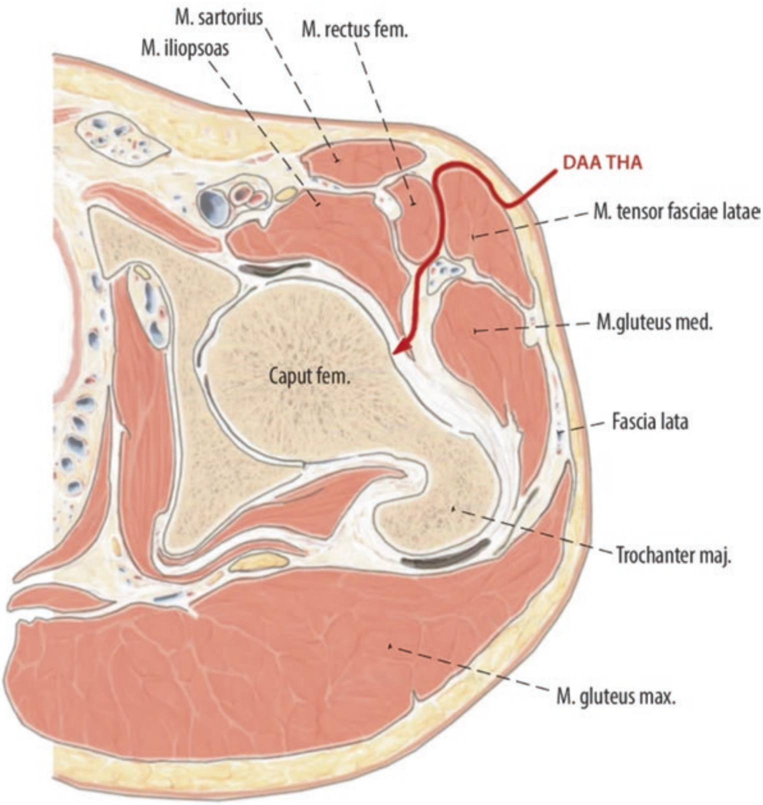

Fig. 3 The trajectory followed during THA performed via the direct anterior approach

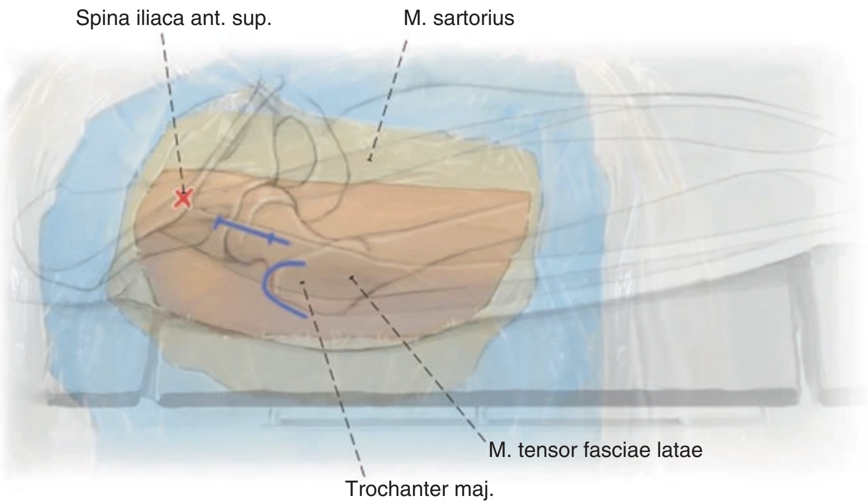

Fig. 4 Incision location landmarks

Once the superficial incision is completed, a retractor is used to achieve a more exhaustive exposure of the interval by separating the tensor fasciae latae and the gluteus medius from the rectus and the sartorial muscles, which are respectively pulled toward the lateral and medial sides. Throughout this procedure, the lateral femoral circumflex vessels are cautiously dissected and cauterized, to prevent excessive bleeding that would preclude the visualization of the operative field, as well as the occurrence of further complications [8].

Incision of the capsule of the hip is then performed with an inverted “T” technique that runs parallel to the lateral surface of the femoral spiral line and extends medially along the inferior segment of the neck of the femur. Subsequently, the dislocation of the head of the femur is achieved via the use of a hip skid, which aids in the execution of an atraumatic luxation, and resection of the femoral neck is conducted after carefully positioning a corkscrew with a detachable handle under the head of the femur, to prevent the occurrence of damages to muscles potentially caused by fragments of bone detached during the procedure [8].

Rotation of the femur at an angle ranging from 20 to 45 degrees is then performed to attain exposure of the acetabulum and facilitate the reaming stage, as well as the ensuing placement of the acetabular cup. Once this passage is completed, the femur is returned into its neutral placement and the traction previously applied to the limb is released.

Comprehensive femoral exposure is subsequently achieved via hyperextension and adduction of the operative leg and the addition of a retractor posterior to the greater trochanter, in order to exert adequate tension on the connective tissues connected to the latter. The femur is then prepared, and the femoral component of the implant is inserted, followed by the reduction of the hip and saturation of the wound [8]. Figure 5b displays the insertion of the acetabular cup, performed after rotating the femur at an angle of about 45 degrees. This passage is followed by release of the traction exerted on the limb, and hyperextension and adduction of the operated leg, to allow for the preparation of the femur and subsequent insertion of the femoral component as displayed in Fig. 5b [75].

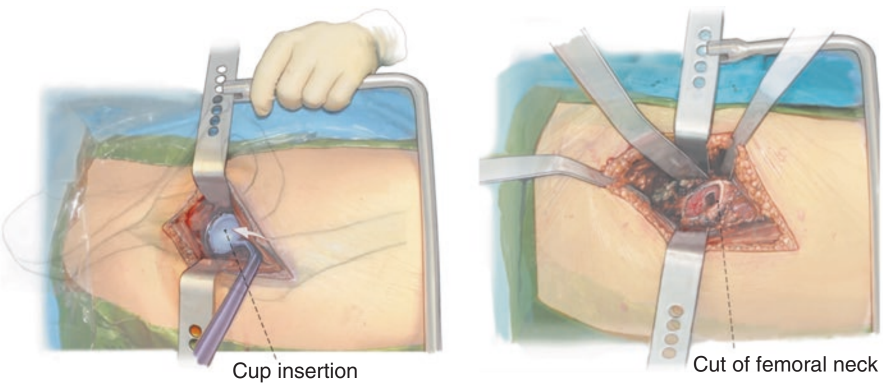

Fig. 5 (**a**) Left image showing acetabular cup insertion. (**b**) Right image depicting the preparation of the femur

The postoperative care in patients undergoing THA via the DAA begins promptly after the procedure, as the experienced pain and correlated use of narcotics is substantially inferior in comparison to other approaches, ultimately leading to a decreased hospitalization period.

Despite the aforementioned advantages, the DAA has been associated with relatively high prosthesis-related complications, which include dislocation, incidence of periprosthetic fractures, and prosthetic loosening, as well as surgical complications such as nerve damages, particularly to the lateral femoral cutaneous nerve, located in close proximity to the operative field during the surgery [9].

Moreover, the DAA has been associated with a steep learning curve for the first 30 procedures performed by a surgeon, throughout which the outcomes of the surgery improved as the surgeon acquired a greater degree of dexterity, ultimately reaching a plateau after roughly 100 surgeries, thus suggesting that the experience of the surgeon has a direct impact on the length of the surgical procedure and intraoperative blood loss, as well as on the postoperative outcomes, which encompass dislocation rates, leg discrepancy, and component placement [10].

2.1 Design of a Learning Curve for THA Performed via the Direct Anterior Approach

The concept of learning curve for the DAA is analyzed in [59], and commonly used in surgical training with respect to the improvement of the performance with increased experience. The curve could be divided into five stages: the first stage represents the beginning of training and is followed by a rapid increase denoting the pace at which the performance of the individuals improves. At some point, both the performance and the progress tend to diminish, leaving space for refinement of the techniques used. The second stage illustrates the point at which the surgical procedure can be conducted autonomously, followed by small improvements as additional experience is gained—constituting the third stage—until reaching the plateau, or fourth stage. Finally, the fifth stage consists of a gradual fall in performance due to age, decreased manual dexterity, and other factors [60]. Therefore, a learning curve was designed in order to ultimately outline the repercussion on the surgical training and safety of the patients, alongside the effectiveness of the procedure in terms of payment, in relation to the operative time. A steep learning curve was obtained for the performance of the first 30 total hip arthroplasties using the direct anterior approach, and the anticipated plateau was reached after performing approximately 100 surgeries. The data obtained for mean operative time showed a substantial decrease throughout the first 30 cases—50 minutes—but an authentic plateau was never obtained, thus demonstrating that improvements relative to the surgical technique can still occur after performing hundreds of procedures [59]. Moreover, results have shown a correlation between complications and revision rates and the experience of the surgeon performing the procedure. In fact, the mean rate of complications was 20.8 ± 12.7% for the early group, whereas revision rates were 1.1 ± 0.9% for the more experienced group, and the data regarding leg discrepancy—which is one of the most common causes of patient discontent—decreased from 3.2 ± 1.4 mm to 2.0 ± 1.2 mm in the late group. In addition, the mean anteversion of the acetabulum was 14.3 ± 1.8° (range: 13–15.6) for the early group and 12.9 ± 1.6° (range: 11.7–14) for the more experienced group, ultimately suggesting that the early group does not risk achieving excessive anteversion, which constitutes a crucial component in the positioning procedure [59].

2.2 Treatment of Protrusio Acetabuli with THA via the Direct Anterior Approach

The condition identified as protrusio acetabuli (PA) is examined in [61]. This disorder is characterized by the deepening of the acetabulum and the femoral head into the lesser pelvis [62], ultimately causing severe hip pain and osteoarthritis. THA is the most indicated procedure for the treatment of this condition, as other approaches—such as triradiate fusion [63] or osteotomy of the valgus intertrochanteric [64]—are particularly limited. Nonetheless, THA performed via the posterior approach presents various complications. From an anatomical standpoint, the stability of the hip is severely debilitated by the decreased surface of the medial wall and osteoporosis; instead, intraoperative complexities arise due to the positioning of the head of the femur, as well as the restricted range of motion (ROM) to achieve its exposure and subsequent dislocation. Furthermore, the placement and fixation of the prosthesis could be undermined by the reduced support provided by the acetabulum and by decreased hip dimensions and consequential misalignment.

To face the complexities arising during the posterior approach and ultimately improve the stability of the newly implanted prosthesis while diminishing the incidence of complications following the surgery, the potential outcomes of fluoroscopy-guided THA performed via direct anterior approach were analyzed in 23 sequential surgeries.

For all the procedures, a single incision was performed, extending from 2 cm posterior and 1 cm distal to the anterior superior iliac spine down to the area ranging from 2 to 3 cm anterior to the greater trochanter, dissecting the tensor fascia lata and allowing direct exposure of the hip capsule following retraction of the sartorius and rectus femoris toward the medial side [65]. Moderate traction was then applied to achieve distraction of the hip, and division of the ligamentum teres was performed. The head of the femur was then dislocated either via external rotation or via fluoroscopy-guided in situ osteotomy if the latter was still trapped within the acetabulum, to ultimately remove it and morcellize it with a Bone Mill for subsequent autografting. Following this procedure, the acetabulum was prepared through the removal of soft tissue and underlying cartilage and later subjected to pressure with the autograft of the head of the femur to create a homogeneous hemisphere prior to the implantation of the real prosthesis [61].

Prior to the procedure, the patients presented displacement of the medial acetabular border beyond the ilioischial line (AK distance) ranging from mild, 1 to 5 mm, to severe, beyond 16 mm, and the mean AK distance recorded postoperatively was successfully reduced to 0 mm. Moreover, the mean values recorded for abduction and anteversion angles of the acetabular prosthesis were 45 and 18 degrees, respectively—achieved with fluoroscopic guidance that allowed accurate cup positioning, whereas the mean value obtained for discrepancy in the length of the limb was 2 mm [61].

THA performed through DA significantly decreases the risk of dislocation in patients affected by protrusio acetabuli via preservation of the tendons underlying the area of the incision, alongside ameliorating the degree of protrusion and achieving positive patient-reported results. The precision of the previously mentioned approach could be further enhanced through fluoroscopy, which allows for the monitoring of the images acquired throughout the surgery to ultimately achieve more accurate placement of the implant while simultaneously reducing any uncertainties that could potentially arise during the procedure [61].

2.3 Exposure to Radiation During Fluoroscopy-Guided Anterior THA

The direct anterior approach procedure might lead to the occurrence of many complications, among which aseptic loosening, dislocation, and development of infections are such complications that can be listed [67, 68].

To prevent the incidence of such conditions and to enhance the placement of the acetabular component—which needs to be inserted within a safe zone consisting of an anteversion of 15°, ±10°, and an abduction of 40°, ±10°, fluoroscopy, analyzed in [66]—has been utilized to guide the execution of THA and in an attempt to achieve better patient outcomes [69, 70]. However, this procedure exposes the patient and the staff performing the surgery to some degree of radiation [71], which was therefore quantified in the systematic review.

Results showed that the average cup anteversion and abduction angles in fluoroscopy-guided THA were 23.1° and 43.4°, respectively, whereas the calculated average for the THA procedure performed using traditional landmarks presented a wider range, and the mean angles were 45.9° for acetabular abduction and 23.1° for anteversion, ultimately confirming the efficacy of THA performed via guided fluoroscopy, as 80% of the procedures successfully placed the implant within the safe zone [69]. Moreover, the average fluoroscopy time for patients undergoing THA was approximately 21.4 s, during which they were exposed to a radiation dose of 1.8×10^{-3} Gy [66]—calculated using a dosimeter—considerably below the threshold established by the Centers for Disease Control and Prevention (CDC), which indicated potential incidence of hematopoietic syndrome following exposure to radiation ranging from 0.7 to 10 Gy, whereas exposure to 10 Gy and over 50 Gy could ultimately lead to the occurrence of gastrointestinal and neurovascular syndromes, respectively [72]. According to these results, it is possible to establish the safety of fluoroscopy-guided THA for all parties present in the operating room at the time of surgery, additionally emphasizing that a surgeon would have to perform over 300,000 THAs utilizing fluoroscopy in order to exceed the minimum dose of 0.8 Gy required to cause radiation-related conditions [66].

3 The Anterolateral Approach

The anterolateral approach (ALA) was first described by Watson-Jones in 1936. This approach implicated the partition of the anterior section of the abductor muscles—which included the gluteus medius and minimus, and the tensor fascia latae—and the capsule of the pelvis; however, numerous alterations have been made to the procedure in the past few decades [11].

Nowadays, the ALA is performed with the patient placed in the supine position, which facilitates the identification of the anatomic landmarks by the surgeon. The incision is initiated proximal to the extremity of the greater trochanter and extended distally along the femoral diaphysis to dissect the fascia, and could be potentially protracted proximally, for a more comprehensive exposure of the femur, or distally, to achieve exposure of the acetabulum of the hip. Figure 6 displays a trajectory of the incision for THA performed via the anterolateral approach with the patient in the supine position [76].

The length of the incision is subjected to variations depending on the characteristics of the patient, which include weight, density of the adipose tissue at the site of the surgery, and musculature [12].

Once the superficial incision is finalized, the fascia is divided anteriorly to the lateral extremity of the greater trochanter to allow for the visualization of both the anterior and posterior surfaces of the gluteus medius.

Subsequently, the anterior portion of the gluteus medius, the gluteus minimus, and the anterior portion of the capsule of the hip are carefully lifted

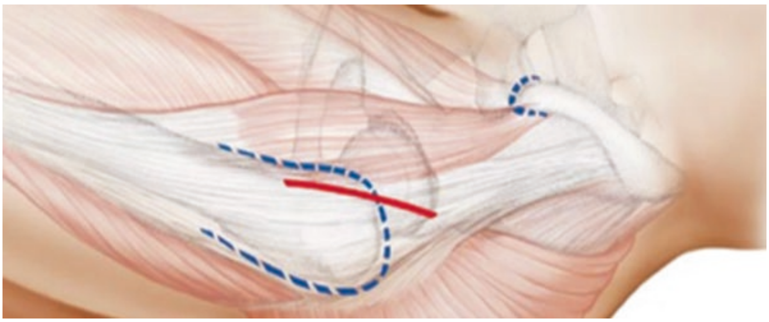

Fig. 6 Anterolateral approach's incision trajectory

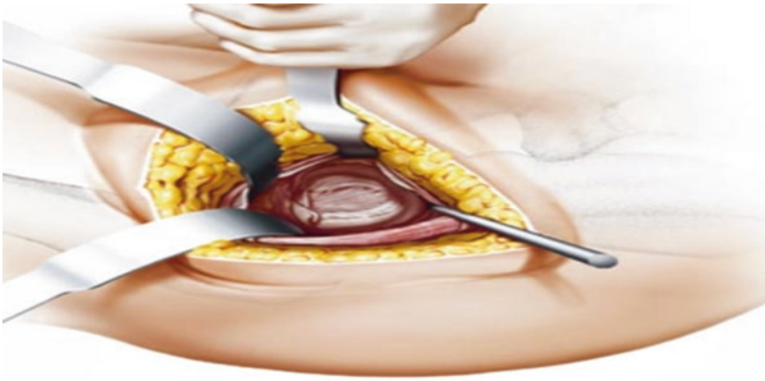

Fig. 7 Acetabulum preparation following osteotomy of the femoral neck

anteriorly to prevent injuries to the superior gluteal nerve. Incision of the superior aspect of the capsule is then executed along the posterior surface of the gluteus minimus, and particular caution is required during the incision of the inferomedial capsule to avoid dissection of the tendon of the iliopsoas muscle. Dislocation of the femoral head and subsequent osteotomy of the femoral neck are then performed [12].

Three acetabular retractors are utilized to achieve comprehensive exposure of the acetabulum after the incision of the medial capsule and the circumferential excision of the labrum. The acetabulum is then reamed, and acetabular component of the prosthesis is positioned. Figure 7 demonstrates the preparation of the acetabulum following osteotomy of the femoral neck [76].

The exposure of the femur is achieved via external rotation and adduction of the operated leg, followed by insertion of two retractors to ultimately facilitate the visualization of the operative field and reduce the potential damage to soft tissues and muscles caused by the equipment used during the procedure. The femoral canal is prepared, the femoral component is inserted, and the wound is then sutured in layers [12]. Figure 8 displays the femur preparation and positioning of the retractors during the procedure [76].

The postoperative care in patients subjected to THA via the ALA consists of physical therapy and in the administration of oxycodone and other nonsteroidal anti-inflammatory medicaments. Moreover, the patients are subjected to a progressive weight-bearing increment to aid in the rehabilitation procedure.

The ALA has been correlated with a particularly low incidence of dislocations, mainly due to the intraoperative preservation of the posterior capsular structure. However, a significant disadvantage of this approach resides in the weakness of the abductor muscles, which might increase the overall number of patients experiencing postoperative limp, ultimately leading to inferior patient-reported outcomes [13].

Fig. 8 Preparation and positioning of the retractors around the femur

4 The Posterior Approach

The posterior approach (PA) has been initially described in 1874 by von Langenbeck; however, the currently performed procedure is more similar to the one popularized by Moore in 1957, as multiple changes have been made to the original technique employed for such approach [14].

The PA is considered the most frequently used approach for THA and is performed with the patient lying in the lateral decubitus position. The incision is initiated roughly 5 cm distal to the greater trochanter, centered on the diaphyseal region of the femur, and is extended proximal to the posterior aspect of the greater trochanter before curving for approximately 5–7 cm toward the posterior superior iliac spine of the hip. Subsequently, another incision is performed longitudinally and proximally to the tensor fasciae latae and iliotibial band, to partition the gluteus maximus and allow for the insertion of a retractor to hold the separated sections in place.

Following the recognition of the piriformis muscle, tenotomy of the short external rotators is carried out proximal to their insertion on the greater trochanter. The short external rotators are then reflected posteriorly, to preserve the sciatic nerve and achieve a more comprehensive exposure of the posterior capsule of the hip [15].

Visualization of the femoral head and neck is attained via capsulotomy, utilizing a “T” technique, and dislocation of the hip is performed after ulterior internal rotation of the operated leg, as well as flexion, adduction, and mild traction of the latter.

An oscillating saw is then employed to osteotomize the neck of the femur, and comprehensive exposure of the acetabulum is obtained via the installation of three retractors. Careful excision of any soft tissues present within the operative field is then performed prior to the acetabular reaming procedure and the insertion of the

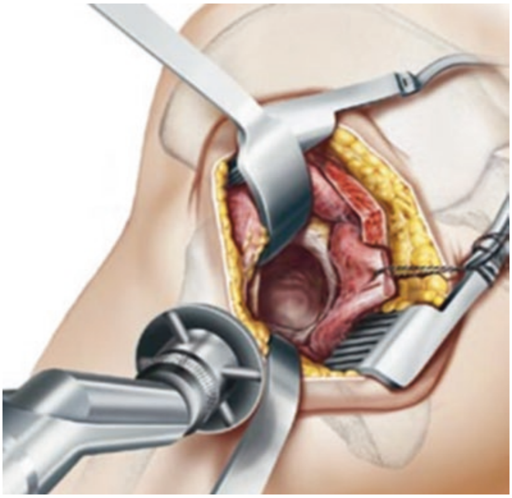

Fig. 9 Preparation of the acetabulum via the reaming procedure

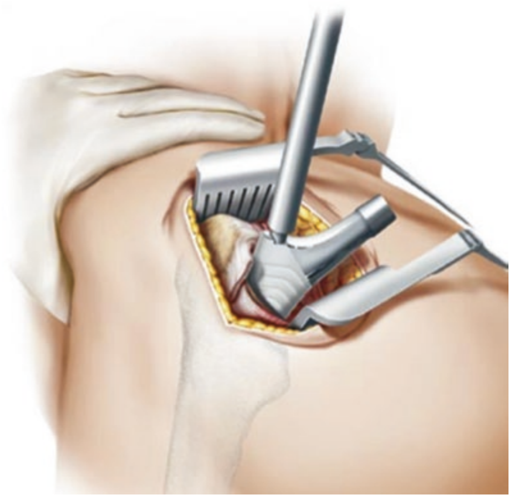

Fig. 10 Insertion of the femoral component of the prosthesis prior to the reduction

cup. Figure 9 depicts the reaming process necessary for the preparation of the acetabulum before the implantation of the acetabular component of the implant [77].

Once the installation of the acetabular component is concluded, the operated leg is rotated internally, flexed, and adducted, to allow for the preparation of the femoral canal and ensuing placement of the femoral prosthetic component. Figure 10 displays the insertion of the metal stem of the femoral component of the prosthetic implant.

Suturation through transosseous tunnels is then carried out to repair the short external rotators and the posterior capsular structure, and the tensor fasciae latae, iliotibial band, and gluteus maximus are sewn via running sutures prior to the reparation of the superficial wound [15].

One of the main complications after THA performed via the posterior approach is the dislocation of the hip, mainly attributed to the technique adopted during the procedure, which foresees the dissection of the posterior muscles and tendons, ultimately resulting in greater instability of the joint and increasing the burden of reintervention [16]. To avoid such occurrence, the discharged patients have to comply with a strict postoperative protocol that thoroughly enumerates the provocative positions that result in the increased risk of dislocations, which include hip flexion past 90°, adduction past the midline, as well as internal and external rotation [17]. Some other complications associated with the PA include injury to the sciatic nerve [18], aseptic loosening, and relatively high infection rates [19].

5 The Direct Lateral Approach

The direct lateral approach (DLA), also referred to as transgluteal approach, has been first described by McFarland and Osborne in the year 1954; however, the current technique used for such approach has been popularized by Hardinge in 1982 [15].

As per the posterior approach, the DLA procedure is performed with the patient lying in the lateral decubitus position on the operating table. The incision is initiated with the hip flexed at a 45° angle and protracted for approximately 10 cm over the greater trochanter, dissecting the iliotibial band and tensor fasciae latae while simultaneously preserving the gluteus medius muscle. A retractor is then utilized to hold the partitioned iliotibial band in place and allow for the incision and subsequent reflection of the greater trochanteric bursa posteriorly.

Figure 11 shows the incision performed to dissect the iliotibial band and tensor fasciae latae while preserving the gluteus medius muscle [78].

Once the comprehensive visualization of the gluteus medius is achieved, the muscle belly of the latter is split along its vertically oriented fibers, and the incision is prolonged until approximately 1 cm distal to the extremity of the greater trochanter. Once partial tenotomy of the gluteus medius tendon proximal to the insertion on the greater trochanter is finalized, the incision is curved toward the vastus ridge, a procedure that requires extreme care to prevent damages to the vastus lateralis muscle. The split between the gluteus medius and gluteus minimus muscles is then reached, followed by slight flexion, external rotation, and abduction of the operated leg to exert tension on the gluteus minimus and allow for partial tenotomy. A retractor is then employed to hold the previously dissected muscles in place and allow for complete exposure of the capsular component of the hip that is promptly dislocated after performing a partial capsulectomy to excise the inferior section of the capsule. An oscillating saw is subsequently used to osteotomize the femoral neck, followed by reaming of the acetabulum and installation of the cup. Comprehensive exposure of the proximal region of the femur is achieved after insertion of three retractors, one positioned laterally to the greater trochanter, to prevent the iliotibial band and tensor fasciae latae muscle from entering the operative field, one proximal to the

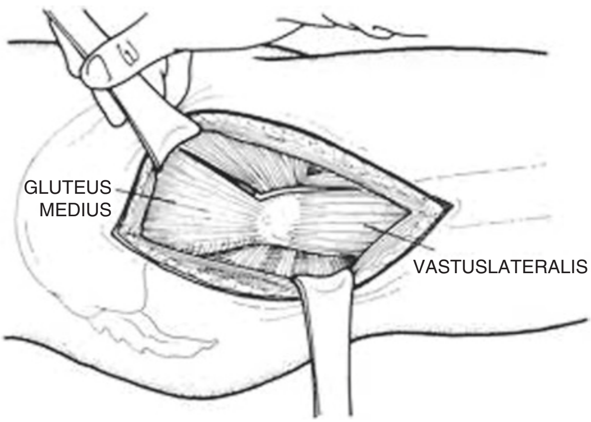

Fig. 11 Structures visualized after the superficial dissection

lesser trochanter, and one posterior to the proximal femur to retract the gluteus medius. Complete visualization of the proximal femur enables the surgeon to proceed with the preparation of the femoral canal, broaching, and placement of the femoral component of the prosthetic implant. Once the installation is completed, the previously tenotomized tendons are sutured, the incision on the gluteus medius is repaired, and the superficial wound is closed.

The DLA has been associated with reduced incidence of major complications compared to other conventional approaches [20]; however, such approach results in a relatively high rate of Trendelenburg gait [21], thus indicating weakness of the gluteus medius and minimus muscles, resulting in the dysfunction in the abductor mechanism of the hip [22], as well as inferior walking velocity, stride, and step length [23]. Some additional complications correlated with this approach are intra-operative fractures and damages to the superior gluteal nerve [15].

6 The Lateral Transtrochanteric Approach

The lateral transtrochanteric approach was initially described by Ollier in 1881 and later popularized by Charnley in 1962 [24]. This approach enables for a comprehensive visualization of the acetabulum, as well as the posterior and anterior capsular components [25]; however, it is not frequently used because of the various postoperative complications associated with it [24].

The procedure is carried out with the patient lying in the lateral position and is performed similarly to the previously described direct anterior approach. The incision is initiated approximately 2–3 cm distal to the greater trochanter, to separate the tensor fasciae latae. It is then protracted proximally and then curved to parallel the gluteus maximus muscle and allow for the exposure of both the gluteus medius and vastus lateralis. After achieving visualization of the anterior capsule, external

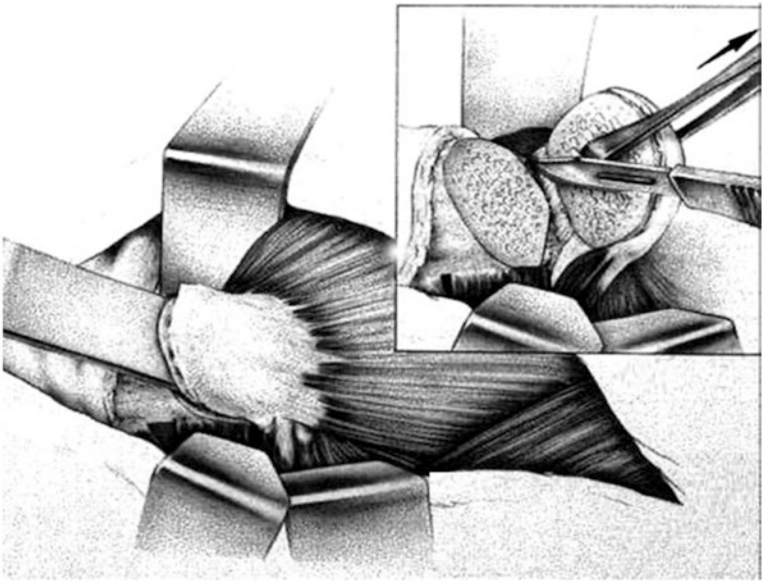

Fig. 12 Visualization of the capsule and resection

rotation of the operated leg is performed to allow for the meticulous dissection of the capsule and to consequently visualize the vastus ridge. Figure 12 depicts the elevation of the trochanter with the use of retractors, while the gluteus minimus fibers are held in place and detached from the capsule via a scalpel. This technique enables for the comprehensive exposure of the capsule that is then resected [79].

Osteotomy of the trochanter is then performed, followed by the use of a Gigli saw to pierce the capsular component. An ulterior dissection angled at 45° is then carried out at the vastus ridge and protracted until reaching the superior border of the neck of the femur, followed by tenotomy of the external rotators and detachment of the residual capsular component. The operated leg is then subjected to adduction to allow for the dislocation of the trochanter [25].

The acetabulum is reamed after dissecting the labrum and the ligamentum teres, followed by implantation of the cup, and preparation of the femur is carried out by shaping the hollow femoral canal and subsequent broaching, prior to the placement of the metal stem of the component. After the prosthetic components are successfully implanted, the capsule is repaired and the gluteus medius, vastus lateralis, and tensor fasciae latae muscles are sutured prior to proceeding with the closure of the superficial wound [26].

Despite the comprehensive acetabular visualization achieved using the transtrochanteric approach, the latter has been associated with greater length of the procedure, increased intraoperative blood loss, as well as major complications including trochanteric nonunion, osteonecrosis, and infections of the surgical site. Moreover, this approach has been correlated with relatively high rates of dislocation, because of abductor muscle weakness, and the need for subsequent revision surgery [24].

7 The Posterolateral Approach

The posterolateral approach has been initially described by Langenbeck in 1874 [27] and subsequently modified to allow for the optimal visualization of the acetabulum and the proximal femur via a caudal extension of the incision.

The surgery is performed with the patient lying in the lateral decubitus position, and the pelvis is cautiously secured and leveled prior to the beginning of the procedure to avoid any potential movements that would result in the inaccurate placement of the acetabular cup. The length of the incision ranges from 7 to 20 cm, depending on the physical peculiarities of the patients, and is initiated and protracted longitudinally over the posterior one-third of the greater trochanter. The distal segment of the incision is continued parallel to the femoral shaft, whereas the proximal portion is curved toward the posterior superior iliac spine. Subcutaneous dissection is then performed, and a Cobb elevator is used to allow for the visualization of the tensor fasciae latae muscle. An ulterior incision is carried out on the fascia, and the gluteus maximus muscle is subsequently dissected following the direction of its fibers. A Charnley retractor is then positioned to hold the dissected muscle in place and allow for complete exposure of the femur and acetabulum, which is further enhanced by flexion of the operated leg at a 90° angle and maximal internal rotation. Figure 13 depicts the dissection of the deeper tissues to eventually access the acetabulum [80].

Incision of the bursa is then performed, and an additional retractor is placed to tenotomize the hip capsule and the short external rotators from their insertion on the femur and allow for the capsulotomy procedure to be carried out. The hip is subsequently dislocated, and the femoral neck is osteotomized to enhance the

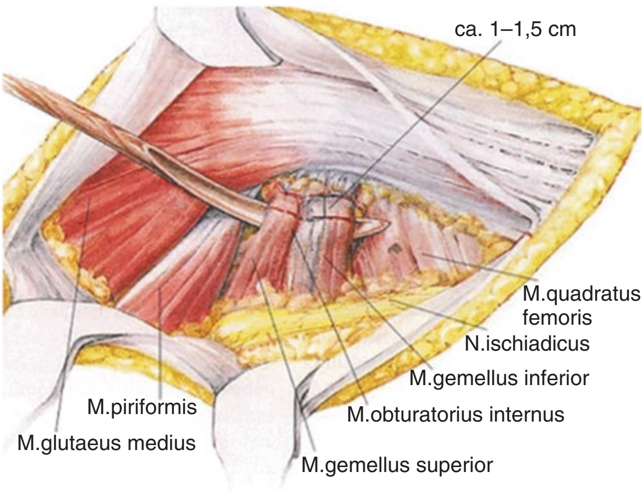

Fig. 13 Dissection of deep tissues

visualization of the acetabulum following the excision of the labrum and pulvinar. The acetabulum is then prepared, and the cup is inserted. Later, the femur is prepared, the femoral canal is shaped, and the femoral component is inserted. Once the prosthetic implant is correctly positioned, the previously dissected muscles are repaired, and the superficial wound is sutured [28].

The posterolateral approach has been associated with major complications, including damages to both sciatic and femoral nerves, dislocation, as well as heterotopic ossification [28].

8 Impact of Patient Positioning on Blood Loss and Rate of Transfusion During Hip Replacement Surgeries for Femoral Neck Fractures

Hip fractures constitute a significant percentage of adult mortality and comorbidity [29]. Besides the surgery, patients have to undergo a strenuous process of rehabilitation, and, in some instances, they might have to receive lifelong moral and physical support.

In younger patients, the occurrence of femoral neck fractures is directly correlated to high-energy traumas, and it accounts for a small percentage of the total cases, whereas the incidence is significantly greater in the elderly as a consequence of low-energy traumas [30].

The postoperative care process is reputed particularly challenging due to the fragility of the patients, which are previously subjected to either total hip arthroplasty (THA)—involving the replacement of both the acetabulum and the femoral head with prostheses—or hip hemiarthroplasty (HA), which foresees femoral head replacement with a prosthesis, rather than a more straightforward internal fixation [30]. Multiple studies have shown the superiority of THA with lateral decubitus positioning, which led to an inferior intraoperative blood loss (about 201 ml) compared to the supine position, a decrease perhaps attributable to the raising of the surgical field above the heart, which results in the lowering the blood pressure, or to the variation in tissue strain-based of the position assumed throughout the surgical procedure [31–34]. However, other studies have documented no differences in terms of blood loss or transfusion frequency for either of the two previously mentioned positions during primary THA. Consequently, the objective of the research was to establish the influence of patient positioning on transfusion frequency and intraoperative blood loss. Results show that the positioning of the patient with femoral neck fractures during the surgical procedure did not cause any differences in the two analyzed parameters, namely, blood loss and transfusion rates [35]. This suggests that, regardless of the approach used by the surgeon, a greater amount of blood is lost due to the fracture itself and the subsequent trauma of the superficial soft tissue [36–39].

9 Treatment of Chronic Hip Pain via Radiofrequency Ablation

The hip joint presents a variety of intra- and extra-articular components that could eventually lead to instances of acute pain, including nerves, ligaments, tendons, and cartilaginous connective tissue [40]. Chronic pain of the hip joint is one of the symptoms correlated to osteoarthritis, rheumatoid arthritis, and osteonecrosis, as well as one of the potential side effects of hip arthroplasty, and ultimately leads to severe operational constraints [41]. This condition is frequently treated via conservative methods, which comprehend physical therapy and administration of nonsteroidal medications to reduce inflammation. Moreover, when these methods fail in the reduction of the pain, other interventions such as local analgesic or corticosteroid injections into the synovial cavity of the affected joint are likely to be pursued, alongside revision surgery or reintervention, which could instead constitute a permanent solution for the treatment of chronic pain.

Occasionally, total hip arthroplasty is not considered as a viable option because of patients' predilections or due to the presence of critical comorbidities and, in some instances, patients subjected to THA display incessant pain without any indications of malfunction in the implanted prosthesis or presence of structural anomalies that could be potentially addressed. Especially in these cases, surgical denervation of the hip joint via radiofrequency ablation (RFA) is considered to ultimately reduce the severe pain experienced by patients [42, 43]. This technique consists of the application of an electrical current to a designated area innervated by nerve tissue to ultimately block the transmission of impulses correlated to pain.

The hip is primarily innervated by branches of the femoral nerve (FN), obturator nerve (ON), and accessory obturator nerve (AON), alongside superior and inferior gluteal nerve, sciatic nerve (SN), and nerve to the quadratus femoris (NQF) [44]. To facilitate the identification of the nerves innervating the anterior capsule of the joint, the latter has been subdivided into four quadrants, namely, the superolateral, the inferolateral, the superomedial, and inferomedial [45]. Branches of the femoral nerve extensively innervate the superolateral, inferolateral, and superomedial quadrants [46], whereas the inferomedial as well as the superomedial quadrants are innervated by branches of the obturator and accessory obturator nerves [45]. As per the posterior capsule of the hip joint, previously collected evidence indicates innervation of the posteromedial quadrant by branches of the NQF, whereas innervation of the posterolateral quadrant is attained by the superior gluteal nerve and potentially the nerve to piriformis [46, 47].

A total of 113 patients were included in the review, 89 of which suffered from osteoarthritis and 15 from avascular necrosis. Additionally, four experienced severe pain following total hip arthroplasty, one presented a dislocation/fracture following the surgical procedure, one presented a dislocation/fracture not correlated to THA, and three exhibited metastases.

Among the studies included in the review, two did not employ prognostic blocks prior to the performance of radiofrequency ablation [51, 53], whereas others utilized blocks targeting intra-articular or articular branches of the nerves innervating the area of chronic pain, without specifying the dosage administered for the procedure or the criteria indicating qualification for subsequent RFA [50]. Additionally, one of the reviewed studies did not specifically discuss the positive outcomes following the block of the articular branches of the FN and ON with a dose of 1 ml of 0.25% bupivacaine [54]. Other studies employed a relatively high dosage of ropivacaine—5 to 7 ml—to perform blockage of the ON and FN, classifying the case as positive if the pain experienced by the patients decreased instantly [56], whereas further studies used two doses of 2 ml of 0.5% bupivacaine to perform blockage of both the FN and ON, ultimately qualifying for RFA only in instances in which the reduction of pain amounted to more than 50% for each of the two performed blocks [52]. A single study performed RFA regardless of the negative outcomes resulting from nerve blocks [55].

All the analyzed studies employed fluoroscopic guidance to aid in the recognition of anatomical landmarks to ultimately target the ON; in addition, the FN was simultaneously approached in most research articles. The most frequently used technique for performing RFA consisted in targeting the anterolateral aspect of the extra-articular joint—using the anterior inferior iliac spine as the anatomical landmark—to successfully access the area innervated by the femoral articular branches; in addition, the anteromedial quadrant was targeted at the incisura acetabuli when approaching the obturator articular branches.

A total of nine studies showed a substantial reduction in the pain scores—ranging from 30% to 80%—reported by the patients during various follow-ups performed from 3 months up to 3 years postoperatively; instead, other studies indicated a relevant diminution of pain up to 6 months following radiofrequency ablation [48–51, 55, 56]. Six studies reported positive outcomes regarding decreased pain at follow-ups performed over 6 months after the procedure [48, 50–52, 57], and one study reported decreased pain lasting up to 36 months postoperatively.

In conclusion, radiofrequency ablation could be used as an alternative option to decrease the chronic pain in patients that are unable or unwilling to undergo THA; nonetheless, further studies should be conducted to ultimately corroborate the safety and effectiveness of the procedure [58].

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Preexisting Conditions Leading to Total Hip Arthroplasty

Abstract There are a variety of conditions that lead to the requirement of total hip arthroplasty (THA), which is performed to ultimately achieve the reduction of the perceived pain and the subsequent improvement of the range of motion of the affected individuals. The following article analyzes some of the aforementioned conditions, giving a thorough examination of each disease from a biological perspective, and providing data regarding the outcomes of the surgical procedures on the patients. The analyzed conditions we cover throughout this work include sickle cell disease, hereditary multiple exostosis (HME), lumbar spinal disorders, developmental hip dysplasia (DDH), renal transplant and hemodialysis, osteoarthritis (OA), and human immunodeficiency virus (HIV).

1 Introduction

Total hip arthroplasty constitutes a suitable solution for the treatment of conditions that include but are not limited to osteoarthritis of the hip joint. In fact, there are a wide variety of conditions that would significantly benefit from the performance of the orthopedic procedure, particularly in terms of pain relief, and increased functionality. In this article, we review the literature to cover some of the aforementioned conditions, providing a thorough examination of the causes leading to the development of each disease, and some of the reasons for the performance of THA to be beneficial for the affected individuals. Such conditions include sickle cell disease, hereditary multiple exostosis, lumbar spinal disorder, developmental hip dysplasia, end-stage renal failure leading to renal transplant and hemodialysis, and human immunodeficiency virus.

E. Tokgöz, *Total Hip Arthroplasty*, https://doi.org/10.1007/978-3-031-08927-5_2

2 Sickle Cell Disease

Sickle cell disease is a recessive disorder derived from the inheritance of hemoglobin S and caused by a point mutation on the 17th nucleotide (in which adenine replaced the thymine present in healthy individuals) on the β-globulin gene located on exon I of both homologs of chromosome 11. It results in the production of red blood cells presenting a sickle shape that eventually causes the blockage of blood vessels, ultimately leading to conditions such as ischemia or breach of the compromised tissue which substantially decrease life expectancy [2].

Avascular necrosis is one of the most common impairments caused by the disease, mainly due to the effects that the blockage of the normal blood flow has on the bone connective tissue.

The head of the femur is the most common site affected by avascular necrosis in patients diagnosed with sickle cell disease, thus impacting operational capacity and leading to osteoarthritis of the hip joint, already presenting previous abnormalities in the morphology of the metaphysis of the femur (characterized by unusually thin trabeculae and cortices) alongside low bone mineral density, which could potentially lead to discrepancies between the joint surfaces of the hip and subsequent collapse of the femoral canal [3]. Therefore, total hip replacement constitutes the most effective and safe procedure to ultimately restore the functional ability of the affected patients, as well as decrease the unbearable pain experienced by the latter [4, 5]. Figure 1 shows the magnification of the red blood cells in patients affected by sickle cell disease. The "sickle"-shaped cells are indicated by the arrows [62].

2.1 *Total Hip Replacement Surgery in Patients with Avascular Necrosis Suffering from Sickle Cell Disease*

The objective of the study undertaken in [1] was to analyze the operational outcomes in patients affected by sickle cell disease presenting avascular necrosis, either with or without congruency of the hip.

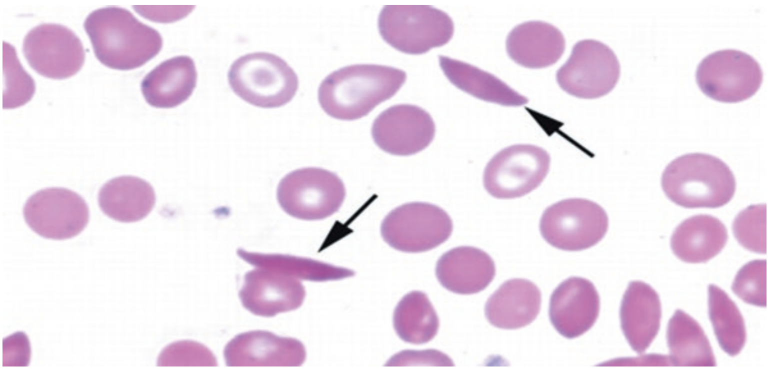

Fig. 1 Red blood cells of individuals with sickle cell disease

Throughout the study, the participants were divided into two groups. Group A consisted of 19 patients with optimal congruency of the hip but presenting an infarct area of over 30%, whereas group B comprised 17 patients presenting joint incongruency with arthritic changes. The entirety of the participants was subjected to THR through a lateral approach, performed after reaching a concentration of hemoglobin of a minimum of 10 g/dl and a hemoglobin S concentration below 30% (in order to avoid the incidence of sickle cell crisis postoperatively). The procedure was performed via an incision realized approximately 5 cm proximal to the extremity of the greater trochanter and extending for 8 cm down the femoral bone, which split the tensor fascia lata to expose the tendon of the gluteus medius [1].

After a comparison of the Harris Hip Score results, it was possible to determine that both groups showed substantial progress in their functionality, particularly group B, which presented a superior improvement throughout the first year following the surgery, potentially attributed to the more severe pain experienced before the THR procedure. The rate of survival 5 years postoperatively corresponded to 94.29%, and the observed deaths were caused by factors unrelated to THR. The incidence of superficial infections amounted to 14.2%, successfully treated with administration of antibiotics, whereas it was significantly lower for deep infections, 2.8%. Moreover, only 2.8% of the analyzed cases experienced aseptic loosening of the stem of the femur, whereas no dislocations were observed [1].

3 Hereditary Multiple Exostosis

Hereditary multiple exostosis (HME), also called denominated hereditary multiple osteochondromas, is a rare congenital disease caused by loss-of-function mutations occurring at the EXT1 and EXT2 genes, which are linked to the synthesis of heparan sulfate and result, according to several studies, in alterations at the molecular and cellular levels [6]. The disease induces the thickening and subsequent distortion of the bone during development, ultimately causing the formation of osteomata – benign formation of new bone connective tissue – around areas characterized by active osteogenesis. The bones implicated in this detrimental process are usually less developed in terms of length, thus causing deformities in the skeletal structure of the majority of the affected individuals, such as structural asymmetry in the os coxae and pectoral girdle, abnormal growth of the ulnar and radial bones leading to the subluxation of the glenohumeral articulation, and distortion of the knee caused by similar abnormalities regarding the tibia and the fibula [8]. In particular, about 25% of HME patients present an anomalous increase in the surface area of the metaphysis and valgus hip caused by deformities occurring at the neck of the femur or in the area between the trochanters, ultimately resulting in a decreased space between the lesser trochanter and the ischial tuberosity, which increases the incidence of femoroacetabular impingement and early arthritis of the joint up to 62% [9, 10]. The population affected by this disease usually presents various clinical manifestations, among which chronic pain syndrome, limited range of motion, deformities – especially regarding the limbs – and alterations of the neurovascular system [6].

Fig. 2 Radiograph of an individual with HME

No medical treatment has been currently identified for HME [6]; therefore, THA has been indicated as the most favorable alternative for patients affected by this condition and by acute osteoarthritis, to ultimately restore the range of motion and provide relief from pain. Figure 2 depicts the radiograph of a patient affected by hereditary multiple exostosis, in which acetabular dysplasia is visible in both hips [63].

3.1 Total Hip Arthroplasty in Patients Affected by Hereditary Multiple Exostosis

The retrospective review performed in [7] included seven patients affected by HME, three of which suffered from bilateral arthritis of the os coxa and femur, therefore requiring bilateral THA. The surgery was performed through the direct lateral approach in eight instances, whereas only two were performed using the posterior approach; moreover, the patients suffering from bilateral exostosis of the hip underwent two surgeries, with the second one performed 12 months after the first procedure. The components of the acetabulum were successfully press-fitted into the acetabulum for all cases, including five requiring ulterior fixation obtained through the use of two screws. The femoral components were categorized using the Mont group classification: four stems were categorized as type 1, a design called single-wedge stem, characterized by flat anterior and posterior surfaces and a widened mediolateral surface with a narrower shape in the distal part [11]. Five stems were instead categorized as type 3b, therefore presenting a conical design with splines along the longitudinal axis to aid in fixation into the compact bone of the femur, and one as type 6, presenting a posterior arch to attain optimal contact when inserted into the proximal femur [11]. The mean follow-up period for evaluation of patients was 5 years, during which the Harris Hip Score was used to estimate the operational outcomes of the procedures – which improved from a preoperative mean of 34 to an 86 postoperatively – alongside a meticulous examination of the results to determine the incidence of joint infections following implantation of the prosthesis, fractures of the femur, and loosening or dislocation of the prosthesis, none of which were ultimately reported [7].

Analysis of the results indicates that the choice of the cup does not constitute a crucial issue, as the structure of the acetabulum is generally maintained. However, accurate placement and stable fixation are achieved when using press-fit cups with a hemispheric design that allows for the insertion of screws. With regard to the femoral components, type 1 and 3b designs are used for femurs presenting exostosis around the circumference of the neck, valgus neck-shaft angle, and wider neck diameter, mainly because of the straight prosthetic structure that allows for optimal meta-diaphyseal fixation. Instead, type 6 designs are more used for cases of pedicled exostosis, in which distortions are not as severe and the head and neck of the femur are not altered [7].

4 Lumbar Spinal Disorders

Osteoarthritis (OA) of the hip and pain in the spinal region frequently coexist. The alterations to which the lumbar region of the spinal cord is subjected frequently lead to severe chronic pain, which could potentially spread to the lower limbs. Therefore, when OA and lumbar spinal disorders (LSDs) occur concomitantly, it becomes more complex to establish the main source of pain in the patients [13]. However, THA has shown positive outcomes in terms of improvement of the pain in the lumbar region in patients already affected by hip osteoarthritis.

Prior to the procedure, the incidence of lower back pain (LBP) ranges from 21.2% to 60.4% [14–16], improving in about 60% of the cases in the postoperative period [15–18]. Nonetheless, relatively worse results have been indicated when THA was performed on patients with coexisting OA of the hip and LSD – compared to the ones not presenting any spinal disorders [13, 19] – and in patients that did not experience any improvements in the perceived pain in their lumbar region [17, 18].

4.1 Low Back Pain Improvement Using Preoperative Techniques After Performing THA: Research in Japan

The goal of the study conducted in [12] was to identify the percentage of patients experiencing improvements in their LBP after undergoing THA and to determine the preoperative spinal factors leading to such improvements.

A total of 318 primary procedures were evaluated, and the LBP was determined preoperatively via the visual analogue scale (VAS), with a score ranging from 0, indicating no pain, to 10, indicating maximum pain. In addition, the patients were asked to complete the Harris Hip Score (HHS), Oxford Hip Score (OHS), and University of California, Los Angeles (UCLA) activity scores within 1 month prior and 1 year following the surgery.

The study under analysis only included patients who received a score of 2 or higher in the preoperative VAS – ultimately involving 151 patients – which indicated the minimal clinically important difference (MCID) for lower back pain and allowed for the subsequent division of the included patients into two groups. The LBP-improved cohort was characterized by patients presenting an improvement higher than 2 points in the VAS score collected 1 year after the surgical procedure or improving from a preoperative score of 2 to a score of 0. The LBP-continued group was instead composed of patients characterized by an improvement in the VAS score of 2 or lower.

Radiographs of the spine were also analyzed with the patients standing in a relaxed position and looking in the forward direction. The parameters regarding the spine were evaluated prior to the surgical procedure. Additionally, the coronal parameters were also examined, including the Cobb angle, obliquity of the pelvis – hence the angle formed between the line joining the superior bilateral portion of the ilium and the horizontal line – and the distance separating the C7 plumb line, and the vertical line located in the central sacral area. Sagittal parameters were analyzed, including the anterior pelvic plane (APP) angle – defined as the angle between the vertical line and the plane passing through the bilateral anterior superior iliac spines and the pubic symphysis, which yielded a positive value in case the APP was rotated more forward than the vertical line – the pelvic incidence (PI), the pelvic tilt (PT), the sacral slope (SS), thoracic kyphosis, sagittal vertical axis (SVA), and lumbar lordosis (LL), alongside leg length discrepancy (LLD) [12].

The surgeries were performed via the transgluteal approach, with or without the mini-trochanteric osteotomy of the anterior section of the insertion of the gluteus medius muscle. This technique provided comprehensive visibility of the acetabulum, thus allowing for more precise positioning and orientation of the prosthetic implant, as well as increased stability for the prevention of dislocation events; however, it has been associated with increased incidence of temporary gait disablement because of the degradation of the abductor mechanism of the hip joint [20].

A total of 119 hybrid, 1 cemented, 26 cementless, 1 reverse hybrid, and 4 augmented plate and cemented implants were used throughout the procedures. Instead, the bearing surfaces employed were metal femoral head on cross-linked polyethylene in 101 instances, and ceramic head on cross-linked polyethylene in 50 cases.

The analysis of the data gathered postoperatively indicated the 62.9% of patients' categorization in the LBP-improved cohort later on had a significantly lower mean value of 4.4 for the Cobb angle when compared to the LBP-continued cohort that had a mean value of 7.2. Additionally, the LBP-continued cohort demonstrated significant sagittal spinal imbalances postoperatively, especially regarding the APP angle, which corresponded to -6.0 ± 10.3, compared to the lower one indicated for the LBP-improved group, −1.8 ± 8.1, thus indicating an increased anterior rotation of the pelvis in the latter [12].

The results obtained for the VAS administered postoperatively, as well as the HHS, OHS, and UCLA scores, showed significantly worse outcomes for the LBP-continued group. In fact, the average score indicated for the VAS was 5.5, compared to the 0 obtained in the LBP-improved cohort. The average result from the HHS was 7.7 points higher in the LBP-improved group, which also displayed a higher average – by 5 points – in the OHS. The UCLA activity scores yielded similar outcomes, ranging from 5 to 6 in the LBP-improved group and from 3 to 6 in the LBP-continued one [12].

The factors that could have led to an improvement in the lower back pain experienced by the patients 1 year after the THA procedure were a low Cobb angle, as well as a high APP angle obtained preoperatively. Instead, factors such as a higher Cobb angle and sagittal spinal imbalances were correlated to constant LBP [12].

5 Developmental Hip Dysplasia

Reconstructive surgeons face many challenges when presented with the demanding procedure of hip joint reconstruction in patients affected with developmental hip dysplasia (DDH) [23]. This developmental condition is caused by mutations occurring at the WISP3 gene [21] and comprises a spectrum of progressive modifications to the femur and acetabulum, which consist in the complete distortion of the bone morphology compared to the normal rapport between femoral head and acetabulum and results in fractures, dislocation, neurovascular injuries, loosening of implants, infections, and impaired functional outcomes. THA surgeries in these patients' results are extremely challenging and characterized by high complication rates compared to cases relative to primary osteoarthrosis, primarily because of the young age, degree of activity performed, and lack of pronounced degenerative alterations of the hips of the patients [23]. The pattern of abnormalities in dysplastic hips is characterized by a shallow acetabulum on the pelvic side, and by a small femoral head with an excessively anteverted neck on the femoral side, which lead to a reduced region of contact between the two articulating bones and therefore resulting in the transmission of a significant stress onto a reduced surface area, ultimately causing articular modifications [23]. Figure 3 depicts various radiographs that illustrate the detrimental effect of DDH on the hip of the individuals affected by this condition. Figure 3a shows the hip of a 13-year-old patient when the disease was first diagnosed. Figure 3b depicts the conditions of severe osteoarthritis of the hip of the same patient at 32 years old, which necessitated surgical intervention (THA) 2 years later, as shown in Fig. 3c. Figure 3d depicts signs of aseptic loosening of the acetabular cup after the primary THA procedure, thus requiring revision surgery. Finally, Fig. 3e illustrates the conditions of the newly implanted prosthesis after revision THA [64].

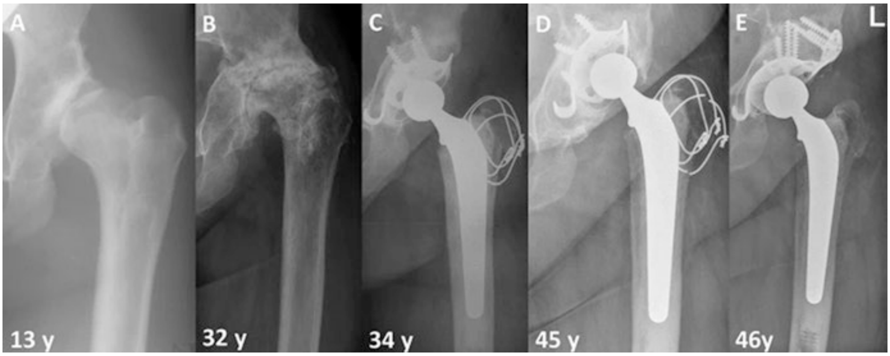

Fig. 3 (**a**) Initial diagnosis of DDH, (**b**) advancement to a severe state of osteoarthritis, (**c**) THA surgery, (**d**) evidence of aseptic loosening of the cup after primary THA, (**e**) implant conditions after revision surgery

5.1 Developmental Hip Dysplasia Requiring Total Hip Replacement

The data gathered in [22] shows that the most suitable acetabular components for this complicated THA surgery are uncemented – either with or without augmentation of the surface area of the bone – which are now extensively used in moderately dysplastic hips as they present significantly low revision rates in both mid- and long-term follow-ups. Instead, cemented acetabular components seem to have a greater percentage of revision rates due to socket loosening or graft collapse, alongside decreased survival rates [24, 25]. In contrast, the use of cemented stems generated better results on the femoral side, whereas the use of proximally fit uncemented component appears to be particularly complicated in DDH patients due to deformities, which often require the addition of modular elements or the execution of osteotomy in an attempt to achieve the ideal fit [30].

Good results were also observed in DDH patients when the hip joint center was restored successfully – via radiographs performed before the procedure and intraoperative image intensifier – even through the use of a small cup characterized by a slender polyethylene liner [26]. However, problems with this specific approach have been encountered in severe cases of dislocation during the restoration of the center of rotation in THA, as the positioning of the anatomical socket might increase the difficulty of hip reduction and further increase the risk of nerve-related injuries [27–30].

Moreover, the greater flexibility in the rectification of rotational deformities and the possibility to preserve the abductor mechanism in femoral shortening via proximal osteotomy and greater trochanter distal advancement is juxtaposed with substantial complications.

In summary, THA in DDH can be adequately addressed with a uniquely designed implant, appropriate osteotomy procedures, and bone grafts, alongside precise placement of cup that allows for reconstruction of the abductor muscles' lever arm and normal hip center, producing better results in terms of biomechanics. Despite the poorer outcomes reported for THA in DDH patients compared to the same procedures in patients not displaying any previous conditions, current evidence indicates a tendency of improving outcomes for pain relief, return to daily activities, functional improvement, and reduction of complication rates [22].

6 Renal Transplant and Hemodialysis

Renal transplant is by far the most widespread solid transplant procedure for patients with end-stage renal failure (ESRF) [36], and its positive outcomes rely on the usage of corticosteroids and immunosuppressors to avoid rejection of the newly implanted organ. However, as a consequence of the low number of donors, the number of patients receiving hemodialysis is progressively growing, and the consequences arising from this procedure, including amyloid deposition around the joint – whose major constituent was determined to be β_2-microglobulin fibrils – or renal osteodystrophy, also affect the hip joint in the long run [34, 35], causing complications such as avascular necrosis, especially concerning the head of the femur [32, 33], ultimately addressed with THA.

Avascular necrosis (AVN) is generally correlated to unusually high lipid levels, which lead to the formation of microemboli and structural alterations within the cells of the endothelial layer of the integument causing the loss of proper vein function of the legs, alongside a more elevated intraosseous strain and osteonecrosis. The administration of high dosages of immunosuppressants seems to constitute one of the primary agents in the development of AVN, and it is therefore suggested to maintain the daily dosage to below 20 mg, as results indicate a risk of avascular necrosis amounting to less than 3% [36].

6.1 Total Hip Arthroplasty Outcomes on Patients with Hemodialysis and Previous Renal Transplant

THA procedures on patients with previous renal transplants or hemodialysis have been analyzed, reporting the data gathered throughout the research [32]. Results show that the comprehensive revision rate for patients previously subjected to kidney transplant corresponds to 16% at 8 years following the procedure, whereas it is slightly lower for hemodialysis patients, with a percentage of 15.7% at a mean of 7 years after primary THA [31], data that could be correlated to the migration of β_2-microglobulin into the interface between bone and implant, thus contributing to early loosening of the latter [32].

Moreover, the use of uncemented implants was reported to have a substantially lower rate of revision surgeries due to dislocation or aseptic loosening for both the renal transplant (RT) group and the hemodialysis (HD) group, but the rate of deep infection calculated for end-stage renal failure patients subjected to hemodialysis was significantly higher – 10.8% – than the one obtained for the RT group, 2.1% [31]. Instead, the risk of aseptic loosening in cemented implants was reported to be significantly higher (33.3%) [31] due to the interface between bone and cement, which suppressed the formation of the bone and resulted in resorption [36] – formally described as the destruction of the bone matrix following the release of proteolytic enzymes and hydrochloric acid by osteoclasts.

Overall, THA performed through a cementless technique is considered to be the most effective alternative for patients who had been subjected to hemodialysis for an extended period of time, as data indicate a less severe stage of bone atrophy and the lack of development of stress shielding due to ingrown fixation compared to cemented THA [32].

7 Osteoarthritis

Osteoarthritis (OA) is the most widespread type of arthritis [37], and it was considered the 11th agent contributing to disability in 2015 [39]. This condition provokes severe pain during or after movements, joint stiffness, decreased flexibility and range of motion, as well as swelling [37], and it mainly affects the joints subjected to significant mechanical stress – such as the hip and the knee – causing structural changes in the hyaline articular cartilage, capsule, ultimately leading to destruction and failure of synovial joint [40]. Some of the risk factors correlated to this condition include age, female sex, deformities of the bones, and particular metabolic disorders. Additionally, another factor that increases the likelihood of developing OA is obesity [37] that is covered in the following paragraph. Figure 4a shows the radiograph of a hip in the initial stage of osteoarthritis, whereas Fig. 4b depicts the rapid progression of the disease and the detrimental effects on the hip of the patient [65].

7.1 Impact of Weight Loss in Osteoarthritic Patients upon Total Hip and Knee Replacement

In patients affected by OA, the structural composition of cartilage is subjected to several alterations, which cause an ongoing depletion of its integrity and consequently increasing its vulnerability to external stresses [38]. In the early stages of osteoarthritis, only the surface of the articular cartilage is subjected to erosion; however, this phenomenon rapidly reaches deeper areas of the bone, which then leads to an increase in the surface of the calcified cartilage zone. Moreover, in an attempt of contrasting this inevitable erosion process, the chondrocytes present within the cartilage increase their synthetic endeavor, ultimately creating products leading to the

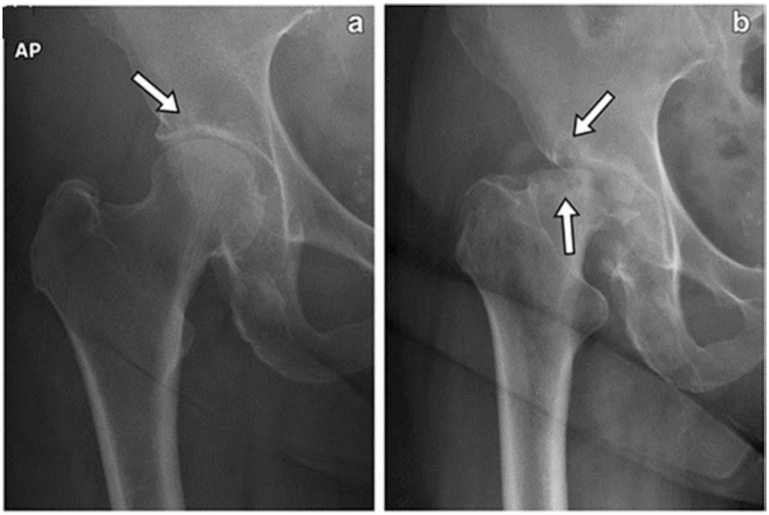

Fig. 4 (**a**) Initial stage of osteoarthritis, (**b**) progressive disruption of the hip joint

degradation of the matrix, alongside proinflammatory mediators [40]. At this point in time, there are no authorized pharmacotherapies that have been proven to successfully prevent or cease the advancement of OA; however, several factors have been correlated to increase risks of developing the disease. Obesity is one of the main factors that provoke the development of OA [41], as results have indicated an increase of 4.6% in the probability of developing such condition compared to people with a healthy weight [42].

Based on these findings, weight loss constitutes one of the main recommendations for OA management [43–47]. This conclusion is backed up by studies indicating that patients experiencing a weight loss of over 7.5% compared to their initial weight displayed inferior risks of TKR. On the other hand, no significant differences were found in terms of increased risk of THR for OA patients experiencing weight loss of >7.5%; however, the risks significantly increased when patients experienced a weight gain of more than 5% [38]. These differences might be attributable to the nature of the joints under analysis. The knee is, in fact, a hinge joint, and changes in mechanical stress on a misaligned knee joint are significantly amplified due to the reduced surface area they act upon [48]. Instead, the hip joint is a ball-and-socket joint, and the greater surface area of the latter would explain the lesser sensitivity to changes in physical force as compared to the knee [38].

8 Human Immunodeficiency Virus

Human immunodeficiency virus (HIV) is a virus that targets the immune system, and, if not treated, it could culminate in acquired immunodeficiency syndrome (AIDS) [49]. The cure for this disease is yet to be discovered; however, because of the development of techniques aimed at its prevention, detection, and management, HIV is now considered more of a chronic disorder, thus allowing the affected population to carry on with their lives without major complications.

As the disorder targets and impairs the immune system of the affected individuals, the latter progressively become immunodeficient, therefore increasing their vulnerability against a wide variety of infections, as well as some kinds of cancer that healthy people are able to fight against [49].

The incidence of hip diseases associated with HIV infection is particularly common, therefore constituting a major issue particularly in South African countries, where HIV is exceptionally widespread. HIV-positive patients are more prone to the development of avascular necrosis of the hip and head of the femur, caused by the reduced mineral density of their bone connective tissue, which ultimately decreases the median age of the affected individuals requiring THA. Despite the success attributed to THA for the treatment of hip diseases, the procedure could potentially lead to severe complications in patients affected by HIV, including possible infection of the joint following the implantation of the prosthesis [51–53].

8.1 HIV Infection and Periprosthetic Joint Infection Correlation in Young Adults upon THA

The main goal of the study conducted in [50] was to gather the outcomes following THA in HIV-positive and HIV-negative patients, to perform a comparison of the incidence of periprosthetic joint infection (PJI) in both groups, alongside the possible correlation between HIV infection and venous thromboembolic events (VTE), revision surgery, and reintervention.

In total, 290 cases in 213 patients were comprised in the conducted analysis, with a mean age of 43 years – ranging from 26 to 54 years. The main factors leading to the performance of THA were avascular necrosis of the hip and femoral head in 78% of the cases, and osteoarthritis in the remaining 22%. The number of HIV-positive patients included in the study amounted to 180, characterized by a mean CD4 count – a value that calculates the functionality of the patient's immune system – of 520 cells/mm^3 [50].

Before the procedure, all patients were subjected to medical assessments – regardless of their HIV status – which included standard AP, lateral X-rays, blood examination, and collection of urine. For the HIV-positive group, the CD4 count was additionally attained.

The surgical procedure was later performed in all the patients, including the six presenting a CD4 count inferior to 350 cells/mm^3, mainly because of the grave symptoms displayed, which resulted in serious incapacitation. The prosthesis chosen for the surgeries was an uncemented Corail®/Pinnacle System, and, following its installation, the patients were administered intravenously with three doses of prophylactic antibiotics. Subsequently, the therapy aimed at the prevention of thrombosis was commenced 12 h after the procedure, and consisted of 40 mg of enoxaparin supplied daily, which was then substituted with 10 mg of rivaroxaban – administered daily – 2 days after the procedure, sustained until 14 days postoperatively.

The obtained results showed a total of six cases of superficial wound infection after the surgery – only one of which was recorded in an HIV-positive patient – and three instances of infection of the joint postoperatively, two of which were observed in HIV-positive patients. One of the patients pertaining to the HIV-positive cohort perished due to pulmonary embolism; nonetheless, no significant difference regarding the incidence of venous thromboembolic events was observed between the two analyzed groups, which corresponded to 4% for the HIV-positive group and 6% for the HIV-negative group. The radiological assessments performed during the follow-up procedure displayed no evidence of subsidence or loosening of the implant, and no dislocations were observed during the follow-up period. Additionally, the outcomes reported by the patients, obtained via the Merle d'Aubigné Hip Score 6 months following the surgery, were analogous for both groups ($p = 0.154$) [50].

In conclusion, no differences were observed regarding the incidence of PJI, VTE, aseptic loosening of the implant, and patient-reported outcomes – obtained at 6 months postoperatively – as well as reintervention, mortality, or revision rates between the two groups at a mean 4-year follow-up [50].

8.2 *HIV-Positive Patients' THA Yielding Positive Functional Outcomes and Low Infection Rates*

The incidence of prosthetic joint infections (PJI) has been constantly increasing despite the innovations and the improvements made to the techniques used for surgery, thus consequently leading to an increase in the requirement for revision surgeries for the treatment of such infections [55]. The HIV status of the patient is considered a substantial risk factor for PJI, alongside other factors including the body mass index and diabetic control [56]. The development of highly active antiretroviral therapy (HAART) has allowed for a more cautious management of HIV, which has now become a chronic condition rather than a fatal diagnosis. However, HIV patients treated with HAART are at increased risk of developing avascular necrosis (AVN) of the head of the femur, as the reported incidence is greater by a factor of 45–100 compared to the rest of the population [57, 58], subsequently augmenting the demand for THA.

The study performed in [54] aimed at evaluating the short- and medium-term results of non-hemophiliac HIV-positive patients subjected to THA in a sub-Saharan hospital, alongside examining patient-reported outcomes and determining the factors leading to poor outcomes and infections. The review included 87 patients that had been subjected to THA between 2010 and 2018, with a minimum follow-up period of 24 months. An examination of the CD4+ count and viral load (VL) was performed to ascertain the status of their immune system, and the surgery was initiated in patients presenting a preoperative CD4+ value over 250 cells/mm^3 and, if that threshold was not reached, the procedure was postponed by 6 months. The Harris Hip Score (HHS) and Oxford Hip Score (OHS) were employed to assess the preoperative status of the patient and postoperative outcomes related to the surgery, and the condition affecting the hip was evaluated via standard radiographic techniques, and later subdivided into HIV related – if determined to be generated by HIV or a detrimental consequence of the HAART – and non-HIV related, in the case of osteoarthritis, protrusion of the acetabulum, and inflammatory arthritis.

The THA surgeries were performed via an altered anterolateral approach, and prophylactic antibiotics – consisting of cefazolin or clindamycin in case of allergies to penicillin – were administered 30 min prior and 24 h after the procedure [54]. Moreover, intravenous tranexamic acid was administered 30–60 minutes prior to the incision.

After the procedure, symptomatic patients received transfusion if the hemoglobin levels were below 8g/dL or 10g/dL, and, after discharge, low-molecular-weight heparin was prescribed for a total of 4 weeks to prevent the formation of blood clots [54].

The complications occurring after the surgery were categorized as early, if occurring before the fourth week, and late, if occurring after the fourth week, and were classified using the Clavien-Dindo-Sink Classification, which uses a grading scale of 5 points depending on the type of treatment needed for a complication [59–61]. The patients were then subjected to systematic follow-ups at 6 weeks, 6 months, 1 year, and then annually, which included the performance of a radiographic examination. Additionally, CD4+ count and HIV viral load were assessed at 6 weeks and then annually.

Out of the 87 patients included in the study, 15 were subjected to bilateral staged THA. The average age was 58.34 years, the average body mass index was 31.56 kg/m^2, the mean value indicated for CD4+ count was 569 cells/mm^3 (ranging from 51 to 1481), and the average VL was <40 copies/mL. Before the procedure, 82 patients were subjected to HAART for an average of 4.7 years, whereas the remaining 5 were not subjected to such treatment before or after the surgery and presented a mean CD4+ value of 658 cells/mm^3 and of <40 copies/mL for the VL.

Avascular necrosis of the femoral head was one of the main factors leading to the THA procedure, observed in 71 patients (69.6%), followed by primary osteoarthritis, detected in 16 (15.7%). Other conditions were instead less frequent and included fractures of the femoral neck (7.8%), inflammatory conditions (2.9%), tuberculosis of the hip (0.98%), hip ankylosis (0.98%), chondrolysis (0.98%), and protrusion of the acetabulum (0.98%) [54].

Fifty-seven patients were subjected to the implantation of ceramic-on-ceramic bearing coupling, 26 to metal-on-metal polyethylene, and 19 to ceramic on polyethylene, and both uncemented and hybrid THAs were executed with DePuy Synthes CORAIL Pinnacle prosthetic implants [54].

The average length of stay was 6.4 days, and the mean size of the femur observed postoperatively was 9. The mean follow-up period was 81.24 months, during which two deaths, unrelated to the procedure, were recorded; moreover, six more patients failed to attend the periodic follow-ups. The mean CD4+ count and VL evaluated during the last follow-up were 621 cells/mm^3 and <40 copies/mL, respectively [54].

In terms of functional outcomes, all patients showed significant improvement in their HHS and OHS, going from a preoperative mean value of 32 for the HHS and 23.62 for the OHS to an 81.51 and 43.43 recorded after the procedure. Additionally, the patients also reported a substantial decrease in their pain, based on the mean improvement of 8.6 on the VAS, and the overall satisfaction rate amounted to 91.4% [54].

After the procedure, the incidence of complications corresponded to 10.78%, with a total of three medical complications and eight related to the surgery. Out of these 11 complications, 4 were categorized as early, whereas 7 were classified as late, and the readmission rates were 3.92% within the first month, and 6.86% from 60 to 90 days postoperatively, whereas no readmissions were recorded in the period ranging from 30 to 60 days. Six PJIs (5.88%) – including three recently diagnosed patients that had not begun HAART – were identified and later verified by needle aspiration, one of which occurred at the site of surgery, whereas five were deep infections. Additionally, the mean VL for the patients experiencing PJIs was lower-than-detectable, and the mean CD4+ count was 523 cells/mm^3 [54].

The THA was required for HIV-related causes in 78.4% of the cases, whereas it was non-HIV related in the remaining 21.6%; moreover, the incidence of complications was 7.5% for patients undergoing THA due to HIV-related causes, and 22.72% when the procedure was required for non-HIV-related motives. No correlation was found between the preoperative value indicated for CD4+ count and VL and the complications or results of the surgical procedure, as 8 out of the 11 patients who experienced complications had a CD4+ count equal or greater than 350 cells/mm^3, and 5 out of the 6 patients that experienced septic complications had a CD4+ count of ≥350 cells/mm^3 [54].

In summary, a substantial risk factor for the development of PJIs is the noncompliance or delayed commencement of HAART, whereas factors such as CD4+ count and VL are not correlated with worse clinical results or greater incidence of complications. Additionally, a substantial increase in functional outcomes can be achieved after THA, which can be safely executed in patients presenting HIV and undergoing HAART [54].

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Surgical Approach Comparisons in Total Hip Arthroplasty

Abstract This article comprises a variety of comparisons between the several approaches employed for total hip arthroplasty (THA), highlighting both the strengths and weaknesses attributed to each approach. Moreover, it provides additional information regarding staged and simultaneous bilateral THA, as well as the most suitable methods for the treatment of femoral fractures in the elderly. Most of the comparisons included in this work provide details that juxtapose one of the most utilized surgical approaches, the DAA, with other conventional approaches and novel technique of supercapsular percutaneously assisted approach (SuperPATH). Additionally, we provide information on comparisons of the relative outcomes of conventional approaches and robotic THA, as well as an examination of the capsulectomy and capsulotomy techniques.

1 Introduction

THA procedure can be performed via a variety of approaches, each presenting specific strengths, as well as weaknesses, mainly correlated to the methodology used to access the hip joint in order to ultimately implant the prosthetic components. The most commonly used approach is the direct anterior approach, and its growing popularity is attributed to the muscle-sparing technique that characterizes it, which allows for superior cosmetic appearance, as well as inferior intraoperative blood loss, shorter hospital stay, and decreased pain perceived by the patient in the initial stages following the surgical procedure [1]. Because of the aforementioned positive outcomes correlated to the DAA, this particular approach has been repeatedly analyzed and compared to other conventional approaches (CAs), some of which are summarized throughout this work. Some of the other analyzed approaches include the SuperPATH, robotic THA, hemiarthroplasty, capsular repair, capsulectomy, and proximal femoral nail antirotation.

In patients presenting bilateral arthritis, the THA procedure can be performed in either one or two stages, thus a brief but comprehensive summary of the relative advantages and downsides correlated to the performance of staged bilateral or simultaneous bilateral THA has been included.

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2 Comparison of Minimum 2-Year Outcomes Following DAA and PA in Primary THA

The data gathered in [2] were retrospectively collected and reviewed and included patients that had undergone primary total hip replacement surgery with the senior surgeon (BGD) and had a minimum 2-year patient-recorded outcomes (PROs), in the period ranging from 2008 to 2016. The PROs employed during the follow-up process consisted of a variety of tests including the Harris Hip Score (HHS), the Forgotten Joint Score-12 (FJS-12), the visual analogue scale (VAS), and patient satisfaction. Additionally, the Veterans RAND 12-Item Health Survey (VR-12 Physical and VR-12 Mental) and Heath Survey Short (SF-12 Physical and SF-12 Mental) were used to analyze both the physical and mental state of the patients.

All the patients included in the study underwent THA through either DAA or PA. For DAA hip arthroplasties—in which acetabular reaming and cup component positioning was performed with the use of fluoroscopic guidance—a traction table was utilized to allow for the capsule to be opened in a "T" shape fashion and closed with absorbable sutures with the patient positioned in the supine position [2]. For THAs performed through posterior approach (PA), the patient was placed in the lateral position to enable the identification of external rotators and their subsequent removal for exposure while simultaneously preserving the piriformis tendon when practicable. The capsule was subsequently identified and incised in an inverted "L" shape fashion and preserved during the surgical procedure to achieve transosseous repair, which was then performed with non-absorbable sutures [3, 4] to reattach the external rotators.

All patients followed a precise postoperative rehabilitation protocol, which consisted of physical therapy and at-home care for 1–2 weeks. An additional 6–8-week long rehabilitation program was then planned to improve patients' strength and range of motion, alongside postoperative follow-up appointments consisting of radiographic evaluation at the 2-week, 3-month, and annual time points [2]. A total of 707 THAs were conducted during the length of the study, among which 470 underwent THA through the DAA and 237 through the posterior approach. Of all cases, 415 out of the 470 cases reported for DAA met the minimum 2-year follow-up, while a greater percentage was recorded for the PA, 215 out of the initial 237. A total of 16 complications were observed in the DAA group, among which 9 patients with superficial infections, 5 resolved with oral antibiotics, and the remaining 4 with irrigation and debridement. Moreover, 1 case of transient femoral nerve palsy and 2 cases of intraoperative femur fractures were observed and resolved over time. Only 3 out of the 16 previously mentioned complications led to revisions, 2 of which were relative to loosening and 1 to periprosthetic femur fracture. Regarding the PA group, a total of ten complications were recorded, among which three ulterior cases of superficial infections, all resolved with oral antibiotics, and a deep infection that required revision surgery. Furthermore, two patients experienced dislocations, which did not require an ensuing surgery following reduction under anesthesia, one patient was diagnosed with deep vein thrombosis, whereas two had sciatic nerve injury. Only one patient required revision surgery due to the loosening of the implant. According to the data gathered throughout the study, the DAA group reported remarkably better results regarding VR-12 Mental, VR-12 Physical, SF-12 Mental, and SF-12 Physical in addition to higher scores of patient satisfaction. The worse outcomes for the PA group might have been due to the potential decrease in THA stability postoperatively since, using this approach, external rotators are inevitably severed while the abductor muscles are preserved. Despite the numerous limitations of this study—among which the lesser length of the follow-up period for the PA group and the non-randomized, retrospective design chosen—it is possible to report favorable outcomes for both groups at a minimum 2-year follow-up, and achievement of superior quality of life accomplishments for the DAA group when compared with the scores registered for the same parameters in the PA group [2].

3 Direct Anterior Approach and Other Conventional THA Approach Comparisons

Total hip replacement is performed through six CAs, namely, the anterior, anterolateral, lateral transtrochanteric, lateral transgluteal, posterior, and posterolateral. Additionally, such approaches have been slightly altered for minimal invasiveness and utilization of shorter incisions to achieve complete visibility of the anatomical landmarks while sparing the underlying muscle tissues to ultimately obtain enhanced patient-reported results in terms of decreased pain, prompter rehabilitation process, and satisfaction regarding the cosmetic appearance of the site of surgery. However, not every patient undergoing THA is a good candidate for a minimally invasive procedure. In fact, patients presenting a body mass index over 30, muscular thighs, or grave deformities could not be subjected to an 8 cm incision, but the procedure could potentially be performed through a slightly reduced incision compared to the traditional one, ranging from 20 to 25 cm [6–18].

Among the several approaches previously listed, the direct anterior approach (DAA) has been described as beneficial, due to the axis followed during the incision, which dissects the internervous and intermuscular planes, therefore sparing both the sartorius and the tensor fasciae latae and leading to a decreased tissue trauma [19–21]. However, the advantages of this technique compared to other CAs are still uncertain, thus increasing the need for a more meticulous analysis of the immediate outcomes following THA performed via DAA compared to other conventional approaches to ultimately treat disorders affecting the hip, as well as fractures.

Data gathered throughout the analysis performed in [5] reported a 15.1-min longer procedure and higher values for intraoperative blood loss—amounting to 51.5 ml—in THA through DAA compared to other conventional approaches. Nonetheless, the visual analogue scale for pain was inferior by 0.8 points 1 day postoperatively, and the values obtained for Harris Hip Score were higher by 2.8

points 3 months following the procedure performed via direct anterior approach, presumably correlated to the incision length, which was 2.9 cm shorter compared to other approaches. Finally, radiological outcomes reported a 4.3° lower anteversion angle, as well as a 1.6° lower inclination angle of the acetabular cup for the DAA compared to other conventional approaches [5], therefore indicating a higher propensity in reaching an excessively flat inclination angle with respect to the optimal values indicated for the inclination of the acetabular cup and for anteversion, which range from 40° to 50° and from 10° to 25°, respectively [22].

Based on the overall results gathered throughout the study, it is possible to assess that the THA performed through direct anterior approach displayed superior short-term results compared to other conventional approaches, specifically regarding reduced postoperative pain, shorter incision, and increased results in terms of performance up to 3 months following the procedure.

4 Direct Anterior and Posterolateral THA Approaches' Comparison

The incidence of dislocation after performing THA through the DAA has been demonstrated to be particularly low; moreover, this approach is associated with a faster recovery in the early period following the procedure [24–27]. However, advocates of the posterolateral approach (PLA) primarily focus on the higher incidence of complications and early revision occurring following THA through the DAA [28–30]. Therefore, the study conducted in [23] ultimately aims at establishing the influence of each of the two aforementioned approaches for THA on the perioperative outcomes and the early results regarding the functionality of the patients. To do so, nine publications including a total of 22,698 patients were analyzed. The DAA cohort comprised 2947 patients, while the population size included in the PLA group consisted of 19,751 individuals.

The mean difference (MD) indicated for the Harris Hip Score (HHS) within 6 months after the surgical procedure was 3.82 for the DAA group, and it was substantially higher than the one indicated for the PLA cohort, showing a statistically significant difference between the two groups. In contrast, the MD indicated for the HHS after 6 months was – 0.17 for the DAA cohort, and no significant difference was recorded between the two analyzed cohorts. The MD reported for the length of hospital stay of the DAA group was – 0.5, significantly lower than the one indicated for the PLA cohort. The MD calculated for length of procedure and loss of blood for the DAA cohort were 19.73 ml and 125.19 ml, respectively, higher compared to the ones recorded for the PLA group and displaying significant differences between the two groups.

The incidence of complications was recorded in seven studies, including a total of 566 patients and revealing a greater rate in the DAA during the follow-up interval. The radiographic results regarding the position of the femoral component after the surgical procedure were analyzed in two studies, involving a total of 133 patients, and displaying an analogous proportion of neutral placement between the two groups. Five studies included, instead, information concerning the inclination angle of the acetabular cup component, which was not statistically significant between the two cohorts and indicated a MD of 0.75 for the DAA group. Furthermore, two studies included data regarding the anteversion angle of the acetabular component, which was significantly inferior for the DAA (with a MD of – 4.30) compared to the PLA group.

In summary, the DAA cohort displayed earlier recovery of their functions compared to the PLA group, despite exhibiting a greater incidence of early complications and a longer intraoperative time (increased by a mean of 19.73 min), alongside a greater volume of intraoperative blood loss, by a mean of 125.19 ml. Finally, the position of the femoral component was analogous between the two groups; however, the anteversion angle displayed in the DAA group was decreased by a mean of 4.3° [23].

5 Postoperative Complication Comparison of the Direct Anterior and the Lateral THA Approaches

Total hip arthroplasty is one of the most commonly performed surgical procedures to treat conditions including osteoarthrosis (OA), osteonecrosis of the femoral head (ONFH), and femoral neck fractures (FNFs), ultimately yielding excellent results in terms of relief from the pain and improvement of the functionality of the patients. The lateral approach (LA) also includes the anterolateral approach, also called Watson-Jones [33], and the direct lateral approach, or Hardinge [33], and has been developed to optimize intraoperative visualizations of both the proximal femur and acetabulum while simultaneously preserving the soft tissue surrounding the posterior surface of the hip joint, thus resulting in a lower incidence of dislocation, ranging between 0.43% and 0.70% [34]. However, such approach has been associated with greater early postoperative pain, heterotopic ossification, and damage to the superior gluteal nerve, alongside longer hospitalization and rehabilitation period [32].

The direct anterior approach (DAA) is considered a variation of the Smith-Peterson anterior approach and is commonly correlated to decreased postoperative pain and shorter hospitalization and rehabilitation process; however, it is associated with severe complications including femoral fractures occurring intraoperatively, lesions of the lateral femoral cutaneous nerve, and early revision [35, 36].

As a consequence, the choice regarding the appropriate surgical approach used to perform the THA procedure remains controversial; therefore, the study conducted in [31] performed a review of the applications of the DAA and LA while also focusing on the assessment of the related complications occurring postoperatively.

Thirteen articles were ultimately included in the study, analyzing a total of 24,853 hips, 9575 of which were subjected to DAA, and 15,278 to LA.

The incidence of surgical infection was reported in six studies, two of which [38, 39] indicated superficial infections, one [37] disclosed deep infections, and three [40–42] reported superficial, as well as deep infections. Overall, no statistically significant difference was indicated between the DAA (1966 hips) and LA groups (1356 hips), as the incidence of surgical site infections was 2.59% and 2.14%, respectively [31].

The postoperative dislocation rate was analyzed in six studies [37–39, 41, 43, 44] including a total of 23,028 hips, showing an incidence of 0.77% for the DAA group, and 0.18% for the LA group, thus indicating a substantially higher incidence for the DAA cohort. Four studies [37, 38, 41, 52, 53] analyzed the rate of malposition of the prosthetic component, comprising a total of 210 hips in the DAA group and 371 in the LA cohort. The obtained results indicated a significantly lower incidence for the DAA group, corresponding to 36.19%, compared to the LA cohort, 54.86%.

The rate of periprosthetic fractures was evaluated in five studies [40, 41, 44–46], which included 6953 hips in the DAA group and 9173 in the LA cohort, and reported an incidence of 1.05% and 0.41%, respectively, thus suggesting a greater rate for the DAA group.

Four articles [37, 39, 41, 44] examined the rate of prosthesis loosening for both the DAA cohort, comprising 7019 hips, and the LA group, composed of 9237. The reported results indicated a higher rate for the DAA group, 0.61%, compared to the 0.37% observed in the LA cohort.

The rate of nerve damages was analyzed in four studies [38, 40, 41, 47] and indicated a substantially higher rate for the DAA group (1478 hips), 0.95%, compared to the LA cohort (468 hips), 0%.

Only two studies [39, 41] evaluated the rate of heterotopic ossification for the DAA group, composed of 74 hips, and the LA one, composed of 102, showing no statistically significant difference between the two cohorts, mainly attributed to the small size of the analyzed sample.

The discrepancy in leg length was examined in four publications [39, 41, 42, 48], including 1661 hips in the DAA cohort and 1055 in the LA one, ultimately showing a significantly lower rate for the DAA cohort (1.87%) compared to the LA group (2.37%). The rate of Trendelenburg gait was analyzed in three articles [39, 40, 42], including a total of 416 hips in the DAA group, and 712 in the LA one, exhibiting an incidence of 1.68% and 4.78%, respectively, thus suggesting a significantly higher trend in the LA group.

The rate of reintervention was examined in six studies [39–44], ultimately displaying no significant difference as the evaluated incidence was 2.70% for the DAA group, composed of 3596 hips, and 2.11% for the LA cohort, composed of 6028.

Infections occurring at the wound site during the DAA have been associated with a variety of factors that increase its incidence, including a higher body mass index for the patients (BMI ≥35 kg/m^2) [49–51]. However, the study didn't indicate any significant differences compared to the LA approach, thus suggesting that the BMI of the included population was inferior to 35 kg/m^2.

In general, the incidence of dislocation observed in the DAA group was significantly higher compared to the LA; however, malposition of the prosthetic component was significantly lower in the DAA group, thus suggesting that the higher dislocation rates observed after the DAA are not correlated to malposition, rather to the release of the tendon and capsule surrounding the hip. The rate of fractures occurring after implantation of the prosthesis and loosening of the latter was substantially higher in the DAA group compared to the LA one, presumably due to the complexity of achieving optimal exposure for the preparation of the femur and subsequent implantation of the prosthesis. The DAA group also demonstrated a higher incidence of nerve damages compared to the LA group, whereas a lower rate of leg discrepancy was indicated for the DAA group showing that the supine position of the patient during such approach led to more precise placement of the implant and consequent control of the length of the limb. Similarly, the DAA procedure impacted the gait mechanics to a lesser extent compared to the LA, mainly because of its muscle-sparing nature that allowed for the preservation of the hip musculature, thus leading to a lower incidence of Trendelenburg gait. As per the rate of heterotopic ossification and reinterventions, no significant differences were observed between the two groups [31].

6 Direct Anterior Approach Comparison to Conventional THA Approaches Using Radiological Analysis

End-stage hip osteoarthritis (OA) is treated through THA, which is considered the most efficacious treatment and can be performed via a variety of approaches. The approach selected to perform the surgery dictates which tissues will be sectioned to reach the joint, the structures that should be avoided, and the difficulties that the surgeon will face when attempting to correctly position the implant [55, 56].

During the DAA procedure, the sartorius, rectus femoris, and iliopsoas are held in position through the use of retractors, while the tensor fasciae latae is mobilized on the opposite side, allowing for optimal exposure of the acetabulum following incision. During the PA, the gluteus maximus is split and the external rotators are detached to ultimately access the acetabulum. When performing THA through LA, the pelvis of the patient is elevated in correspondence to the anterior superior iliac spine to generate enough surface to displace the femur during exposure of the acetabular cavity [55, 63].

Among the conventional approaches previously listed, the DAA is achieving popularity [57], and its recognition is attributable to the conjecture regarding prosthesis stability and satisfaction of patients—ranging from 89% to 95%—alongside a more rapid rehabilitation period and reduced pain following surgery [58–60, 63].

The achievement of appropriate positioning of the femoral stem and acetabular cup—which will substantially minimize their component's wear—constitutes one of the major challenges during the THA procedure, as positive clinical outcomes can be achieved by the positioning of the rotation center of the hip at an inclination of 40° and an anteversion of 20° [61, 62]. Correct positioning of the prosthesis could be potentially accomplished via the use of robotic-assisted surgery or intraoperative fluoroscopy [54].

7 Variation in Short-Term Outcomes Based on the Surgical THA Approach

Surgical variations of THA are performed to improve the functionality and reduce the pain experienced by the patients in the early postoperative period [65].

The primary goal of the systematic review performed in [64] was to compare the short-term outcomes following the most frequently used THA approaches, namely, the DAA, PA, DL, and AL, up to the 12th week following the surgical procedure, further considering the minimally important clinical difference (MCID) to ultimately establish whether the observed differences were clinically important, set to 1.9 for the visual analogue scale (VAS) [66]—characterized by a score ranging from 0 to 10—and to 7–10 for the Harris Hip Score (HHS) [67], which ranged from 0 to 100. The postoperative data used for the comparison included the functionality of the patients at 6 and 12 weeks and the pain scores—calculated using the VAS and the HHS—gathered at day 1 (POD 1) and 2 (POD 2), as well as 2 and 6 weeks. The overall consumption of opioids after the procedure was also registered when available. Moreover, the incidence of complications postoperatively was recorded, including data regarding reinterventions, the occurrence of fractures during the procedure, aggravation of the wound, deep infections, as well as dislocations [64].

The DAA showed superior outcomes calculated via the HHS during the follow-up performed at the sixth week postoperatively compared to the DL and the PA; nonetheless, the results didn't reach the set range of 7–10 identified to achieve the MCID. Moreover, no statistical difference was indicated in the HSS during the follow-up procedure at the 12th week following the various surgical approaches when compared to the DAA [64].

In terms of postoperative pain, the VAS scores recorded on day 2 and after 2 weeks showed inferior results in the DAA cohort compared to DL; however, the calculated differences—corresponding to 0.9 and 1.3—didn't reach the set value of 1.7 established to achieve the MCID. The data recorded for length of hospitalization indicated a shorter timeframe following the AL approach when compared to the DAA, whereas no significant differences were observed when comparing the DL and PA to the DAA [64].

Five studies reported the overall opioid consumption of the patients, while one examined the same parameters during the follow-up performed at the second week. No significant differences were observed in the study performed by Barrel et al. [74] regarding the opioid consumption in the DAA and PA groups on the first and second day following the procedure; instead, the study performed by Taunton [68] documented a higher consumption in the PA when compared to the DAA. Similarly, a higher opioid consumption during the second-week follow-up was observed by Cheng et al. [69] in the PA compared to DAA. Lower overall consumption of opioids was additionally demonstrated in the study performed by Brismar [70] and Nistor [71] for the DAA when compared to the DL. Furthermore, Mjaaland [72] observed a lower consumption on the day of the surgical procedure for the DAA compared to the DL; however, no other differences were recorded in the data gathered for the corresponding analyses. Finally, no differences were observed in the overall postoperative consumption when comparing the AL and the DL approaches in the study performed by Martin et al. [73]. The complication rates were recorded in 19 out of the 25 analyzed studies, reporting a total of 20 reinterventions, 21 aggravations at the wound site, 24 fractures occurred during the procedure, 12 dislocations, and 8 deep infections, ultimately indicating no significant differences between the various analyzed approaches.

In summary, the analyzed data indicated no relevant differences in the early period following THA among the various approaches, as well as differences in the complication rates and pain scores; however, the data recorded for opioid consumption indicated a lower trend following the DAA [64].

8 SuperPATH

The supercapsular percutaneously assisted approach (SuperPATH) is a modification of the anterior and posterior approaches [75]. This minimally invasive procedure has been initially outlined by Stephen Murphy in 2004 and has been correlated with a variety of advantages compared to other conventional approaches. In fact, the SuperPATH approach utilizes a reduced superficial incision and doesn't foresee the dislocation of the femoral head, thus preserving the muscles and tendons, as well as the capsule, and only applying a minimal amount of stretch to the aforementioned structures. This approach only involves the release of the piriformis tendon, which is—unlike what experienced for the anterior approach, during which the piriformis tendon inevitably retracts posteriorly—then repaired in its natural position, a technique that ulteriorly decreases the dislocation rates to a 0.2—0.3% range. Figure 1a depicts the approach to the hip capsule. The incision is started at the extremity of the greater trochanter and continued proximally. The subcutaneous fat is then incised and electrocauterized, to prevent excessive bleeding, followed by incision of the gluteus maximus. The bursa of the posterior segment of the gluteus medius is incised, and the latter is then retracted anteriorly to allow the visualization of the piriformis tendon, followed by additional incision and retraction of the gluteus minimus anteriorly. Exposure of the capsule is achieved via the use of several retractors. Figure 1b shows the preparation of the capsule, which is incised in line with the superficial incision [143].

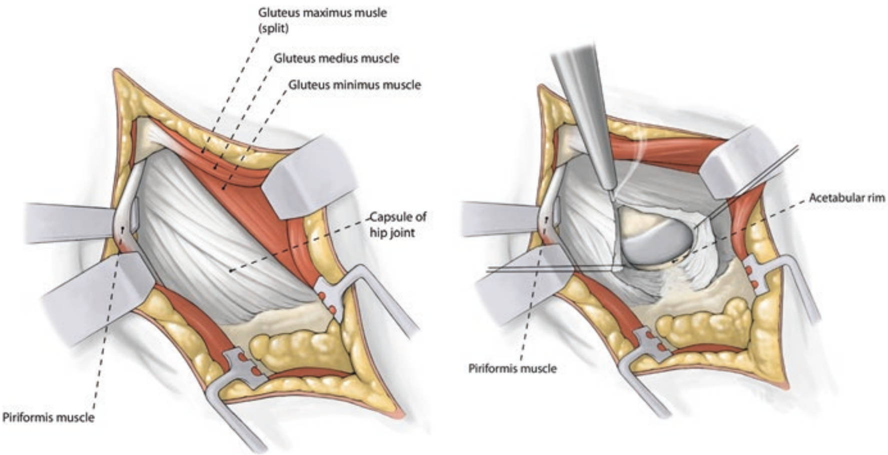

Fig. 1 (**a**) Left image shows the approach to the capsule via the SuperPATH, (**b**) right image depicts the preparation of the capsule

8.1 Short-Term Effect Comparison of Direct Anterior Approach and SuperPATH in THA

Among the various CAs, two have been outlined as minimally invasive, DAA and SuperPATH. The increasing demand regarding the performance of minimally invasive procedures originated from the dissatisfaction of previously operated patients with the cosmetic appearance of the site where surgery was executed, alongside the goal of a prompter rehabilitation process and decreased costs [77]. The results gathered in [76] have indicated the superiority in outcomes of THA SuperPATH compared to DAA, as it exhibited better results in terms of decreased operation time, length of incision, intraoperative loss of blood, and severity of pain in the initial stage following the procedure. The DAA was characterized, in fact, by a 12.8-min longer operation time compared to SuperPATH constituting a significant advantage for the latter as the prolonged time of surgery is correlated to a more elevated rate of superficial infection—augmenting by about 6% for every 10-min increase in operational time [78]—as well as perioperative complications including higher readmission rates, wound dehiscence, and kidney problems [79]. Moreover, the incision performed during the direct anterior approach was approximately 4.3 cm longer, and the intraoperative blood loss recorded was 59 ml higher than the one observed for SuperPATH, attributed to bleedings of branches of the lateral circumflex femoral artery, exposed during the DAA procedure [76]. Moreover, the DAA registered a 0.8 points higher mean pain VAS 1 day following surgery, which might be attributable to the innervation of the area subjected to the procedure, as THA through DAA is performed in an area highly innervated by branches of the cutaneous lateral femoral nerve, femoral nerve, and obturator nerve, while only branches from Th12 and ilio-hypogastric nerves are exposed while performing THA through SuperPATH. The mean HHS recorded 3 months postoperatively ranged from 85.9 to 94.6 points for the DAA, and from 72.3 to 89.6 for SuperPATH; however, no differences in HHS were observed 3, 6, and 12 months after surgery. In conclusion, the comparison of data indicated superior short-term results for THA performed through SuperPATH, but both approaches resulted equivalent in acetabular cup position and functional outcome of the surgical procedure [76].

9 Simultaneous Bilateral THA Outcomes' Performance: A Single Surgeon Performance

Patients presenting bilateral arthritis of the hip frequently undergo THA, either in one or two stages. Previous research has shown that these two procedures shared similar outcomes in terms of complications, both prior and following the surgery, and revision rates; however, the transfusion rates were significantly higher in one-stage procedures, whereas the length of hospital stay was longer, and the intraoperative blood loss and cost of the surgery were considerably higher for bilateral surgeries performed in two stages [81–85]. The previously mentioned data were obtained from studies characterized by several limitations, including a small number of participants, absence of reported post-discharge results, and integration of statistics obtained by different surgeons; therefore, the review conducted in [80] aimed at analyzing the reported outcomes of simultaneous bilateral THA performed via direct anterior approach by a single surgeon (WJH).

The patients were divided into two groups, one subjected to simultaneous bilateral THA via DAA and a second one consisting of participants undergoing staged bilateral THA through the same approach, with a mean time between the procedures of 31.5 months. The same technique was used throughout all the procedures, involving the insertion of a cementless tapered femoral stem without the use of fluoroscopy, and patients were administered with cefazolin—or an analogous antibiotic if the patient presented severe allergies—intravenously, to prevent the spread of bacteria, and with aspirin to preclude the risk of deep vein thrombosis.

Results showed a significantly shorter mean value for length of stay for the group undergoing simultaneous bilateral THA (1.8 days) compared to the one subjected to the staged bilateral procedure (2.8 days); however, the rate of transfusion of packed red blood cells amounted to 3.5% for the simultaneous bilateral cohort. Moreover, the simultaneous bilateral group displayed a percentage of 0.39% for infections at the site of surgery or following implantation of the prosthesis and formation of hematoma, and 0.77% for periprosthetic fractures, subsequent surgery, and readmissions. The negligible complication rates encountered throughout the previously analyzed study highlight the safety of the simultaneous bilateral procedure for younger patients with suitable indications, therefore presenting a lower body mass index and fewer health conditions [80].

10 Conventional and Robotic-Assisted THA Outcomes' Follow-Up Comparisons

Despite the growing success of THA, multiple complications—including aseptic loosening or malpositioning of the prosthetic component—keep on arising [87, 88]. To avoid incurring in any complications, the demand for robotic-assisted THA has been concomitantly increasing. Two robotic systems have received approval by the FDA (Food and Drug Administration) for the performance of THA: the ROBODOC, which assists specifically with installation of the acetabular component following the input of patient's information obtained through a computed tomographic scan—to generate a three-dimensional virtual design of the anatomy of the latter—as well as preparation of the femoral canal, and the Mako, which uses computed tomographic (CT)-guided navigation to develop an initial plan regarding the performance of the surgical procedure, to subsequently aid in the preparation of the acetabulum and the positioning of the cup, alongside osteotomy of the femoral head and the replication of the offset and length of the leg [86, 97]. Figure 2 shows the THA procedure performed with the Mako platform, which is one of the two robotic systems approved by the FDA [144].

Robotic THA has exhibited superior results in terms of accuracy in the placement of the implant [89, 90]; however, the related costs considerably increase compared to the one indicated for the conventional procedure. Additionally, more accurate positioning of the implant is not always an indicator of enhanced patient-reported outcome measures (PROMs). Thus, the goal of the study performed in [86] was to establish whether robotic-assisted THA generated enhanced patient-reported outcomes and decreased the incidence of dislocation and complications compared to manually conducted THA.

Analysis of seven articles including a total of 658 patients with 335 of whom underwent robotic THA while the remaining 323 were subjected to the manual

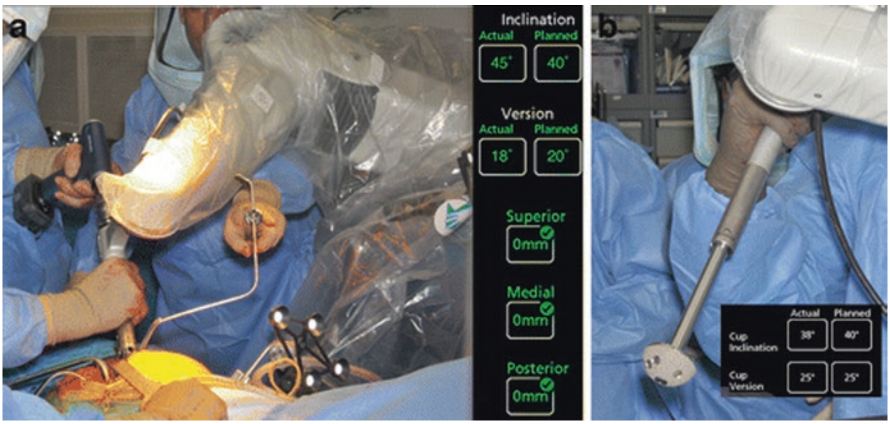

Fig. 2 THA performed with the Mako platform

surgical procedure. Thirteen different PROMs were recorded in the seven articles, mainly including the HHS [91–94, 95, 96] and the WOMAC scores [91, 92, 96]. Four of the seven studies didn't show any substantial differences between the manually performed and the robotic-assisted procedures, whereas three reported enhanced PROMs in the robotic THA group during one of the evaluations performed postoperatively [91, 93, 96]. Robotic-assisted THA resulted in more accurate positioning of the implant; however, despite this favorable report, a greater incidence of dislocations was found in the robotic-assisted group compared to the one undergoing manual THA [93–95], thus indicating that implant stability depends on a variety of factors aside from components' positioning. Moreover, data regarding operative times for robotic THA were considerably higher—107.1 ± 29.1 min—compared to the manually performed procedure, 82.4 ± 23.4 min [93].

In summary, robotic THA is currently evolving, but, according to available data extrapolated from other articles, the PROMs obtained for robotic THA are analogous to the ones obtained for manual THA, further highlighting the greater efficiency of robotic THA in terms of implant positioning which, however, does not seem to be an indicator of fewer incidence of complications or revisions [86].

11 Capsular Repair and Capsulectomy

The THA procedure could be performed via capsulectomy, consisting in the excision of the joint capsule, and then replacing with a pseudocapsule with no active neurophysiological roles, as no nerve endings are present in the recently operated area [99–108, 117], or reparation, in the case of capsulotomy, which could potentially result in increased postoperative pain and decreased range of motion (ROM) due to the reconstruction of the capsule over the previously installed prosthetic component [101, 103–105, 107–114, 117].

11.1 Comparison of Capsular Repair and Capsulectomy in THA

Dislocation constitutes one of the main complications following THA [115, 116]; however, the right approach to use to prevent such complications is still uncertain. Therefore, the systematic review conducted in [98] evaluated the various outcomes correlated to capsulectomy and capsular repair, especially regarding the incidence of dislocation, length of the procedure, and blood loss, and the results were further evaluated based on the approach used during the surgical procedure.

A total of 31 articles were included in the study, comprising 17,272 patients and 17,481 hips. The mean age of the patients at the time of the procedure was 62.6 years, and the mean follow-up period was 37.7 months. All the patients included in the study were subjected to THA, and 209 out of the 17,272 underwent bilateral THA, which consisted of the same procedure performed via the same approach on both sides. Capsular repair was performed in 7928 instances (45.4%), whereas capsulectomy took place in the remaining 9553 cases (54.5%).

The difference in blood loss was statistically significant, and the cohort subjected to capsular repair displayed a lower value, with an average of 465.2 ml, compared to the value indicated in the capsulectomy procedure, which corresponded to 709.2 ml. However, the procedure was substantially longer in the capsular repair group, with an average time of 102.5 min, compared to the capsulectomy cohort that resulted in operational time averaged to 96.08 min. Moreover, 345 dislocations were reported in the 17,481 THA surgeries analyzed, thus indicating a dislocation incidence of 1.97%. In particular, the rate of dislocation observed after the capsulectomy procedure corresponded to 3.06%, whereas the one identified for the capsular repair was significantly lower, corresponding to 0.65%.

The THA surgery was performed via the anterior approach in 2142 hips, 1718 of which were then subjected to capsular repair, whereas 424 underwent capsulectomy. The overall incidence of dislocation observed after the anterior approach was 1.3% (28 instances). More specifically, a dislocation rate of 3.7% (16/424) was observed in the capsulectomy group, while a significantly lower rate was determined for the capsular repair group, corresponding to 0.69% (12/1718).

The lateral approach was utilized on 6189 hips, 2308 of which underwent capsular repair, and 3881 of which were subjected to capsulectomy. The overall incidence of dislocation recorded for the THA procedure performed via the lateral approach was 2.86% (166 cases). In particular, the dislocation rate observed in the capsulectomy cohort was 3.89% (151/3381), and, similarly to the results observed for the anterior approach, the dislocation rate recorded for the patients subjected to capsular repair was substantially lower, corresponding to 0.64%.

The posterior approach was performed on 9150 hips, with a comprehensive incidence of dislocation of 1.65% (151 instances). 3902 hips were subjected to capsular repair through the same approach, whereas 5248 underwent capsulectomy. Again, the rate of dislocation was significantly higher in the capsulectomy cohort, with a percentage of 2.4% (126/5248), compared to the 0.64% (25/3902) found in the capsulotomy group.

In summary, the capsular repair procedure showed a significantly inferior amount of blood loss during the surgical procedure; however, it was associated with a longer operational time that could potentially constitute a disadvantage when treating elderly patients with comorbidities, as every additional minute spent in the operating room substantially increases the risk of adverse events. Capsular repair was also associated with inferior dislocation rates for all the analyzed approaches, ranging from 0.64% to 0.69%, compared to the much higher percentages observed for capsulectomies, corresponding to 3.7% after the procedure performed via the anterior approach, 3.89% after the lateral approach, and 2.4% after the posterior approach [98].

12 Fractures

The optimal treatment of extracapsular fractures to the proximal femur is an ongoing effort; however, the use of proximal femoral nail antirotation (PFNA) might constitute a viable option for the management of such fractures because of the relatively low incidence of complications compared to other techniques [118]. The PFNA device consists of a small intramedullary nail characterized by a helical blade design, which results extremely advantageous for the direct fixation of the head of the femur and the compaction of the trabecular bone, ultimately speeding up the fracture healing process [119].

Femoral neck fractures are usually treated with internal fixation in young, more active patients. In contrast, this procedure is not indicated for older patients mainly because of their slow fracture healing process requiring a longer hospital stay, which could potentially lead to ulterior complications [122, 123].

In the elderly, the more suitable procedure for the treatment of femoral fractures is hemiarthroplasty (HA), which foresees the replacement of only half of the impaired hip joint [120]. Figure 3a depicts the prosthesis used for the HA procedure, whereas Fig. 3b shows the implant used for THA surgery [145].

This procedure has several advantages compared to the THA surgery, including inferior length of surgery and decreased intraoperative blood loss [121]. During the HA procedure, the damaged femoral head is replaced with a prosthetic component that increases the stability of the femur and simultaneously restores the functionality of the hip [4]. The preparation of the femur in HA proceeds similarly to the THA surgery; in fact, the femoral canal is hollowed out prior to the insertion of the metal stem; however, in contrast to THA (in which the entire joint is replaced), only the

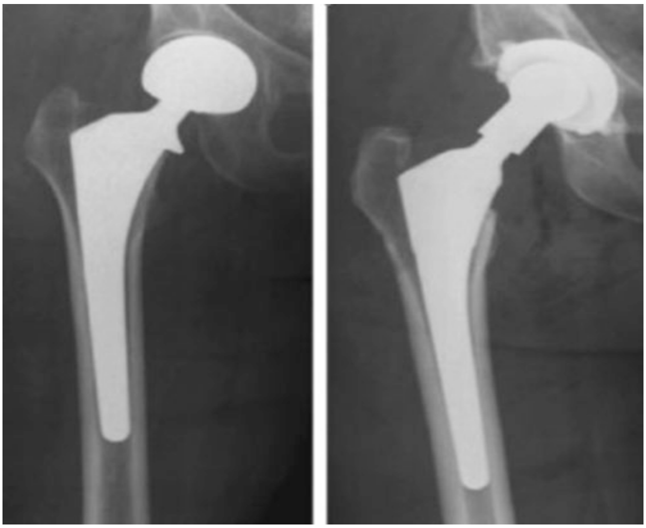

Fig. 3 (**a**) Left shows the implant used for HA, (**b**) right shows the implant used for THA

femoral head is substituted. HA has been correlated to a variety of complications, which are analogous to the THA procedure. Such complications include infection, formation of blood clots, dislocation, and loosening of the femoral stem.

What follows would be additional information on the comparison of hip replacement and PFNA for the treatment of intertrochanteric fractures, and the attempts for optimal procedure search for the treatment of femoral neck fractures in the elderly.

12.1 Hip Replacement and Proximal Femoral Nail Antirotation Procedures' Outcome Comparisons for Elderly with Intertrochanteric Fractures

Intertrochanteric fractures are particularly common among older people (95%), mainly because of the higher incidence of osteoporosis, which increases the likelihood of incurring fractures following minor traumatic events [123, 124]. The conservative treatment of the latter requires patients to remain in bed for a prolonged period of time, thus increasing the risk of experiencing serious complications, such as pneumonia, deep vein thrombosis, and infections of the urinary tract. Therefore, intertrochanteric fractures are usually treated with surgery [125, 126]—which accelerates functional recovery and increases the life quality of the patients [127]—in particular hip replacement (HR) and PFNA. Nonetheless, the choice regarding the appropriate approach to use is still being debated [128–130].

The technology involved in the performance of HR is particularly advanced, especially regarding prosthesis stability, which allows for a faster postoperative motion recovery [131, 132]. However, the procedure is significantly longer and characterized by a higher blood loss rate and a more extensive surgical incision, factors that might increase the risk of incidence of comorbidities in the elderly [133]. An alternative approach, the proximal femoral nail antirotation, was delineated based upon prior ameliorations of technologies relative to internal fixation. It presents various benefits compared to HR, including a shorter operation time, potential preservation of the head and neck of the femur, as well as good fixation effect favoring a better healing process [134]. However, internal fixations are frequently correlated to a greater risk of complications, including metal malfunction and puncture of the femoral head, alongside higher reported fatality rates (amounting to approximately 21.4%), presumably related to the longer time spent in bed after surgery, and deferral of activities involving weight load [135]. Based on these premises, HR exhibits more benefits relative to the treatment of intertrochanteric fractures in the elderly. In general, the choice of appropriate treatment for intertrochanteric fractures in the elderly should be based on a careful analysis of the patients' clinical characteristics, alongside a perioperative process of muscle strengthening to ultimately reduce intraoperative hemorrhage and avoid the incidence of ulterior complications [122].

12.2 Hemiarthroplasty and THA Procedure Comparisons for Femoral Neck Fracture Treatment

Femoral neck fractures (FNF) comprise fractures of the head of the femur up until the base of the femoral neck occurring as a result of exposure to torsion, which ultimately threatens the blood supply and limits the bone healing process [136, 137]. Such fractures are often categorized using Garden's classification, ranging from types I and II—which include stable fractures with no displacement or lesser degree of displacement—to types III and IV, which integrate unstable fractures resulting from the shifting of the fracture end, thus causing more severe damages [137–139]. Figure 4 illustrates the four different stages of Garden's classification, which is employed to categorize FNFs based on the degree of displacement [145].

In the elderly, femoral neck fractures are commonly listed as type III or IV in Garden's classification and present several downsides, such as venous thromboembolism and falling pneumonia. These fractures could be treated via either THA, which foresees the replacement of both the femoral head and the acetabulum of the hip and provides, thus, better functional results, or hemiarthroplasty, which only replaces the head of the femur, therefore presenting several benefits including decreased procedural trauma and blood loss, alongside complications such as the increased risk of elevated pain following the surgery and wear of the cartilage of the acetabulum [136]. As a result, the appropriate surgical technique to use for the treatment of FNFs is still disputed [140, 141].

As mentioned above, hemiarthroplasty presents many benefits compared to THA, including reduced trauma, shorter procedure, and inferior intraoperative loss of blood; however, it is associated with a longer hospital stay and increased risk of revision surgery, as the acetabulum is not replaced during the procedure, thus potentially leading to a higher incidence of prosthesis dislocation, deterioration of the cartilage surrounding the acetabulum, and infections derived from the sterility of the prosthesis. Moreover, hemiarthroplasty presents a significantly higher risk of contracting pneumonia and incurring in renal failure, whereas no differences with THA

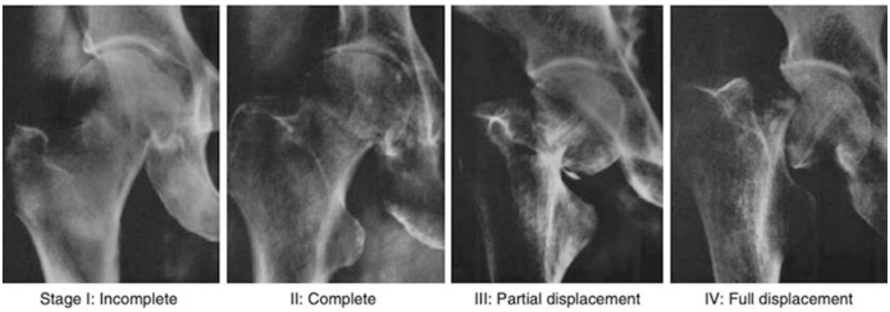

Fig. 4 Stages of Garden's classification; from left to right, the leftmost image is Stage 1 that is incomplete, while the image next to it is Stage II displaying complete phase. The third image from left is Stage III displaying partial displacement, while the rightmost image is full displacement

were identified with regard to the incidence of other complications such as myocardial infarct, venous thromboembolism, and infection [136].

13 Hemiarthroplasty and THA Procedural Differences of Elderly Orthogeriatric Patients

In order to establish the most suitable method for the treatment of femoral neck fractures (FNF), surgeons must carefully analyze a wide range of factors, including the individual necessities of the patients, as well as the presence of comorbidities and ambulatory capacity, to ultimately determine whether the patients should be subjected to hemiarthroplasty or THA. Thus, the study performed in [142] aimed to identify the differences in the results obtained after THA or hemiarthroplasty for the treatment of FNFs in the elderly, solely subjected to orthogeriatric co-management.

The 5554 patients elected for the study were further divided into two groups, one comprising 4662 patients undergoing hemiarthroplasty, with an average age of 85, and a second one consisting of 892 patients treated with THA, with a mean age of 79. However, some of the patients (54.8%) were excluded from some of the performed analyses because of lack of information; therefore, each examination ultimately displayed the overall number of included patients. The main observed parameters included ambulatory ability 120 days after the fracture, complications associated with surgery, as well as fatalities recorded during hospitalization or within the first 120 days following the procedure, and the quality of life calculated 7 and 120 days after the surgery, measured using the EQ-5D-3L questionnaire. Moreover, some independent variables that could have potentially impacted the results of the procedures were included, namely, the American Society of Anesthesiologists (ASA) classification, with a grade ranging from 1 to 5, the Identification of Seniors At Risk (ISAR) score, as well as other factors such as sex, age, length of hospitalization, presence of additional injuries, and anticoagulation.

The patients included in the hemiarthroplasty group observed to be significantly less healthy compared to the THA cohort, presenting an ASA grade of 3 or higher in 80% of the cases, whereas the same score was indicated in approximately 58% of the cases in the THA group. Likewise, 85% of the patients undergoing hemiarthroplasty received an ISAR score of 2 or higher at the time of hospital admission, whereas a lower percentage of the patients undergoing THA, corresponding to 58%, obtained analogous scores. The incidence of fatalities following the surgical procedure was greater in the hemiarthroplasty cohort (6%) than in the THA group (3%); moreover, the ambulatory capability was superior in the patients belonging to the THA group (28%) at the 120-day postoperative follow-up, determined after a careful examination of the EQ-5D-3L questionnaire. Nonetheless, the incidence of complications correlated to the surgical procedure was inferior following hemiarthroplasty (4%) compared to the 8% indicated after THA, which is further observed to increase to 10% postoperatively during 120-day follow-ups. Instead, the rate of readmissions was determined to be statistically insignificant, with a rate of 5% for the hemiarthroplasty cohort and 7% for the THA one; similarly, no substantial differences were found regarding the ambulatory ability of patients 120 days after the two surgical procedures and before the injury. Finally, the quality of life at 120 days following the surgery was substantially higher in the THA group (0.9) compared to the other analyzed cohort (0.81).

In conclusion, THA is more indicated for patients presentin;g a superior health status and requiring greater mobility, supported by enhanced ambulatory capacity and quality of life achieved after the surgery. Instead, hemiarthroplasty is advised for patients presenting multimorbidity to preclude the necessity of further procedures and the incidence of ulterior complications [142].

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Perioperative Patient Care for Total Hip Arthroplasty

Abstract Total hip arthroplasty (THA) is a lengthy surgical procedure that requires a personalized approach depending on the characteristics of the patient. For this reason, this surgery requires a meticulous preoperative planning, as well as a careful postoperative recovery protocol to promote the achievement of positive outcomes while simultaneously preventing the occurrence of any major complications that could negatively impact the well-being of the patient. In this article, we summarize some of the activities performed in the perioperative stages of THA as well as the attentive care of the patient throughout all the phases of the surgery.

1 Introduction

The term patient care encompasses all the activities and decisions, made by surgeons, nurses, and physical therapists, in the perioperative stages of the THA procedure, which ultimately aim at enhancing the well-being of the patient after the surgery. The patient care in the preoperative phases primarily include a thorough planning of the surgical procedure, based on the mental and physical state of the patient, as well as decisions regarding the use of the most suitable analgesics to reduce the postoperative pain, and decrease the convalescence period, whereas the decisions made during the intraoperative stage are related to the correct choice of anticoagulants to avoid complications such as deep vein thrombosis. Finally, the postoperative care for THA involves a variety of factors, including the constant communication of the patients with the healthcare workers—which has been proven to have significant positive effects on their mental and physical well-being—the role of the nursing staff in the management of the pain experienced by the patient after the surgery, and the extensive rehabilitation procedure led by physical therapists to ensure the recovery of the functionality of the patient. Throughout this article, we analyze some of the aforementioned procedures aimed at targeting the positive outcomes of the THA surgery.

E. Tokgöz, *Total Hip Arthroplasty*, https://doi.org/10.1007/978-3-031-08927-5_4

2 Active Communication of THA Patients with Healthcare Providers

THA is considered as an efficacious method for the treatment of patients suffering from severe hip pain, mobility discomfort, and rigidness [1, 2]; however, there are a variety of factors that substantially increase the likelihood of incurring in severe complications. Such factors include an increased length of surgery, a more sedentary lifestyle, and deficient environmental adjustability, and could potentially lead to a more elevated incidence of blood vessel and nerve lesions, dislocation, and loosening of the implant [3, 4]. Moreover, deep venous thrombosis (DVT) has been shown to be one of the most frequent complications following THA, with an overall incidence rate of 19.78%. It is a condition caused by anomalies correlated to the coagulation of blood in the deep veins of the lower limbs, which partially or entirely obstruct blood vessels and are reputed to be one of the main factors leading to sudden deaths following the surgical procedure. In addition, the occurrence of deep vein thrombosis is increased in elderly patients, especially the ones already presenting severe comorbidities, primarily because of the decreased elasticity of their blood vessels which ultimately result in frequent damages to their walls [4].

The estimated time of both physical and mental recovery following THA is particularly extended, and, during that time span, patients are particularly inclined to generate negative thoughts, which might ultimately lead them to the development of anxiety or to a state of depression. These negative feelings experienced by the patients presumably arise from the high expectations regarding a utopic rapid recovery of their normal range of motion, which is unlikely to occur because of the deficiency of medical expertise or because of the insufficient understanding of the complexity of the surgical procedure on the part of the patients. Therefore, it is of vital importance for recently operated patients to communicate with healthcare workers, leading to an improvement in their relationship, as results have shown that involvement can ensure their safety, alongside playing a key role in the execution of the postoperative rehabilitation protocol [5]. Active communication of patients with the healthcare providers has a positive impact on their psychological state, mitigating anxiety, increasing their confidence (especially regarding the decision-making process), and resulting in enhancements in patient satisfaction and better clinical outcomes [1].

3 THA Outpatient Self-Efficacy

Communication is a key aspect of everyone's life, allowing people to perform tasks via the direct exchange of information [7]. However, the communication between the doctor and the patient is not always equitable; in fact, the doctor could potentially be the only one engaging in the conversation, whereas the patient would consequently assume a more passive role, ultimately causing some sort of obstacle in the communication between the two parties [8].

The concept of self-efficacy refers to the belief that one individual holds regarding their capability of performing a specific task and achieving the desired goal. This perspective has been shown to have a positive impact on human behavior [9], increasing the functionality and well-being of the patients, alongside improving the outcomes of a wide variety of conditions in the elderly [10]. Therefore, communication self-efficacy is being increasingly used as a method to improve the satisfaction reported by the patient and reduce the incidence of medical errors [11].

Some of the main components of the THA postoperative period are the rehabilitation process and health education that primarily takes place during communications. The lack of valid tools to evaluate the communication self-efficacy performed by the patients throughout their medical experience led to the development of the Patient's Communication Perceived Self-Efficacy Scale (PCSS), an instrument used to assess the outpatient confidence regarding the ability of an individual to efficiently perform activities related to the communication with doctors [9]. Such instrument is composed of 16 items and is characterized by a structure that meticulously analyses three factors of self-efficacy, specifically self-efficacy in "Provide and Collect information," "Express concerns and doubts," and "Verify information" ultimately giving a rise to a reliable method for measuring the patient communication self-efficacy [12].

The study conducted in [6] aimed at evaluating the test-retest reliability, the structural validity, and the internal consistency of the PCCS to ultimately design the Bayesian network modeling of the PCSS adopted in China for a sample of outpatients previously subjected to total hip replacement (THR). The test-retest reliability is a key aspect that allows to measure the consistency of the results when performing a specific assessment at different points in time [107]; instead, the structural validity evaluates the adequacy of the scores in indicating the dimensionality of the measured aspect [108]. Finally, the internal consistency indicates the ability of all the elements of a scale to describe the same notion [109].

A total of 167 patients were included in the study performed in [6] to evaluate the structural validity of the PCSS adopted in China, displaying a median (IQR) score of 57. Out of the 167 previously recruited patients, 6 were excluded from further evaluations because of a lack of information due to the absence of follow-ups. Therefore, only 161 patients were included to evaluate the test-retest reliability and the Bayesian network concept is used for analysis.

The results gathered at the end of the study demonstrated a good fit index in terms of structural validity and internal consistency for the three-factor model adopted in the Chinese version of the PCSS, with the only exception consisting in the root mean square error of approximation. The test-retest reliability indicated a narrow limit of agreement between the two analyzed points in time, which ranged from −7.6 to 7.2. Moreover, the design of the Bayesian network indicated that one of the main predictors of good communication between the patients and their physicians was the level of education of the patients, alongside their ability to consistently interact with the doctors. In summary, the performed study demonstrated the structural validity and test-retest reliability of the PCSS adopted in China to ultimately carry out a reliable evaluation of the self-efficacy of the outpatients regarding their communication with the medical staff after total hip replacement.

4 Tools Used for Comorbidity Assessment in THA

The number of patients deciding to be subjected to THA is gradually increasing, concomitantly with the effectiveness of the surgical procedure [14], mainly attributed to the more meticulous evaluation of the state of health of the patients preoperatively, which then allows for the design of a more individualized procedure depending on the factors that could potentially cause severe harm. In fact, research indicated approximately 83% of the patients subjected to hip surgery also present concomitant conditions [16], which could negatively impact the results of THA in a variety of ways, in particular by increasing the incidence of complications, thus subsequently elevating the overall cost of the rehabilitation, and by decreasing the range of motion of the patient in the near future [17]. Considering the multiple negative effects that the occurrence of comorbidities could potentially have on the outcomes of the surgical procedure, a careful examination of such conditions is crucial to ensure the achievement of successful outcomes [18].

A total of 26 articles contained information on the instruments utilized to evaluate the comorbidities presented by the patients. Among the most commonly used indices, the Charlson Comorbidity Index (CCI) appeared in 18 out of the 26 analyzed publications, the Elixhauser Comorbidity Method (ECM) was presented in 6, and the modified frailty index (mFI) was used in 5. The CCI allows for the prediction of the future health status of patients presenting multiple comorbidities, as well as the incidence of mortality following hospital admission and potential rehospitalization [19]. The mFI, instead, indicated the decline in the physiological performance of patients, related to both aging and the presence of comorbidities, to aid in the recognition of patients at high risk of complications following the procedure. Finally, the ECM comprises 30 variables, each corresponding to a specific disease identified with an ICD (International Statistical Classification of Diseases and Related Health Problems) code, which facilitates the collection of data. The main results included the life quality, functionality, and mortality, (evaluated in 8 papers), complications (featured in 10), overall length of stay (indicated in 6), readmission (presented in 5), reintervention, satisfaction, and transfusion of blood (evaluated in 2). Instead, delays or cancellation of surgery, comprehensive expenses for the treatment and care, risks related to possible falls, and administration of painkillers were examined in 1 out of the 26 papers. An ulterior analysis of the selected publications led to the design of 11 indices to subsequently anticipate the outcomes of THA, which were further subdivided into four sections based on the scope of the utilized tools. Such subsections included diagnosis, medical and demographic factors, prescription, and general health status [13].

The American Society of Anesthesiologists (ASA) physical status classification and the CCI are the most widely employed comorbidity evaluations in patients undergoing THA. These tools provide a reliable prediction of the outcomes of the surgical procedure, including life quality, functionality, fatality rates, length of hospital stay, and readmissions; however, the ASA resulted more accurate in the prognosis of adverse events, as well as the length of stay, dismissal, and health status of the patients following THA. Nonetheless, this tool could display inconsistency in the analyzed outcomes because of its subjective character [15], thus implicating the need for additional instruments to ensure accurate prediction of the results. The ECM is considered the third most frequently utilized comorbidity index, extremely useful in the prediction of severe complications [20], and more accurate than ASA in the anticipation of THA outcomes [21]. However, due to the high quantity of variables, the collection of data is particularly complex. Another commonly used tool is the mFI, characterized by an excellent predictive character, especially regarding the predicted length of stay, the incidence of complications, reinterventions, and fatalities following the surgical procedure [22], alongside long-term functional outcomes (WOMAC) [23]. The Functional Comorbidity Index (FCI) is less frequently employed, but it can successfully prognosticate the functionality and quality of life of the patients undergoing THA while simultaneously including factors such as obesity and mental state; however, it is not as efficient as the CCI in the prediction of fatality rates. The RxRisk-V performs an accurate calculation of THA outcomes based on the prescriptions taken by the patients, albeit potentially causing errors when one particular medication is employed to treat two comorbidities [24]. The Index of Coexistent Disease (ICED) includes both the physical and operational status of the patients; nonetheless, it is not as commonly used as other tools [25]. The Cumulative Illness Rating Scale (CIRS) can be convenient for research because of its analysis of individual anatomical systems [26]. Other tools, such as the RRATHR (Readmission risk after a total hip replacement) and CMS-HCC (Centers of Medicare and Medical developed Hierarchical Condition Category), are not employed because of their complicatedness and their poor predictive ability [27].

In summary, the CCI and ASA are the most frequently used comorbidity indices despite their imprecise determination of the health status of the patients. Their common use is attributed to their straightforwardness, which makes them easy to analyze, ultimately leading to a faster evaluation on the part of the clinicians [13].

5 Preventive Effectiveness of Anticoagulants on Venous Thromboembolism Following Total Hip or Knee Arthroplasty

Venous thromboembolism (VTE) is a frequent complication following surgeries involving prosthesis implantation and encompasses deep vein thrombosis (DVT)—consisting in the development of blood clots in the veins of the legs, which could either partially or entirely obstruct venous blood flow, as well as pulmonary embolism (PE)—in which previously formed blood coagula drift toward the blood vessels of the lungs, ultimately blocking them [29].

Among the most used anticoagulants, factor Xa inhibitors have proven their superiority compared to other ones as frequently used. More specifically, rivaroxaban has shown an inferior risk of incurring in deep vein thrombosis compared to other medications when used in total hip or knee replacements; however, some studies have reported a relatively high intraoperative blood loss rate [30], whereas others have documented a negligible hemorrhage throughout the procedure [31, 32], thus generating controversies.

The objective of the study conducted in [28] was to perform a broad comparison of the most frequently used anticoagulants to subsequently establish which would have resulted more effective in the prevention of the formation of coagula of blood, thus indicating a lower incidence of DVT and PE.

After identifying enoxaparin as the reference group due to its reliability in preventing elevated bleeding rate alongside occurrence of venous thromboembolism, results have indicated the superiority of other anticoagulants, namely, apixaban, edoxaban, and darexaban, compared to the latter. Other low molecular mass heparins, in particular dalteparin and bemiparin, have also demonstrated positive outcomes relative to the prevention of pulmonary embolism, whereas tinzaparin and reviparin were extremely efficacious in the preclusion of increased bleeding rates. In addition, rivaroxaban and dabigatran successfully prevented venous thromboembolism effectively but displayed unfavorable results concerning the regulation of clinical hemorrhage. The three novel factor Xa inhibitors analyzed throughout the study, namely, fondaparinux, erixaban, and betrixaban, have been proven to be particularly efficacious. Additionally, betrixaban was classified first in the prophylaxis of both major and minor blood loss. In contrast, warfarin—a vitamin K antagonist—turned out to be inadequate for the prevention of VTE, as well as ximelagatran and acenocoumarol. According to the obtained data, the safest and most efficacious anticoagulants to be used during procedures such as total hip or total knee replacement are apixaban, edoxaban, and darexaban. Despite the increased rates of causing clinical hemorrhage, rivaroxaban is identified to be particularly efficacious in the prevention of VTE.

6 Anchor Strategy and PROM Utilization for Determining Clinically Important Differences in THA

One of the main obstacles faced by the investigators when analyzing the quality of life of patients in randomized trials is the determination of the relevance of any of the discovered differences. For this reason, the use of patient-reported outcome measures (PROMs) to achieve postoperative assessments is significantly increasing, as they appear to be extremely helpful in the provision of scores regarding the status of the patients to be later examined by clinicians [33]. In addition, the concept of minimal clinically important difference (MCID)—consisting of the smallest difference in PROM scores reputed important by the patients—is being incrementally used for questionnaire assessments due to its capability of interpreting the outcomes of a given surgical procedure, as well as establishing the differences and performing a comparison of one particular intervention as opposed to another [34, 35].

Two methods have been outlined to calculate the MCID, one consisting of the sole distribution of the responses, and a second one presenting an ulterior question, denominated "anchor," to allow for categorization of the obtained results and enable the differentiation between patients who have experienced changes—both positive and negative—in their status from those who have not experienced any differences [36, 37].

For the study performed in [33], patients were asked to complete the Hip Osteoarthritis Outcome Score (HOOS), as well as the Oxford-12 questionnaire—both before and at 6 and 12 months following the procedure—to ultimately establish whether the anchor could be represented by any of the items present within the questionnaire. Results have shown that the MCID outlined for French-speaking partakers was consistent with other literature data previously reported. Moreover, in order to represent the anchor, the chosen item had to be general enough to be able to determine hypothetical improvement; in fact, more specific questions were less prone to show progress compared to items targeting broader topics such as life quality or experienced pain.

7 Nurse-Led Pain Management Following Total Knee/Hip Replacement

The number of THR and total knee replacements (TKR) has been increasing significantly because of the increment in degenerative conditions. However, one of the most common symptoms experienced by patients following surgery is pain, presumably deriving from incorrect strategies employed to address its management and accounting for over 50% of patient dissatisfaction in THR and 75% in TKR [39]. Inadequate control of post-surgical pain is correlated with decreased exercise, malnourishment, difficulty sleeping, and delay in the healing process [40]. It is therefore important to maintain the perceived pain under control, to enhance a prompt recovery of the patient's body functions, as well as reduce the occurrence of potential complications including extended opioid use, elevated morbidity, and progression into chronic pain [40, 41, 44], which are some of the major complications that can occur due to the excessive pain. This could be achieved by meticulous postoperative acute pain management, which is divided into pharmacologic—which foresees the use of opioid analgesics [43] and presents many side effects such as bowel dysfunction, nausea, or vomit, particularly if administered for extended periods [44, 45]—and nonpharmacologic [42].

This second, less invasive, approach is solely conducted by nurses [46–49] and consists of a variety of methods aimed at reducing postoperative pain. Some of the aforementioned methods employed to ultimately decrease the pain experienced by the patients include massages, music therapy, relaxation therapy, and touch therapy. Further studies have shown that massages have a positive impact on the patient, ultimately decreasing the experienced pain by elevating the pain threshold through a more elevated release of endorphins. Touch therapy is analogous to massage treatment, and its results include reduction of the intensity of pain, anxiety, as well as respiration rates. Finally, cognitive-behavioral treatments—such as music, relaxation, or distraction—were also included in the nonpharmacologic list of approaches conducted by nurses, as results have shown a substantial decrease in pain intensity through the use of a secondary stimulus that drew the patient's attention, temporarily distracting them from the source of pain [46].

The results gathered throughout the study conducted in [38] confirmed the positive outcomes hypothesized for nurse-led nonpharmacologic pain management, which was particularly effective following patient education, therefore indicating this procedure as optimal to reduce the postoperative pain experienced by patients through noninvasive intervention and with negligible risk of side effects. In conclusion, to achieve an optimal outcome in pain management, nonpharmacologic intervention should be complemented with the assumption of opioid analgesics.

8 Acute Pain Trajectory Design Following THA

Pain is defined as chronic when it perseveres past the conventional healing time—over 3 months postoperatively—and it may be related to psychological factors, such as anxiety or depression, or result from stress [54]. In order to ameliorate the outcomes following THA and augment the recovery of patients, appropriate pain management around the time of surgery is imperative [50]. This could be achieved by analysis of data-driven guidelines, which could furnish information relative to the comprehensive notions for adequate pain management, alongside a thorough explanation of relative advantages and limitations of analgesics and corresponding techniques. In addition, the number needed to treat (NNT) could also be employed to determine the effectiveness of different analgesics. It consists of the overall number of patients subjected to treatment with a specific analgesic necessary to reach a percentage greater or equal to 50% for pain relief experienced by a single patient, compared to the placebo. However, these two approaches present several limitations, which led to the development of procedure-specific pain management recommendations (PROSPECT), with the goal of providing suggestions to ultimately assist with the perioperative decision-making process [51].

In cases in which primary systemic analgesia does not generate the expected effects in terms of pain management, other multimodal methods—such as local infiltration analgesia (LIA) or peripheral nerve blocks—are integrated to achieve the optimal results [51–53]. However, there is uncertainty regarding the proper analgesic technique to use, as some of them do not often last throughout the entire length of the severely painful phase, or do not result beneficial for certain surgical procedures [51]. Therefore, the design of a suitable analgesic plan would allow for pain relief that aligns with both the timeframe and severity of the postoperative pain, and it could be achieved through the development of pain trajectories that identify the average pain progression following surgery, thus including reports about the time of most acute pain experienced by the patients, as well as an indicative timeframe for when that pain subsides. This elaboration would also enable the detection of patients that deviate from the standard trajectory, ultimately indicating hypothetic complications or evolution into chronic pain, which could be treated with ulterior interventions [54].

The developed pain trajectories demonstrate that the average pain experienced by patients tends to diminish by 4–8 h upon the surgical procedure, following which the pain should reduce to tolerable levels even when subjected to a basic analgesic plan. The initial timeframe of intense pain could be potentially targeted with spinal anesthesia (SA)—as results have shown that patients subjected to this treatment experienced considerably less pain compared to other anesthetic measures—combined with either nerve blocks or LIA [50].

9 Impact of THA on Life Quality of Couples and Conjugal Relationship

Disorders correlated to arthritis cause severe pain in the affected individuals, thus potentially impacting the social interactions of the latter, especially with regard to their conjugal relationships [56]. Osteoarthritic individuals are more prone to develop health conditions in addition to experiencing a graduate worsening of their mental health [57], therefore influencing their relationship with their spouses [56] that are oftentimes feel forced to provide constant assistance and consequently structure their lives to comply with the daunting responsibilities that this role implicates. In fact, various studies have confirmed that the partners of individuals affected by chronic pain disclosed significantly inferior levels of conjugal satisfaction and life quality, alongside a higher incidence of depression [58, 59].

Joint replacement surgery constitutes a viable option to reduce the pain experienced by the patients, as well as their emotional suffering, while simultaneously improving their motor functionality that could potentially lead to an improvement in the quality of their marital relationship and the physical and mental health of the spouse.

The study conducted in [55] aimed, therefore, at establishing the perception of the spouse on the impairment and pain experienced by the patient both before and after hip replacement, as well as determining the positive outcomes of the surgery on the private and conjugal life of the spouse.

The study included 29 heterosexual couples, married for an average of 36.7 years; the mean age of the patients was 68 years old, while it was 67 years old for the spouses.

The information was gathered before the surgical procedure and after the patients fully recovered (signaled by a Harris Hip Score of 100) either over the phone or in the clinic. The interviews were conducted individually by separating the couples to ensure the collection of authentic data, and these interviews were structured to address specific questions. Such questions included the perception of the acuteness of the pain experienced by the patient, which was rated on a numerical rating scale (NRS), and of the degree of disability, which is instead measured via the Pain Disability Index (PDI) and comprises seven distinct areas of everyday life. Out of these seven areas, items 1 through 5 corresponded to activities performed voluntarily, while items 6 and 7 were reputed imperative [60]. Both the NRS and the PDI were rated on a scale from 1 to 10, with 0 indicating no pain and 10 expressing intolerable pain for the NRS, whereas for the PDI, a value of 0 indicated no perceived disability, and 70 denoted complete disability [55]. The results gathered via the interviews indicated an inferior perception of the pain preoperatively on the part of the patients, which indicated an average of 7.4 points (out of 10) compared to the mean of 8.3 reported by their spouses. Similarly, the patients estimated their postoperative pain at 0.9 points, whereas their spouses indicated substantially higher scores, averaging 1.4 on the decimal scale used as reference. Instead, the mean score calculated for PDI preoperatively was 33.6, and the pain experienced by the patients primarily impacted activities performed voluntarily rather than the obligatory ones, in particular leisure activities [55]. As seen in the NRS for pain, patients' spouses reported higher preoperative PDI scores in all the seven areas of everyday life, excluding sexual behavior and activities aimed at self-care, for which they reported lower scores compared to the patients. Following the procedure, the patients indicated a substantial decrease in disability—20.7 for voluntary activities and 5.2 for obligatory tasks—whereas the spouses indicated an average improvement corresponding to 28.7 points, 23.6 for voluntary activities, and 5.1 for the obligatory ones. After THA, the patients indicated various factors that contributed to the improvement of their life quality, among which increased mobility (93%), decreased pain (72%), and improvement in their social interaction, especially with family (38%), are observed. Among the main benefits indicated by the spouses, the possibility to resume social activities with their partners was shared by 72% of the patients' spouses, alongside the fact that they didn't have to witness their partner in pain (52%), a reduced burden caused by the necessity to take care of their beloved one and a subsequent sense of independence (59%), an enhanced conjugal relationship (52%), as well as social life (28%) and, finally, possibility to travel (28%). In conclusion, the performance of total hip arthroplasty has positive outcomes in the lives of both the patients and their spouses, resulting in a substantial reduction in the pain affecting the patients and a subsequent improvement in their social interactions, alongside a decreased burden in the caregiving tasks performed by the spouses, ultimately improving their marital relationships [55].

10 Physical Therapy

As previously mentioned, THA is a surgical procedure aimed at decreasing the severe pain experienced by the patients and subsequently increasing their quality of life. However, aside from the surgery itself, the patients have to undergo an extensive physical therapy cycle in order to ensure successful outcomes and proper recovery of their functionality [61].

The rehabilitation procedure begins the day after the surgical procedure with patient education—to instruct the patients on the proper methodology to initially perform daily activities, while simultaneously avoiding certain movements, including flexion of the hip past 90°, adduction past the midline, and both internal and external rotation [62]—and the slight mobilization via exercises performed directly in bed, with the goal of strengthening the hip and increasing its range of motion [61].

The length of stay after the surgical procedure is extremely subjective. In fact, some patients are discharged with assistive devices after one night, whereas others require 2 or even 3 days. In some cases, the discharged patients might experience some mobility limitations, which inevitably prevent them from returning home. In such instances, they will continue their physical therapy protocol at a subacute rehabilitation institution, until sufficient functionality is gained to allow them to return home safely. The rehabilitation cycle will then continue either directly at home—a choice that is mainly reserved for people that are unable to leave their home—or, in cases that the patient does not experience any limitations in terms of travel, it can be continued at an outpatient clinic. The extensive protocol initially foresees indications on how to perform daily activities safely—such as how to climb the stairs or how to properly move in and out of the bed—followed by the strengthening of the hip and maximization of balance and proprioception. These exercises aim at reinforcing the musculature around the operated hip, to allow the patient to slowly transition from the use of assistive devices to an unassisted ambulation by the end of the outpatient physical therapy cycle [61].

Impact of Progressive Resistance Training to Healing During Early Postoperative THA

Progressive resistance training (PRT) is among the most frequently used rehabilitation techniques after procedures involving joint replacement [63]; however, the efficacy and security of this physiotherapeutic approach are still at the center of debates [65]. The PRT protocol should be started shortly after the surgical procedure, considering the loss of muscle mass and strength experienced by the patients [66, 67].

The research carried out in [64] analyzed the effects of progressive explosive-type resistance training (RT) performed in osteoarthritic patients scheduled for THA. It included 80 patients, 3 of which were then lost during the follow-up protocol. Each of the sessions was conducted twice a week for a total of 1 h, and lasted for a total of 10 weeks [64]. The warm-up consisted of a 10-min-long exercise on the stationary bike, followed by a series of four random exercises executed unilaterally on exercise machines with maximal acceleration of the load. The pain experienced by the patients was measured using the visual analogue scale (VAS) ranging from 0 (no pain) to 10 (extreme pain) and was registered before and after each training session [64]. The participants reported a VAS score of ≤5 in 95% of the cases right after the training session, whereas the remaining 5% reported a score of ≥5. Instead, a score of ≥5 was reported in 1/3 of the cases the day after the session throughout the first 2 weeks of the protocol, correlated to the inevitable soreness resulting from the exercises [64]. The remaining 2/3 of the patients indicated, instead, a VAS of ≤5 the day following the training. Progressive explosive-type RT substantially improved the preoperative pain level and the functionality of the OA patients attending the sessions while simultaneously increasing their muscle strength and, consequentially, their life quality [64].

The study performed in [66] analyzed, instead, the effects of PRT after the THA surgical procedure. A total of 73 patients were included and randomized into either intervention group (IG) or control group (CG); however, only 62 completed the 10-week-long protocol. The rehabilitation protocol designed for the IG consisted of unloaded exercises performed at home 5 days a week, and PRT carried out twice a week. Instead, the CG solely performed unsupervised home-based exercises every day of the week [66].

In terms of power achieved during leg extension, no significant differences were observed between the two groups, as the IG showed an improvement of 21%, while the CG enhanced their performance by 17% [66]. Instead, the IG displayed superior outcomes with regard to walking speed and stair climb efficiency, improving their isometric muscular strength by 18–26%, and by 21–26% in their functional performance assessments, whereas the CG only exhibited an improvement of 4–12% and 11–20%, respectively. No significant differences were observed in the 20 m walking speed and in the hip dysfunction and osteoarthritis outcome score questionnaire (HOOS) administered at the end of the rehabilitation protocol [66].

The research conducted in [68] analyzed the effectiveness of the home-based PRT protocol compared to the one performed at the hospital. In order to do so, 25 patients were assigned to the home-based PRT cohort, and 24 were randomized into the control group, which conducted the training session at the hospital [68]. The two cohorts were subjected to a variety of assessments, which included the maximal voluntary contraction (MVC) of the quadriceps femoris of the operated leg, the sit-to-stand score in 30s (ST), the timed up and go (TUG), the stair climb performance (SCP), the 6-min walk test (6MWT), and the evaluation of the lean mass of the operated leg via a dual-energy X-ray absorptiometry (DEXA) scanning [68]. The MVC was conducted while the patients were sitting on a medical table with their arms across the chest. The dynamometer (instrument used to measure the force, torque, or power [69]) was placed over the tibia, and the patients were then asked to energetically contract and straighten the leg. The ST score was calculated based on the number of times the patient was able to stand from a standardized chair in 30 s, with their arms across the chest [68]. Figure 1 illustrates the various phases of the sit-to-stand assessment.

The TUG analyzes the time (in seconds) it takes for the subjects to stand from a standardized chair, walk to a cone placed 3 m away at a comfortable speed, and walk back to ultimately sit on the chair. Figure 2 depicts the various steps that characterize the TUG test.

The SCP assessed the time it takes for the patients to climb 14 steps (20 cm in height) at a comfortable speed [68]. Figure 3 illustrates the technique adopted for the stair climb test performed on the patients

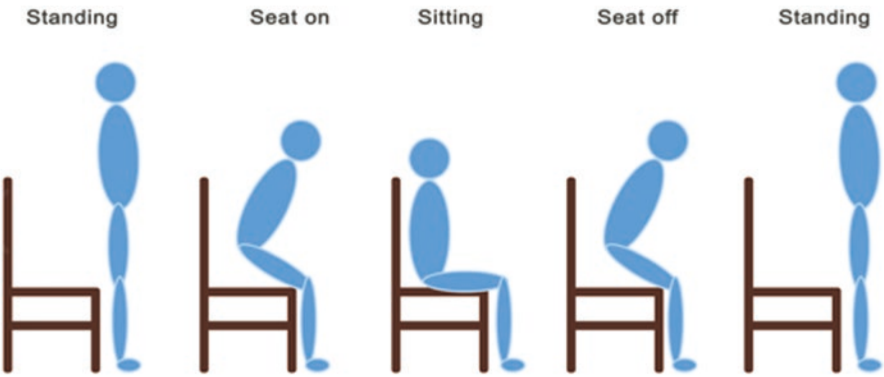

Fig. 1 ST assessment [111]

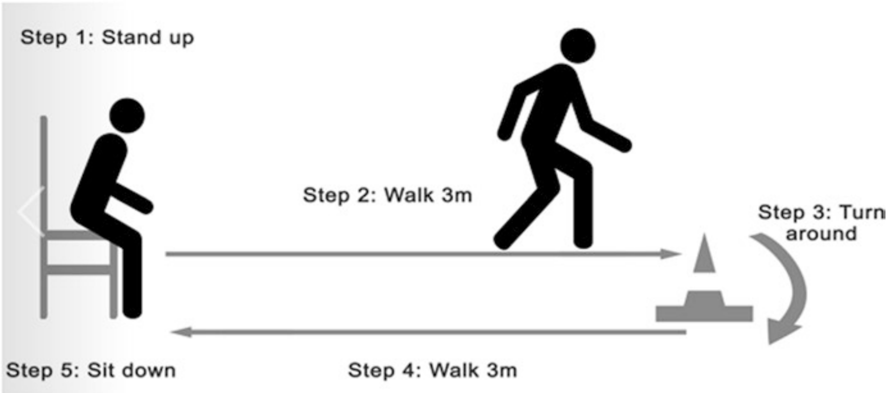

Fig. 2 TUG assessment [110]

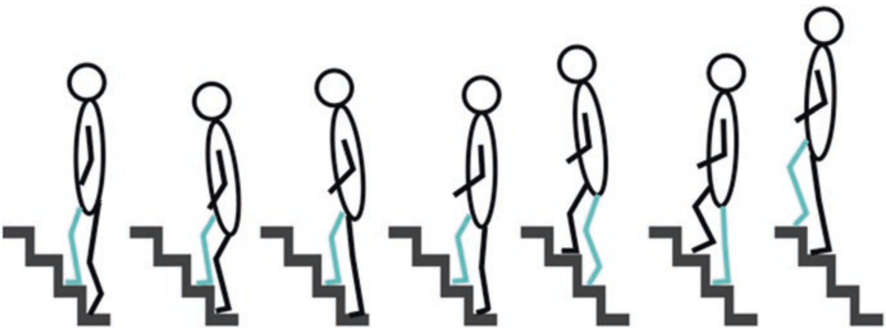

Fig. 3 SCP test [112]

The 6MWT measures the distance the patients are able to cover in a corridor over a 6-min time period. Finally, the DEXA was conducted using a pencil-beam scanner to ultimately calculate the total and regional bone mass and lean fat, to determine if the home-based protocol resulted in a more elevated muscular mass in the operated leg compared to the one performed in the hospital [68].

Only 26 patients completed the 1-year-long protocol, 13 of which were part of the home-based PRT cohort, while the remaining 13 were part of the control group [68]. Both groups showed significant improvements compared to the baseline values, and no significant differences between the two groups were observed for most of the conducted assessments, which included the MVC, the ST score, and the calculation of the lean mass of the involved leg [68]. However, differences were observed in the SCP and the 6MWT, throughout which the control group showed superior outcomes compared to the home-based PRT cohort. The obtained results demonstrate that the home-based PRT protocol could be potentially applied to THA patients, but without attaining the same results in terms of functionality as the inhospital protocol [68].

The study conducted in [70] aimed at evaluating the results of early maximal strength training performed after THA. The participants were randomized into a maximal strength cohort and a conventional rehabilitation group for a total of 4 weeks, after which they were all subjected to conventional rehabilitation [70]. The results obtained for work efficiency at the end of the designated 1-year period demonstrated superior outcomes in the maximal strength cohort, both at 6 and 12 months postoperatively, by 29% and 30%, respectively. Similarly, the values for the leg press assessment performed on the healthy leg and the force development of the involved leg were superior in the maximal strength cohort 12 months after the procedure, by 36% and 74%, respectively [70]. Additionally, the performed study indicates that the maximal strength training protocol should be conducted for a more extended period of time while simultaneously coupled with aerobic endurance training, to ultimately achieve complete recovery after the surgical procedure [70].

The research conducted in [71] evaluated the effects of resistance training in the elderly in the initial stages after the THA procedure. A total of 36 patients were initially included in the study, and subsequently randomized into three groups: the home-based standard rehabilitation (SR) group, the SR plus unilateral lower-limb resistance training (RT) cohort, and the SR plus unilateral percutaneous neuromuscular electrical stimulation (ES) group [71]. The research was designated to last for 12 weeks, during which the patients were tested twice, at week 5 and at the end of the protocol. The outcomes of interest were the length of stay (LOS), the functional performance, the muscle cross-sectional area (CSA), and the maximal strength of the quadriceps femoris muscle. The LOS was delineated as the period of time from the day of admittance into the hospital until the day of discharge. In terms of functional performance, the maximal gait speed was evaluated over a 10-meter distance, and the stair-climbing performance was assessed based on the time it took for the patients to climb ten steps (20 cm in height). Additionally, the sit-to-stand test consisted of five repetitions to evaluate the ability of the recently operated patient to stand from a conventional chair [71]. The muscle CSA of the quadriceps was obtained via a computed tomography, which was performed for 5 seconds on a slice of 8 mm in thickness. Finally, the strength evaluation was calculated as the maximal moment of isokinetic extension of the knee during the concentric contraction of the quadriceps femoris muscle [71].

Only 30 patients completed the 12-week-long protocol. The average LOS was significantly shorter for the RT group (10 ±2.4 days) compared to the SR cohort (16 ± 7.2 days) [71]. Additionally, the aforementioned functional abilities improved in both the RT and in the ES groups at 3 months after the beginning of the training protocol. Maximal gait speed increased by 30% in the RT group, while it only increased by 19% in the ES group. The stair-climbing performance improved by 28% in the RT cohort and by 21% in the ES group [71]. Similarly, better outcomes were observed in the RT group for the sit-to-stand test, which improved by 30% compared to the improvement of 21% displayed by the ES group [71]. On the contrary, no improvements were observed in the SR group at the end of the protocol compared to the baseline values. The strength exerted by the quadriceps femoris muscle CSA decreased by 13% in the SR group at the fifth week postoperatively, remaining 9% below the baseline value at the end of the protocol. Instead, the CSA of the involved leg of the RT cohort increased 12% over the baseline value at week 12 [71]. Finally, the CSA performed on the ES group decreased by a value of 4% at the first follow-up, whereas it increased up to 7% at the end of the training sessions. The maximal strength increased by a value ranging from 22% to 28% in the RT cohort, while it remained unaltered in the remaining two groups. In summary, the performed study demonstrated the effectiveness and safety of resistance training when performed in the elderly in the first stages after THA, which resulted in an increase in the muscular mass, peak torque, and functional performance and a decrease in LOS [71].

The study conducted in [72] analyzed the effects of ulterior mobilization and strength training on the hip muscles of THA patients in the first week following the orthopedic procedure. A total of 39 patients were included in the research and subsequently subdivided into an intervention group (IG) and a control group (CG). The results of interest—calculated the day before and 6 days after the surgical procedure—included the range of motion of the hip, the circumference of the thigh, the muscle endurance of the gluteal muscles, the one-leg stance, and the 6-minute walk test. Additionally, a questionnaire was administered to the patients to evaluate the perceived pain at rest and during the exercise on a scale from 0 (best condition possible) to 10 (worst condition possible) [72].

Both groups demonstrated a decline in hip flexion compared to the value registered prior to the procedure; however, the results observed in the CG were inferior compared to the IG. In terms of hip extension and hip abduction, the IG showed increased motion compared to the CG [72]. The IG and CG showed a similar magnitude increase in the circumference of the thigh compared to the one assessed before the surgery; however, the muscle endurance of the gluteal muscles decreased to a similar magnitude in both groups [72]. With regard to the one-leg stand performance, a decrease in the holding period of the CG was observed, whereas no differences were seen in the IG compared to the values gathered before THA. Similarly, the mean distance covered during the 6-min walk test decreased in the CG, while it remained unchanged in IG. Finally, the administered questionnaires demonstrated an improvement in both groups in terms of the pain scores obtained after the procedure compared to the preoperative ones [72]. According to the results of the conducted study, additional targeted mobilization and strength training are advised to achieve a faster improvement of the gait performance [72].

10.1 Rehabilitation Process and Operational Efficiency-Related Complications Following THA and TKA

Osteoarthritis (OA) is a condition that results in the gradual erosion of the cartilage of the joint and is categorized as one of the most relevant disturbances of the connective tissue and locomotor system—affecting approximately 9.6% of men and 18% of women over the age of 60—mainly attributable to the advanced age of the population, alongside decreased physical exercise and augmented obesity rates [74, 75]. While milder cases could potentially be addressed with local muscular tissue strengthening or weight loss, total replacement of the joint constitutes the proper approach for the treatment of grave instances of osteoarthritic hip or knee [76–78], which have a substantial influence on the execution of daily activities, as well as on the quality of life because of the joint pain and movement limitations experienced by the affected population [79].

The goal of the study conducted in [73] was to ultimately determine the results of the rehabilitation procedure following both total hip (THR) and total knee replacement (TKR).

The participants were requested to respond to a survey administered via phone in the form of a formalized recorded interview, which included questions relative to the assessment of the parameters used throughout the rehabilitation process and the subsequent outcomes of the latter. The verbal descriptor scale (VDS) was employed to assess the intensity of the chronic pain experienced by the patients, including categories ranging from "no pain" to "unbearable pain." Evaluation of the data indicated that 70% of the participants were complacent with the management of the rehabilitation procedure of local health authorities, whereas about 20% resulted in disappointed, mainly because of the inadequate quality of the healthcare system or due to the unavailability of an orthopedic surgeon in close vicinity. The analysis of the results gathered via the verbal descriptor scale indicated that approximately 50% of the subjects, mainly belonging to the TKR group, endured moderate to severe pain. In addition, 57% of the participants were able to walk independently, whereas the remaining 43% was required to use an external support. In order to achieve better outcomes in terms of operational efficiency and rehabilitation adequacy, a constant assessment resulting from the communication of the main parties of the rehabilitation process should be performed, to ultimately supervise the results, from a medical and social standpoint, of delicate surgeries such as THR or TKR [73].

11 Analgesics

Both total hip and knee replacement surgeries generate severe pain in the patients subjected to the procedure, particularly after the sixth hour of the first postoperative day [83–85], once the effects of the analgesics administered intraoperatively have terminated. The triggering factor correlated to the pain onset is the incision, which directly affects the sensory receptors located around the surgical site, and subsequently causes a variety of inflammatory responses [83, 86, 87]. Additionally, other factors leading to severe pain might be strictly correlated to the implant, the remodeling of the bone, as well as potential nerve injuries [80].

A wide variety of methods have been therefore employed to decrease the pain experienced by the patients, including peripheral nerve blocks and intravenous analgesics; however, a high percentage of patients still necessitates the administration of other narcotic medicinal drugs to ultimately relieve the pain [84].

What follows next focuses on the outcome analysis relative to the experienced postoperative pain after the administration of methylprednisolone or local infiltration analgesia with bupivacaine.

11.1 Postoperative Pain Management and Convalescence of Elderly Through Elevated Dose Administration of Methylprednisolone Prior to THA

The study performed in [82] aimed at establishing the efficacy of perioperative administration of methylprednisolone in patients over 65 years undergoing total hip arthroplasty (THA).

A total of 92 patients over 65 years of age were selected for the analysis and to later receive unilateral THA in concordance with the protocol established by the ERAS, therefore through the use of multimodal analgesia to achieve a prompt recovery in the operated patients [81]. However, 15 patients were subsequently removed from the analysis because of comorbidities that restricted glucocorticoid usage.

Before the procedure, intravenous agents consisting of 2.0 g of cefazolin—to stop the blood flow—and 8 mg of ondansetron, to reduce nausea and vomiting, were administered. All the patients received spinal analgesia and successive compartment block at the fascia iliaca on the operated side, before being subjected to THA via the lateral approach. The VAS/NRS tools were used to determine the appropriate approach for optimal pain management every 6 h at rest. If the score was higher than 4 points, administration of oxycodone hydrochloride was performed with a subcutaneous dose of 0.1 mg for every kg of body weight. Instead, when the calculated score ranged from 2 to 4, paracetamol and metamizole were computed for 1 kg of the body mass [82].

The patients were later subdivided into two groups, and the study was performed in a double-blinded fashion. The M cohort consisted of 39 patients and was administered intravenously with methylprednisolone at a dose of 125 mg, whereas the control group (K) was characterized by 38 patients that received saline solution as the placebo. The effects of the fascia iliaca compartment block were significantly longer in the M cohort, and only 8 patients out of the 39 (20.51%) required the administration of oxycodone hydrochloride after obtaining a VAS/NRS score at rest greater than 4, compared to the 36 cases observed in the K group (94.73%). The average length of hospitalization after the surgical procedure was shorter in the M group (4.89 days) compared to the control cohort (5.47 days), ultimately leading to decreased risk of complications potentially caused by infectious agents [84, 88–94], as well as thrombosis, cardiocirculatory, and respiratory complexities. The averages were influenced by the longer length of stay observed in two patients—each belonging to one of the two designated groups—who experienced postoperative delirium, thus significantly increasing the complexity regarding the rehabilitation process. Laboratory analyses were conducted to establish the levels of inflammatory markers in the body, demonstrating a higher level of leukocytosis in the study group during the first postoperative day, which then abruptly declined by the third day following the surgery [82]. Instead, the same group was characterized by lower C-reactive protein (CRP) levels, whereas no differences were observed in the values collected for CRP in drainage fluids between the two cohorts. Moreover, the administration of methylprednisolone did not impact the glycemic curve of the patients, thus indicating the safety of the medication.

In summary, the administration of a single dose of methylprednisolone in patients over 65 years of age subjected to unilateral THA substantially reduces the experienced pain, as demonstrated by lower VAS/NRS scores obtained at rest. Moreover, the overall number of inflammatory markers in the M group was significantly inferior, in particular regarding the levels of CRP throughout the entire postoperative analysis, whereas it was initially higher for leukocytosis levels, and then followed by a sharp decline during the second and third day following the surgery [82].

11.2 Inability to Prevent Perioperative Blood Loss Following Local Infiltration Analgesia with Bupivacaine During THA

Total hip arthroplasty is a lengthy procedure, correlated to a wide variety of complications, some of which include severe pain and substantial intraoperative blood loss [96]. Various advancements have been therefore made in the techniques used to perform such procedures, as well as in the methodology employed for the perioperative management of the patients, to ultimately alleviate the trauma caused by the surgery and increase the positive outcomes relative to the rehabilitation protocol [96, 98, 99].

One of the most frequently used methods for the management of pain in the initial period following total hip and knee arthroplasty is local infiltration analgesia (LIA) [98, 100, 101], consisting of various solutions of local anesthetics diluted in standard saline [98], and could also include adrenaline, which has been demonstrated to provide additional advantages in the reduction of perioperative blood loss, as well as rates of blood transfusion in TKA [102], particularly when combined with tranexamic acid [103]. LIA is beneficial for pain management following THA [99, 104]; however, it doesn't appear to have any beneficial effects on the volume of blood lost perioperatively [97, 105, 106].

The study undertaken in [95] hypothesized that LIA performed with bupivacaine and adrenaline would substantially decrease the amount of blood lost perioperatively in patients undergoing THA and infiltrated with a solution of at least 350 ml, subsequently decreasing the volume of blood needed for transfusion. A total of 99 patients were included in the study and further subdivided into two cohorts presenting no significant differences in factors including age, weight, body mass index (BMI), or approximate volume of blood: a first infiltrated group, consisting of 55 patients, and a non-infiltrated group, composed of 44. The patients included in the study were subjected to THA via the standard lateral Hardinge approach, followed by standard spinal anesthesia [102]. The local analgesic mixture consisted of 100 ml of saline solution, 50 mg of bupivacaine, and 1 mg of adrenaline, and was administered after the finalization of the surgical procedure, but before the wound was sutured, thus allowing for injection into the soft tissues surrounding the acetabulum and encompassing the capsule, as well as the gluteus medius and vastus lateralis and the underlying subcutaneous tissue. Moreover, two drains were utilized to collect fluids for a period of 48 h after the surgery, one of which was inserted into the joint, and a second one inserted under the tensor fascia lata muscle following the saturation of the gluteus medius [95]. The drainage output was then used to record factors such as hemoglobin levels (Hb), hematocrit (HTC), and red blood cell count (RBC) upon 24 h and on the fourth day following the surgical procedure. All patients exhibiting parameters within the normal range were discharged after 4 days. In contrast, the ones displaying Hb levels inferior to 10g/100 ml after the first analysis or below 9 g/100 ml on the fourth postoperative day were signaled for blood transfusion, which subsequently delayed the discharge process by 48 h to allow for meticulous supervision of the parameters. The values gathered after the delay period then replaced the ones obtained during the second analysis, to provide more accurate results regarding the final levels obtained for the aforementioned parameters.

The operational time was similar for both groups, presenting an average of 90.81 min in the infiltrated cohort and a slightly inferior one of 90.56 min, in the group not subjected to infiltration. Moreover, the values obtained for Hb, HTC, and RCB levels in both groups at 24 h and 4 days postoperatively—or at the time of discharge in case transfusion was required—were considered statistically insignificant. After correction of the results due to the greater size of the acetabulum in the non-infiltrated group, the values indicated for drainage output on day 1, day 2, and total output failed to show any significant differences; however, a direct correlation was identified between the size of the acetabulum and blood loss. Patients belonging to the infiltrated group necessitated an average transfusion of 1.53 units of blood, whereas the group not receiving the infiltration required a mean of 1.61 units. Additionally, transfusion was not needed in 18 out of the total 55 patients included in the infiltrated group, and in 12 out of the 44 comprised in the non-infiltrated cohort [95].

A similar procedure to the one indicated for the drainage output was performed for blood loss, thus adjusting the total estimated amount based on the size of the acetabulum, ultimately showing no significant difference between the two analyzed groups.

In conclusion, the data obtained throughout the study rejected the hypothesis speculating the potential advantages correlated to the injection of a solution—consisting of regional anesthetic and adrenaline—around the surgical site targeted by THA with the goal of decreasing the volume of blood loss perioperatively and subsequent transfusion rates. However, the size of the prosthetic component, in particular the acetabulum, has been proven to be a potential indicator of a greater volume of blood loss [95].

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Complications of Total Hip Arthroplasty

Abstract Despite the worldwide success achieved by total hip arthroplasty (THA), this procedure is nonetheless associated with a variety of complications that could have deleterious outcomes on the patient's life. The effects of the surgery are frequently evaluated using the patient-reported outcome measures (PROMs), which are short questionnaires used to assess the health gains perceived by the patients through an analysis of a variety of factors, including pain, range of motion, and ability to return to their daily activities following the major orthopedic procedure. The article reviews some of the main complications and adverse events associated with the THA procedure, providing a detailed description, the perceived health status of the patients evaluated using the PROMs, and data regarding the potential factors increasing the incidence associated with each individual complication.

1 Introduction

The total hip arthroplasty procedure is performed to ultimately relieve the pain experienced by the patients, as well as improve their range of motion and lead to a better quality of life [1].

However, the surgery could potentially lead to several adverse events that negatively influence the outcome of the procedure, decrease the overall satisfaction of the patient, and substantially increase the costs correlated to healthcare [2]. Such challenges include postoperative task deficit, as well as other severe complications, including loosening of the implant frequently leading to dislocations, fractures, nerve damages, postoperative delirium, and heterotopic ossification [3]. In some instances, these challenges could lead to revision surgery, which is a particularly complex procedure requiring thorough preoperative planning [4]. The aforementioned complication could be associated with the employed surgical technique, the perioperative medical treatment, and the postoperative management and rehabilitation; furthermore, they could also arise as a result of the symptomaticity of the patient—such as the excessive wear of the prosthetic component [2].

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Patient-reported outcome measures (PROMs) are among the most used evaluation methods to assess the perceived health status of the patient following the surgical procedure, also providing useful information for the evaluation of the overall effect of the intervention.

2 Patient-Reported Outcome Measures

PROMs not only assess the functional outcomes of the procedure—which include the physical, social, and cognitive capabilities of the patient—but also examine the adverse events correlated to the surgery (such as tiredness, uneasiness, and pain) and multidimensional constructs, which specifically encompass the health-related life quality [5]. A wide variety of PROMs is being used to assess the perceived health gains of the patients undergoing THA, some of which include the Harris Hip Score (HSS), the Oxford Hip Score (OHS), the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC), the modified d'Aubigne and Postel Method, and the EQ-5D-3L questionnaire.

The HSS is a questionnaire consisting of four subscales that add up to 100 total points, with higher scores indicating a greater degree of functionality perceived by the recently operated patient. The first scale measures the intensity of the pain experienced by the patient (up to 44 points), and the second one is composed of the activities performed on a daily basis and the gait (47 points). The third and the fourth scales measure the absence of deformities (4 points) and the range of motion (5 points), respectively [6].

The OHS is, instead, based on the responses given by the patients to a total of 12 questions regarding daily activities. Each of the 12 questions presents five options, and the ones corresponding to normal functionality are associated with a score of 1, which then increases proportionally up to 5 based on the degree of perceived disability. The scores of all the answers are then summed, thus yielding a minimum score of 12 points—indicating normal functionality—and a maximum score of 60, which indicates grave disabilities [7].

The WOMAC includes three portions. The pain subscale is composed of five questions, the stiffness part is characterized by two questions, and the physical function section—the most substantial of the three—is composed of 17 questions. Each question is scored on a scale from 0 (none) to 4 (extreme), and the scores obtained for each of the three subscales are then added together. The minimum score obtained for each subcategory is 0, whereas the maximum score corresponds to 20 for the pain section, 8 for the stiffness subscale, and 68 for the physical function portion [8].

The modified d'Aubigne and Postel Method is extremely useful in the examination of pain, mobility, and gait. The various items are evaluated on a scale from 1—indicating the worst condition of the patient—to 6, which indicates their best condition, and are then summed to yield a minimum of 3 points and a maximum of 18 [9].

Finally, the EQ-5D-3L questionnaire comprises a total of five dimensions, each presenting ranging from no problems (level 1) to extreme problems (level 3). The five dimensions are mobility, daily activities, personal care, discomfort/pain, and anxiety/depression [10].

3 Postoperative Task Deficit

Despite the substantial improvements of the affected patients following the THA surgery, results show that the recovery in the period ranging from 6 to 12 months is not analogous to the functionality observed in healthy individuals [11, 12]. In fact, the functionality of patients undergoing THA corresponds to approximately 70% compared to healthy individuals prior to the procedure and increases by 10% in the first 6 to 8 months following the surgery [11]. Among the most frequently used tools for evaluation of post-surgical outcomes, the patient-reported outcomes (PROMs) provide a detailed analysis of several areas of function through the administration of questionnaires [13], clinical evaluations estimate the functions of the body—including the range of motion of the hip joint—and medical imaging measures the various structures of the body, e.g., offset of the femur.

Moreover, the timed "up and go," or TUG, test is another frequently used test to denote the degree of motor functioning of the patients [14], and it consists of a practical test that analyzes multiple skills performed on a daily basis to ultimately evaluate the progress achieved during rehabilitation regarding mobility [15]. When used in the presurgical stage, this test functions as a reliable predictive indicator of the length of stay following the procedure, the ability to ambulate up to 6 months after surgery [16], and the risks of complications such as deep vein thrombosis [17].

3.1 Deficient Functional Task Analysis of Patients After THA

The goal of the study conducted in [18] was to use the TUG test to establish the point at which patients displayed substantial differences in terms of deficits compared to the healthy control group, both prior and following THA, and to analyze the variations of these stages after the surgical procedure. Moreover, the alterations and deficits recorded in the overall TUG time were also analyzed and compared to the corresponding data gathered for each distinct phase.

To achieve this goal, a total of 123 patients were included in the research, 71 of which were diagnosed with primary osteoarthritis of the hip and the remaining 52 were healthy individuals, assigned to the control group. Among the 71 patients diagnosed with OA, 38 were subjected to THA via the mini-invasive Rottinger approach—a lateral approach involving dissection of the deep fascia anteriorly to the greater trochanter and carried down until reaching the neck of the femur—[19]

the mini-posterior approach is applied to 29 patients [20], and 4 patients had the lateral approach surgery. A dual-mobility cup was implanted in all 71 cases.

In order to perform the measurements, a total of 35 reflective markers were attached over the entire integument of the patients, and their trajectories were calculated at 100 Hz using an eight-camera optoelectronic system, later filtered at 6 Hz using a fourth-order Butterworth design [21]. The participants were then asked to perform a specific set of actions at a self-selected speed, which included sitting on an armchair—with its seat positioned 47 cm off the ground—standing up, walking up to a line positioned 3 meters away, turning around, and walking back to the armchair before sitting on it. This evaluation was performed both prior and 6 months following the surgery in patients affected by hip osteoarthritis, whereas it was only performed once in the healthy control group.

Analysis of the results obtained with the TUG test before the surgery highlighted a significantly higher deficit, corresponding to −41% (the negative correlation indicating abnormal functioning), in the walking phase of the THA patients compared to the healthy group, which appeared to be the most significant deficit even 6 months after the procedure, but with an inferior mean, corresponding to −22%. The average times calculated during the TUG tests were 14.9 ±4.1 s prior to the surgery and 12.9 ±2.8 s 6 months following the surgery, thus displaying an overall improvement of 11%, nonetheless still presenting a higher average time—by 20%—compared to the control group, which performed the task in 10.7 ± 2.1 s. In general, patients undergoing THA displayed a substantial improvement in the performance of all the tasks of the TUG test. However, they still presented significant deficits when compared to the control group, thus indicating an enhancement in their functionality but a partial restoration of the latter by 6 months after the procedure [18].

4 Dislocations

One of the major complications following THR is dislocation, which substantially impedes the performance of daily tasks for recently operated patients and increases their dissatisfaction [22]. Approximately 60 to 70% of THA dislocations occur in the first 6 weeks after the surgical procedure, whereas only a small population percentage, around 1%, will incur in dislocation several years after the surgery, usually correlated to implant wear, destruction of the soft tissues, or infections [23].

The term dislocation refers to the loss of articular contact between the previously implanted artificial components of the joint, perhaps attributable to the failure in meeting biomechanical requirements to achieve complete stability of both the pelvis and femur [24]. Figure 1 shows the pelvic radiograph of a patient experiencing dislocation after the total hip arthroplasty procedure [25].

Dislocation could be caused by three mechanisms: malpositioning and loosening of the acetabular or stem components of the prosthesis, leading to unstable contact between the articular surfaces; muscular insufficiency of the patient, leading to an excessive range of motion; and contact between the bony femur and bony

Fig. 1 Dislocated hip after THA

pelvis, or between the neck of the femoral stem and the acetabular component, leading to primary and secondary impingement, respectively [24]. In terms of patient-related factors leading to instability and subsequent dislocation, a higher incidence has been indicated for patients affected by neuromuscular conditions, including cerebral palsy, muscular dystrophy, dementia, and Parkinson's disease. Additionally, in patients of 80 years of age or older, a higher risk has been attributed to sarcopenia—a disorder affecting skeletal muscles and resulting in a progressive loss of muscular mass—to the loss of proprioception, which substantially increases the risk of incurring in falls and potentially leading to dislocation, and noncompliance to the postoperative rehabilitation protocol. One of the procedure-related risk factors leading to implant dislocation is the elected surgical approach, as the methodology chosen to perform the surgical procedure has a direct impact on the stability of the operated joint. In fact, the posterior approach has been associated with higher dislocation rates compared to other conventional approaches, mainly because of the detachment of both the external rotators and the external joint capsule, whereas the transgluteal approach has been correlated with the weakening of the abductor muscles, attributed to the partial detachment of the gluteus medius. The alignment of the implants constitutes another major factor in the stability of the operated joint. Based on the Lewinnek safe zone, the desired measurements regarding the position of the femoral and acetabular cups correspond to an inclination of 40°± 10° and an anteversion of 10° ± 20°, and failure in meeting the aforementioned requirements will result in instability of the hip. The experience of the surgeon also affects the outcome of the procedure, as studies have shown that the level of experience acquired by the surgeon is inversely proportional to the risk of postoperative dislocation.

The incidence of dislocation is further influenced by the materials chosen for the prosthetic implant [24], as well as its design [23]. In fact, the service life of the components and the wear resulting from their constant friction are two of the main prosthesis-related factors ultimately leading to late dislocations [24]. In terms of implant design, several studies have indicated that the use of femoral heads with larger diameter substantially diminishes the risk of dislocation while simultaneously increasing the range of motion and jumping distance of the patient [26].

4.1 Transfer of Gluteus Maximus and Mass Graft (Capsulorrhaphy) for Hip Dislocation Prevention Following THA

The age of the patients, abductor weakness, female sex, and previous revision surgeries [22, 27] are among the main identified factors that could potentially increase the risk of dislocation, whose reported rate ranges from 1.7 to 4.8% following primary THA and significantly increases after revision THA (5.1–27%). In addition, the use of a femoral head with a size inferior to 32 mm was determined to be an ulterior risk element for re-dislocation, therefore suggesting the use of a larger head size to ultimately decrease the incidence of dislocation. Furthermore, the presence of medical comorbidities has been shown to have a significant impact on dislocation rates, particularly osteonecrosis of the femoral head (ONFH), mainly due to the intraoperative administration of corticosteroids, which result in a decreased rigidity of the tissues surrounding the surgical site, therefore allowing the patients to engage in activities foreseeing an augmented motion range compared to what they should supposedly undertake, thus increasing the likelihood of incurring in re-dislocation [27].

To prevent dislocation and in an attempt to increase stability, transfer of gluteus maximus to the femoral intertrochanteric region—to replace the abductor and thus cover the defects present within the pelvic structure—[28–31] alongside hip joint capsule enlargement, through the use of synthetic mesh, was performed. The procedure was then followed by patient education, who were instructed to avoid vulnerable positions such as flexion of the hip above a 90° angle, internal rotation beyond 0°, and adduction across the medial section of the body [32]. The previously analyzed procedure may ultimately aid in the prevention of re-dislocation of the hip; nevertheless, further assessments should be performed to corroborate the usage of mesh and gluteus maximus transfer for routine surgeries.

4.2 Dislocation and Revision Incidences in Patients Subjected to THA Receiving Lumbar Spinal Fusion Prior to or Following the Surgery

Lumbar spine fusion (LSF) could potentially increase the risk of impingement and dislocation [33–35] because of the substantial decrease in the mobility of the hip joint following its performance, thus causing an alteration in the biomechanics of the femur in an attempt to reestablish appropriate balance and stance. Such limitations in mobility could occur in two forms, namely, struck-standing and struck-sitting. Struck-standing alludes to the excessive rotation of the anterior aspect of the pelvis and excessive inward curvature of the spine in the lumbar region while sitting, potentially leading to increased incidence of impingement of the anterior aspect and subsequent posterior dislocation of the head of the femur when the hip is flexed [36]. Instead, struck-sitting refers to the excessive rotation of the posterior aspect of the pelvic and flattening of the normal curve of the lumbar region of the vertebral column while standing [37], a phenomenon that heightens the incidence of impingement occurring posteriorly and ensuing dislocation of the femoral head anteriorly when the hip is extended [35, 36].

The main goal of the study performed in [38] was to ascertain the presence of hypothetical differences in the occurrence of dislocation and revision surgery in THA performed either prior to or following LSF. A total of five studies were included in the analyzed review, comprising 43,880 LSFs performed prior to the surgery and 25,558 executed after. A higher incidence of dislocations occurring in the early postoperative period was detected in [39] for patients subjected to THA following LSF—2.8% occurring in the first 90-day period and 4.6% within 2 years—attributed to the already limited mobility of the hip joint, later subjected to the insertion of a new prosthetic implant which inflicted ulterior damage to the soft tissues and muscles of the patients. Instead, patients receiving LSF after undergoing THA displayed a higher incidence of late dislocations, with a percentage of 0.2% occurring within the first 90 days and 1.7% at 2 years, thus signaling an 8.5-fold increase [39]. A longer average time to dislocation was observed in [40] when THA was performed before LSF—15.33 ± 5.86 months—compared to when it was executed after, 11.71 ± 18.23 months.

In another study, a decreased incidence of revision surgeries determined to be required after dislocation as the time separating THA and ensuing LSF augmented, with a percentage of 24% after 1 year, 23.8% after 2 years, and 20% after 5 years, thus highlighting the importance of the healing process of both the muscles and soft tissues following THA [41]. Other studies assert the increased limitation in the mobility of the hip joint when LSF is executed after the THA procedure, because of the ulterior rigidity caused by the vertebral fusion [42] (which increases the incidence of dislocation), thus additionally stressing the substantial advantages in terms of biomechanics when the condition affecting the vertebral column is corrected prior to performing THA, a decision that allows for the optimal determination of the position of the acetabular cup, and increasing the stability of the joint [42].

In general, regardless of when it is performed, lumbar spinal fusion is observed to constitute a substantial risk factor for dislocation in THA [38].

4.3 Dislocation Incidences Following the Direct Anterior THA Approach

The DAA surgery is generally performed with the patients positioned supine, to simplify the utilization of intraoperative imaging, which substantially increases the accuracy of the installation of the acetabular component and the restoration of the length and offset of the leg. The supine position of the patients is correlated to decreased alteration in the position of the pelvis within the surrounding soft tissue, which allows for the comprehensive visualization of the acetabulum even without the use of technological instruments, ultimately enabling more precise placement of the acetabular component of the prosthesis compared to other approaches performed with the patient positioned laterally [43].

The DAA is associated with a decreased incidence of dislocation [44, 45], alongside inferior instability compared to other approaches, such as the direct posterior (DP), the anterior lateral (AL), and the direct lateral (DL) [44, 46–49]. Nonetheless, the DAA presents an abrupt decrease in the learning curve for the surgeons performing such procedure after operating via other approaches, a factor that could potentially increase the occurrence of periprosthetic fractures, as well as other complications [50–52]. Similarly, an increased rate of periprosthetic fractures has been indicated for surgeons who had already surpassed the initial learning curve.

One of the major risks of dislocation is the decreased mobility of the spinopelvic complex, which modifies the kinematics of the acetabulum and the femur [53–57], and ultimately raises questions regarding the appropriate surgical approach to perform for managing such issue.

The objective of the study performed in [58] was to assess the incidence of dislocation in a large, nonselective cohort of patients subjected to THA through the DAA, later subdividing the results based on the characteristics of the patients, risk factors, and surgeon factors. Moreover, the incidence of complications, reinterventions, and revisions was also analyzed.

All the surgeries were performed by seven surgeons, and no patients were excluded due to comorbidities or factors that could have potentially increased the risk of instability. The patients who experienced dislocations following the surgery were then examined to establish their body mass index (BMI), the time at which such dislocation occurred—categorized as early or late dislocation by reference to a 1-year threshold—as well as its direction, the position of the acetabular prosthetic component, measured using the Lewinnek safe zones [59] and based on the last anteroposterior (AP) pelvic plain film obtained before the dislocation had occurred, and the need for ensuing revision surgery.

A total of 2831 hips in 2205 patients were included in the study, with an average age of 64.9 years, and a mean BMI of 29.2 kg/m^2. The scores obtained via the American Society of Anesthesiologists (ASA) classification was I in 96 cases (3.4%), II in 1728 (61.0%), III in 968 (34.2%), IV in 38 (1.3%), and V in one instance (0.04%); moreover, the average follow-up period after the surgery was 61.4 months. All the procedures were performed using hemispherical acetabular prosthetic components with hard-on soft bearings with no face changing, lipped, or constrained liners, and no dual-mobility constructs were employed. Forty-three hips (1.5%) were subjected to the insertion of a 28 mm head, while other insertions included a 32 mm head in 590 hips (20.8%), a 36 mm head in 1909 hips (67.4%), a 40 mm head in 288 hips (10.12%), and a 44 mm in only one hip (0.04%) [58].

The dislocation rate obtained at the end of the study corresponded to 0.46%, as the overall number of dislocations amounted to 13, 11 of which (0.38%) were defined as early—since they occurred before the aforementioned 1-year threshold—whereas the remaining two were traumatic in nature, and documented 902 and 1556 days following the surgery. Out of the 13 recorded dislocations, only five (38.5%) were subjected to revision because of the instability of the joint: one was resolved via an elevated lipped liner, two were subjected to modifications and ensuing installation of a constrained liner, and two sustained the revision of the femoral component because of prior installment of undersized femoral stems. The subdivision by age yielded an incidence of dislocation of 1.65% for patients under the age of 50, 0.62% for patients within the age range of 50 to 59, 0.43% between the age of 60 and 69, and 0.17% for patients over 75 years old, whereas no dislocations were reported in the age range 70–74; moreover, the dislocation rate evaluated for females was slightly higher (0.63%) compared to the one measured for men (0.24%). The dislocated hips were located within the Lewinnek safe zone for anteversion in 11 cases, whereas the acetabular component of the remaining two was in an excessively vertical position, which was measured at 55° and 54° of abduction. During revision surgery, a 32 mm head was installed in five hips, a 36 mm one was employed in six hips, whereas the 40 mm one was used in two cases. Only two dislocations were recorded in 666 patients presenting decreased mobility of the spinopelvic complex (0.30%). In both instances, the patients had been previously diagnosed with degenerative lumbosacral pathology (2/627: 0.32%), whereas one of the patient's experiencing dislocation had been also subjected to spinal infusion prior to the procedure (1/104: 0.96%). The incidence of dislocation was 1.14% after THA performed by surgeons in their learning curve, 0.15% when the procedure was performed by surgeons who had surpassed the learning curve, and 1.11% for a single surgeon—who had transitioned to the DAA after 15 years of practice—and had performed 8 out of the 13 procedures that then resulted in dislocation.

The incidence of periprosthetic fractures of the femoral bone amounted to 0.67% (19 instances), 7 of which occurred within the first month following the surgery (0.28%), whereas 14 occurred within the first 90 days, yielding an overall incidence of periprosthetic fractures of 0.86% in non-cemented constructs, and 0.14% in the cemented ones. Among other complications, surgical debridement and antibiotics were required in 12 hips (0.42%) following the superficial breakdown of the wound, and a total of 15 infections following the installation of the prosthesis were reported (0.53%), one of which took place within the first month, and five within 90 days (0.18%). Final recorded data indicated a reintervention rate of 1.94% and implant survivorship of 98.98% [58].

In summary, the results obtained in the analyzed study demonstrated a particularly low incidence of dislocation for the DAA, as well as fractures, periprosthetic joint infection, complications at the wound site, reintervention, and revision. Additionally, no differences in the dislocation rates of patients diagnosed with the pathology of the lumbosacral region were observed [58].

5 Metal Debris Complications of Dual-Mobility THA Implants Due to Acetabular Components' Corrosion

Patients at high risk of dislocation are presented with the option of undergoing THR with dual-mobility (DM) constructs, which consist of a small femoral head articulating within a mobile polyethylene liner that additionally articulates within a fixed acetabular shell. All the components of the previously described construct enhance the stability of the patient by increasing the head-neck ratio, jump distance, and range of motion [60]; however, the combination of products used contributes to the creation of a new interface that could potentially undergo corrosion and cause subsequent adverse reactions to metal debris (ARMD).

The systematic review conducted in [61] shows an estimated incidence of 0.3% of ARMD following modular dual-mobility (MDM) constructs, which is significantly higher compared to the one registered for non-metal-on-metal (non-MOM) primary hip replacements, corresponding to 0.032% [62]. The obtained results indicate a calculated median of dislocation of 0.8% and a percentage of 3.3% for revision rates. The mean calculated levels of serum cobalt postoperatively corresponded to 0.81 μg/L, while it was slightly lower compared to the one calculated for chromium, which was estimated to be around 0.77 μg/L, and about 1.8% of the patients included in the study displayed measurements of ≥7 μg/L—the cutoff value recommended by the Medicines and Healthcare products Regulatory Agency—for cobalt or chromium [61]. Despite the elevated levels of serum ions, there is currently no evidence that correlates the latter to an increased probability of adverse reactions to metal debris or worse clinical hip function scores. The only indication thus far is to address the postoperative care process with meticulous attentiveness [61].

5.1 Constrained Acetabular Liners' Outcomes and Survivorship upon Primary THA and Revisions

Some of the most frequently adopted techniques for the treatment of hip instability include revision of the implant for misalignment, the increase of the size of the femoral head—usually leading to the substitution of the polyethylene liner—to achieve a greater range of motion (ROM) without incurring impingement, or conversion to dual-mobility or more constrained acetabular liners (CALs) [63–66].

CAL requires the input of greater force to lever out the head of the femur, which is mechanically captured by the implant and results in a decreased motion of the primary arc of the hip, which could result in early impingement. Highly constrained liners have been shown to transmit higher strain across the various interfaces of the implant, ultimately augmenting the risk of polyethylene wear, aseptic loosening, and recurrent dislocation [66–69].

The superior-ROM CAL is instead characterized by a constraining mechanism granted by a polyethylene liner extending past the middle part of the head of the femur. The reduction of the head necessitates a "snap" into the liner, and the mechanism is protected by a locking ring placed around the rim of the liner which decreases the opening of the cavity. The additional polyethylene structure present in the insert significantly expands the area of contact of the acetabular component with the femoral head, ultimately preventing the latter from displacing [70].

The tripolar CAL's constraining mechanism is instead granted by a bipolar component stabilized through a locking mechanism located on the peripheral ring [71].

The study conducted in [72] aimed to determine the most frequent complications deriving from the usage of CALs, as well as dislocation rates and survival of the implant compared to other methods.

A total of 37 studies were analyzed, including 4152 hips. The average age of the patients at the time of the surgery was 69.7 years, and the average follow-up period was 6.9 years.

The results indicated an overall complication rate of 22.2% [69, 71, 73–107], with an incidence of dislocation corresponding to 9.4%, 5.2% for aseptic loosening, 4.6% for infection, and 3.4% for fractures occurring after the implantation of the prosthesis.

The reintervention rate indicated at the time of the follow-up corresponded to 20.1%. Dislocation was the major factor leading to reintervention, with an incidence of 9.2%, followed by infection, which occurred in 4.6% of the cases. Moreover, the reintervention rates for aseptic loosening of the acetabular cup corresponded to 2.9%, whereas it was slightly lower for stem aseptic loosening, 1.5%. Finally, breakage of the implant and occurrence of fractures accounted for 2.2% of the overall reoperation rate, whereas infections accounted for 4.6% of the reinterventions. Overall, about 79.9% of the CAL implants didn't result in any reinterventions after the average 6.9 years to the follow-up procedure.

The preoperative Harris Hip Score (HHS) were recorded in 9 [73, 76, 77, 81, 90, 91, 98, 99, 103], out of the 37 included studies, whereas the postoperative HHS was indicated in 16 [71, 73, 76, 77, 81, 83, 88–93, 96, 98, 99, 102, 107], with an average score corresponding to 73.4 points. Moreover, the nine studies that included data for HHS both before and after the procedure indicated an improvement from an average score of 39.3 points preoperatively, to a mean of 72.5 postoperatively. Two studies [83, 91] indicated a mean Oxford score recorded preoperatively of 16.8, whereas four studies [82, 85, 90, 93] observed a mean score of 36.9 at the latest follow-up. Moreover, the Western Ontario and McMaster Universities Arthritis Index was reported both preoperatively and postoperatively in the study performed in [96], indicating an average score of 54 before total hip replacement, and of 63.8 after the surgery. Finally, the study performed in [94] gathered the modified d'Aubigne and Postel Score both before and after the surgery, indicating a preoperative score of 5.3 and a postoperative score of 9.6.

In summary, the CAL implants are particularly effective in the treatment of patients presenting a high risk of instability and dislocation after the primary THA procedure or revision THA. This statement supported by the overall reintervention rate of 22.2% indicated in the study which was, however, higher compared to other implants such as dual-mobility acetabular cups or femoral heads presenting a larger diameter. Despite the higher percentages indicated for complications, the functional scores substantially increased after the installation of the CAL implants, which also showed a survivorship rate of 79.9% after 6.9 years [72].

6 Periprosthetic Fractures

Periprosthetic fractures (PFs) have been identified by the UK National Joint Registry as the third most common cause of revision, with an overall incidence rate of 3.5% after primary THA, which is predicted to further increase at a rate of 4.6% per decade over the next 30 years [108]. Moreover, they have been associated with a particularly high mortality rate, corresponding to 17.7%, and approximately 80% of the fatalities occur within the first 3 months after the surgical procedure [109].

PFs can be subdivided into early and late fractures, depending on when they occur after the initial THA surgery. Early PFs occur within the first year following the procedure, whereas late fractures occur after the first 12 months [110]. Such fractures are typically diagnosed via conventional radiographs, which allow for the visualization of radiolucent lines around the prosthetics or the cement component of the implant, or via computed tomography, which provides more detailed imaging of the fracture lines and hypothetical loosening of the implant [111]. The surgical procedure aiming at the correction and treatment of PFFs is associated with relatively high complication rates, mainly due to the age of the patients and to the presence of substantial comorbid diseases and requires, therefore, expertise in both revision THA and fixation of the fracture [108].

There are a variety of factors that predispose the patient to the development of PFs, among which the female gender, the presence of comorbidities—such as rheumatoid arthritis—the advanced age, and the presence of vast osteolytic lesions, which refer to areas of substantial loss of calcium from the bone, in younger patients with elevated levels of physical activity [110]. In addition, osteoporosis has been categorized as an independent factor for the development of PFs, as the presence of this disease substantially weakens the bones, increasing the likelihood of incurring in fractures [111].

The Vancouver classification is the most widely used method for the categorization of femoral periprosthetic fractures, taking into account the location and pattern of the fracture, as well as the stability of the implant, and its eventual loosening.

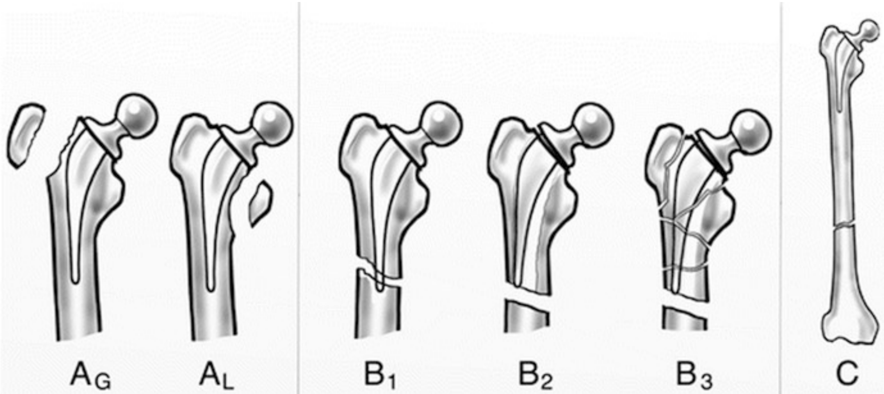


Fig. 2 Vancouver classification

Type A fractures occur in the trochanteric region and are further subdivided into AL, affecting the lesser trochanter, and AG, impacting the greater trochanter. Type B fractures occur around the femoral stem or slightly below it and are further subdivided into B1, in which the prosthetic implant remains well-fixed; B2, characterized by the loosening of the implant; and B3, in which the implant is loosened and the bone surrounding it presents relatively poor quality. Finally, the ones categorized as type C include fractures occurring well below the implant [112]. Figure 2 shows the categorization of periprosthetic fractures based on Vancouver classification [113].

6.1 Intraoperative Fractures During THA: Diagnosis and Management

The incidence of intraoperative periprosthetic fractures (IPPFx), as well as the potential risk factors, assessment, administration, results, and an overall estimation of the cost associated with these complications during primary THA, is studied in [114].

Primary THA has been associated with a rate of IPPFx ranging between 0.1% and 1% for cemented implants, while the same rate for the cementless procedure is significantly higher, corresponding to approximately 5% [115]. Other periprosthetic fractures could potentially occur at the acetabular component; however, these occur less frequently, as the reported incidence corresponds to 0.4% [115].

IPPFx have been associated with a variety of factors that could potentially increase the risk of incurring in such complications, including the increased age of the patients and female sex [116], both of which are primarily due to the decreased density of the outer surface of the bones.

The incidence of IPPFx has been reported to be particularly high for the THA procedure performed via the direct anterior approach (DAA), especially during the learning curve period of the surgeons [117, 118], mainly attributed to the significant stress exerted on the tendons attaching to the trochanteric region of the femur and on the femur itself, which are already subjected to substantial strain during the preparation of the femoral canal and subsequent impaction of the prosthetic stem component [119].

The most commonly used acetabular implants are cementless and have been categorized as hemispherical, peripheral self-locking—characterized by a rim larger than the diameter of the true cup by 1.8 mm—and elliptical, which have a peripheral flare [120], and the greater incidence of IPPFx has been associated with the elliptical peripheral self-locking acetabular components. As for the cementless femoral stems, the highest risk of IPPFx has been associated with type-2 implants, characterized by "fit-and-fill" stems and comprising about 90% of periprosthetic fractures, whereas the type-6 implants (anatomic stems) have been associated with a 10% risk, correlated to the variation in the geometry of the proximal femur, which could potentially impact the overall distribution of the mechanical strain [121]. IPPFx of the femur could occur during the compression of the trabecular bone during stem broaching—due to the geometry of the instrument, cutting, or pattern of the compaction tooth, alongside the elected technique for performing the surgery—or during the impaction process of the implant, due to the geometry of the femoral component, as well as the previous preparation of the femoral canal and the technique used for the procedure [122].

IPPFx prevention constitutes a key factor for the reduction of fatality rates and worse clinical results, and it could be achieved via a meticulous preparation of the surgical procedure, as well as a thorough evaluation of the potential risk factors. According to current guidelines, women of age 65 and older should be screened with dual-energy x-ray absorptiometry to determine the bone mineral density of the patient [123], whereas an assessment of the osteoporosis state should be performed for men [124].

During the analysis of the acetabulum to assess the presence of hypothetical fractures, suspicions might arise when the reamer size of the prosthetic component and the implant itself are significantly larger compared to the template established during the radiographic evaluation performed preoperatively, or if the implant is not stable after its placement, thus requiring further radiographic evaluations to determine whether the fracture is present. In that case, the entire fracture should be exposed, because fractures previously deemed negligible could potentially spread in the proximity or into the sciatic notch, ultimately impacting the stability of the implant and requiring removal of the latter to evaluate the morphology of the fracture and acetabulum. Nondisplaced fractures identified during the surgical procedure could be left in situ when the components are stable and fixed via the addition of acetabular screws, followed by a rehabilitation procedure to achieve optimal healing of the bone, which involves protected weight-bearing with progressive increase after a period ranging from 6 to 8 weeks. However, if the components are unstable, an examination of the integrity of the vertebral column should be performed. In case of severe discontinuity of the pelvis or substantial instability of the fracture, a column reconstruction plate should be utilized to ultimately stabilize the posterior aspect of the column, to then perform the conventional surgical procedure to reconstruct the acetabulum. However, if stabilization of the components is not achieved after the utilization of the column reconstruction plate, temporary fixation to allow for the healing of the fracture could be accomplished via the use of cup-cage or bone grafting techniques [125].

The process of femoral fractures' identification should be performed similar to the one used for the acetabulum, with particular attention given to the radiographs due to the difficulty in the diagnosis of nondisplaced fractures. Additionally, similar to the administration of IPPFx for the acetabulum, the procedure followed for femoral intraoperative fractures includes stabilization, prevention of its spread, preservation of the alignment of the prosthetic components, and stability [116]. The management of PPFx is further subdivided based on the type of femoral fractures. Fractures of the proximal metaphyseal region and perforation of the trabecular bone (type-A1) are commonly addressed via grafting of the bone, whereas nondisplaced, calcar fractures (type-A2) require further examination to ascertain the distal magnitude of the fracture. However, if identification of the fracture is achieved following the insertion of the prosthetic component, the latter should be extracted to allow for the examination of the metaphysis and diaphysis of the femur, and stabilization and prevention of spread could be achieved by utilization of metal or polymer cables along and distal to the fracture site [116]. Intraoperative diaphyseal fractures (type-B) are addressed through fixation with cerclage cables in case of stability; however, if the implant is not stable, a longer component is required to engage the diaphysis and ultimately prevent the spreading of the fracture. If the diagnosis is made after the surgical procedure, the management of the PPFx should be performed through the same weight-bearing process indicated for fractures to the acetabular component, thus via a protected weight-bearing with a progressive increase of 6 to 8 weeks. The incidence of fractures distal to the stem (type-C) is not as frequent for primary THA procedures; however, they could potentially result during the dislocation of the native hip due to excessive torsion or following trialing.

Calcar fractures occurring during the surgical procedures are usually addressed via the fixation of the lesser trochanter with cable or wire, a technique that has reported optimal clinical outcomes and decreased risk of spread of the fracture, alongside increased stability of the prosthetic implant [126]. Instead, fractures of the greater trochanter may occur in patients presenting osteoporosis or osteopenia, particularly during extension or removal of the broach after preparation of the intramedullary canal. However, such fractures do not necessitate fixation unless the stability of the implant is compromised, or displacement of the fracture occurs [127].

The overall cost of healthcare for patients experiencing IPPFx and PPFx, $30,114 and $53,669 respectively, was significantly higher compared to the one indicated for patients not experiencing any fractures during or after the THA procedure [114], thus emphasizing the importance of timely recognition and analysis of potential risk factors to reduce the incidence of complications [125].

7 Postoperative Delirium

Postoperative delirium (POD) is a complication that consists of a sharp decrease in the cognitive capabilities of the affected patients, resulting in a fluctuating state of confusion or disrupted psychological state [128], affecting up to 50% of the elderly undergoing orthopedic surgery [129]. Its overall incidence ranges from 9% to 87%, depending on the age of the patient and the degree of stress to which they are subjected during the surgery [130]; moreover, it is correlated to higher fatality and morbidity rates, alongside increased length of hospitalization and worsened surgical results [129, 131].

Postoperative delirium is often misdiagnosed; in fact, over 50% of the overall cases is often unrecognized by the clinical stuff; therefore, it is important to determine whether the patient is experiencing POD via the analysis of the three outlined motor types of delirium: irascible, uneasy, or agitated patients are probably experiencing hyperactive delirium, whereas hypoactive delirium could be diagnosed to patients displaying reduced motor activity, lethargy, or unawareness. Finally, the third motor type of POD consists of behaviors that present characteristics of both hypoactive and hyperactive delirium [130]. Moreover, an accurate diagnosis of POD could be achieved through the Confusion Assessment Method-Intensive Care Unit (CAM-ICU), or via the Mini-Mental State Examination (MMSE). The CAM-ICU is a reliable tool that combines the level of consciousness experienced by the patient with an examination of their mental status, whereas the MMSE allows for the evaluation of cognitive dysfunctions, as well as the monitoring of the fluctuations of the patient [130].

Besides the age of the patient, there are a variety of risk factors associated with the development of delirium following orthopedic procedures, which include the presence of comorbid diseases, psychopathological symptoms, functional impairment, and dementia [130].

This condition could be potentially prevented via specific interventions, which include an orientation protocol, carried out by the clinical staff and aimed at helping the patient familiarize with the surrounding environment; a sleep protocol, to enable the patient to rest uninterruptedly during the night; an early mobilization protocol, to increase the range of motion of the patient via daily physical therapy; and a vision and a hearing protocol, allowing the patient to easily gain access to visual and hearing aids, respectively [130].

7.1 Delirium-Related Factors Impacting Patients Following THA and TKA

Surgeries such as hip and knee replacement are the most frequently performed procedures in the orthopedic field, primarily treating patients over 60 years of age and yielding positive outcomes in terms of pain reduction and improvement of functionality [132, 133]. Nonetheless, the incidence of complications—such as postoperative delirium (POD)—might affect the rehabilitation process, as well as the outcomes of the surgeries. Such complication is examined in [134]. The main goal was to identify potential factors leading to the development of POD in patients subjected to either hip or knee replacement surgery, to ultimately gather data that could aid in the elaboration of an optimum preoperative approach to decrease the occurrence of postoperative delirium. Twenty-two studies with an overall number of patients amounting to 11,934 were analyzed, and 1841 cases of POD were identified. The comprehensive rate of POD was 17.6%, with a slightly lower incidence following the knee replacement procedure (16.4%), and a higher one for the hip replacement surgery (18.8%), with a greater incidence following longer operational times, more elevated intraoperative blood loss, and administration of general anesthesia. The mean age of patients experiencing postoperative delirium was slightly higher—0.43 years—compared to the one indicated for the patients not incurring in such complication, and age was indicated to be one of the predictive elements for incidence of POD, with a combined odds ratio of 1.12 following adjustment for bias of the articles, mainly attributed to the stress experienced intraoperatively by the patients. Throughout the research, the cognitive abilities of the patients were determined using the Mini-Mental State Examination (MMSE)—a questionnaire consisting of 30 points—which indicated cognitive impairment when the obtained score resulted lower than 24. Eleven of the analyzed studies indicated a significantly lower MMSE score in patients affected by POD, ultimately establishing a correlation between decreased cognitive abilities and incidence of postoperative delirium. Other factors that could potentially lead to POD include cerebrovascular events, stroke, and other neuropsychiatric diseases such as dementia—mainly due to inflammation, stress, and damage to nerve cells [129, 135]. Moreover, disorders affecting the nervous system, such as Parkinson's disease, were also identified as potential risk factors for POD, alongside other psychiatric illnesses, and sleep perturbation. Eight studies signaled a higher incidence of POD in patients scoring 3 or higher in the American Society of Anesthesiologists' (ASA) classification. Similarly, five studies indicated higher scores in the Charlson Comorbidity Index (CCI) for patients experiencing POD compared to patients not affected by such disorder. Preoperative laboratory tests performed in some studies demonstrated an inferior level in overall proteins, albumin, and hemoglobin in patients affected by POD [134].

In conclusion, the advanced age of the patients undergoing hip or knee replacement is a potential factor leading to a higher incidence of POD, potentially correlated to changes affecting the neurotransmitters involved in stress regulation as well as the systems implicated in the transduction of nerve signals [136]. A greater risk of POD was indicated in patients obtaining a score greater than 3 in the ASA or overall higher scores in the CCI, suggesting that patients presenting reduced physical abilities were more prone to developing postoperative delirium. Individuals with preexisting cognitive abnormalities—including memory deterioration and disorders related to the identification of visual and spatial correlations between objects—[137] are at higher risk of experiencing POD, as well as the ones affected by neuropsychiatric disorders and cerebrovascular conditions. Moreover, patients subjected to knee replacement developed POD more often than the ones undergoing hip replacement, perhaps due to the longer duration of the surgical procedure, increased intraoperative blood loss, and greater pain postoperatively, which could potentially facilitate the generation of the delirious state [138]. Finally, patients receiving general anesthesia were more prone to developing POD, perhaps due to the decreased output of the cardiac muscle, alongside decreased blood flow to the central nervous system and subsequent vasoconstriction at the cerebral level [139].

8 Nerve Damages

The reported incidence of nerve damages ranges from 0.6 to 3.7% after primary THA, further increasing up to 7.6% after revision THA. Such injuries could be caused by a variety of factors, including compression, stretch, ischemia, as well as transection [140]. Figure 3 shows the nerves originating from the lumbar plexus [141].

Compression damages affect the structure of the nerve itself, as well as its vascular supply, and occur mainly during the perioperative stage of the procedure. Stretch injuries emerge primarily during the intraoperative manipulation of the patient, therefore during the dislocation—before the installation of the acetabular implant—or the leg-lengthening procedures. Neural ischemia, described as the insufficient blood flow to the nerve which causes the inability to meet its metabolic demands, typically results after prolonged compression, presumably as a result of the positioning of the patient. Finally, transection or laceration of the nerve is correlated to the direct trauma caused by the instruments used intraoperatively, therefore including scalpel, screws, retractors, and electrocautery [140].

Nerve injuries are diagnosed via a meticulous clinical assessment performed both prior and following the THA surgery. In fact, complaints of numbness or weakness by the patients could be indicators of previous minor damages to nerves that could potentially increase the risks of undergoing additional surgical procedures, whereas the diagnosis of nerve lesions or damages after the procedure is essential in the determination of most suitable treatment to be used for ultimately addressing the issue [142].

The main risk factors associated with nerve lesions following THA are the female sex, history of surgery, spinal problems, anatomic anomalies—such as hip dysplasia or congenital dislocation of the hip—and excessive leg lengthening [143].

Because of its location, the sciatic nerve has been determined to be the most commonly affected nerve after THA, constituting about 90% of the cases [142]. The sciatic nerve is, in fact, located deep to the piriformis muscle, and then extends distally deep to the muscles of the gluteus and superficial to the external rotators, therefore making it extremely vulnerable during the placement of the retractors in the posterior aspect of the acetabulum, and during the traction, both anterior and lateral, of the femur [144]. The femoral nerve is the second most commonly damaged nerve during the total hip arthroplasty procedure [142]. It originates at the L2, L3, and L4

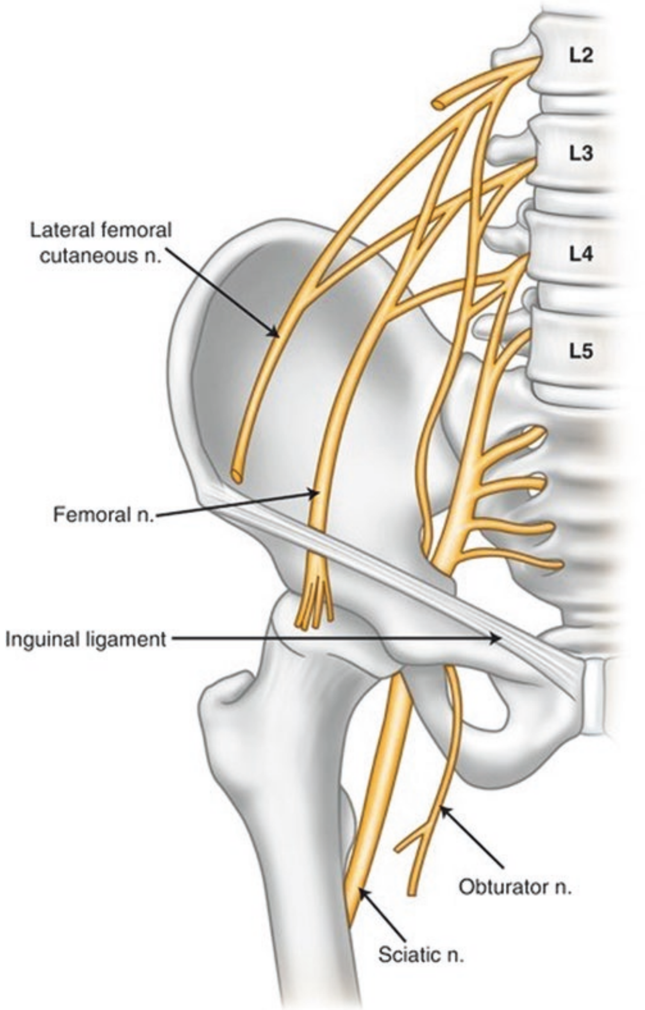


Fig. 3 Anatomy of the lumbar plexus

nerve roots and travels through the psoas and the iliacus muscles to access the thigh, a location that makes it particularly vulnerable to stretch damages [144].

As mentioned in the previous paragraph, the treatment of neural injuries is strictly correlated to the nature of the injury. If the cause of the injury is not immediately detected, no treatment to decrease the hypothetical compression or stretch of the nerve is advised, as it could recover without any interventions. If the lesion is discovered during the procedure, a prompt repair is usually performed in an attempt to minimize the damage; instead, if signs of severe lesions are detected during the postoperative assessment, further surgical intervention is required. The motor deficits correlated to neural damages are often treated with physical therapy, mainly aimed at strengthening the muscles involved in the dorsiflexion movement of the ankle, and the stretch antagonist muscles [142].

8.1 *Lateral Femoral Cutaneous Nerve Damage Rate via the Direct Anterior THA Approach*

One of the downsides of the DAA is the potential risk of incurring in damages to the lateral femoral cutaneous nerve (LFCN) [145]. The LFCN is a sensory nerve arising from the dorsal branches of the second and third lumbar vertebrae. It emanates from the lateral margin of the psoas major muscle and crosses the iliacus muscle obliquely to reach the anterior superior iliac spine while piercing the tensor fascia lata underneath the ligament of the groin and running both distally and laterally through the subcutaneous layer of the integument of the anterolateral surface of the thigh [146]. Damages to such nerve would result in numbness or burning sensation in the region of the anterolateral thigh, and, in some instances, it could result in dysesthesia—which is defined as stinging, burning sensation, or even pain experienced at the cutaneous level [147]. Multiple studies have indicated that the branches of the LFCN are inevitably impacted in about 32% of the procedures due to the variations in the anatomy of the patients [146], whereas others have reported no damages to the branches of the aforementioned nerve. Therefore, the primary aim of the research was to determine the risks correlated to LFCN damage following the execution of primary THA.

In order to do so, a total of 45 studies including 17,076 THA procedures were evaluated, reporting an overall incidence of LFCN lesions corresponding to 680 (3.95%). The included studies were subdivided into two groups. Group A consisted of 6 studies, analyzing 1113 cases and primarily focusing on the lesions of the LFCN occurring after the DAA, whereas group B comprised 39 studies, which evaluated a total of 16,741 cases and only mentioned such lesions, not providing a standardized definition of the latter [145].

Among the studies included in group A, only one provided an exhaustive description of the follow-up intervals performed on the patients and the evolution of their symptoms [148]. Two articles analyzed the patients at two [149] and three intervals [150], and the remaining publications evaluated the potential factors resulting in lesions of the LFCN, alongside the impact of the latter on the quality of life of the patients. Additionally, other studies analyzed the occurrence of LFCN lesions in independent groups at various intervals after the surgical procedure [151–153]. Out of the 1113 patients included in cohort A, a total of 345 lesions were reported, thus indicating a median occurrence rate of 28%. However, no calculations were made regarding the correlation of sample size and lesion rates because of the small number of articles included in this cohort. The incidence of lesions reported for group B was 2.00%, with a total of 335 cases observed in 16,741 patients, and a negative correlation of $r_s = -0.39$ was indicated between the population size and the number of affected patients. Moreover, a positive correlation of $r_s = 0.521$ was recorded regarding the incidence of lesions and year of the publication of the 45 analyzed articles, with recently published studies reporting a higher incidence of LFCN damages. In summary, the reported incidence of lesions to the LFCN ranged from 0 to 83%, indicating higher rates in the articles primarily focusing on such lesions and in the more recently published ones [145].

9 Heterotopic Ossification

Heterotopic ossification (HO), or heterotopic bone formation, is a disorder that foresees the transformation of mesenchymal cells into osteoblasts, which deposit calcium and minerals, therefore provoking the development of extraskeletal bone connective tissue in soft tissues or muscles and ultimately resulting in the progressive loss of mobility of the joint and functionality of the patient [154]. Figure 4 shows the evidence of HO after the THA surgical procedure.

Fig. 4 Sign of HO after THA [211]

Such condition could arise following injuries to the central and peripheral nervous systems, with an incidence rate ranging from 10% to 20% and from 20% to 30%, respectively [154], or traumas to the musculoskeletal system occurring mainly during orthopedic procedures such as THA, for which the reported incidence rate ranges from 2% to 90% [155]. The higher reported rate is commonly associated with comorbidities, which include hypertrophic osteoarthropathy, and idiopathic skeletal hyperostosis, as well as other factors such as the male gender, history of surgery of the hip joint, and age over 65 years [156–161].

The main indicators of early onset of the disorder, which include fever, localized swelling, or joint soreness, are particularly hard to distinguish from bone infections or thrombophlebitis—formally described as the formation of blood clots that subsequently block one or multiple veins [154].

The main methods exploited for HO prophylaxis are radiation, which slows down the mitotic process of the cells and hinders the differentiation of the cells within the mesenchyme region into osteoblasts [162], and nonsteroidal anti-inflammatory drugs (NSAIDs) [162–170], which inhibit the enzymatic activity of cyclooxygenase (COX) to ultimately regulate the generation of prostaglandins.

The decision regarding the appropriate prophylaxis administration is based on a variety of factors, including the action of the elected instrument and the possible deleterious outcomes. In fact, the immune system of patients at high risk for HO is subjected to a strong inflammatory response [171–173], thus favoring the use of NSAIDs to mediate such inflammation instead of other prophylaxis techniques such as radiation. Additionally, the likelihood of facing deleterious outcomes for a designated prophylaxis protocol might eliminate its use. For example, the use of COX-II selective or other nonselective NSAID is inadvisable for patients presenting cardiovascular, renal, or gastrointestinal problems [174, 175].

9.1 Efficacy Comparison of NSAID and Radiotherapy for Prophylaxis of Heterotopic Ossification on High-Risk Patients After THA

The main aim of the study performed in [176] was to examine the effects of radiotherapy and NSAIDs in high-risk patients previously subjected to THA, alongside of comparing the effectiveness of nonselective NSAIDs and COX-II selective NSAIDs [176].

The severity of HO observed in the patients was categorized into none, mild, and severe, corresponding to 0, 1–2, and 3–4 respectively, using the Brooker classification scale. Moreover, a similar categorization was used in studies not employing the aforementioned classification scale, in which 0 corresponded to none, 1–2 corresponded to faint, and 3–4 corresponded to widespread.

For the 37 articles analyzed, with a total of 8653 patients, 5043 of which were treated with NSAIDs (58.28%), 1260 received the radiotherapy (RT) prophylaxis (12.56%), and the remaining 2350 didn't receive any treatment (27.16%).

The low-risk population was analyzed in 24 out of the 37 publications, including a total of 4302 patients treated with NSAIDs, and 2124 not receiving treatment. The results obtained in these studies reported the lack of formation of HO within a range of 47.3% and 90.4% of the overall study sample, mild formation was observed in 2.8–52.7%, and severe formation in none to 10.4% of the patients. The studies including a control group not receiving any treatment reported a range of 21.4% to 68.8% of the study sample not experiencing HO formation, whereas mild formation ranged between 8.3% and 55.6%, and severe formation was between 3.2 and 32.1%.

The remaining 13 studies analyzed a population at high-risk for HO, 4 of which included NSAID prophylaxis, 12 RT treatment, and 4 integrated a control group not receiving treatment. NSAID treatment was administered to 741 patients, RT prophylaxis was performed on 1260, and the control group comprised 226 patients. The results reported in the studies evaluating RT prophylaxis indicated a range of 28.6% to 97.4% of patients not developing HO, mild HO formation was indicated in 1.9% to 66.7% of the population, and severe formation was observed in 0% to 11.9% of the sample size. The studies including NSAID treatment reported a range of 76.6% and 88.9% of the overall population not developing HO formation, mild formation was between 11.1% and 23.4%, and severe formation was between 0% and 1.8%. Additionally, the publications integrating control groups reported a range between 15.8% and 73.6% for lack of formation of HO, mild formation ranging from 26.4% to 68.5%, and severe formation occurring in the range of 0.0% and 42.1% of the population.

With regard to the effectiveness of the NSAID treatments used for the studies, the incidence of risks leading to the development of HO after the THA procedure following administration of COX-II and other nonselective NSAID drugs was not statistically significant.

The patient-recorded outcomes were reported in 5 of the 37 included studies, 3 of which used the Harris Hip Score (HHS)—2 analyzed the outcomes following NSAID prophylaxis and 1 reported the outcomes after RT treatment [177–179]—and 2 used the Marie d'Aubigne, one of which included the outcomes following NSAID treatment, whereas the other one analyzed the outcomes following both RT and NSAID prophylaxis.

Out of the five aforementioned studies, four reported no significant differences in terms of patient-reported outcomes between the cohort subjected to treatment and the control groups when the occurrence of HO was not statistically different [177, 179–181]. However, the only study reporting a significant difference in the occurrence of HO between the two groups also indicated a statistically significant difference in the HHS scores recorded after the THA surgery [178].

In summary, the treatment with NSAIDs reported a lower occurrence of formation of HO after the surgical procedure in patients presenting both high- and low-risk compared to the RT prophylaxis modality and the lack of treatment for the control groups, mainly attributed to the anti-inflammatory action of the administered drug. Moreover, the administration of COX-II and nonselective NSAIDs' treatments didn't display a statistically significant difference. Finally, the augmented severity of HO was correlated with decreased scores for patient-reported outcomes, primarily due to the decreased range of motion and functionality of the patients experiencing such condition [176].

10 Revision THA

Revision total hip arthroplasty is performed in instances if the prosthesis implanted during the primary THA procedure fails. The expected lifespan of the artificial joint is 10–20 years, after which the prosthesis won't result as efficacious and consequently lead to the requirement of revision surgery; however, there are a variety of factors that substantially decrease the implant's lifespan. Such factors include dislocation, mechanical failure, and infection [182]. Recurrent dislocation could be potentially caused by the misalignment of the femoral and acetabular components, weakness of the muscles that surround the hip, or traumatic events, which ultimately cause the head of the femur to displace out of the acetabular cup. Mechanical failure is, instead, commonly correlated to wear, which is caused by the continuous friction between the prosthetic components and results in the detachment of small portions of the implant. It is, therefore, particularly common in younger patients with increased levels of physical activity. The consequence of the detachment of such particles is a strong response generated by the patient's immune system, which could lead to osteolysis (the gradual destruction of the bone tissue surrounding the prosthesis) and the subsequent loosening of the implant, which will cause further loss of bone due to its excessive movement within the surrounding specialized connective tissue. Another form of mechanical failure is breakage, which is often the result of traumatic events such as falls or motor vehicle accidents. Finally, infections of the prosthetic implant could be caused by bacteria entering the bloodstream from any location within the body and will result in localized hip pain and fever [182].

The revision surgery consists of the removal of the previously implanted prosthesis while simultaneously preserving the surrounding bone. Moreover, if cement was employed during the primary THA procedure, the removal of the latter is performed alongside the implant removal. This passage is followed by the preparation of the bony surfaces of the pelvis and the femur, in order to properly accommodate the revised implant. In cases of excessive bone loss recorded, bone grafts or metal augments are used to compensate for the lack of bone connective tissue. The insertion of the new implant is often accompanied by the addition of several screws to maintain the newly positioned acetabular cup in place until the bone tissue is formed. Revision THA is a particularly complicated procedure, and it could possibly give rise to a variety of complications, including ensuing dislocation, infection, formation of blood clots, loosening of the implant, and lack of attachment between the reamed bony surfaces and the newly implanted prosthesis [4].

10.1 A Practical Performance of Revision THA in Low-Resource Settings

One of the main concerns regarding the THA procedure is the survivorship of the prosthesis, which is expected to endure for 15 years in about 89.4% of the patients, to then decrease to 70.2% of the patients after 20, and to 57.9% after 25 years [183]. Therefore, considering the decrease in the average of the patients undergoing such procedures, the overall percentage of revision surgeries is predicted to increase over the years [184].

Jehovah's witnesses are part of a Christian denomination that, because of their literal interpretation of the Bible, refuse to accept blood, thus creating a variety of issues when requiring surgery.

The case study performed in [185] describes the revision THA procedure performed on a Jehovah's witness in a low-resource hospital in the Caribbean. The patient, 61 years old at the time of the surgery, was subjected to revision THA 4 years after the primary procedure required for post-traumatic osteoarthritis resulting from a motor vehicle accident, which caused a combined injury of the acetabulum and the pelvic ring.

Prior to the surgery, his blood examinations were within the normal parameters, displaying hemoglobulin levels of 14.1 g/dL, serum creatinine of 0.96 mg/dL, C-reactive protein of 7.8 mg/dL, and rate of erythrocyte sedimentation of 12 mm/h. The procedure was performed under general anesthesia via a modified Hardinge approach, practiced with utmost care to prevent the removal of excess tissue during the development of the surgical planes.

Following dislocation of the hip, the femoral stem was easily removed, and synovial fluids, alongside samples of the tissues obtained from the femoral canal, were collected for further analysis. An isolated femoral revision was then performed after confirming the stability of the acetabular cup, notwithstanding its eccentric wear and excessive anteversion.

Following the removal of the excess heterotopic ossification (HO) on the soft tissues surrounding the posterior aspect of the acetabulum, rotation of the hip was performed to enable access to the femoral canal, which was subsequently rinsed and subjected to the cemented insertion of the same femoral stem. However, the joint resulted unstable, presumably because of the excessive anteversion and wear of the acetabular cup, alongside the laxity of the tissues following the removal of the HO, thus leading to the revision of the acetabulum with a cemented all-polyethylene cup.

Before the installation of the cup, the stability of the acetabular cage was confirmed, and 2mm holes were drilled to facilitate the interdigitation of the cement used in the procedure. The cup was then inserted and cemented, with an abduction angle of 40° and an anteversion of 10°, and a femoral component with a 36 mm head and 8 mm neck was used. After the installation was completed, the wound was then soaked for a total of 3 min with dilute povidone-iodine solution. Moreover, prior to the suturation, a meticulous examination with a layered watertight approximation of the soft tissues was performed to locate any potential bleedings.

After the surgery, the patient was administered with an intravenous antibiotic for a total of 5 days (cefuroxime 1.5 g, three times a day), and anticoagulants (rivaroxaban, 10 mg daily) were administered 24 h following the procedure, corresponding to the beginning of the mobilization procedure. Despite the low hemoglobin levels recorded postoperatively (9.8 g/dL), the patient disclosed minimal pain and was able to continue his physiotherapy cycle [185].

Hemoglobin optimization performed preoperatively is among the various suggestions presented to successfully perform revision THA in a low-resource setting. In fact, this technique is particularly useful for the elimination of the origins of blood loss and the maximization of the production faculty of hemoglobin before the procedure. Moreover, natural erythropoiesis is strongly advised via the daily intake of supplements of 325 mg of ferrous sulfate (three times a day), 500 mg of vitamin C (two times a day), 1000 mcg of vitamin B12, and 1000 mg of folic acid (once a day) [186].

Hypotensive anesthesia constitutes another key technique because it allows for the minimization of bleedings occurring intraoperatively via the reduction of blood pressure. The technique suggested in the [185] aimed at decreasing the mean arterial pressure by 30%—ultimately maintaining systolic blood pressure within 60 to 80 mmHg—and involved the use of heavy 0.5% bupivacaine, without morphine in the primary cases, alongside an epidural catheter, later removed for revision procedures once the surgery was completed. However, in some instances, patients could refuse the administration of neuraxial anesthesia, therefore requiring the injection or inhalation of propofol with either sevoflurane or isoflurane.

The third suggestion involves meticulous planning of the procedure, to avoid unpredictable complications during surgeries in which the transfusion of blood does not represent a viable alternative, followed by the administration of a 100 ml local analgesic cocktail—composed of 17.5 ml of 0.5% bupivacaine, 30 mg of ketorolac, 500 mcg of adrenaline, 750 mg of cefuroxime, and normal saline—into the soft tissues to ultimately decrease the blood loss. Moreover, thromboprophylaxis should be started 24 h following the surgery—unless unsuitable—via thromboembolic deterrent stockings, alongside early manipulation and aspirin (81 mg, administered twice a day).

Finally, the administration of 1 g of tranexamic acid intravenously, both during the incision and after the suture, has been shown to be particularly effective to achieve the reduction of blood loss after surgery without increasing the incidence of thromboembolic events [187].

10.2 Dual-Mobility Implant Utilization for Revision THAs

Revision THA (R-THA) is considered a particularly complicated procedure, characterized by technical complexities, as well as increased incidence of complications, especially when compared to primary THA [188]. Aseptic loosening and instability of the prosthetic components are among the main factors leading to failure of R-THA, caused by a variety of aspects including impingement of the prosthesis on the bone, decreased quality of the bone and surrounding soft tissues, and misalignment of the implants, specifically regarding acetabular and femoral offset, which have been respectively defined as the distance separating the center of the head of the femur and the true acetabulum, and the distance separating the center of the head of the femur and its axis [189, 190].

To decrease the incidence of dislocation and simultaneously increase the stability of the joint, dual-mobility (DM) implants are being used more frequently, as they are characterized by a large polyethylene liner in correspondence to the internal bearing—the point of articulation between the polyethylene and the proximal head of the femur—and do not result in increased limitations at the interface between the bone and the implant, further ameliorating the load dispersion interface [191, 192]. Figure 5 illustrates a conventional dual-mobility cup used combined with a cementless stem revision [193].

Numerous studies have indicated the disadvantages related to the use of DM including intraprosthetic dislocation (IPD) of the bearing surfaces, wear increment of the polyethylene (PE) leading to aseptic loosening, and higher incidence of infection; however, such complications are less common in new-generation DMC and PE [194, 195]. Therefore, the study performed in [196] aimed at gathering information concerning the DMC employed for R-THA.

A total of eight articles including 1777 revision THA procedures were examined with 49.9% including the use of a DM acetabular cup and the remaining

Fig. 5 An example of a DM implant

procedures completed using standard fixed-bearing (FB) implants. The average age of the patients ranged from 57 to 73 years, and the percentage of women was slightly higher (53%) compared to the one indicated for men (47%). The average follow-up period after the procedure ranged from 12 to 60 months for all the examined articles.

The data gathered regarding the survival of the implant reported a risk ratio of 1.08, specifically 1.12 for the FB cup and 1.05 for the DM implant, thus indicating a statistically significant survival rate favoring the DM cohort. Similarly, the recorded data relative to the incidence of dislocation indicated a risk of 0.13 for the DM group and 0.37 for the FB group, with an overall risk ratio of 0.22, and data for aseptic loosening revealed a decreased risk for the DM implants, corresponding to 0.29, compared to the one recorded for the FB group, with a comprehensive risk of 0.51. No statistically significant differences were identified between the two analyzed cohorts when comparing the incidence of infection, which was measured to be 0.94 overall.

In summary, the utilization of DM implants for revision surgery is more effective compared to standard FB cups, specifically regarding the survival of the implant and incidence of dislocation, whereas no significant differences were observed in terms of increased risk of infection between the two examined implants [196].

10.3 Intrapelvic Pseudotumor Occurrence with Deep Vein Thrombosis by Using a Metal-on-Metal Bearing Surface Implant Following THA

The use of metal-on-metal (MoM) implants—characterized by a metal femoral head directly articulated with a metal acetabular cup [197]—was particularly widespread in the late 1990s, but was then gradually abandoned because of the greater incidence of revision compared to other implants [198], which is currently thought to be correlated to the adverse reactions stemming from the metal debris [197], potentially triggering an inflammatory reaction, alongside necrosis of the surrounding tissues, ultimately resulting in the formation of a pseudotumor and subsequent compression of the adjacent nerves [199]. Figure 6a shows the signs of corrosion at the taper junction of the femur of a MoM implant. Figure 6b shows similar signs of wear at the taper of the stem [200].

The case report conducted in [201] presented a patient—a 61-year-old woman—that had undergone bilateral THR for osteoarthritis and Crowe I acetabular dysplasia. During the procedure, the left hip was subjected to the implantation of the Biomet MoM bearing prosthetic component, which yielded good results up to 15 years postoperatively. After 15 years, the patient started experiencing swelling on her left lower extremity, which was then diagnosed as an occlusive thrombus located within the posterior tibial veins and the left superficial femoral vein. Moreover, the patient presented a mixed cystic and a solid left adnexal mass, which

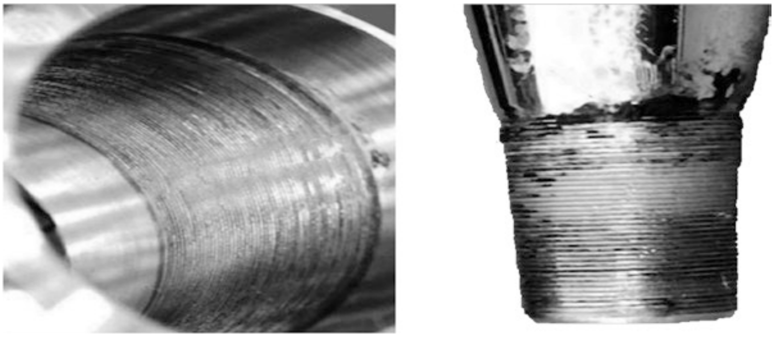


Fig. 6 (**a**) Left, wear at the taper junction of the femur, (**b**) wear at the taper of the stem

constricted the external iliac vein. Heparin drip was therefore started to treat her condition, and the patient was later discharged on apixaban. Despite the intake of medications, the patient's swelling was still extending throughout the left lower limb, nonetheless not resulting in pain or any other perturbations of her functions. After a close analysis of the computed tomography scan, a mass located within the left distal psoas muscle was identified. Further magnetic resonance imaging confirmed the presence of a heterogeneous mass arising on the anterior surface of the left prosthetic implant and extending through the inguinal canal to reach the retroperitoneum.

All the performed blood tests yielded results within the normal range; however, elevated levels of cobalt (5.9 compared to the 3.0 ng/mL used as reference), and slightly inferior but still significant chromium levels, corresponding to 2.7, were recorded compared to the reference value of 3.0 ng/mL.

The patient was therefore subjected to a surgical procedure divided into two stages: the first stage aimed at excising the pseudotumor through the pelvic retroperitoneal and the inguinal approaches, whereas the second part, sustained 3 months after the first surgery, consisted in the revision of the left implant through the posterior approach, and foresaw the installation of an active articulation dual-mobility femoral head.

During the first follow-up, performed 2 months after the second procedure, the patient only displayed a slight swelling in her upper thigh, perhaps due to the irreparable damage of the venous valves previously compressed by the mass. Additionally, a venous duplex ultrasound of the affected area was performed 1 month later, showing no trace of deep vein thrombosis, thus leading to the discontinuation of apixaban, which was then substituted by the intake of aspirin daily.

In summary, the use of MoM implants is associated with an increased risk of complications correlated to the excessive wear of the prosthetic component, which could lead to the dispersion of metal debris and ultimately result in an inflammatory reaction and subsequent necrosis of the adjacent tissues [201].

10.4 *Femoral Revision of THA Through the Direct Anterior Approach Interval*

Revision THA has been associated with high readmission (10%) and reintervention rates (22%), as well as complications occurring after the procedure (18%) [202–205], alongside higher morbidity and length of hospitalization and increased loss of blood [206]. Therefore, surgeons might decide to re-examine the approaches used during primary THA to determine whether or not changes to the previously used approaches should be introduced to perform femoral revision surgery, in an attempt to reduce the complications and the overall costs, as well as achieve better outcomes. Therefore, the main goal of the study performed in [207] was to evaluate the outcomes of revision THA on the femoral stem via the DAA interval, to ultimately determine the incidence of complications, such as dislocations, nerve damages, fractures, and infections, alongside examining the outcomes related to the clinical procedure and the functionality of the patients.

The surgical procedure was performed by four surgeons using the direct anterior approach, with an average operative time of 135 min. To perform such procedure, the incision was performed slightly posterior and lateral to the anterior margin of the tensor fasciae latae (TFL) muscle, starting distally to the anterior superior iliac spine (ASIS) and extending distally to allow access to the diaphysis of the femur while simultaneously curving the incision laterally for cosmetic causes. Once the margin was identified, the IT band was split longitudinally and subsequently mobilized from the vastus lateralis muscle, allowing the area surrounding the femoral diaphysis to be accessed and the connected muscle fibers to be dissected. Medial mobilization of the vastus lateralis was performed laterally and distally to the greater trochanter, sparing a muscular bridge between the vastus and the medial gluteus to guarantee adequate blood supply to the bones [208].

The DAA interval was performed on 149 patients, 16 of which were subjected to bilateral revision surgery. The average age of the patients was 68.9, the mean body mass index (BMI) was 28.6, and the average follow-up period after the surgical procedure was 4.2 years. In the period following the procedure, a total of six fatalities were recorded, but the causes were not related to the revision surgery or the hip, which resulted asymptomatic during the last performed follow-up.

The factors leading to revision surgery were aseptic stem loosening in 131 patients, fractures that occurred after the implantation of the prosthesis in 29 cases, stem misalignment in 1 case, and failure of the implant in 4 patients. Moreover, the primary THA procedure was performed through the direct lateral approach in 105 instances, the DAA in 59 cases, and the posterior approach only in 1 case.

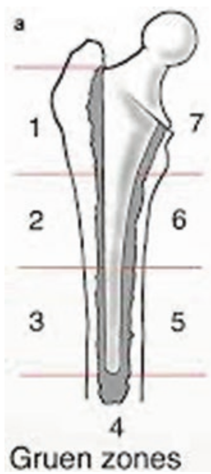
During the procedure, the endofemoral approach was performed in 156 hips, whereas the transfemoral approach was only used in 9 instances; moreover, ulterior revision of the cup was carried out in 52 cases. With regard to the femoral prosthetic component, a modular stem was employed for 52 hips, a standard stem was used in 113, and femoral allograft was utilized in 10.

Revision THA performed via the DAA in the analyzed study presented 14.5% of complications, alongside an overall number of ten hips (6.1%) requiring re-revision for dislocations, in six instances, and infections, in the remaining four (2.4%). Ulterior revision surgery performed on four of the six dislocated hips ultimately modified the acetabular cup into a dual-mobility one, whereas the remaining two were corrected with constrained liners, to ultimately decrease the risk of dislocation. Moreover, the four hips suffering from infections were subjected to a revision plan divided into two stages, consisting of the explanations of the implants and subsequent implantation of spacers permeated with antibiotics, which were then removed during the second stage of the revision procedure—after 3 to 6 weeks—to allow for the implantation of a new stem component and cup. Four patients experienced intraoperative fractures/fissures, three concerning the lesser trochanter and treated with cerclage cable, and one of the greater trochanter, which was instead treated with a claw plate. Femoral nerve palsy was observed in four patients. Moreover, the placement of 16 stems was mildly varus, whereas only one was valgus; nonetheless, the patients experiencing these slight misalignments were not affected by any sort of pain, and were otherwise asymptomatic; therefore, no revision surgery was necessary in the 17 aforementioned cases [207].

Gruen zones [209] were used to classify the radiolucent lines employed for further analysis, to evaluate the various regions of the interface between the prosthetic component and the surrounding bone. Seventeen percent of the radiographs displayed nonprogressive radiolucent lines; however, the stems resulted asymptomatic in all cases. Heterotopic ossification was documented in 13 patients, but none of them displayed any symptoms. Figure 7 shows the Gruen zones for the categorization of femoral stem loosening [210].

Finally, the Western Ontario McMaster Universities Osteoarthritis Score (WOMAC) used to establish the level of pain and functionality experienced by the patients improved from a mean value of 52.5 calculated preoperatively to a value of 27.2 measured 1 year following the surgery.

Fig. 7 Gruen zones 1–7



In summary, the results observed in the analyzed study fail to demonstrate that the incidence of dislocation following DAA for femoral revision surgeries is lower compared to other approaches, and other parameters calculated throughout the study, including complication rates and patient-reported outcomes, are analogous to the ones indicated in other studies in which other surgical approaches were analyzed [207].

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Medical Improvement Suggestions for Total Hip Arthroplasty

Abstract Total hip arthroplasty (THA) is one of the most commonly performed orthopedic procedures to relieve the hip pain arising from a variety of conditions that include but not limited to osteoarthritis. THA is usually correlated to positive outcomes; however, it could potentially lead to a variety of complications that contribute to the creation of a stigma associated with the procedure.

1 Introduction

Total hip arthroplasty is performed in cases of the damaged hip joint. Such damages could be correlated to external factors (i.e., motor vehicle accident leading to fractures), or to a variety of diseases, among which osteoarthritis, human immunodeficiency virus, sickle cell disease, hereditary multiple exostosis, lumbar spinal disorder, developmental hip dysplasia, and end-stage renal failure (consequently requiring renal transplant and hemodialysis) [1].

Despite it being considered as one of the most successful orthopedic procedures employed globally, THA is nonetheless correlated to several complications, which ultimately indicate the presence of space for substantial improvements.

From a medical perspective, there are several considerations that could aid in the advancement of the procedure, each of which is related to the following:

- Surgical approach
- Comparison of the surgical approaches
- Perioperative patient care
- Postoperative complications

The following section provides brief information on the surgical approach improvements. What follows is potential research that can be conducted in surgical approach comparisons that incorporates the use of technology. Perioperative patient care improvement opportunities are listed in the following section. The last section is devoted to postoperative complication-related improvement opportunities by incorporating technologies. These ideas can help to identify various aspects that

E. Tokgöz, *Total Hip Arthroplasty*, https://doi.org/10.1007/978-3-031-08927-5_6

could lead to substantial improvements that relate to the THA surgery. Such considerations might be considered minutiae; however, if employed concomitantly, their use could aid in the achievement of better outcomes.

2 Surgical Approach Improvement Opportunities

THA can be performed via a variety of approaches that mainly differ in terms of the positioning of the patient on the operating table, as well as the site of the incision, which subsequently impacts different superficial and deep structures based on the modality elected to perform the surgery. Such approaches are the direct anterior—associated with a critical learning curve—the anterolateral, the posterior, the direct lateral, the lateral transtrochanteric, and the posterolateral [2].

The use of fluoroscopic guidance is investigated in [3]. With reference to this subject area, further research could be conducted on the use of fluoroscopy during the performance of any of the currently employed approaches for the performance of THA. In fact, one of the main concerns about this technique was the exposure to radiations; however, several studies have demonstrated that the negligible exposure to which the patient and all the members of the staff present in the operating room at the time of the procedure has no effect on their health. The use of fluoroscopy would lead to a more accurate positioning of the implants, thus perhaps leading to a lesser number of postoperative complications [2].

3 Comparison of the Surgical Approaches' Improvement Opportunities

Each of the surgical approaches has been correlated with several advantages and complications that are strictly related to the methodology employed to access the hip. In fact, the deep and superficial structures impacted during the incisions vary depending on the approach chosen to perform the surgical procedure. The current literature provides variational results on the success rates and effectiveness of the surgical approaches taken due to the variability of the physiological cases and the effectiveness of the surgical procedure not to mention the post-procedural complexities arising from the aforementioned differences. Thus, one potential area of improvement can be the selection of a single approach to perform both primary and revision THAs. In fact, the choice regarding the more suitable approach is dictated by the characteristics of the patient, as well as the dexterity of the surgeon [4]. In addition, to aid in the choice of the approach, further research should be conducted on the incidence of complications encountered after each approach, as studies provide contrasting information on the topic [4]. In the cases when the primary and revision THAs are different, another study can be conducted on the success rates of their comparisons based on the physiological conditions. Due to the complexity of the data, it might be essential to employ deep learning techniques to analyze the corresponding data [5].

4 Perioperative Patient Care Improvement Opportunities

In the healthcare system, every single decision made by surgeons or nurses is aimed at enhancing the well-being of the patient. Therefore, considering the importance of communication for the achievement of better postoperative outcomes, further research should be conducted on the PCSS (Patient Communication Perceived Self-Efficacy Scale) used in every country, to ascertain the validity and reliability of the instrument. In fact, for comparative results to be attained and extracting meaningful outcomes upon research, a unified framework can be generated for data collection and analysis.

Regardless of the elected surgical approach, the postoperative rehabilitation protocol is similar for all THA patients, nonetheless presenting slight variations based on the characteristics and responses of each patient: a prompt mobilization procedure initiated the day after the surgery, followed by exercises to strengthen the muscles of the hip, and education of the patient, ultimately leading to exercises aimed at enhancing the ambulatory capacity of the recently operated patient to slowly transition from the use of assisting devices to an unassisted ambulation. In order to decrease the pain experienced by the patients in the initial stages after the procedure, as well as accelerate the physical therapy cycle, another area of improvement could be the preoperative care of the patient, with a focus on the choices regarding the analgesic administration prior to the beginning of the surgical procedure. Along the lines of the aforementioned suggestion, primarily aimed at reducing the postoperative pain and duration of the rehabilitation protocol, a more comprehensive examination should be conducted regarding the most effective way to reduce perioperative blood loss during the THA surgical procedure, as studies have failed to determine the efficacy of local infiltration analgesia with the addition of bupivacaine for the reduction of the overall volume of blood lost [6]. Finally, further research should be conducted on the physical therapy itself, in order to identify and develop a more efficient protocol that could speed up the progression of the patient from assisted to unassisted ambulation while simultaneously decreasing the risk of incurring in complications via a focused rehabilitation primarily aimed at strengthening the hip musculature.

5 Postoperative Complications

THA is usually correlated to positive outcomes; however, this complicated orthopedic procedure could also give rise to a variety of complications, among which dislocation, postoperative task deficit—defined as the inability to recover complete functionality in THA patients as opposed to the one observed in healthy individuals—periprosthetic fractures, postoperative delirium, nerve damages or lesions, and heterotopic ossification. Most of these complications substantially decrease the life expectancy of the implant, thus leading to the requirement of revision THA, a surgery that is performed in cases in which the prosthesis implanted during the primary procedure fails, and that is usually correlated with increased complexity and higher incidence of complications.

The occurrence of such complications substantially decreases the scores indicated by the patient-reported outcome measure, or PROMs—which are evaluation methods used to assess the health status perceived by the patient—ultimately enhancing the uncertainties of the population regarding this orthopedic procedure.

One improvement opportunity would be a more detailed qualitative and quantitative data collection through the surveys. This collected data can be related to biomechanical aspects and feelings of the patients about the effectiveness of the implants. The collected data can be then further analyzed using advanced data analytics techniques including AI [5]. Noting that the complications during surgery change, and therefore physical therapy needs of the patients change, the physical therapy needs of patients for various conditions should be investigated [7]. Noting the recent developments in robotics-assisted physical therapy applications upon THAs, further research on the efficacy robotics, virtual reality, and gaming strategies' usages for treatment of patients can be researched as a part of the THA post-surgical physical therapy approaches [8].

6 Conclusion

This article encompasses a variety of areas that could potentially lead to substantial improvements with regard to the THA procedure. Under a medical perspective, along with the utilization of technologies, advancements to THA could be achieved via the implementation of the following aspects:

- Examination of the personal information of the patient for a thorough planning of the procedure
- Determination of the dosage of analgesics necessary to handle the severe pain experienced by the patient in the initial stages after the surgery
- Prioritization of patient-doctor communication
- Integration of fluoroscopy
- Choice of surgical approach based on the peculiarities of the patient and the expertise of the surgeon
- Personalized physical therapy cycle aimed at strengthening the hip musculature and enhancing the ROM of the patient to increase their functionality
- Using advanced technologies, such as robotics, virtual reality, and gaming for better physical therapy and treatment

- Utilization of data analysis methods such as deep and machine learning strategies for better characterization of results on more comprehensively collected data sets

Some of these techniques are currently utilized; however, it is still uncommon for them to be employed simultaneously. The concomitant use of these methods could potentially lead to better outcomes correlated to the surgical procedure itself, as well as patient satisfaction, thus progressively eradicating the stigmas associated with THA.

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Biomechanics of Total Hip Arthroplasty

Abstract Biomechanics of total hip arthroplasty (THA) is one of the areas where physiology, engineering, and physics meet. In this article, we will cover biomechanical impacts of cement versus cementless implantation use, implant fixation techniques with their optimal design considerations based on anatomical positions and surgery type, impact of pre-planning on biomechanics of THA, impact of using robotics on THA applications, and challenges that may be faced with biomechanical instrumentation.

1 Introduction

A human adult's skeleton is made up of 206 bones which is reduced from 270 bones at birth, approximately 300 joints, and 800 muscles [2]. Additionally, bone mineral density, activity of hormones, oxygen availability for consumption within the body, blood pressure, etc. are secondary level factors that impact the biomechanical regulation of the body at a secondary level with the motor task management. The design of this sophisticated network system not only requires an extensive coordination and balance but also arises the need for an extremely advanced management system. In local surgeries such as total hip arthroplasty (THA), paying attention to impacts of interrelated local components' spatiotemporal biomechanical behaviors at all six degrees of freedom can be the main drivers of the observations.

Physiological and implant failure mode analysis and functional recovery after THA are analyzed for surgical success. Femoral offset (FO) changes following THA can help with analysis of hip muscle activities to observe functional physiological restoration noting that FO accuracy and functional recovery are correlated [18]. Analysis of 13 hip muscles' moment arms of 18 unilateral THA patients in vivo revealed a potential improvement of abductor and external rotator function upon 2–3 mm of FO restoration; an increased FO observed to reversely correlate with length of both the flexor and adductor moment arms during the gait and stance phases, respectively. A decrease of both abductor and external rotator moment arms during the whole gait and a decrease in extensor moment arms during the stance

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phase are correlated with a decreased FO after THA [18]. This approach can particularly help with presurgical planning for functional restoration of the hip.

The sophistication of interrelated human body network has a weight distribution of impact; pathological issues that exist in locations such as spine can have more impact than other locations. Lumbar pathological issues such as abnormal spinopelvic motion can increase the risk of hip dislocation even with the Lewinnek et al. [99] “safe zone” placement of acetabular component that assumes anteversion 15° ± 10° and inclination 40° ± 10° angles [1, 18]; however, the “safe zone” is recently questioned in several studies and may not accurately predict THA instability based on the anteversion and inclination measurements [87]. The dislocation rate after THA is observed to be as high as 92% and as low as 75% in the spinopelvic abnormality cases [18].

Testing on biomechanics of THA following hip osteoarthritis aims to fulfill daily activity demands such as sit-to-stand (STS). It is very natural to measure hip loadings during movements including hip kinetics and kinematics to investigate success of a THA. One-year follow-up of 11 THAs and control groups revealed improvement of loading asymmetry without following any surgical convention. Increased contralateral limb loading is the consequence of other kinetic changes along with the change in the limb differences that are naturally seen after THAs. The progression rate of limb difference after THA is still uncertain [4].

The biomechanics of pre- and post-6-month surgical differences of THA are analyzed using sit-to-stand, walking, turning, and turn-to-sit tests that are bundled into a timed up and go test in [5]. This test is particularly useful for determining the functional deficits and rehabilitation strategies to fix these issues. All four tests resulted in improved averages. High deviation results of walking measurement revealed the walk test to be the largest variational test among the four tests with the walking test presenting the main deficiency. In this process, quantitative measures can be attained by using an inertial measurement unit (IMU) for functional deteriorations from the normal physiological loadings.

Robotic-assisted THA comparison with traditional surgeries is one of the most recent techniques utilized for biomechanical analysis. Accuracy of achieving the planned horizontal and vertical centers of rotation, combined offset, cup inclination and anteversion, and correction of leg length discrepancy are some of the biomechanical considerations measured for comparative results on manual and robotic-assisted surgeries [6]. There are mixed results attained in the literature for using robots for THA with biomechanical consequences; however, precision of robots is determined to be much higher in the literature for particularly cup placement precision when compared to manual THA.

Biomechanical data of THA patients that underwent anterolateral surgery is collected during the post-surgery gait training by using crutches and a mobile robot that assisted them during walking in a clinical setting [11]. In comparison to the control group that had no use of robotics for gait training, the analysis revealed the robotic-assisted group to have significantly higher absolute walking speed, higher relative walking speed (0.2 vs. 0.16 m/s, $p = 0.043$), or shorter relative cycle time. This particularly impacts the time that the patients spend in the clinic.

Biomechanics of minimally invasive direct anterior THA approach on primary osteoarthritis patients by preserving muscle integrity around the hip joint is investigated in [7]. Hip biomechanics for forward, lateral, and backward walking locomotor tasks are analyzed using recorded kinematic, dynamic, and EMG parameters along with the gait variables, hip muscle activation, and locomotor performance analysis. Joint motion range is observed to be the same, while gait and hip functionality are observed to improve after surgery in comparison to the control group during 6-month follow-up for some of the tasks [7].

Dual mobile cups' biomechanical effectiveness has been observed and reviewed in the literature. Dual-mobility cups particularly help with pain and mobility over the years and observed to be effective THA implantation in prevention of dislocations under volatile conditions. This is mainly due to the ability to structure the femoral head large enough to be able to design an effective implant; however, the locking mechanism's failure between the mobile liner and femoral head is determined to be the major biomechanical challenge faced with the first-generation dual-mobility cups [8]. The new-generation cups are observed to be biomechanically more stable and reliable than their ancestors [26].

An extensive study conducted to analyze 3-month follow-ups of about one-third of a million THA patients revealed 44% of the 0.34% failed implants to be associated with stem design (collarless stem and triple-tapered design) and finishing (non-grit-blasted finish). Stability and resistance as a part of biomechanical improvements are observed in vitro due to medial calcar collar modification in the design [9]. Authors determined cementless stem design influencing the risk of early periprosthetic femoral fracture revisions.

It is observed to be natural having leg length changes after THAs, and biomechanical reasoning is investigated in the research literature. The design and placement of the implant are main factors with interlocking of medullary canal and implant. Flexible structure of the bone and the strength of the material used for the implant eventually cause the sinking of the implant into the bone and causing the imbalance. The design of the femoral implant can be targeted to achieve fixation of the medullary canal and implant in the mediolateral dimension or anteroposterior engagement of the bone. It is concluded by the authors that osseointegration of the cementless THA and postoperative leg length discrepancies are impacted by the femoral challenges; optimal intra- and extra-medullary geometry fitting and offset restoration of cementless femoral stems are major common challenges among the implants used, and they cannot necessarily offer optimal fit or offset restoration [10].

Finite element analysis is one of the methods used for periprosthetic femoral fracture (PFF) fixation upon THA by altering the loading and boundary conditions along with the isometric and physiologic loadings. The major issue in the use of FE method on PFF is the standardization of the technique and methods used [12]. The increase in the overall rigidity of the construct eventually is determined to increase the stability of the fracture as a result of the motion across the fracture or the overall stiffness of the instrumented femur [27]. The increase in rigidity is due to:

(a) Changing the rigidity of the connectors based on one of the following:

1. By using screws instead of cables (see, e.g., [33]).
2. By using cables instead of wires (see, e.g., [34]).
3. By using double wrapped wires compared to single wrapping (see, e.g., [74]).

(b) Plate and strut modifications changing stiffness (see, e.g., [83]).
(c) Using longer revision stems (see, e.g., [82]).

Due to variability of clinical techniques used, unclarity of how a designed experiment would perform at an optimal level needs to be explained clearly. Construct stiffness appears to be the focus of majority of the work in progress, but it may be misleading due the possibility of a highly stiff plate causing stress shielding in the underlying bone. In this case, either the fracture heals or the construct itself does not fail. More studies on biomechanical quantification of such outcomes for periprosthetic femoral fracture are needed [12, 81] (Figs. 1, 2 and 3).

A physiological factor that plays a crucial role in THA applications is hip center, and there are two biomechanical factors: hip center rotation and acetabular component coverage rate that can be used for attaining measurable outcomes. Maintenance of muscle function is highly related to the natural rotation center [89]. Noting that one of the major challenges of THA is cup dislocation, micromotion and peak stress levels that follow acetabular cup placement can be quantified as the biomechanical properties. In [13], acetabular cup insertion is simulated and evaluated by using

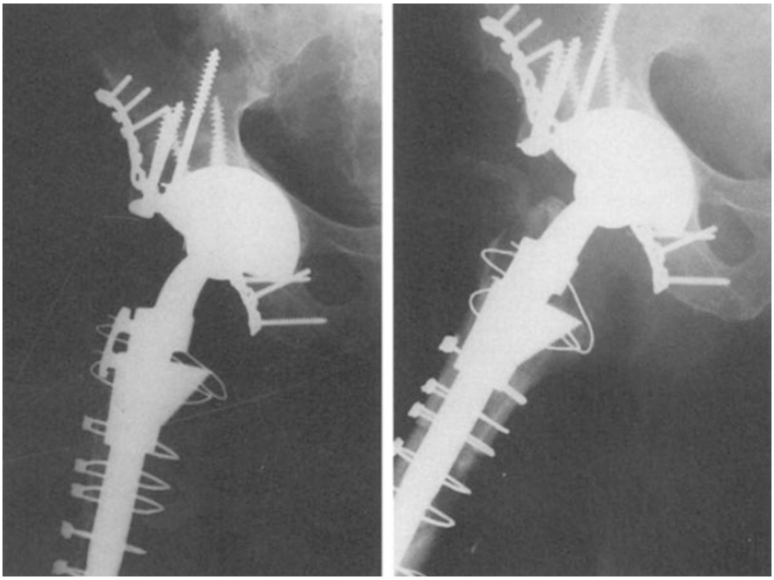
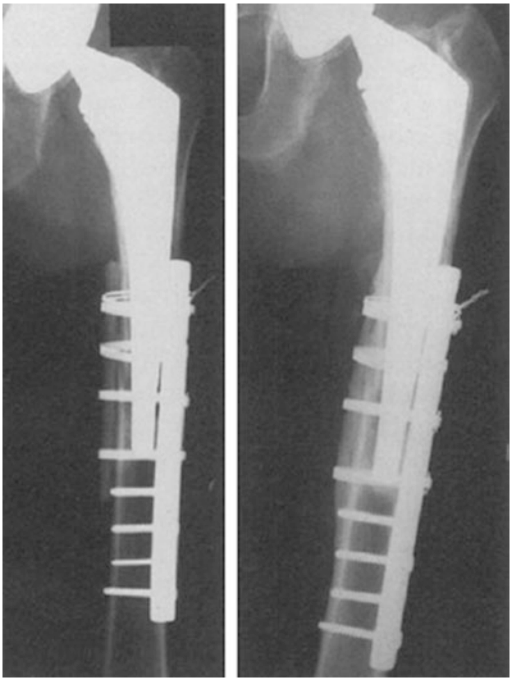


Fig. 1 A male with massive pelvic and femoral osteolysis. Image on the left is postoperative AP of acetabular reconstruction with bone grafting and posterior column buttress plating. (Image on the right is AP of acetabular reconstruction 5 years postoperatively)

Fig. 2 *Left to right* contemporary and historical femoral component images of Zweymüller, Exeter, Corail, St. Georg, Silent & Resurfacing, CFP, Meta, and Charnley documenting the wide variety of designs with head size diameters

Fig. 3 A man underwent bilateral, primary, press-fit THAs for arthritis associated with ankylosing spondylitis. Eight months post-op, upon twisting his leg, the person sustained an oblique femur fracture about the prosthesis. An Ogden plate, allogenic tibial strut bone grafts, and screws and cerclage bands are used to stabilize the fracture through open reduction and internal fixation. The fracture healed after a period of restricted weight-bearing. At 3 years after surgery, the patient ambulated pain-free. X-rays reveal graft incorporation



finite element analysis of micromotion and stress levels measured. Conventional reaming technique is shown to cause more micromotion of the cup with the peak stress level intensification to be more in the superior cup section than the anatomical technique, while stress level intensification was uniform for the anatomical technique. Authors concluded that anatomical technique might be a more suitable approach for primary THA [13]. Additionally, the anatomical technique is shown to produce favorable changes in the acetabular rotation center and the preservation of bone stock.

Two of the surgical workflow techniques used as a part of hip reconstruction are "acetabulum first" (AF) and "femur first" (FF) that can be applied as a part of direct anterior approach of THA [14]. By preparing the femur first, the calcar planning assist in femoral retraction, potentially improving exposure during acetabular preparation, while AF is known to be the traditional method. Physiological and biomechanical data is analyzed for determining the effectiveness of the two techniques. Given that the two groups that were evaluated for AF and FF exhibited similar demographic characteristics, significantly better hip center reconstruction capability is attained for the FF group's femoral offsetting, leg length, and horizontal and vertical hip centers. No other significant changes are seen between the two groups on the scores of hip disability and osteoarthritis outcome as well as hemoglobin change, joint replacement operation time, and complication rate [14]. Patient-reported outcomes are reported in this study.

A factor that impacts dislocation following THAs is the tension generated by soft tissue. Femoral offsetting plays a major role in prosthesis stabilization; therefore, finite element modeling of the acetabular component, a liner, bones, muscles, and a stem for hip flexion and internal rotation is used for impacting the offsetting changes the most [17]. Femoral offset (FO) and quadratus femoris muscle stretching are significantly and directly correlated, and therefore this muscle provides the growth of the initial passive force. Simulated intraoperative tests indicated the muscle serving as a stiff band and providing hip prosthesis stabilization.

Biomechanics of the hip also directly relate to the lumbar spine [92]. Dislocation and revision after THA are not unusual for patients with lumbar spine fusion surgery [98]. Poor patient-reported outcomes are attained after THAs of patients with prior lumbar fusion when compared with those without the procedure [15].

Biomechanical performances of THA before and after lumbar spine surgery (LSF) are investigated in [16]. The 3-month dislocation rates of 2.8% and 0.2% are determined for THA before and after LSF, respectively, favoring THA completion prior to LSF. On the contrary, 2-year rates of 4.6% and 1.7% are determined for THA after and before LSF, respectively, favoring THA after LSF. Cumulatively, THA prior to LSF has 7.4% of dislocation rate within 2 years, while the same rate is 3% for THA after LSF. Potential reasons behind the differences between the two approaches are hypothesized to be the impact of muscle strengthening for tolerating spinopelvic mobility alterations caused by LSF, adequate bony growth period, and tissue healing. Analysis of approximately 70,000 patients that had gone under THA and LSF sequentially with 63.2% pre-LSF and 36.8% post-LSF showed no statistically significant differences in all-cause revisions, dislocations, and aseptic loosening [19].

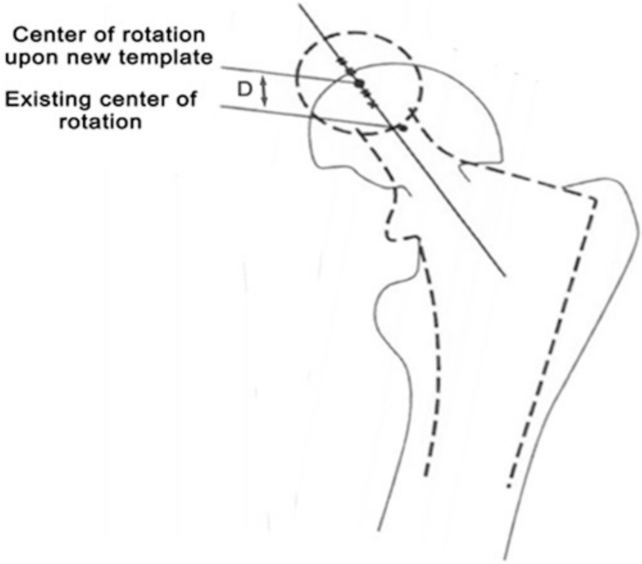


Fig. 4 Templating new center of rotation upon an increase in limb length obtained by this prosthesis

Hip functioning biomechanics is an important factor for leg length changes after THA. Of the 90 THA patients, right after surgery, 3-month, and 12-month follow-ups resulted in 62%, 43%, and 33% longer limb observations of the patients respectively with an initial observation of 9 mm on average of longer limbs [20].

The modularity of the stem-neck of the implant changes the dynamics of the biomechanical consequences of THAs without a doubt [21]. Improved restoration of limb length as well as hip anteversion and retroversion are observed by using modular implants for THA, while early failure and longevity of the modular design that relates to corrosion, dissociation, and fractures have been reported in the literature (see, e.g., [3, 95]) (Fig. 4).

Hip rotation and adduction moment analysis postoperatively during gait for determining symmetrical offset from the sides of the body are analyzed for understanding biomechanical consequences of THA in [22, 43]. Femoral neck anteversion and hip rotations changed equally both in internal and external directions after THA during walking with improvement on the quality of overall gait pattern. It is concluded in [22] that the gait pattern changed in addition to the femoral neck anteversion, hip rotation center height, leg length, and femoral offset.

Well-known major factors on the biomechanics of THA include nail and plate choices with the corresponding design. An example to this is the use of slotted nails connected to a stem that act as intramedullary load carriers. Typical physical phenomena for biomechanical testing include construct stiffness and number of cycles to the failure. Bending in different directions for measuring construct stiffness along with cyclic testing under progressively increasing physiologic loading is one way of performing mechanical testing until catastrophic construct failure is attained. In [23], two methods of femora instrumentation are used: a retrograde slotted nail coupled to the prosthesis stem and a locking plate with a locking attachment plate. Mediolateral, torsional, and axial bending construct stiffness are investigated via nondestructive tests along with cyclic testing under accelerating physiologic loading. Connected to the prosthesis stem, docking nail construct is found to provide an intramedullary fixation that is biomechanically weaker in stable fractures compared to the plate construct.

PFFs are analyzed by several researchers. A cadaveric experimentation by Lehmann et al. [100] utilized cementation on osteoporotic bone structure with no lesions or preexisting fractures on the contrary to the other studies that used bone mineral density matched cadaveric femora. Simulation of the stable fracture pattern is conducted by leaving no space for osteotomy. The fracture between the two intramedullary femur implants decreased the fracture strength and the plate of the implant provided stability.

Another cadaveric study on PFF with cemented approach without leaving any fracture gap is conducted in [101] that utilized:

1. Four-point bending using mediolateral and anteroposterior forces.
2. Axial compression testing during abduction and forward flexion.
3. Torsion applied to the femoral head anteriorly.

Testing on stiffness comparison of the plate structures with cables and screws showed screws providing either same or a much stiffer environment than the cables.

The biomechanical performances of two fracture plates on a single fracture by using three-point bending with a 20 mm transversal fracture gap left on the hip stem prosthesis tips and sinusoidal axial loading is investigated in [102] on synthetic specimens. The two-plate construct provided highest stiffness as one may expect due to the use of additional plate fixation. The use of a plate with allograft strut also provided high stiffness when compared to a plate structure that had a single locking mechanism.

Cadaveric research on embalmed femora is conducted using prosthetic cementation on a transversal fracture with a 10 mm gap distal to the stem tip under axial and cyclic compression loadings in [103]. Anchoring analysis of the constructs resulted in outstanding stability of bicortical screw placement in comparison to unicortical screw fixation. Failure mode analysis indicated similar average force occurrences for both constructs' failure. Under cyclic loading, fatigued material occurred for bicortical screw placement resulting in implant failure due to bone recovery.

A stable fracture pattern is generated after osteotomy under a high loading modality, 2500 N, for cadaveric specimens using cement with 10 mm of gap distal to the stem tip using sinusoidal cyclic loading in vertical direction in [104]. As expected, bone mineral density is determined to be impacting the failure mode significantly. The type or length of the plate did not demonstrate a significant difference at fracture site for rotation and displacement.

Experimental PFF fixation by using three bone plate repair methods is applied to a synthetic femur by leaving a 5 mm fracture gap near the tip of a total hip implant in [105]. A 3D FE model is used for experimental analysis on synthetic specimen with cemented prosthesis. Experimental and FE strain results agreed strongly indicating plate-screws with additional proximal cable fixation to be the best choice for healthy bone among the constructs generated by using cables, screws, and the combination of these two options. In the case of osteoporotic bone, a plate structured with only cables was found to be the best option. Highest stiffness is attained when cables and screws are used with the biomechanical stability established followed by screws only. Testing of cable use without proximal holes clinically is determined to be the best option for clinical applications.

Cadaveric research on embalmed femora using cemented prosthesis with straight metal carriage bolt and 20 mm fracture gap left distal to the hip stem is conducted in [106] with axial compression to failure. The compression caused by the fragments is observed to be neutralized by the gap left between the proximal and distal fragments of the fixed fracture. Axial stabilization is determined to be much better for the cable and screw combination than cable fixation. Variation of load at failure did not alter significantly for locking and non-locking constructs, while cables are observed to have much less load at failure than these two constructs.

Another cemented prosthesis on cadaveric specimens with 10 mm gap placed distal to the tip of the prosthesis is used by applying cyclic axial bending and synchronal sinusoidal axial loading in [107]. The locking plate generated for experimentation with proximal bicortical and unicortical screw fixation had higher cycle number along with better stability and higher strength than proximal unicortical screw fixation structure of the conventional compression locking plate. Osteosynthesis in periprosthetic fractures is observed to be possible through the use of bicortical screw positioning that yielded less movement causing interfragmentary osteotomy.

Uncemented prosthesis is used on synthetic specimen with the femur and plate construct designed based on distal of the femur on the distal of the osteotomy in [108]. PFF fixation is tested by integrating bicortical screws into locking attachment and compression plate constructed group and compared with the use of cerclage wire as a part of a locking attachment plate. The system with bicortical screws is observed to have larger number of cycles to failure and significantly stiffer construct than the system with cerclage wire. Locking attachment plate with bicortical screw placement on the prosthesis stem laterally can have better stability of the PFF fixation.

Research on cadavers with the utilization of 70 mm fragments cut from the diaphysis of the femur are used without any prosthesis or fracture in [109]. Axial load is applied until occurrence of failure on bicortical and unicortical screw fixation methods that are shown to have higher stiffness and strength in comparison to the cerclage wire fixation. Finite element method is used for confirming the biomechanical results of the two screw-based methods.

Double plating with uncemented prosthesis is used on synthetic specimen by applying cyclic sinusoidal axial loading until construct failure occurs in [110]. The group with non-contact bridging plate (NCB) is determined to have higher axial stiffness and cycles to failure, although femoral stem fixation of both NCB and locking attachment plate were successful. Stiffness and cycles to failure were higher for NCB group, while low rigidity of Locking Attachment Plate's (LAP's) main plate resulted in less stability.

Using cement on synthetic specimen in [111], a 6 mm gap is left near stem tip with osteotomy occurring at 20 mm distal to the tip of the stem. Following axial and torsional loads, cement-filled osteotomy gap is reloaded with axial torsional loads. Mantle cement failure is not detected for stabilized cement with the use of locking plate fixation of PFF. Stem migration in the axial and medial directions are not statistically different at a significant level in comparison to the control group.

Cement is used on synthetic specimens with fracture occurring at 15 mm below the tip of the stem in [112]. Incremental load is applied until axial load failure is attained. Intraprosthetic fixation method is introduced with screws fixing the fracture plate both to the bone and cemented hip implant. In comparison to the unicortical locked-screw plating, intraprosthetic fixation method is determined to have higher failure loads than the unicortical locked-screw plates. By preserving the strength of cemented implant to the femur, intraprosthetic fixation provided increased primary stability.

Cemented prosthesis is used in [113] on a fracture of 10 mm away from the tip of the stem using cadaveric specimen. Bicortical screws are utilized for proximal plate fixation and axial bending and cyclic testing is applied until failure occurs. Instrumentation by using locking compression plate fixed proximally with LAP construct that incorporated screws and cerclages is shown to have significantly longer lifetime than using cerclages only. Osteoporotic bone structures can be possibly supported using cerclage cable-screw combination. Stability of fixation can be achieved by using cerclages with one or more screws.

One of the limited studies on synthetic specimen using uncemented prosthesis with no gap left at the fracture site is conducted in [114]. In this study, proximal fixation using bicortical screws instead of unicortical screws is used. Axial compression, lateral bending, and torsional/sagittal bending are tested. Stiffness of torsional/sagittal bending and load to failure are observed to be the highest by using proximal bicortical screw placement. Integration of unicortical screws to cable fixation is proven to increase axial stiffness. Proximal fixation is observed to not impact lateral bending.

Another study that used synthetic specimen on uncemented prosthesis with a 10 mm fracture gap at level of prosthesis tip is conducted in [115]. Cyclic rotational and cyclic axial loadings are applied along with force loading until failure occurs. Greatest stiffness and largest failure load values with the least displacement of the construct at fracture site are seen for medial strut allograft with plate fixation; PFF fixation treatment near the tip of THA is shown to be mechanically better than the used alternatives in the research.

Cemented prosthesis on synthetic specimen on two different groups is studied in [116] to compare gap and no gap options. Using 25 mm gap distal to the tip of the stem, one of the groups had midshaft osteotomy, while the other had midshaft 5 mm gap. Axial compression, vertical loading, and lateral bending with axial loading are applied until catastrophic failure is attained. Comparison of biomechanical performance between constructs under these different situations indicated significantly higher stiffness for LAP with locking compression plate under axial loading with the existence of a gap.

Another study that used cemented prosthesis on synthetic specimen considering both fracture gap and no gap is conducted in [117]. Upon applying fixation by using screws, or screws with cables, in preference to cables and wires, application of unicortical screws in conjunction with cables resulted in forcing of proximal screws into the bone that caused screw loosening fixation to the bone. The fracture reduction rate is observed to impact the stability and bending of the bone as a result of testing the models that contained gap and no gap. As expected, bridging length is also determined to be a factor impacting the fixation construct stability. Among the loading paradigms with different angles, unicortical screw was the stiffest fixation.

Uncemented prosthesis on synthetic specimen is tested in [118] with transverse and distal cuts at level of implant tip along with 10 mm gap under cyclic sinusoidal axial loading. The use of bicortical screws for proximal fixation resulting in better bone purchasing but more dramatic failures with fracture patterns is realized in comparison to unicortical screws used. Unicortical screws are determined to have pullouts of the screws failing the structure without any bone fractures.

Cemented prosthesis on synthetic specimen with proximal fixation using bicortical screws by leaving a gap of 25 mm distal to the prosthesis tip is placed in [119]. Torsional rotation and axial loading experiments indicated torsional failure of the cable-based design as a result of loosening through the rotation of the femur. Cracks are observed to occur at the screw insertion locations of the unicortical screw design and the unicortical-cable construct. Upon testing unicortical, unicortical and cable, and bicortical screw-based locking constructs, bicortical screw fixation is determined to stand against stronger forces and showed more resistance in axial loading. The use of cable indicated weaker force handling capability compared to the other designs.

On cadaveric specimen with the use of cemented prosthesis, bicortical fixation is used by applying axial loading and displacement with cyclic testing on a 10 mm fracture distal to the tip of the prosthesis in [120]. The main takeaway of this research is stiffer structure of locking attachment plate supported with double locking compression plates along with higher cycles and load to failure rates in comparison to two locking attachment plates with a single locking compression plate design. Noting that the two constructs utilized three plates in total, a stiffer and more stable design is attained by using compression plates than locking plates.

The use of a clamp on a locking attachment plate by using cadaveric specimen with cemented prosthesis on a 10 mm fracture distal to the tip of the stem is done in [121] for the first time for the treatment of PFF. It is observed that clamp use on a plate is also well-suited as it is the case for locking compression plate use after applying cyclic axial loading until failure is attained. Biomechanical testing on a femoral hook plate (hook) and a LAP placed subtrochanterically indicated similar plate stiffness levels, while LAP design had more cycles to failure and higher fixation strength and failure that highly depends on bone mineral density. Bicortical screw fixation is a more effective way than the hook method subtrochanterically noting that the results are dependent of bone stock quality and bone mineral density.

Cemented prosthesis is used on cadaveric specimen by applying axial loading and far cortical locking technology on a 20 mm fracture below the tip of the stem by using axial loading [122]. PFF fixation by using far cortical locking method with bicortical screw use is observed to be more effective on overall stiffness of the construct than the bicortical screw fixation by using locking plates. The observed increase in stiffness however caused increased fracture movement.

Uncemented prosthesis on synthetic specimen with double plating on a distal cut and a horizontal cut 5 mm distal to the stem tip is studied in [123] by applying cyclic loading in axial compression. The number of cycles prior to failure and stiffness is determined to be higher for double-plated structure than the locking attachment plate with locking compression plate.

Cemented prosthesis on cadaveric specimens using four-point bending with torsional and axial compressions on a fracture 25 mm distal to the tip of the stem and a 5 mm fracture gap is conducted in [124]. Locking attachment plate with locking compression plate is determined to be less stiff in medial-lateral, torsional, and compressive abduction directions than the locking compression plate and allograft design. Load to failure tests are determined to not have significant differences. Anterior-posterior bending and compressive flexion didn't have significant differences in the two methods as well.

Biomechanical comparisons of long and short stems using plate and cerclage settings are analyzed in [125]. Four distinct group combinations of short and long stems with locking plate fixation and cerclage systems are evaluated for their effectiveness through design analysis. Cerclage systems with four titanium cerclage bands and two stabilizers are tested with both short and long stems. Similarly, non-contact bridging plates with five proximal unicortical and four distal bicortical screws are tested with long and short stems. Cerclage systems demonstrated stiffer, stronger, and more resistance to cyclic failure under osteosynthesis than the plate designs when Vancouver B1 fractures occur. Long stems are observed to be biomechanically working better than the short stems making them a suitable fit for Vancouver B1 fractures. Short stem-cerclage system has the highest sinking of the implant into the bone.

On synthetic specimens in [126], cemented prosthesis is tested to measure correlation between the biomechanical performances and the corresponding distances between the plate and stems. The measurements included the plate and stem interaction by measuring the gap and no-gap conditions. Varying non-contact bridging plate placements with 40 mm distance is defined to be the closeness of the gap with a differentiation of 20 mm tracing. Early failure was significant when there was a gap or an overlap of 20 mm. Strain decreased as distance of the gap increased; therefore, the least strain is detected for axial and torsional loading in the farthest distance. These observations provoked the need for careful plate allocation for healing Vancouver type-C PFF that could lead to future fractures in accordance with the impacted stress risers.

Biomechanics of PFF fixation using uncemented hip implant with no fracture gap left after the osteotomy is observed in [127] for simulating a stable fracture pattern using several wire, cable, and clamp options. Cobalt-chrome and synthetic cables, hose clamp, and monofilament wire are used in experimentation. Cobalt-chrome cable and hose clamp are the stiffest constructs and the change in loads didn't alter the stiffness much. In both angular and axial directions, maximal load support and minimum implant failure are attained for metallic constructs that are supported by a locking system.

Biomechanics of cement's impact on PFF fixation by using a variety of locking screws is investigated in [128, 130]. Uni- and bi-cortical combinations with a variety of drilling sizes are tested with the existence and absence of flattened tip and NCB in [128]. Upon this attempt of mimicking typical plate fixation setup, it is concluded that unicortical screw systems preserved cement integrity and no cracks are detected. In comparison to the unicortical systems, bicortical screw systems cause more cement damage due to their stronger pullout ability and increase the risk of cement damage. Increasing diameters of the screws that are directly drilled into the cement are negatively correlated with onset cracks and pullout resistances; cement-related cracks and pullout resistances decreased as the drilling diameter increased.

Noting that the typical cement is advised to be mixed by using vacuuming technique, the biomechanical impact of hand mixing of the cement and direct drilling of the screws into this cement is tested in [129] by observing variational nature of screw types, cement thickness, and screw placement. Layered cement damage is analyzed upon insertion of four screws as a part of each one of the three techniques: bicortical non-locking, unicortical locking, and bicortical locking screws. The use of four screws with LCP plate is a consequence of its shortening. The impact of screw type didn't have statistically significant impact on the number of cracks ($p = 0.52$). While crack damage formation and cement mantle thickness were not significantly related, crack formation and screw position were significantly related ($p = 0.019$). Screws' cement and prosthetic stem contact is observed to be the main factor on the change in the number of cracks. The four categories observed included no contact to be between screw and cement mantle and screw to touch cement mantle, and it partially resides within it, screw resides entirely within the cement mantle, and screw is directly in contact with the periprosthetic stem. It is concluded that screws positioned completely within the cement mantle or even touching the prosthetic stem are observed to have significantly more cracks than screws that are partially located within the cement mantle. The placement of screws within the placed cement or in direct contact with the stem is expected to decline crack formation in the cement during plate osteosynthesis of periprosthetic femur fractures [129].

Biomechanical performances of constructs can be evaluated in several different ways. The effect of different plate fixations and different configurations of constructs that evaluate cable, wire, and/or screw positions are two of the commonly seen evaluation methods that will be explained below.

A fixation method utilized in [131–133] is differentiation of plates that depend on plate comparisons using the following:

- Rigidity (flexible vs. rigid).
- Formation material (titanium vs. stainless steel).
- Thickness.
- Support (use of cables, different screw types, double plating, locking, multidirectional).

- Position of plating (anterior, lateral, etc.)
- Stem design and dimensioning (long vs. short, etc.)

Upon the failure of initial rigid fixation attempt by using a polyaxial femoral plating following THA, research on effectiveness of the refracture fixation attempt utilizing polyaxial femoral plating as a flexible fixation method is utilized in [131]. Biomechanical effects of fixation methods using FE modeling and Vancouver type C fracture on a clinical case are compared in the study. It is observed that short bridging used for PFF rigid fixation can defeat fracture movement and prevent healing to eventually cause failure. On the contrary, non-locking plate with a longer bridging utilizing flexible fixation promoted healing better. The length of bridging appeared as the most impactful parameter on fracture location and stiffness. The path to optimum fixation construct design is conjectured to be by using a computational approach as such in [131].

Another study that focused on biomechanical conditions of plate fixation and fracture stability is conducted in [132]. Finite element analysis using locking plate of Vancouver type B1 PFF fixation is conducted on varying materials (stainless steel vs. titanium), bone quality, and fracture stability conditions. Even though unstable fracture conditions caused higher stresses and strains on the plate, biomechanics of the stem for good bone quality under partial weight-bearing allowed single locking plate design to help callus formation without significant risk of plate fracture. In the case when weight-bearing conditions change and not partial anymore, additional fixation may be necessary.

Another study investigating the impact of plate and screw combinations with varying screw numbers, stem sizes, and plate types is conducted in [133]. Categorization of PFF fixation depended on the Vancouver B1 and B2 fractures. In their study, six different categories of designs are explained with proximal allocation of unicortical screws and distal allocation of the bicortical screws are tested in these designs unless stated otherwise. Two of the designs, eight- and ten-hole locking plates, tested the placement of three and four unicortical and only four bicortical screws, respectively. The third design utilized double plating by using two eight-hole locking plates incorporating three of both unicortical bicortical screws. The fourth design is redesigned of each one of the first three designs by using a longer stem (201 mm) with the adjustment of cement mediolaterally due to the needs of the changing environment. The fifth option utilized the 201 mm stem of the fourth design and added an eight-hole plate with three unicortical and two bicortical screws as well as one distal unicortical screw placement that is an exception to the unicortical screw use in the study. The sixth design is extension of the abovementioned first three designs to 241 mm stem. The first three designs with short stems are designed for Vancouver B1 type fractures, while third–sixth designs targeted fixing Vancouver type B2 fractures.

Similar to [132], a single locking plate used for the treatment of Vancouver B1 fractures under partial weight application is determined to be sufficient. Vancouver type B2 fracture fixation by using long stem revision and fracture gap bypassing is determined to be the best option. Both Vancouver B1 and B2 fracture fixations can be considered by using long stems.

Another research that analyzed PFF fixation by differentiating plates is [138] based on a mechano-biochemical model. Bone remodeling by using biochemical similarities and mechanical impacts is analyzed through the developed model. Three unicortical and five bicortical screws are used for bone mineral density analysis with lateral and anterior plating. The simulation results indicated bone loss of up to approximately 70% beneath the plate, while local bone formation is detected up to an additional 100% at most of the distal and proximal screw holes. The maximum and average bone losses for the anterior and lateral plating of the femur are found to be not much different from each other, while the regions of bone losses for anterior plated femur are determined to experience greater bone loss compared to the lateral plating.

Another fixation method utilized in the literature is the formation of Ogden constructs to investigate the biomechanical performances of different variations of the design typically consisting of different cable, wire, or screw position configurations [130, 134].

The biomechanical performance of different configurations of cables, wires, and crew positions is tested in [130] computationally. Four different screws are used in three fixation methods consisting of placement of three cable-screw combinations proximal to the fracture with the only difference between the methods being the positioning of the cable-screw pairs proximally. It is concluded that the choice of the location impacts the fixation strength and the option that yielded the best fixation strength has the potential to reduce the refracturing of the bone. This best option determined is expected to yield to the highest stiffness that may achieve the optimal mechanical stability. Finite element analysis agreed with the experimental results.

Periprosthetic Vancouver B1 fixation using four different modeling originated from an Ogden construct is tested in [134]. The first model used three wires proximally and two bicortical screws distally; the second model used three wires and two unicortical screws proximally, and two bicortical screws distally; the third model utilized three wires proximally, and two bicortical screws and three wires distally; and the fourth model utilized three wires and two unicortical screws proximally, and two bicortical screws and three wires distally. It is concluded that the original Ogden construct is less effective than its by-products. Displacement and stress are decreased in the second model as a result of adding two screws at the site of the fracture. Measured fracture displacement or stresses didn't alter noticeably as a result of adding wires below the fracture in the third model. The use of distal and proximal screws is observed to provide better fixation of the Vancouver B1 fixation in the tested models.

Stiffness and bone's peak stress levels are analyzed in [135] to identify femur conditions after THA both for intact, injury, repair, and healing situations. A 5 mm fracture gap is simulated for fixation by using plate and screws along with mimicked femur with a hip stem from the intact position to the complete fracture reunification. Higher bone stress and lower stiffness are attained right after gap fixation in comparison to the intact case among the four situations; highest likelihood of reinjury appeared to be likely during this post-surgical healing stage. Restorage of the stress levels to the intact conditions is observed in the healed femur. The authors suggest to pay attention to the stress levels and adjusting them for the developed implant designs due to the observed potential adverse effects of stress shielding and high stresses realized throughout the surgical process including fracture healing period. 1500 N of force application is determined to yield the perfect agreement of the finite element and experimental strain analysis.

Treatment methods of varying fracture types using canal thickness ratio, fracture angles, and fracture locations is investigated in [136]. Canal thickness ratios represented poor, average, and best bone quality, while unstable transverse occurred at zero degrees, stable long oblique at 76 degrees, and short oblique at 146 degrees. The three fractures developed included the tip of the stem, 4 mm below the tip of the stem, and 14 mm below the tip of the stem. In conclusion, topology of PFF and bone quality are recognized to be the critical elements of the treatment regardless of the Vancouver classification.

Finite element analysis of PFF fixation under Vancouver type B1 fractures in both normal and osteoporotic bones is conducted in [138]. Biomechanics of axial and torsional loading to observe stiffness, stress, and relative displacement are compared using the same finite element analysis for three options consisting of LCP (traditional locking titanium plate), double circle cable, and multidirectional locking plate. Stiffest and most stable option is determined to be the multidirectional locking plate mechanism among the three options that also outstand under evenly distributed stress levels for both axial and torsional loading conditions.

A review of the studies on biomechanics of experimental and computational PFF fixation methods up to 2017 is described and compared in [25]. This summary concluded the validation of computational results with experimental data. Computational studies are observed to be useful in studying fixation methods or conditions (such as bone healing) that are difficult to study in vivo or in vitro with some issues. The need to determine optimality conditions for PFF fixation is the consensus of the reviewed studies.

The biomechanical impact of femoral component lengthening on leg length discrepancy and hip function is observed to be high in [20] with 98% of the 56 patients experiencing it. On average, 62% of these patients experienced this lengthening right after surgery by 9 mm, while 43% experiencing it after 3 months and 33% experiencing after 12 months. It is concluded that the impact of femoral component is significantly impacting patient's perception of discrepancy of length after THA.

Vancouver type B1 fracture is simulated during a cemented THA by using a transverse osteotomy in [23]. Stiffness of the construct was observed via nondestructive tests using four-point mediolateral, torsional, and axial bending. Cyclic load testing until catastrophic construct failure is applied. Cycles to failure, stiffness, and failure load between a retrograde slotted femur nail construct docked to a THA stem and a lateral locking plate in a human periprosthetic femur fracture model are compared in the study. The testing on fresh-frozen human anatomic femora indicated mediolateral bending stiffness to not differ at a statistically significant level, while it displayed a biphasic profile with significantly increased stiffness in both groups. Plate designs provided significantly higher torsional stiffness, cycles to failure, and failure load than the nail constructs. The docking nail construct is observed to be biomechanically weaker in stable fractures while providing an intramedullary fixation with connection to the prosthesis stem in comparison to the plate construct.

The impact of using technology as a part of preoperative templating in THA is observed in [28]. This templating is a mandatory procedure to achieve appropriate offset and leg length equality that impacts the biomechanics of THA outcomes. Side differences in femoral morphology are prone to errors resulting from templating method used on the contralateral hip. Biomechanical stability can be measured by using the distance of the lesser trochanter to the femoral head center (LTFHD) that is frequently used as a reference parameter for preoperative planning and intraoperative validation during THA. Analysis on side-to-side asymmetry of the LTFHD, femoral length, femoral head diameter (FHD), and femoral antetorsion on 50 cadavers by using linear regression with correlation on the impact of 3D computed tomography (CT) indicated statistically significant side differences for LTFHD and FHD. Even though 8% of the investigated specimens revealed a LTFHD of more than 4 mm, which should be anticipated during THA to avoid unsatisfiable results, LTFHD is determined to be a reliable key performance indicator in [28] for preoperative templating and intraoperative validation during THA with a high correlation between sides.

The biomechanical impact of polyethylene wear and femoral offset was evaluated in several articles [22, 24, 139] that relate to dislocation rate and implant loosening with the corresponding follow-ups. In [22], authors reported a trend toward lower polyethylene wear in the hips with an adequately restored FO considering the ability of THA to restore FO within 5 mm of the native contralateral FO. No statistical significance is determined between the linear and volumetric wear rates on this small sample sized study. Lateralized offset stems on the contralateral side on one side of THA and bilateral THAs using standard offset stems on the other side are tested in [24]. The wear is determined to be significantly increasing during restoration of FO. The volumetric wear is determined to increase in [139] under-restoration of FO with respect to preoperative values. Highly cross-linked liners or hard bearing surfaces can be utilized to counteract the wear [29]. Larger femoral heads improve implant stability and reduce femoral offsetting by means of modularity.

Reasons for THA implantation failure are complicated and can include patient-, material-, and non-patient (such as inadequate surgical technique)-related factors. Femoral head-neck interface by fretting and corrosion damage is determined as another factor contributing to THA failure [31, 64, 69]. Determination of the exact reasons of the degradation process appears to be not possible; however, the following factors are determined to impact the implant failure:

- Body mass index [58]
- Taper length [58]
- Time in situ [68]
- Mixing of alloys [71, 75]
- Femoral head size [77, 78]
- Flexural rigidity [80]

- Female taper angle [78]
- Taper-angle mismatch [88]
- Taper diameter [91]
- Stem surface roughness [68, 83–85, 93, 96, 97].

Effectiveness of cemented and uncemented fixation types on the liner wear risk is analyzed theoretically by using FEA in [35]. The key intraoperative factors playing roles in determining the wear risk during surgical planning that are used in modeling included head material, head size, liner thickness, cervical-diaphyseal angle, and center of rotation positioning. Biomechanical restoration analysis was based on two types of 3D liner models' simulation of ultrahigh-molecular-weight polyethylene. Liner thickness and acetabular fixation techniques are determined to be significantly related to wear risk. A proper prevention technique to the cause of polyethylene liner wear is observed to be the use of a cemented fixation with a thick liner in the right center of rotation (Figs. 5 and 6).

THA dislocation rate's exposure to cup positioning and abductor mechanism's reconstruction are evaluated on cementless THA operations of 1318 patients on the data collected in a span of 20 years in [36]. The radiological assessment of a 28 or 32 mm femoral head sized THA cups based on positioning and hip rotation center

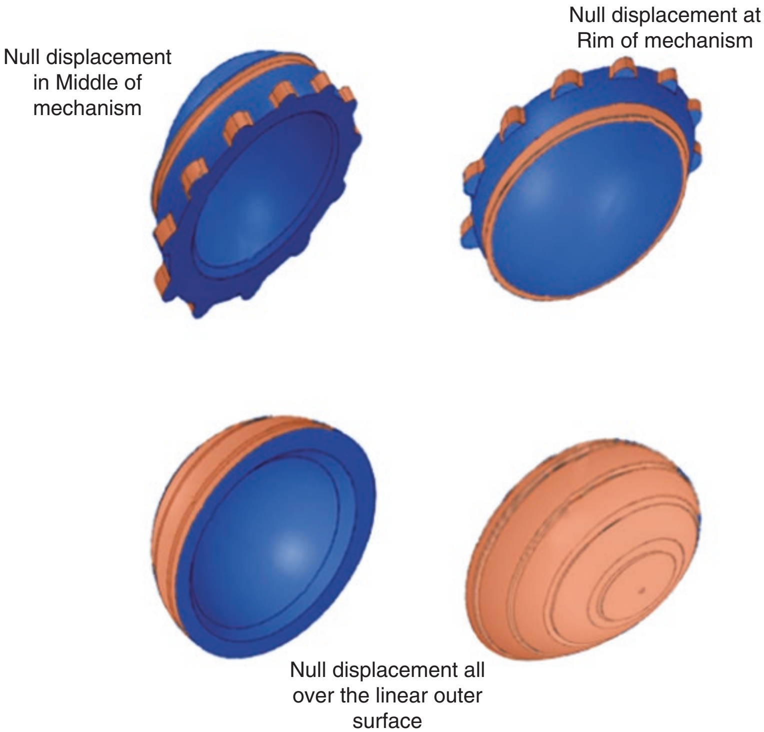


Fig. 5 Cementless (left) and cemented (right) acetabular fixation for 3D model liner [35]

Fig. 6 Bringing the center of rotation back down to original position will overlengthen the patient's leg. Oblong cup filling acetabular defect with restoration of limb length [140]

and reconstruction of the abductor mechanism is conducted by measuring the lever arm distance and the height of the greater trochanter. It is concluded for the observed 38 dislocations by using multivariate regression analysis on the implant and physiological data that these dislocations are most associated with the following:

- A greater distance to the anatomic hip rotation center.
- Acetabular inclination and version angles for hips outside two safe windows for cup position.
- Lever arm distance and height of the greater trochanter abductor mechanism.
- Hip's abductor muscle weakness.

Analysis on 1212 THAs that utilized dual-mobile acetabular cup (DMAC) and 1196 THAs that had a standard fixed-bearing design resulted in advantages of using DMAC for dislocation rate reduction in [37]. A slightly significant risk ratio and a statistically significant difference favoring of the DMAC group was determined only for primary (or revision) arthroplasties, traumatic fractures, or elective patients with diagnosis of osteoarthritis, avascular osteonecrosis, or rheumatic arthritis.

Biomechanical loading of THA analysis by varying femoral stem length is studied in [39] on all procedures that had gait analysis occurring at a mean of 31 and 79 months postoperatively for the short and long stem THA, respectively. There are no lower limb loading differences observed by reducing the femoral stem length after testing a range of practical walking activities. A shorter stem appeared to be desired during gait when compared to a conventional stem used for THA.

The importance of patient positioning in the supine and lateral decubitus positions is researched in [40] to identify their key biomechanical roles in restoration of normal hip anatomy for THA success. Primary unilateral THA for osteoarthritis on two groups with both 100 patients by multiple surgeons are performed in [40]: a group with supine THA with anterior approach and another group that had lateral decubitus THA with direct lateral or posterior approach. Parameters impacting hip reconstruction in the coronal plane including discrepancies in leg length, center of rotation displacements in the vertical and horizontal directions, femoral offset, and total offset parameters are analyzed using postoperative anteroposterior pelvic radiographs. Assuming a surgical target of reconstructing both leg length and total offset within 5 mm of native anatomy, the supine group is determined to be more than twice as likely to achieve expected research-specific goals with fewer outliers. Leg length and total offset are determined to be more consistent and accurately restored by using the anterior approach in the supine position.

The use of cortical contact state of short and conventional stems in different femoral canal types and stem positions is analyzed in [41] using a CT-based 3D templating software. Upon classification to femoral canal types, the influence of stem position on the contact state is determined by evaluating different situations of stem anteversion and stem positions. Regardless of the stem position based on a single type of femoral stem, it is shown that the short and conventional stems are both capable of attaining the same proximal cortical contact in any femoral canal. Extension and flexion stem positions are determined to increase the distal contact, especially in conventional stems. The distal contact is observed to increase for the retroverted stem insertions. It is important to note that the pattern of adaptive bone remodeling not only varies with different stems but also observed to strictly relate to the stem design and to the location of femoral stem's fixation on the bone; therefore, it depends on the surrounding bone location where the corresponding stresses are created and transferred.

For furthering success of THA, additional modularity is incorporated into the design of the femoral component such as neck-shaft angle and anteversion that is open to adjusting intraoperatively. The clinical effect of the increased modularity on hip anatomy is investigated in [42] by changing the anatomical parameters following conventional THA with a prosthesis of predetermined neck-shaft angle. Measured parameters included hip center of rotation, femoral anteversion, neck-shaft angle, offset, and stem alignment both pre- and postoperatively. Pain scores and values attained from a functional assessment before and 1 year after surgery are evaluated to determine operative anatomical changes. Postoperative reduction of anteversion is observed to increase the torsional moment on the prosthesis in [30] that may relate to risk of loosening [32]. Anteversion is also shown to have a strong influence on hip contact forces in the proximal femur [38]. One-year follow-ups in [42] did not show any adverse effects, but long-term observations are mentioned to be a necessity. The postoperative changes are found to have no influence on function and pain. High pre- and post-operative variability of femoral anteversion and neck-shaft angles were found by using a standard uncemented femoral component with a significant decrease of the post-operative anteversion and slight increase of the neck-shaft angles that had no impact on the clinical outcome.

Biomechanical analysis of patients that had gone through a THA and LSF over a 17-year period starting in 2000 is investigated in [44]. It is found that approximately 1% of 67,919 THA patients experienced LSF; these patients had increased risk of mechanical complications during THA, and risk of revision arthroplasty is also observed to upscale slightly in these patients.

The impact of changing the reaming technique is analyzed in [53] on THA patients. Center of rotation (COR) displacement is observed by utilizing a standard reaming technique such that the acetabulum is reamed immediately peripherally and referenced off the rim. It is concluded that significant COR displacement can occur medially and superiorly upon reaming the acetabulum to the floor. COR displacement is due to the preoperative acetabular floor depth, and it cannot always be compensated by using a high offset stem.

Another factor that impacts THA biomechanics is metallosis that is defined as the accumulation and deposition of metallic particles secondary to abnormal wear from prosthetic implants that may be visualized as abnormal macroscopic staining of periprosthetic soft tissues [45, 54]. THAs are subjected to integration of high mechanical loads and host bone; therefore, cobalt-based alloys, cobalt-chromium-molybdenum, and cobalt-chromium-tungsten-nickel are used widely as a long-term permanent implant due to their high corrosion resistance, higher strength, and hardness [3]. Due to lower incidence of metal-on-metal (MoM) implant dislocations, thin metal acetabular components that could allow for large diameter femoral heads, and an articulation that is anticipated to produce less volumetric wear, MoMs are thought to be advantageous over other procedures [46]. Polymer-cement interface and cementless approaches along with modular designs are also investigated in many articles as a part of THA.

A more integrated material degeneration approach in regenerative engineering is tribocorrosion that combines the effects of corrosion and tribology principles including wear. Friction, lubrication, and wear contribute to tribology, while chemical and electrochemical interactions between materials and their environments are related to corrosion [48, 49]. Corrosion and wear may act synergistically. In vivo applications of tribocorrosion results in biotribocorrosion that deals with mechanical loading and electrochemical reactions occurring between elements of the tribological system when exposed to biological environments [47]. Biotribocorrosion application affects medical implants by leading to the release of wear particles and metallosis that have been identified as the major factor of joint replacement complications. Further applications and analysis for THA in this area of research are needed.

Analysis on biomechanics of 22 cementless femoral component THA procedures and 15 hip resurfacing procedures' evaluations as a part of THA on young patients is conducted in [56]. The failure rate for THA using femoral revision of mechanical failure is identified as 1.3% on an average of approximately 8 years of follow-up. On an average of approximately 4 years of follow-up, the mechanical failure rate of the femoral component for hip resurfacing is determined to be 2.6%. It is concluded by the authors that the enthusiasm for hip resurfacing should be tempered by these data.

Instability and impingement have been shown to cause increase of dislocation that is associated with spinal stiffness [55]. A dislocation rate of 0.41% of 12,365 patients undergoing THA from 2016 to 2018 is determined in [59]. Dislocation rate quantification after primary THA based on comparison of standard and high-offset femoral components is accomplished in addition to determination of how offset differences affect impingement-free range of motion in a stiff spine cohort. Fifty-one patients sustained a dislocation with 49 utilizing a standard offset stem. High-offset stems facilitated greater range of motion (RoM) in the impingement model before bony impingement and resulted in lower dislocation rates. Surgeons are recommended to consider the use of high-offset stems and pay attention to offset restoration in the setting of high-risk THA due to spinal stiffness.

A correct and personalized biomechanical restoration of the hip is mentioned to require appropriate preoperative planning in [61]. The radiographic review is a secondary biomechanical factor since it is the first and fundamental step in the planning. Misled planning can happen as a result of limb or pelvis malpositioning. Acetate templating on digital X-ray, digital 2D templating on digital X-ray, and 3D digital templating on CT scan are the methods that are observed to provide correct templating. Factors playing a role in comparison with different templating methods include time efficiency, costs, reproducibility, and accuracy. Digital templating allows a permanent record of planning and can be electronically viewed by different members of surgical teams, and 3D templating is intrinsically more accurate.

Performances of minimally invasive surgery to the standard-invasive approach in THA are compared in clinical trials. Upon a database search with the evaluation of 4761 patients' qualitative and quantitative data in [66], minimally invasive group is determined to have less total estimated blood loss, shorter surgical duration, and a shorter length of stay in hospital, while the standard-invasive group is found to have a higher value of the Harris Hip Score. Cup inclination and anteversion, stem alignment, and limb length discrepancy are investigated for the analysis of component positions. Any relevant differences are considered through the statistical analysis of variation across the two approaches. Noting that the component positioning influences the biomechanics and the duration of the implants [65], no relevant differences are found between the two approaches that make a difference in component positioning [66].

Short stems in THA are becoming increasingly popular. For instance, in Germany, approximately 10.4% of all primary THAs are performed using a cementless short stem [67]. Patients with poor bone quality and osteoporosis have cemented short stem THA as a potential alternative approach. While there are no new-generation short stem THA with cemented fixation available on the market, prototypes of the Optimys stem fabricated using polished steel are used in a recent in vitro biomechanical study demonstrating that the concept of a line-to-line cementation technique could be further pursued for the development of a cemented short stem in THA [60]. This result is confirmed in a computed tomography-based, finite element analysis performed in [62] that quantified the biomechanical performance of the short stem design. Hence, cemented short stems are determined as a promising alternative for use in osteoporotic bone.

Biomechanics of the movement patterns during a sit-to-stand (STS) task before and after THA are compared to a control group in [70]. 3D motion analysis of 45 THA patients and 23 healthy control group members is conducted. Asymmetric inter-limb movement with lower vertical ground reaction force (VGRF) and smaller moments on the operated limb are observed preoperatively. Three-month THA follow-ups of the patients' movement symmetry showed significant improvements; however, patients continued to have lower VGRF and smaller moments on the operated limb compared to non-operated limbs and control limbs.

Effectiveness of the use of metal augments in revision THA is biomechanically investigated in [72] in comparison to traditional techniques. A minimum of 2-year follow-ups are conducted upon 74 THAs revised using metal augments with a cementless hemispherical cup and 77 THAs revised using the jumbo cup. Radiological and clinical observations along with biomechanical parameter measurements are collected. The biomechanical uses of metal augments are identified to help restoring the COR position better, avoid using a larger cup, reduce head-cup difference, rebuild femoral offset, and decrease leg length discrepancy. Radiological and clinical outcomes in the short term are also determined to be more satisfactory.

Elderly face challenges upon failure during THA that may lead to being bedridden. Loosening and fracture type of failures can occur three times more frequently compared with failures of the stem fix in the femur. In [73], frequency analysis of the hammering sound is used for analyzing the possibility of fixation evaluation as a part of implanting a cup into the acetabulum. In this study, by using a system consisting of a tablet PC and directional microphone, the peak frequency at which the amplitude reached the maximum was determined, and judgment processing (stable, unstable) of cup fixability was performed in real time. During the hammering period, the frequency leading to fracture is observed to decrease in both biomechanical test materials and orthopedic models. Variation of the maximum peak frequency is observed to decrease when fixation was acquired, and the frequency stabilized. Hence, it is suggested that this method can serve as a fixability evaluation method of acetabular cups because analysis can be performed in real time during surgery, for which prevention of intraoperative fracture can be expected.

Mechanics of the gain differences between man and woman is analyzed in [76] upon THAs. Linear regression is used for analysis of 64 women and 60 men. Combined biomechanical variables are predicted up to 24% of the variation in pain improvement and up to 27% of the variation in functional improvement. Women subjects are identified to have increased passive adduction RoM and peak external rotation moments that are associated with pain improvement. Passive flexion RoM and peak adduction moments are determined to relate to functional improvement. Men are determined to have increased peak external rotation moments that are associated with pain improvement. Peak extension moments and passive flexion RoM are associated with functional improvements.

Drop-weight impact testing is applied to determine the biomechanics of impact resistance of the acetabulum with simulated bones of different density as a part of cementless cup insertion in [79]. Osteoporotic and healthy bone models are mimicked by using low- and high-density polyurethane foam blocks, respectively. Acetabular cancellous bone and acetabulum's medial cortex are demonstrated by using polyurethane blocks and composite sheets, respectively. It is determined upon testing that the osteoporotic bone model's impact resistance was significantly lower than that the healthy bone model. Impaction resistance in the osteoporotic bone model is found to be equivalent to that of healthy bone model when a thick medial wall was present.

Importance of accurate positioning of the acetabular component is investigated in [86] as a part of total hip replacement by determining the influence of the orientation of the acetabular component on the probability of dislocation. Anteversion and abduction of the acetabular component of 127 hips' radiological results that dislocated postoperatively are compared with a control group of 342 patients. The results in this study demonstrated the importance of accurate positioning of the acetabular component for reducing the frequency of subsequent dislocations. Radiological lowest at-risk values for dislocation are determined as 15° for anteversion and 45° for abduction.

Short-stemmed implants, known as metaphyseal stems, have several advantages including small implant size, coating with an active substance that promotes secondary stability, the possibility of using a minimally invasive technique, and the possible modularity of the implant enabling a more accurate restoration of correct biomechanical conditions in the operated joint (offset) [90]. A metaphyseal stem enables more physiological load transfers, and the risk of unexplained, post-arthroplasty thigh pains is eliminated. A comparison of the biomechanical features between the classical stem, the anatomical stem, and the metaphyseal stem showed, in the latter case, higher physiological load transfers at the femoral neck region and beneficial effects for osteointegration and bone remodeling at this region, preventing the adverse effect of stress shielding [50]. Particularly, short stems are gaining popularity in THA as they preserve the bone stock and simplify the implantation process. Good bone stock is expected to be high for advising a short stem to a patient. Cementation can recover the clinical use of short stems for patients with poor bone stock. Quantification of the biomechanical performance of a cemented short stem and comparison of two cementing strategies with the one that has stem one size smaller than the rasp with the other technique that had stem and rasp size identical is implemented in [94]. Upon finite element analysis, validated by experimental data, the two cementing techniques resulted in nonsignificant differences in stiffness and strength. Displacements as calculated from finite element analyses had strong similarity to the ones measured by digital image correlation. Stresses calculated during level walking are determined to be far below the fatigue limit for bone and bone cement. For osteoporotic bone, this study suggests that cemented short stems are a promising solution; the two cementing techniques covered provide similar outcomes.

Acetabular reinforcement components are essential in restoring proper biomechanical functioning of the hip, following THA [51]. Acetabular reinforcement components' aseptic loosening and mechanical failure are among the main causes of their reduced service life. An alternative to acetabular implants that typically feature a structural solid layer that provides load bearing capacity, coated with a foam of uniform porosity to reduce stress shielding and implant loosening concept, and a 3D printed cage consisting of a multifunctional fully porous layer with graded attributes that integrate both structural function and bone ingrowth properties is introduced in [96]. The results are attained via analysis of the mechanics of materials with density-based topology optimization, additive manufacturing constraints, and bone ingrowth requirements integrated into the problem formulation.

Micromotion is another concern in biomechanical analysis of designed implants. For instance, in the case of cementless fixation, micromotion at the bone-implant interface has been reported to affect bone ingrowth [52]. Low micromotion, typically below 28 μm, results in bone ingrowth, while excessive micromotion that can be assumed to be above 150 μm results in the growth of fibrous tissue inhibiting biological fixation [57]. Micromotion on bone-implant interface mainly depends on the implant primary stability that relates to several factors including implant macrogeometry, elastic modulus mismatch with the bone, fixation technique, and the bone tissue quality with its defects [63]. The micromotion is calculated as the relative sliding distance between the bone and the implant surfaces in [96]. A reduction in the maximum contact stress on the bone surface by 21.4% and a decrease in the bone-implant interface peak micromotion by 26% are attained upon numerical analysis. These numerical results indicate implant long-term stability and enhanced bone ingrowth. Even though a clinical loading case of one-legged standing is used for the analysis, the attained numerical results need to be further analyzed using different loading scenarios such as walking, running, and stair climbing.

2 Conclusion and Future Work

In this work, a wide range of biomechanical studies that relate to THA are covered. One of the main outcomes from the observations is the researchers' ultimate goal to find optimality conditions for THA. As one can imagine, knowing physiological conditions, it is a challenge to find a universal method that optimizes needs of THAs. There are valuable outcomes attained such as the importance of minimal invasiveness that ended up with less total estimated blood loss, shorter surgical duration, and a shorter length of stay in hospital when compared to the standard-invasive group that had a higher value of the Harris Hip Score [66]. Noting the number of variables that plays in biomechanics of THA, it is a certain challenge to come up with practical methods to make THA much better. Additionally, if minimal invasiveness appeared to provide much better results than THA, a question would be the impact of noninvasiveness prior to THA. For instance, investigating if early psychological treatment can help individuals prevent from going through THAs can be a valuable research outcome to reduce the increasing number of THA patients. Many attempts have been made to prepare patients before surgery with the aim of reducing stress and improving outcomes [141]. This stress alone could be impacting patient in a negative way and increase the level of dissatisfaction. The current practice in elective orthopedics does not routinely include psychological interventions despite evidence that psychological factors such as personality, anxiety, depression, and negative thinking styles can influence outcomes and recovery from surgery [142]. In fact, there is very limited research and investment on impact of psychological treatment on patients to prevent going through THA, and majority of the literature focuses on the impact of psychological treatment either pre- or post-THA outcomes. Hence, we propose researchers and medical professionals to help potential THA patients psychologically and recommend therapy if applicable to decline the ever-increasing number of THA patients. Further research and analysis of data regarding to this suggestion are needed.

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All-Inclusive Impact of Robotics Applications on THA: Overall Impact of Robotics on Total Hip Arthroplasty Patients from Manufacturing of Implants to Recovery After Surgery

Abstract Advancement of robotics in recent years started to impact the number of robotic-based total hip arthroplasty (THA) applications with the corresponding success observed on surgical outcomes. There are robotic systems such as Kuka's LBR iiwa Third IEEE International Conference on Robotic Computing (IRC), 2019), Mako (Tarwala and Dorr, Curr Rev Musculoskelet Med 4(3):151–6, 2011; Domb et al. Clin Orthop Relat Res 472:329–336, 2014; El Bitar et al. Am J Orthop (Belle Mead NJ) 44:265–269, 2015; Tsai et al. Int J Med Robot 12:288–295, 2016; Suarez-Ahedo et al. HIP Int 27:147–152, 2017; Domb et al. J Arthroplasty 30:2208–2218, 2015; Kayani et al. HIP Int 31:311–319, 2019; Heng et al. J Arthritis 7:4, 2018; Kong et al. Int J Surg 77:174–180, 2020; Kanawade et al. J Arthroplasty 30:392–397, 2015; Banchetti et al. J Health Soc Sci 3:37–48, 2018; Perets et al. Int J Med Robot 14:e1912, 2018; Illgen et al. Surg Technol Int 30:365–372, 2017), Robodoc (Bargar et al. J Arthroplasty 33:810–814, 2018; Honl et al. J Bone Jt Surg Am 85:1470–1478, 2003; Nakamura et al. Clin Orthop Relat Res 468:1072–1081, 2010; Schulz et al. Int J Med Robot 3:301–306, 2007; Bargar et al. Clin Orthop 354:82–91, 1998; Lim et al. Comput Aided Surg 20:41–46, 2015; Chen et al. Chinese J Traumatol 25, 2021; Hananouchi et al. J Orthop Res 25:1062–1069, 2007), Orthodoc (Nishihara et al. J Arthroplasty 21:957–966, 2006), da Vinci, and CASPAR (Siebel and Käfer Z Für Orthop Ihre Grenzgeb 143:391–398, 2005) that are used as a part of surgeries, and these robots' success levels are investigated with their strengths and weaknesses for their use in THA surgeries, while some other studies compared successes of robotic-oriented and traditional THA operations. Much of the focus of robotics intervention so far is based on robotics use during surgical applications, while robotics has many pre- and post-surgical impacts on patient well-being and recovery. In this review, in addition to outlining the use of robotics as a part of preoperative, during, and postoperative surgeries from a general perspective, biomechanical implications are pointed out by incorporating manufacturing and healthcare factors. A theoretical probabilistic measure of success for use of robotics is derived for measuring success starting from the beginning of manufacturing processes of implants until the impact of robotics use for full recovery with the corresponding post-surgical applications, and this approach can be also applied in other

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transplantation strategies. Suggestions for potential future research directions of THA and related biomechanical considerations are outlined based on recent advancements on millirobots, artificial intelligence, additive manufacturing, and robotics.

1 Introduction

THA surgeries have a well-known success record in applications particularly in recent years of observations. The advancement of robotics applications in industrial settings aligns with the increasing success rate of robots' use as a part of surgical procedures as observed by researchers. Development of robotic systems for THA applications can be grouped into two: robots that are developed in the past that are no longer available for research and surgical uses such as CASPAR and robots such as Mako [4] that assists with THA surgeries for THA implantation that operates with high accuracy, and surgical operations continue today with more research conducted on such robots. Affordable robots for surgical uses would increase their use along with the increased robotics training need for doctors. While majority of the research focus has been on robotics use toward surgical success and assisting surgeons, the role of robotics in surgical operations goes well beyond what meets the eye, and this is also the case for general implantation-based surgical procedures. Implant failures can happen due to mechanical problems that can be related to implant's materials used, design, and cement quality that takes us to the manufacturing aspect of implants. Additionally, one should not forget the postoperative healing period during which the robotic-assisted gaits may have positive impact on the recovery of the patient. In this review, the impact of robotics use on THA patients will be covered from three distinct perspectives with their interrelated outcomes: the impact of robotics use during THA surgeries as well as the impact of robotics' use on other THA factors that need to be investigated both pre- and postoperatively. The results of these three distinct sections are all correlated, and robots can be used in all three sections that impact the implant and surgery success.

2 Preoperative Impacts of Robotics on THA

The importance of precision and quality of the implant cannot be underestimated from manufacturing perspective. The American Association of Hip and Knee Surgeons (AAHKS) [5] stated the identification of implanted prosthesis in operative report to be one of the approved final measures of primary THA [53]. This measurement description requires determination of the percentage of patients undergoing THA whose operative report identifies the prosthetic implant specifications including the prosthetic implant manufacturer, the brand name of the prosthetic implant, and the size of each prosthetic implant that can vary significantly. The attained success rate is an indicator of implant success therefore playing a significant role in the decisions made in the corresponding future implantation use. Noting that robotics can increase precision in manufacturing processes, and therefore quality, the percentage of success in implantation can increase with robotics applications from development of a product standpoint [54]. From an application perspective, impact of robotic milling for stem implantation in cementless THA is observed in [55], and the 10-year follow-up results showed successes of both manual and robotic-based surgeries. This research is limited to robotic milling used for stem implantation, and robotics has a much extensive coverage and impact on THA applications.

Additive manufacturing of bioimplants has come a long way over the last two to three decades that impact the biomechanical stability of the implants [1]. The use of preoperative robotics can impact bioimplantation in two different ways as a part of additive manufacturing. The method of mixing, processing, and applying biocompatible materials for implant production playing a crucial role in biomechanical success of the implant that correlates with the mechanical failure of the implants after surgeries. For instance, material jetting is an additive manufacturing process that utilizes droplets of build material that are selectively deposited to the location of interest [1]. A robotics application in this methodology is the material jetting of biomaterials on implants; for instance, the robots used for printing liquid like gel on 3D printed materials can be particularly useful in cement printing and applications. A multi-process additive manufacturing system can utilize a robot to transfer the object between two or more different additive manufacturing machines during fabrication [39]. Given that there is growing demands in THA implantation, particularly from younger, more active patients or patients with compromised bone quality, a wear-resistant material of choice such as CoCr alloy is typically used in femoral heads for total hip arthroplasty that can be 3D printed [7]. Life of THAs is often reduced due to debris generation and Co and Cr metal ion release from taper junctions that are observed in vivo [8]. The size of printing can be customized for surgical applications. Given that the size and shape of the hip to be replaced changes per patient, mechanical and biomechanical needs for the corresponding application change [12]. Accuracy of the acetabular cup's placement is improved based on the matching of the planned cup placement and the actual surgical cup placement. Compared to conventional manual THA, robotics applied for THA improves precision and reduces outliers in restoring the planned center of hip rotation [44]. Noting that hip rotational motions are more variable across individuals during gait, the robotic-based THA help to reduce the issues that could arise during walking when compared to non-robotic surgeries [44]. The hip is externally rotated approximately 5° and remains so throughout loading response and early midstance during the initial contact. The hip begins to rotate internally within 2° of neutral rotation by the middle of terminal stance and then reverses direction and externally rotates to its peak of 15° of external rotation during initial swing [45]. The robotics THA application would be expected to be closer to these expected rotational values when compared to the traditional surgical approaches.

4D printing is introduced as the printing method that allows using 3D printing techniques in creation of an object that can change its shape or properties in a way that its reaction to varying conditions can be predicted over time when exposed to water, air, heat, or an electric current [6]. Given the definition of 4D printing, mimicking of cartilages, tendons, and muscles as well as other biological elements may not be too far off from artificial development using 4D printing [9]. In 4D printing, robotics impacts the strength of composed material implants during implant sizing that directly impacts the biomechanical behavior of the implant's failure and stability based on experienced motions in the hip. Materials' additive manufacturing particularly aids with resolution of the architecture, the solidification of mechanisms, post-treatment processes, and functional applications that are based on the materials to be printed, and robotics has a strong stand throughout all the corresponding steps. Robots take place in revolution of 3D printing sizes from centimeters to meters that incorporate biomechanical strength to the implants introduced, allowing large size printing such as artificial hips [2]. This allowed the implants to be printed as a single metallic item instead of development through machining. Due to this practical availability of printing tools, as a part of surgical procedures and preparations, it is possible to personalize 3D surgical implant planning by using robotic planning systems to create a 3D computerized model of the individual patient's hip joint. Therefore, visualizing and planning of the surgery to match the unique anatomy of each patient are possible via robotics with mechanical parameters entered in such systems [5]. There are different methods of testing manufactured implants' success. For instance, biomechanical testing of manufactured hip implants can be tested for their successful material composition via finite element analysis [10]; however, this approach has many limitations since neither the homogeneity of the materials nor the composition of the implant can be analyzed in depth. The benefits of using robotics in industrial applications go well beyond what can be covered in this work with their substantial capabilities [13]. For instance, arthrokinematics refers to the movement of joint surfaces with the angular movement of bones in the human body which occurs as a result of a combination of rolls, spins, and slides [63]. Noting the advancements in robotics and 4D printing, a potential research investigation area for hip arthrokinematics improvement can be the impact of robotics use with 4D printing on hip arthrokinematics. Analysis of the corresponding micromotion and design of the total hip joint can be investigated for future implantation success. More research on manufacturing techniques that utilize robotics for material distribution over the implant can help determining a variety of compositions and improve the material homogeneity of the implant. Robotics applications not only help with the design of the implant material but also help with the improvement of biomechanical factors that are needed for recovery of the patient with the corresponding factors such as placement of materials and the design of implant for handling cyclic loadings. The image on the left below demonstrates an example of how 4D printing would look like if printed using a 3D printer, and the image on the right shows bioink printing at Zurich University of Applied Sciences (Fig. 1).

3 Impacts of Robotics During THA Surgery

The impact of robotics during surgical procedures is an extensively studied area due to the increasing interest of robotics use in surgical procedures. Robot-assisted surgeries are shown to improve clinical outcomes and reduce revision rates [52]. The

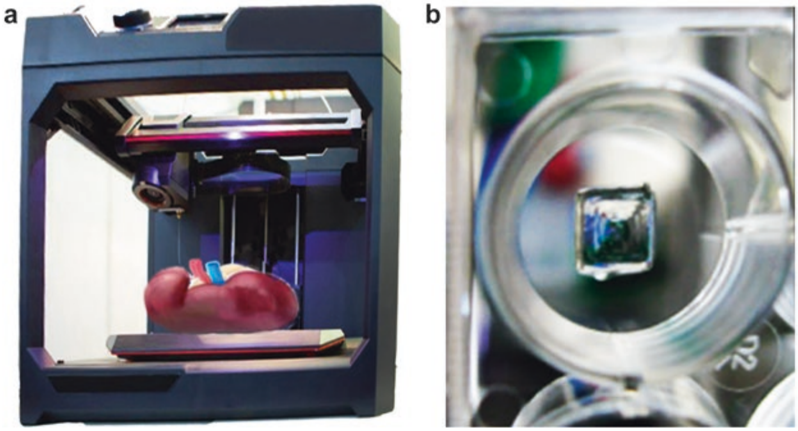

Fig. 1 (**a**) 3D printed organs may become a reality in our lifetimes – but what about 4D printing? (**b**) A structure printed with bioink at Zurich University of Applied Sciences (ZHAW)

proportion of surgeons utilizing robot-assisted arthroplasty increased from 6.8% to 17.7% just in the New York area from 2007 to 2017 [49]. The increase in the research literature is partially due to the testing of new robotic-based technologies introduced such as Kuka's LBR iiwa [50]. Robotics allows better mechanical control and stability in applications that may help reducing human errors; however, it also has its own challenges such as surgeon training, extended surgical hours, and economical costs [16]. Improvements in applications of the robotics during surgery include improving the accuracy when cutting the femur, reaming the acetabulum, and placing the implant components. It has been shown that the use of robotics can help with reducing inaccuracy as much as 94%. This particularly helps to minimize risks of leg length discrepancies, dislocations, and other complications of conventional hip replacement surgeries. There are limited number of extensive studies that compare robotic-assisted and manual THA surgeries. If we focus on robotic-assisted THA in comparison to manual THA that included 20 or more participants for both surgical strategies, we see limited number of articles. For instance, in a review that covered 7 of such articles, approximately 51% of the 658 patients had gone under robotic-assisted surgeries. Patient-reported outcome measures (PROM) appeared to be low statistically ($p < 0.05$) in most of these studies. Assessment of radiographic outcomes indicated robotic THA results to be more consistent and accurate for component placement in six studies [5].

There are well-known robots used during surgeries such as Mako [4, 17–28], Robodoc [29–36], Orthodoc [37], da Vinci, and CASPAR [38]. The direct cutting of bone to the final planned cut or indirect planning landmarks to adjust placement or holding of cutting jigs has been conducted using robots. The applications of robotics can be divided into three categories if we base the applications to surgical incisure/cutting operations [40]: (1) autonomous, (2) haptic control [19, 41], and (3) boundary control [42, 43]. Autonomous applications are 100% robotics based with the mechanical limitations depending on the mechanical stability and physical stand placement of the robot. Haptic control requires surgeon involvement in several applications such as cutting, milling, or drilling in which case mechanical stability of the operations may alter between robot and surgeon. Boundary control allows independent task management without direct human manipulation by using algorithms based on associated preprogramming with defined parameters of bone resection. Robodoc (THINK Surgical®) surgical system [15] was the first active robotic system used in THA surgery that allowed complete robotic assistance without continuous control by the surgeon throughout the procedure. For instance, the placement of the polyethylene-based cartilage on the bone by using a robot is a fine application of the robotics for implant production.

The robotic systems can be completely manual, hybrid, or fully automated depending on surgeons' involvement in the process. da Vinci surgical system is a manual robotic system that requires surgeons' full control during the surgery and used for many different surgical applications (Fig. 2).

Robodoc is a robotic system used for hip surgeries that utilizes CT scans that are converted into three-dimensional virtual images for preoperative planning and computer-guided drilling [48]. Preoperative CT scans are used for Robodoc computer assistance for milling a femoral canal automatically and stem implant positioning. Majority of the surgical applications of Robodoc, 50% (four out of eight), has been posterolateral [31, 34, 37, 55], while 37.5% (three out of eight) was posterior [29, 33, 36], and only one was anterolateral [30].

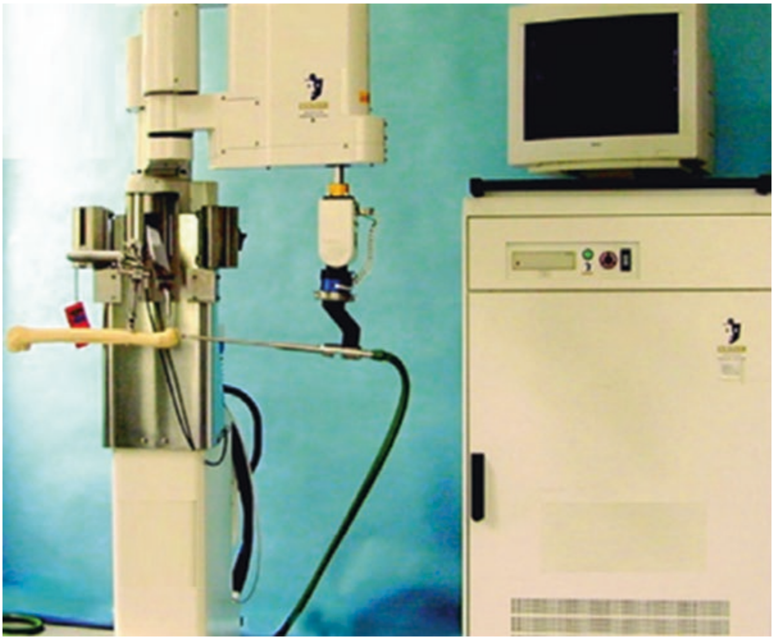

Fig. 2 An image of a Robodoc surgical system [84]

There are no differences found between the robotics and manual procedures in [34] at 1-year and 5-year follow ups, while robotic-assisted THA had significantly higher outcomes at 2- and 3-year follow-ups. The only study that determined robotic-assisted surgery to cause higher dislocation and revision rates was [30]. The rest of the studies didn't show a statistically significant difference; however, the outcomes were positive for robotic-assisted surgeries. For instance, one of the comprehensive studies focusing on the application of Robodoc system investigated in the United States and Germany was designed to address potential human errors in performing cementless THA [3]. The system consists of a preoperative planning computer workstation called Orthodoc and a robotic arm with a high-speed milling device as an end effector. One- and two-year follow-ups were conducted on 127 and 93 patients, respectively. Radiographs were evaluated by an independent bone radiologist and demonstrated statistically better fitting and positioning of the femoral component in the Robodoc® group. There were three cases of intraoperative femoral fractures in the control group and none in the Robodoc® group that were observed as the differences.

Majority of the studies focused on Robodoc comparison with manual surgeries focused on stem placement. Bargar et al. [29] observed better trends in clinical outcomes for robotic-assisted THA when compared to manual surgical procedures with no statistical significance after 14 years of follow-ups. Hananouchi et al. [36] did not find significant differences between robotic-assisted and manual THA surgeries by analyzing the Merle d'Aubigne scores. Robotic-assisted THA surgeries are observed to have higher dislocation rates, revision rates, and longer intraoperative times by Honl et al. [30] when compared to the manual THA. Lim et al. [34] did not find any significant differences determined between the robotic-assisted and manual operations in short-term observations. Bargar et al. [33] did not find any statistically significant difference in the THA functional outcomes after 2 years of surgery. Upon 1- and 5-year follow-ups, Nakamura et al. [31] did not find any significant differences for the manual THA operations, while the robotic-assisted THA is observed to have significantly better scores during the 2- and 3-year follow-ups. During the 2-year follow-up, Nishihara et al. [37] did not find any intraoperative femoral fractures. The longest follow-up period was by Nakamura et al. [55]; upon 10 years follow-up, no significant differences were determined in functional scores between the two methods.

There are several models of Mako technologies that are utilized for THA applications. Mako THA system (Stryker®, Mahwah, NJ) utilizes predefined physiological parameters and preprogrammed algorithms to allow surgical procedure without surgeon's control. The design of "MAKOplasty THA®" (Stryker) allows direct posterolateral and anterior approaches for assisting with the acetabular cup and navigation of the femoral stem that enhances the ability to navigate the femoral osteotomy line and the femoral rotation. The surgeon is still responsible for the appropriate approach for the surgery; however, specific anatomical landmarks are predetermined for placement of acetabular component by using the coronal plane measurements determined in [46] prior to each surgery by using patient-specific CT scan and CAD information. These measured markings and Mako's ability to track the landmarks throughout the surgery make the robot a success during the surgery [47]. Mako robots are used in several surgical procedures including posterolateral [72, 76], posterior [21, 24, 73–75], posterior or direct anterior [17, 71, 77, 79], and direct lateral [80]. There are two major recent studies in this area of interest with more than 100 observations with at least 2 years of follow-up after surgeries. Domb et al. [71] compared acetabular cup placement using direct anterior or posterior surgical approaches using Mako robotics on 66 patients and manual application on 66 patients with a p-value of 0.479. Banchetti et al. [26] also compared Mako robotics application on 56 patients to manual applications on 51 patients based on acetabular cup placement and determined a p-value of 0.7276 after a 2-year follow-up. Observations in the THA literature comparing manual versus robotic surgical success differences did not find high statistical differences between robotics and manual surgical methods; however, this outcome may be due to the high success rate of the manual THA.

Clement et al. [36] observed Mako robots to present significantly greater functional outcomes when compared to manual operations. Hadley et al. [80] observed several of the robotic-assisted scores to be significantly higher than the manual THAs. Analysis by Singh et al. [79] showed significant differences between the robotics and manual THA outcomes. While Kamara et al. [74] reported complications and determined comparable complication and revision rates between cohorts of manual THAs, Kong et al. [24] identified comparable scores between manual and robotic THA surgeries and therefore did not find differences between the robotic-assisted and manual THA operations as a result of Mako use. Manual THA is determined to have less stability and weaker functional outcomes than the robotic-assisted surgeries by Bukowski et al. [72], while overall complication rates are found to be same for the two methods upon 1-year follow-up. Two years after surgery, functional outcome scores of robotic-assisted surgery is determined to be better than the manual counterpart, while the pain levels are determined to be higher in these patients by Perets et al. [77]. One-year follow-up of both robotics and manual follow-ups by Peng et al. [78] did not indicate any differences in gait asymmetry between the two cohorts. Five years following THA surgeries, Domb et al.'s [71] patient-reported outcome measures indicated robotic-assisted surgeries to perform better than the manual counterpart. Using Mako Stryker, Shibanuma et al. [82] compared the robotic arm and traditional surgical procedures and concluded robotic-assisted surgery reducing postoperative pain and surgical time as well as reduced days of independent walking.

Kuka's LBR iiwa robot is a recent robotics technology that is used as a haptic device to provide high-force feedback for an orthopedic surgeon while performing the reaming of the acetabula in a virtual environment [50]. It is shown that the designed robotic-based system solution is intuitive and reliable from users' perspective. From a biomechanical standpoint, mechanical properties on hip reaming, resulting in a tissue-based material model of the acetabulum for force feedback virtual reality hip reaming simulators, are modeled in [51]. The resulting forces were delivered using Kuka's iiwa robotic arm as a force feedback device. Mechanical data is attained using high-force surgical interventions as baseline data for material models and biomechanical considerations; the model developed by the authors is mentioned to allow THA surgeons to train with a variety of machining hardness levels of acetabula for haptic VR acetabulum reaming [51].

Cyclic loading and motion of the hip joint induce micromotions at the bone-implant interface of cementless total hip replacements. Osseointegration and long-term survival are observed to be impacted by initial stability of THA [62]. Noting the impacts of robotics on cup placement precision, while fixation of femoral stems achieves good clinical results and therefore biomechanical success, the fixation of acetabular components remains as a challenge (Fig. 3).

As much as the robots may be useful for surgical procedures, surgical teams' experience limitations on design and implementation of surgical robots may relate to exploring how to provide haptic feedback in robotic surgery [14, 15]. Additionally, a critical factor to be incorporated in robotic surgery is the use of techniques such as drilling [36]. The selection of hole drilling location and method of incision with the corresponding site selection can be identified and specified during computer-assisted systems with the use of robots for surgical procedures. This approach can either be used as a guide to the surgeon or provide information to the robots that can be used for surgical procedures. One other implication of robotics is cost-related considerations.

CASPAR systems are used similar to Robodoc; preoperative CT scans are used for this system with computer assistance for milling a femoral canal automatically

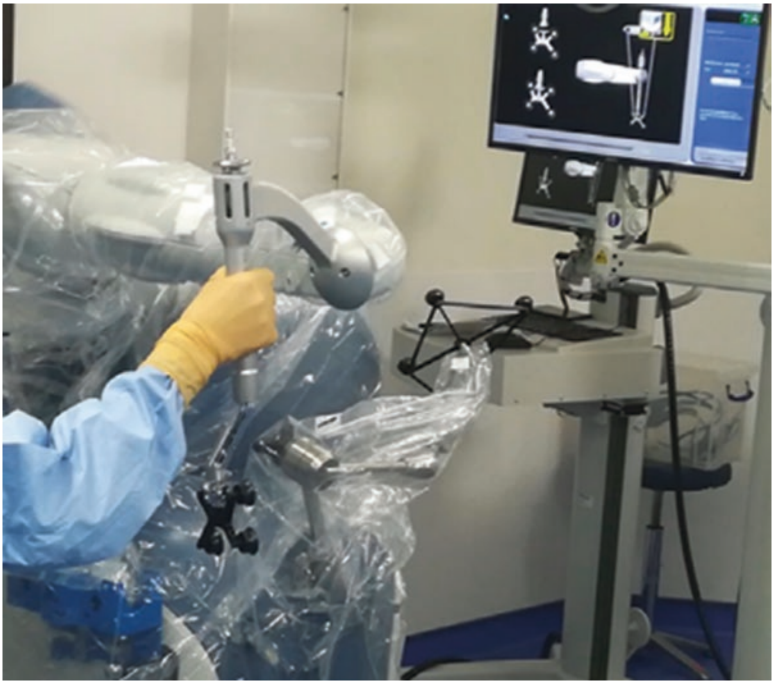

Fig. 3 An image of a Mako surgical system [84]

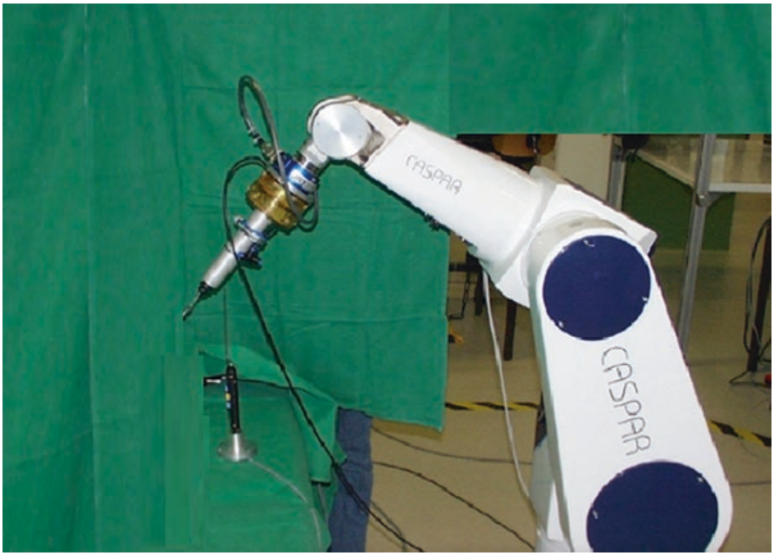

Fig. 4 An image of a CASPAR surgical robot

and stem implant positioning. Revisions of surgeries, complications, and heterotopic ossification appeared to be higher for CASPAR systems, although both positive and negative results are attained as a part of the surgical procedures from robotics application perspective; CASPAR robots are no longer available for surgical procedures [81] (Fig. 4).

4 Impacts of Robotics on Postoperative THA

Research on robotics applications of postoperative THA patient treatment is limited even though post-surgery patient training is an important phase of recovery that also impacts the success of THA surgeries. It has been shown that mobile robot-based gait training after THA improves walking in biomechanical gait analysis; preoperational data indicated no significant differences in gait parameters, while patients from the intervention group that had robotics support showed a significantly higher absolute walking speed [11]. It is concluded that the significance of higher walking speed of patients indicates the robotic-based gait training on crutches may shorten length of stay (LOS) in acute clinics. The number of patients in this research was limited to 30 THA patients that required further investigation on larger number of patients. There are several other studies that govern the advantages of using robots for assisting patients postoperatively independently from THA. In a more general study covering patient recovery for using robot-assisted gait self-training, Scheidig et al. [83] investigated the effectiveness of robots for self-training of patients under real clinical environment conditions and determined the group with additional robotics training showing statistically significantly better gait parameters postoperatively when compared to the non-robotic group.

5 Implications of Robotics on Implant Biomechanics

Hip dislocations or fractures are two main injury types that can result in prosthetics placements, Implantation, or treatment [64]. Hip dislocations are classified into anterior and posterior dislocations based on the dislocation of the femoral head. Posterior dislocations are much more common than the anterior ones due to the arrangements of the ligaments and tendons; an anterior dislocation results from a large-scale force in combination with several muscle activations including abduction, lateral rotation, and extension of the joint such that the femoral head has some room to start sliding and move out of acetabulum.

Typical total hip arthroplasty implant is made up of four components: femoral stem, femoral head, liner, and acetabular cup. Some of the materials tested from the beginning of THA implant development for its four components included ceramics, composites, glass, metal alloys, and polymers that try to meet biocompatibility expectations and satisfy optimality and feasibility conditions to recover biomechanical factors such as fatigue resistance, stiffness, toughness, withstanding static and dynamic loads, and high resistance to mechanical and chemical wear [65, 66]. To the best of our knowledge, while most of the attention is given to the behavior of the bone after implantation, the material density distribution of the implant itself didn't get any attraction from the researchers and manufacturers for testing. It is well known by some of the manufacturers that the density distribution per unit volume has a strong impact on the designed components [67]. For example, given a manufactured stem, an unevenly distributed mass per volume can result in uneven distribution bone loading that could result in implant failure sooner than later due to cyclic loading. This could also have strong impact on the acetabular cup and the head. Additive manufacturing and robotics can reduce the uneven distribution of density and balance the loads in the expected ways [68]. Similarly, production and polyethylene manufacturing can also have important implications on the developed and manufactured liners. Manufacturing-based factors can have big impact on transplantation development and manufacturing. The current methods of implant production can also work; however, it is possible to advance them using robotics.

Another critical element that needs to be improved for biomechanical research testing is the use of robotics for cyclic load testing on implants. A simulator using a robot for cyclic loading and testing for total shoulder arthroplasty (TSA) implant is recently developed and used [69]. In dental applications, to replicate the human mastication force cycle, a robotic mastication simulator is introduced in [70] to record the required interactive loading by using specifically designed force sensors. A robotics simulator can be developed for THA applications for implant testing.

6 Conclusions and Suggested Future Works

Sequential applications of robotics in all stages of preoperative, during, and postoperative THA can build up to form a strong probabilistic impact on the success of surgeries that can be calculated easily by using the Bayesian method depending on the application, and the statistical success rate can be estimated by considering either one of the three stages outlined above. It is not possible to calculate such a probability based on the current research outcomes since preoperative and postoperative successes of robotics applications have not been observed extensively; therefore, research focusing on impact of robotics applications in additive manufactured materials and success rate of postoperative robotic-based patient support play a critical role in implants' long-term biomechanical success. From a manufacturing standpoint, biomechanics of materials can be impacted by several considerations including but not limited to the following [56]:

- X1: Composition of the biomaterial
- X2: Mechanical factors
- X3: Material properties
- X4: Surface topography
- X5: Molecular landscape

Precision of these key performance indicators can be improved by using robotics. For instance, composition of the biomaterial can be structured by using robots with precision on the implantation design. Mechanical factors come into play with the precision in dimensioning of the manufactured implant. Material properties would be impacted through the homogenous mix through the use of a robot for material application such as cement production. Surface topography can be detailed through robotics application with the use of camera and sensors on the robot. Molecular landscape can be the application of the use of a robot for fluidic items to be applied on the implant and their drying through automation. Assuming each one of these indicators have n_i sub-indicators for all i such that $1 \leq i \leq 5$, one can calculate the probability of the indicators to be $P\left(X_{i,n_i}\right)$ as the main factors impacting the biomechanical structure of the implant; therefore, the probability of manufacturing impact can be calculated as the product of all factors' probability by calculating

$$P_1 = \prod_{i=1}^{5} P\left(X_{i,n_i}\right)$$

During the surgery, some of the factors that are outlined throughout this work that can be improved by involvement of the robots include but not limited to the following:

- Y1: Human error
- Y2: Cutting
- Y3: Part placement

Supposing that these j indicators have m_j sub-indicators for all $1 \leq j \leq 3$, one can calculate the probability of the indicators to be $P\left(Y_{j,m_j}\right)$ as the main factors impacting the biomechanical structure of the implant; therefore, the probability of robotics impact during the surgery can be calculated in this particular example as the product of all factors' probability by calculating

$$P_2 = \prod_{j=1}^{m_j} P\left(Y_{j,m_j}\right)$$

Post-surgical impact of robotics has shown to provide benefits with some of the following factors potentially impacting the results:

- Z1: Biomechanical patient support
- Z2: Stability
- Z3: Weight load distribution
- Z4: Stay time in patient care unit

Similar to the pre- and during surgery calculations, given the above mentioned k indicators that have l_k sub-indicators for all $1 \leq k \leq 4$, one can calculate the probability of the indicators to be $P\left(Z_{k,l_k}\right)$ as the main factors impacting the biomechanical structure of the implant; therefore, the probability of robotics impact during the surgery can be calculated as the product of all factors' probability by calculating

$$P_3 = \prod_{k=1}^{l_k} P\left(Z_{k,l_k}\right)$$

Finally, given all stages of the probabilities of success that the robotics provide from the beginning (i.e., preoperative) to the end (postoperative), the overall success of robotics application can determined to be $P = \prod_{a=1}^{3} P_a$. The above-mentioned case can be generalized by incorporating all key performance indicators and multiplying their probabilities. Assuming an implant follows all robotic-based protocols for production and implantation, probability *P* is a measure of success rate for determining the overall impact of the implant on a fully recovered patient, including factors such as implant's production, transplantation, and healing period. Reduction of factors down to a specific area of interest, such as biomechanical success, would allow to calculate the corresponding probabilistic success for such area of interest.

Noting the literature cited in this work, robotics has a lot to offer for future surgeries and additive manufacturing [35], while some of the researchers and practitioners happen to observe that robotics and traditional THA surgical applications don't have statistically significant differences [59, 60]. We must note that the positive impact of robotics may weigh more toward its application success during pre- and post-surgical procedures instead of the robotics applications during surgery. To the best of our knowledge, there are no research articles indicating manual surgeries resulted better than their compared robotics surgical methods, while the literature indicates either same or better results of robotic-based surgical procedures in comparison to the traditional methods.

One other area of future improvement can be towards the utilization of millirobots in THA applications; millirobots are considered to be insect-scaled robots that can adapt to unstructured environments, operate in confined spaces, and interact with a diverse range of objects. The continued development of millirobots, however, requires simple and scalable fabrication techniques [58]. Particular areas of interest, such as biomechanical impacts of millirobots, can be investigated further for advancement in this area of interest that has not been studied by the research communities yet.

Artificial intelligence (AI) is used for preoperative planning for revision arthroplasty surgery that involved the identification of the failed implant. Using a predictive artificial neural network (ANN) model, the authors developed a machine learning algorithm using operative big data to identify an implant from a radiograph and compared the developed algorithms that optimize accuracy in a timely fashion [61]. While the application of AI advances the preoperative surgical procedures, noting the strength of the computational powers of servers and computers today, the use of AI for decision-making to operate robots can be investigated today.

Lastly, even though THA is a very successful surgical procedure, implants are eventually prone to fail; therefore, psychological treatment might be the key to prevent patients to go through THAs and have a better and happy life. Noting that younger populations appear to go through THA procedures at their early stages of life and the number of THA patients is increasing, doctors and researchers can investigate the impact of psychological therapy to prevent patients going through THA. The current practice in elective orthopedics does not routinely include psychological interventions despite evidence that psychological factors such as personality, anxiety, depression, and negative thinking styles can influence outcomes and recovery from surgery [85]. In fact, there is very limited research and investment on impact of psychological treatment on patients for preventing them to go through THA; the majority of the literature focuses on the impact of psychological treatment either pre- or post-THA outcomes. Robotics can be used to better psychology of THA candidates and may help them to recover without going through THA. The origin of this improvement idea arises from the power of the mind—the fact that everything stems from the brain and the ways of thinking impacts the entire body; the role of the nervous system is very important. This is likely to leave us with one of the most important advancements in THA research from a psychological standpoint: Can we prevent THA candidates to go through THA by integrating psychological treatments into robotics and help patients heal naturally? The outcomes of this idea not only can help to reduce the number of THA patients but also can help younger populations to have a healthier future.

Some of the researchers indicate stand-alone use of robots to be far off from operating on their own in the near future [57]; we believe such claim should be tested. Current advancements in distributed computing, artificial intelligence, robotics, virtual reality, and additive manufacturing can make not only the hip arthroplasty applications better but also other biomedical applications stronger. For instance, integrated systems that incorporate all of 3D and/or 4D printing implant applications, several robots following AI commands and predefined surgical steps that provide and attain real-time feedback from a program using reinforced learning can advance robotics use toward robotics applications in the near future. These technologies can also be used to improve psychological state of patients to prevent them go through THA.

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Biomechanical Success of Traditional Versus Robotic-Assisted Total Hip Arthroplasty

Abstract Total hip arthroplasty (THA) is known to be a very successful surgical technique. Restoration of normal biomechanical functions and physiological hip restoration are key surgical goals for success of THA. Robotics is a recently tested method for advancing outcomes of THA. In this review, the advantages and disadvantages of robots' use during THAs from a biomechanical standpoint are analyzed. It has been observed that analysis of revision rates, hip dislocation, accurate cup positioning, and implant design and placement plays a crucial role in biomechanical success. Additionally, robotics technologies are proven to have better precision and cup placements when compared to surgeon-only THAs. Challenges faced for robotics' use during THA include surgeon training, extended surgical hours, and economical costs. Analysis of dislocation and revision rates provides mixed results for robotics success during THAs; however, these mixed results can be due to factors such as surgeon's success during the surgery, programming success of the robot for the particular application, and planning of the surgery noting that robots are shown to have successful precision in the literature.

1 Introduction

Total hip arthroplasty (THA) is one of the most successful orthopedic operations ever devised with the end goal of restoration of the normal hip physiology [3]. The progress in hip implant development motivated researchers to focus on several aspects of failure modes with biomechanical consequences [1]. Revision surgeries occur frequently after THA to correct recurrent dislocation of hip implant due to ever-changing factors including implant design, cup positioning and femoral head diameters impacting the outcomes of THA [4], surgeon's successful reconstruction of the hip biomechanics [5], and the surgical technique applied [2]. Several of these biomechanics-impacting factors can be improved while some others are still debated. For instance, the debate on whether the direct anterior approach (DAA) or the posterior approach (PA) allows better restoration of hip biomechanics after THA continues [6], while 10-year follow-up on THA by using new generations of dual-mobility

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cups results in very few to no implant-related dislocations [7, 8]. An extensive analysis on 337,647 THA procedures revealed 0.34% of early revisions for periprosthetic fracture with 44% of these incidences occurring within 90 days of surgery, and the factors that played key roles are observed to be collarless stem, non-grit-blasted finish, and triple-tapered design [9]. In parallel to classical THA surgical techniques, robotic-assisted surgical procedures are tested for success over the years.

Advancement of robotics recently started to impact the number of robotic-assisted THAs with the measured successes observed on surgical outcomes. Robotic systems used during THAs included Kuka's LBR iiwa © [15, 71], Mako © [18–30, 67], Robodoc © [31–38], Orthodoc © [39], da Vinci ©, and CASPAR © [40]. Success levels of robots were measured with their strengths and weaknesses in different ways after THA surgeries. Several advantages of these robotic systems' utilization included high accuracy of implant positioning and orientation [10], minimal invasiveness during surgeries that result in less recovery time, and higher patient satisfaction upon realizations on patient-reported outcome measures (PROM) [11]. Some of the challenges of using such robotics systems included surgeon training, extended surgical hours, and economical costs [12]. This review focuses on advantages and disadvantages of using existing modern robotic systems and their comparisons to the traditional surgeon-based THA factors from a biomechanical perspective. Next section is devoted to a variety of robots used for THA surgeries with their pros and cons observed in the literature. The last section contains concluding remarks on the robotic-assisted versus surgeon-driven THAs and potential improvements on THAs in future applications.

2 Robotics and Manual THA Operational Differences

The impact of robotics during surgical procedures is an extensively studied area due to the increasing interest of robotics use in surgical procedures. Robot-assisted surgeries are shown to improve clinical outcomes and reduce revision rates [13]. The proportion of surgeons utilizing robot-assisted arthroplasty increased from 6.8% to 17.7% just in the New York area from 2007 to 2017 [14]. New robots such as Kuka's LBR iiwa are also introduced for THA use, and testing of such robots increased the results attained for robotic-assisted THAs in the research literature [15]. Robotics allow better mechanical control and stability in applications that may help reducing human errors; however, it offers challenges such as training the surgeon to be able to use robots in THA applications, surgeries lasting longer, and expenses that are associated with robots' utilization and maintenance. Improvements in applications of robots during surgery include improving the accuracy when cutting the femur, reaming the acetabulum, and placing the implant components. It has been shown that the use of robotics can help with reducing inaccuracy as much as 94%. Precision in implant sizing and location particularly helps to minimize risks of leg length discrepancies, dislocations, and other complications of conventional hip replacement [17]. There are limited number of extensive studies that compare robotic-assisted and manual THA surgeries. If we focus on robotic-assisted THA in comparison to manual THA that included 20 or more participants for both surgical strategies, there are only 7 peer-reviewed articles. In these studies, approximately 51% of the 658 patients had gone under robotic-assisted surgeries. Even though PROM appeared to be statistically insignificant (i.e., $p < 0.05$) in most of these studies, assessment of radiographic outcomes indicated robotic THA results to be more consistent and accurate for component placement in six studies. The robot brands used in applications go well beyond these seven studies.

There are well-known robots used during surgeries such as Mako® [18–30], Robodoc® [31–38], Orthodoc® [39], da Vinci®[16], and CASPAR® [40]. The direct cutting of bone to the final planned cut or indirect planning landmarks to adjust placement or holding of cutting jigs has been conducted using robotics. The applications of robotics can be divided into three categories depending on the applications to surgical incisure/cutting operations: (1) autonomous, (2) haptic control [20, 41], and (3) boundary control [42, 43]; therefore, robotic systems can be fully automated, hybrid, and completely manual depending on robot's involvement during the process. Autonomous applications are fully robotics driven with the mechanical limitations depending on the mechanical stability and precision of the robot along with the precision of the algorithm that robot follows. Depending on the application, the results of a robotics use can be harmful noting that the robot would not necessarily follow the footsteps of a successful surgeon. Haptic control requires surgeon involvement in several applications such as cutting, milling, or drilling in which case mechanical stability of the operations may alter between the robot and the surgeon. Boundary control allows independent task management without direct human manipulation by using algorithms based on associated preprogramming with defined parameters of bone resection. Robodoc (THINK Surgical®) surgical system [44] was the first active robotic system used in THA surgery that allowed complete robotic assistance without continuous control by the surgeon throughout the procedure. In particular, the placement of the polyethylene-based cartilage on the bone by using a robot is a fine application of the robotics for implant production; however, in many applications, complete control robots are not found to be feasible for safety reasons.

Da Vinci robot developed and manufactured by Intuitive Surgical Inc., displayed in Fig. 1 (reproduced and used with permission from © 2018 Intuitive Surgical, Inc.), is a completely manual surgical robot system requiring surgeon's full control during the surgery and used for many different surgical applications. Biomechanical analysis of robots' effectiveness during THAs is mainly focused on hybrid systems' analysis that requires comparison of robotic-assisted surgeon THA outcomes to manual surgeries.

Robodoc, a technology developed by Curexo Technology Corporation, Fremont, California, USA, is a robotic system used for THAs utilizing CT scans that can be converted into three-dimensional virtual images for preoperative planning and computer-guided drilling [45]. Preoperative CT scans are used for Robodoc computer assistance for milling a femoral canal automatically and stem implant positioning. Majority of the surgical applications of Robodoc, 50% (four out of eight),

Fig. 1 An image of da Vinci robot simulator (permitted by CESI of Hartford HealthCare)

has been posterolateral [32, 35, 39, 48], while 37.5% (three out of eight) was posterior [14, 34, 37], and only one was anterolateral [31]. Accurate positioning cup placement is observed in several of these studies [32, 34, 39] impacting the biomechanics of THA and a reduction on revision surgeries.

There are studies in the literature which resulted in minimal statistical significance between hybrid and manual surgeries. For instance, no differences are found between the hybrid and manual procedures in [35] after 1-year and 5-year follow-ups, while robotic-assisted THA had significantly higher outcomes at 2- and 3-year follow-ups. Honl et al. [31] reported 18% (13/74) attempted hybrid surgeries among the 154 THAs needing conversion to manual implantations as a result of failure of the system, and the rest of the surgeries were manual; dislocation rate was higher in hybrid surgical procedures with 11 occurrences in 61 patients accounting for approximately 18% while the same rate was 3 occurrences in 8 manual operations with $p < 0.001$. The research outcomes in other Robodoc applications were mainly positive for robotic-assisted THA surgeries. For instance, one of the comprehensive studies focused on the application of Robodoc system investigated in the United States and Germany that was designed to address potential human errors in performing cementless THA [46]. The system consisted of a preoperative planning computer workstation called Orthodoc®, and a robotic arm with a high-speed milling device as an end effector was used. One- and two-year follow up- were conducted on 127 and 93 patients, respectively. Radiographs were evaluated by an independent bone radiologist and demonstrated to be statistically better fitting and positioning of the femoral component in the Robodoc group. There were three cases of intraoperative femoral fracture in the control group and none in the robotic-assisted group.

The majority of the studies focused on stem placement for Robodoc-assisted THAs' comparison with manual surgeries. Bargar et al. [34] observed better trends in clinical outcomes for robotic-assisted THA when compared to manual surgical procedures with no statistical significance but favoring use of robotics; the Robodoc system is determined to be safe and effective in producing radiographically superior implant fit, eliminating femoral fractures, and better implant positioning for biomechanical success. Hananouchi et al. [37] did not find significant differences between robotic-assisted and manual THA surgeries by analyzing the Merle d'Aubigne scores. Lim et al. [35] observed on average about 10 min longer operational milling time for robotic-assisted surgeries; however, superior results are attained for stem alignment and leg length equality by using robots. As a result, there were only two intraoperative femoral fractures occurred in the manual rasping group. During the 2-year follow-up, Nishihara et al. [39] did not find any intraoperative femoral fractures. Upon 10 years follow-up, Nakamura et al. [48] did not determine any significant differences in functional scores between the two methods. Bargar et al. [38] determined robotic-assisted surgeries to require less revision rates as a result of 14-year follow-up with $p > 0.05$, while Honl et al. [31] determined the opposite as a result of 2-year follow-ups. Upon Robodoc use, dislocation rates are determined to be higher than the manual surgeries in [31, 34], and [32], while opposite is observed in [38]. Figure 2a demonstrates the Robodoc surgical system's hardware components [65], and Fig. 2b displays the Robodoc's robotic arm in action during a live surgery.

There are several models of Mako technologies that are utilized for THA applications. Mako THA system, developed by Stryker®, Mahwah, NJ, utilizes predefined physiological parameters and preprogrammed algorithms to allow surgical procedure without surgeon's control. The design of MAKOplasty THA® by Stryker Corporation allows direct posterolateral and anterior approaches for assisting with

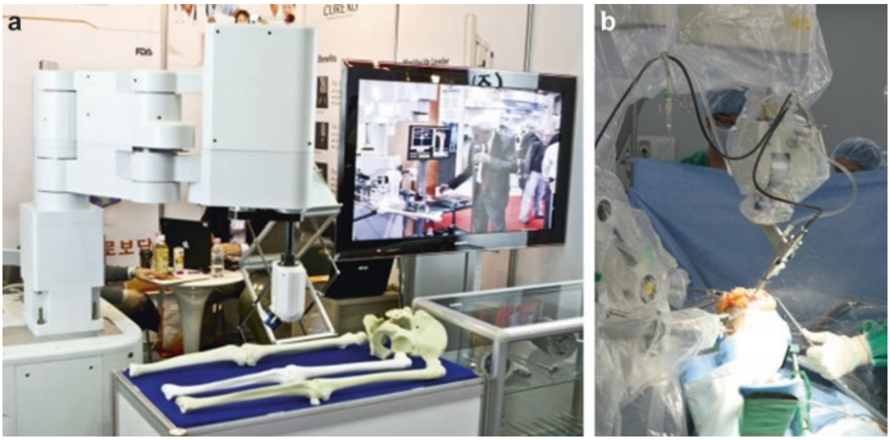

Fig. 2 (**a**) Robodoc surgical system by Curexo Technology Corporation [65]. (**b**) Robodoc's live operation use during a surgery [66]

the acetabular cup and navigation of the femoral stem that enhances the ability to navigate the femoral osteotomy line and the femoral rotation. The surgeon is still responsible for the appropriate approach of THA; however, specific anatomical landmarks are predetermined for placement of acetabular component by using the coronal plane measurements determined prior to each surgery by using patient-specific CT scan and CAD information [47]. These measured markings and Mako's ability to track the landmarks throughout the surgery make the robot a success during the surgery [49]. The precision of coronal plane tracing makes it biomechanically more precise when compared to the manual counterpart. Mako has been used in a variety of surgical approaches including posterolateral [51, 55], posterior [22, 25, 52–54], posterior or direct anterior [30, 50, 56, 57], and direct lateral [58]. Mako systems' success rates are analyzed by observing surgical revision rates, cup displacement, and hip mechanical stability.

There are two major recent studies in this area of interest with more than 100 observations with at least 2 years of follow-up after surgeries. Domb et al. [50] compared acetabular cup placement using direct anterior or posterior surgical approaches using Mako robotics on 66 patients and manual application on 66 patients with a p-value of 0.479. Banchetti et al. [27] compared Mako robotics application on 56 patients to manual applications on 51 patients based on acetabular cup placement and determined a p-value of 0.7276 that favors advantages of robotics usage after a 2-year follow-up. Comparison of manual and robotic surgical success differences did not find high statistical differences between robotics and manual THA surgical methods; however, this outcome is likely to be due to the high success rate of the manual THA. Clement et al. [52] observed Mako robots to present significantly greater functional outcomes when compared to manual operations. Hadley et al. [58] observed success of robotic-assisted THAs to be significantly higher than the manual THAs. Analysis of 896 manual and 135 robotic-assisted THA by Singh et al. [57] showed significant advantages of using robotics for 1-year hip disability, osteoarthritis outcome score, and joint replacement scores. Kamara et al. [53] reported robotic techniques delivering significant and immediate improvement in the precision of acetabular component positioning that also has challenges of using robotics. Kong et al. [25] identified comparable scores between manual and robotic THA surgeries when posterior approach is used. Kong et al. [54] did not find differences between the robotic-assisted and manual THA operations as a result of Mako use. Manual THA is determined to have less stability and weaker functional outcomes by Bukowski et al. [51] than the robotic-assisted surgeries, while overall complication rates are found to be the same for the two methods upon 1-year follow-up. Two years after surgeries, functional outcome scores of robotic-assisted surgery are determined to be better than the manual counterpart, while the pain levels are determined to be higher for THA patients by Perets et al. [56]. One-year follow-up of both Mako system-assisted THA and manual surgery follow-ups by Peng et al. [55] did not indicate differences in gait asymmetry between the two cohorts. Contralateral hip mechanics analysis based on the range of motion, walking speed, and gait mechanics for hybrid and manual THAs are compared. No differences are found in peak range of motion in the frontal or axial planes for hybrid surgeries, while net sagittal plane range of motion was significantly reduced. After 5 years, Domb et al. [50] analyzed PROMs indicating robotic-assisted surgeries to perform better than the manual counterpart. Using Mako Stryker, the robotic arm and traditional surgical procedures are compared in [60], and it is concluded that robotic-assisted surgery reduced postoperative pain and surgical time as well as reduced days of independent walking. The revision rates of robotic-assisted surgeries determined to be either same [59] or lower [50, 51, 56] for the use of Mako surgical systems, while only one study determined Mako systems to have 1% more revision rate than manual THA [53]. The dislocation rates observed for Mako systems utilization is controversial; lower dislocations are determined in [51, 54] while the contrary is observed in [50, 53]. Figure 3 displays the Mako surgical system integrated to da Vinci robot in a surgical room.

Kuka's LBR iiwa robot is a recent robotics technology when compared to Mako and Robodoc that is used as a haptic device to provide high-force feedback for an orthopedic surgeon while performing the reaming of the acetabula in a virtual environment [15]. It is shown that the designed robotic-assisted surgery is intuitive and reliable from users' perspective. Mechanical properties on hip reaming are modeled in [51], resulting in a tissue-based material model of the acetabulum for force feedback by using virtual reality (VR) hip reaming simulator. The resulting forces were delivered using Kuka's iiwa robotic arm as a force feedback device. Mechanical data is attained using high-force surgical interventions as a baseline data for

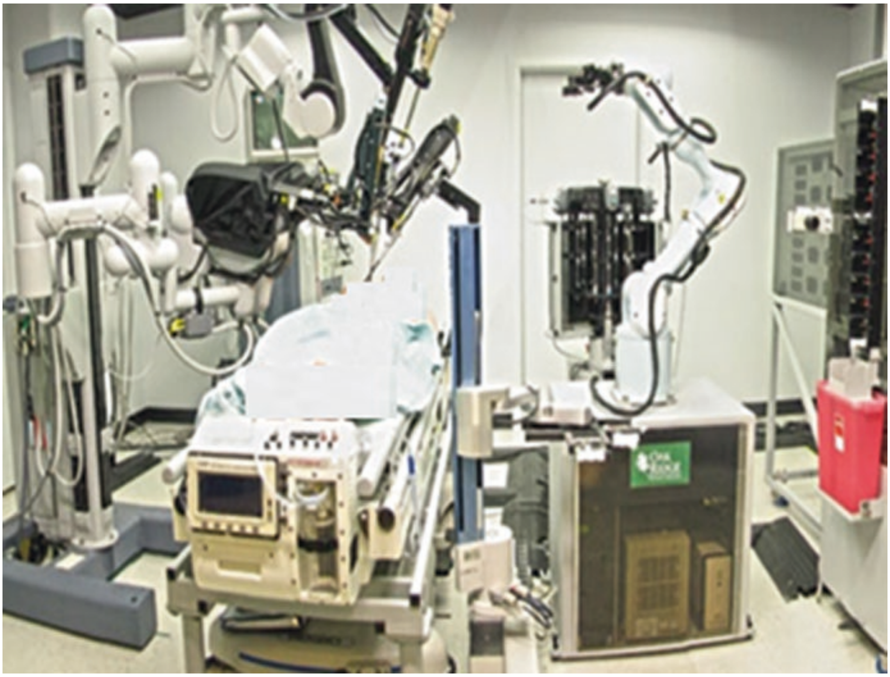

Fig. 3 Mako surgical system shown on the side robotic-assisted surgery [68]

material models and biomechanical considerations; the model developed by the authors allows THA surgeons to train with a variety of machining hardness levels of acetabula for haptic VR acetabulum reaming [51].

Cyclic loading and motion of the hip joint induce micromotions at the bone-implant interface of cementless total hip replacements. Osseointegration and long-term survival are observed to be impacted by initial stability of THA [61]. Noting the impacts of robotics on cup placement precision, while fixation of femoral stems achieves good clinical results and therefore biomechanical success, the fixation of acetabular components remains a challenge.

As much as the robots may be useful for surgical procedures, surgical teams' level of experiences may limit the design and implementation of surgical robots that may relate to exploring how to provide haptic feedback during the robotic surgery [62, 63]. Additionally, a critical factor to be incorporated in robotic surgery is the use of techniques such as drilling [37]. The selection of hole drilling location and method of incision with the corresponding site selection can be identified and specified during computer-assisted systems with the use of robots for surgical procedures. This approach can either be used as a guide to the surgeon or provide information to the robot that can be used for surgical procedures. Figure 4 is an image of a Kuka robot used for medical technology to attain optimum solutions for robot-based medical products [70].

CASPAR systems are used similarly to Robodoc; preoperative CT scans are used for this system with computer assistance for milling a femoral canal automatically and stem implant positioning. Revisions of surgeries, complications, and heterotopic ossification appeared to be higher for CASPAR systems, although both positive and negative results are attained as a part of the surgical procedures from robotics application perspective; CASPAR robots are no longer available for surgical procedures [64].

Fig. 4 Kuka robot used for medical technology: optimum solutions for robot-based medical products [70]

3 Conclusions and Future Research Directions

THA is one of the most successful orthopedic operations ever devised with the end goal of restoration of the normal hip physiology [3]. Restoration of normal hip anatomy and biomechanics is a key surgical goal for success of THA [40]. Analysis of revision rates, hip dislocation, accurate cup positioning, and implant design and placement plays a crucial role in biomechanical success. The majority of the research results focused on two robotic systems, Mako and Robodoc, which are used for THA. Robotics technologies are proven to better precision and cup placements during THA. Challenges faced for robotics use in these applications include surgeon training, extended surgical hours, and economical costs. Consequences of biomechanical success can be measured by analyzing dislocation rates and revision rates. Neither Mako nor Robodoc systems display a consistent positive outcome for either one of dislocation rates or revision rates; however, the surgical follow-ups have shown high PROM values and better accuracy rates for implant sizing and location that help to minimize risks of leg length discrepancies, dislocations, and other complications of conventional hip replacements. Newer technologies such as Kuka can be used with VR. Future of the advanced and successful THAs may be upon the successful integration of technologies such as robotics, VR, and Artificial Intelligence (AI). Noting that robotics systems have existing success records in THA for assisting surgeons, factors such as surgeon's success, programming of the robot for THA procedures, and physiological conditions can be other factors impacting the successful outcomes of robotic-assisted surgeries.

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Optimization for Total Hip Arthroplasty Applications

Abstract Optimization in total hip arthroplasty (THA) is the ultimate intend of surgeries at all phases of the treatment including during, pre-, and post-surgery stages. There are many factors that play key roles in THA optimization that relate to surgeon, patient, implant, and method of surgery. In this work, we present studies that are related to optimization of THA from a variety of perspectives that are categorized into experimental and mathematical optimizations. Improvements for THA operations are recommended in the conclusion section.

1 Introduction

Optimization in total hip arthroplasty (THA) is a common objective of many researchers, and it has been the goal of several articles with different objectives of THA. Different optimization approaches have been followed mainly in numerical and somewhat using theoretical and mathematical optimization. In the next section, we will cover work completed with regard to THA of computational optimization techniques with their aims and objectives. What follows would be the theoretical optimization methods that are very rare to see in THA applications. The conclusion section is devoted to potential work that can be accomplished in optimization improvement opportunities that could take place in THA applications from both computational and theoretical perspectives.

2 Experimental Optimization for THA Success

Experimental optimization described in this section aims to cover the THA research done with data collected and optimal values attained based on the research outcomes. For instance, a review of the studies on biomechanics of experimental and computational periprosthetic femoral fracture (PFF) fixation methods up to 2017 is described and compared in [1]. This summary concluded the validation of computational

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results with experimental data's completion to be essential. Computational studies are observed to be useful in studying fixation methods or conditions (such as bone healing) that are difficult to study in vivo or in vitro with some issues. The need of optimality for PFF fixation is the consensus of the reviewed studies.

In [2] optimization of periarticular injection techniques is investigated by identifying and mapping the periarticular neural anatomy of the hip as a part of THA. Taking into account of both gross and microscopic neural anatomy of the human hip joint with particular key areas of hip mechanoreceptors and free nerve endings, the hip joint is supplied by the femoral, obturator, sciatic, and superior gluteal nerves, as well as the nerves in the quadratus femoris. It is noted that the maximum concentration of sensory nerve endings and mechanoreceptors is found at the anterior hip capsule, especially superiorly. The labrum innervation is maximized 120 degrees from 10 o'clock position clockwise. Hence, after the cup and liner are placed, periarticular injections should be infiltrated toward the remnant labrum 120 degrees from 10 o'clock position clockwise. Another optimization technique is to construct an optimal solution during the surgery. A single intraoperative AP pelvis x-ray is found to be a quick, reliable, and inexpensive means of determining acetabular abduction, acetabular medialization, leg length, and femoral alignment in [3]. Plain x-ray can be easily used to assess screw position and cup seating. This approach allows the surgeon to make a decision on changing the position of the prosthesis if needed before the conclusion of the case. In cases where changes are needed, reliable correction was produced in 97% of cases. In some instances, however, intraoperative considerations are such that these considerations will supersede generic alignment and leg length targets.

The use of computer-assisted surgery for improving prostheses implantation for computer-aided surgery has been proven reliable with accuracy and reproducibility in the positioning of the implants. Several navigation devices are used, and the anterior pelvic plane (APP) is used as the reference for characterizing the patient's orientation in 3D. In an attempt to generalize for optimization purposes, the "plane of Lewinnek" or "safe zone" is introduced in [4] based on superficial anatomical landmarks with pubic symphysis and both superior anterior iliac crests. The sophistication of interrelated human body network has a weight distribution of impact; pathological issues that exist in locations such as spine can have more impact than other locations. Lumbar pathological issues such as abnormal spinopelvic motion can increase the risk of hip dislocation even with the Lewinnek et al.'s (1978) "safe zone" placement of acetabular component that assumes anteversion 15° ± 10° and inclination 40° ± 10° angles [5]; it is noted that the "safe zone" is recently questioned in several studies and may not accurately predict THA instability based on the anteversion and inclination measurements [6]. The dislocation rate after THA is observed to be as high as 92% and as low as 75% in the spinopelvic abnormality cases [5]. In an attempt of investigating the relationships between APP and sacral slope in [7] upon measuring 328 patients' lateral radiographs of the pelvis in standing position, poor correlation between APP and sacral slope suggests using the reference to the APP for the per-operative orientation in the 3D space while individually adjusting the preoperative planning to the sacral slope. The importance of preoperative planning is emphasized in [8] as the first step in adult reconstructive surgery of the hip. Proper execution helps to minimize intraoperative problems and avert complications. It is also observed to reduce surgical trial and error that eventually reduced operative time. Clinical results can be ultimately improved in addition to possible operational planning shortening for a new implant system and technical skill improvement for performing THA. Figure 1 displays a sleeve that is placed to maximize stability and ingrowth of a previously detected osteotomy that distorted the proximal femoral anatomy.

It is observed to be natural having leg length changes after THAs, and biomechanical reasoning is investigated in the research literature. The design and placement of the implant are main factors with interlocking of medullary canal and implant. Flexible structure of the bone and the strength of the material used for the implant eventually causes the sinking of the implant into the bone and causing the imbalance. The design of the femoral implant can be targeting to achieve fixation of the medullary canal and implant in the mediolateral dimension or anteroposterior engagement of the bone. It is concluded by the authors that osseointegration of the cementless THA and postoperative leg length discrepancies are impacted by the femoral challenges; optimal intra- and extramedullary geometry fitting and offset restoration of cementless femoral stems are major common challenges among the implants used, and they cannot necessarily offer optimal fit or offset restoration [9].

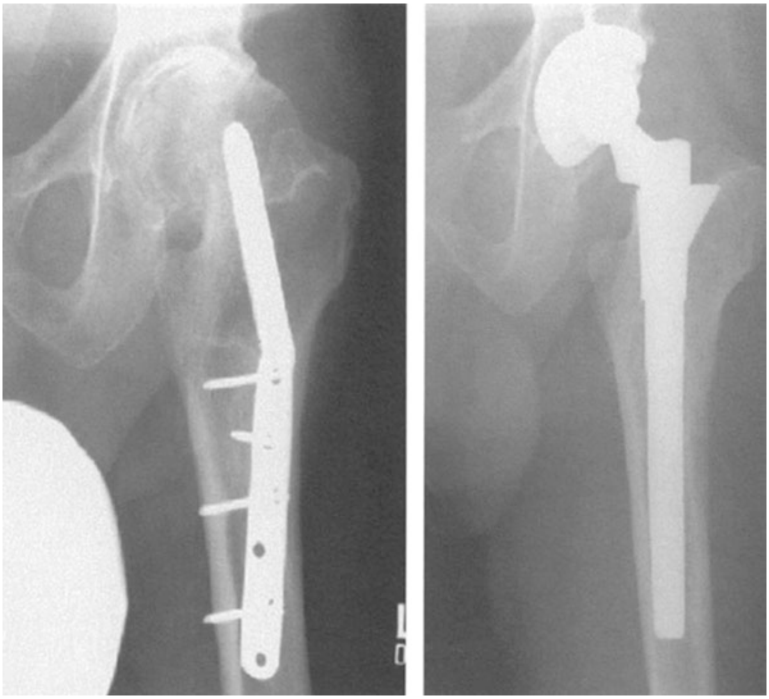

Fig. 1 A sleeve is placed to maximize stability and ingrowth of a previously detected osteotomy that distorted the proximal femoral anatomy [73]

Biomechanical data of THA patients that underwent anterolateral surgery is collected during the post-surgery gait training by using crutches and a mobile robot that assisted them during walking in a clinical setting [10]. In comparison to the control group that had no use of robotics for gait training, the analysis revealed the robotic-assisted group to have significantly higher absolute walking speed, higher relative walking speed (0.2 vs. 0.16 m/s, $p = 0.043$), or shorter relative cycle time. This particularly impacts the time that the patients spend in the clinic.

Finite element analysis (FEA) is one of the methods used for PFF fixation upon THA by altering the loading and boundary conditions along with the isometric and physiologic loadings [69]. FEA is useful for determining optimized hip implant 3D modeling to improve mechanical strength by optimizing stress and strain distribution. The major issue in the use of FEA on PFF is the standardization of the technique and methods used [11]. The increase in the overall rigidity of the construct eventually determined to increase the stability of the fracture, as a result of the motion across the fracture or the overall stiffness of the instrumented femur [1]. The increase in rigidity is due to the following:

A. Changing the rigidity of the connectors based on one or more of the following:
   (a) By using screws instead of cables (see, e.g., [12]).
   (b) By using cables instead of wires (see, e.g., [13]).
   (c) By using double-wrapped wires compared to single wrapped (see, e.g., [14]).
B. Plate and strut modifications changing stiffness (see, e.g., [15]).
C. Using longer revision stems (see, e.g., [16]).

Due to variability of clinical techniques used, unclarity of how a designed experiment would perform at an optimal level needs to be explained clearly. Construct stiffness appears to be the focus of majority of the work in progress, but it may be misleading due the possibility of a highly stiff plate causing stress shielding in the underlying bone. In this case, either the fracture heals or the construct itself does not fail. More studies on biomechanical quantification of such outcomes for periprosthetic femoral fracture are needed [11, 70–72].

The biomechanical performance of different configurations of cables, wires, and screw positions is tested in [17] computationally. Four different screws are used in three fixation methods consisting of placement of three cable- screw combinations proximal to the fracture with the only difference between the methods being the positioning of the cable- screw pairs proximally. It is concluded that the choice of the location impacts the fixation strength and the option that yielded the best fixation strength has the potential to reduce the refracturing of the bone. This best option determined is expected to yield to the highest stiffness that may achieve the optimal mechanical stability; FEA agreed with the experimental results. Optimization of hip implant prosthesis' structure including stem, head neck, and acetabular cup with the objective of minimizing aseptic loosening, bone resorption, and stress shielding in the implant is investigated in [18] by utilizing the topology optimization tool of FEA. The authors reported that weight reduction and stress distribution behavior of the implant under varying conditions are better understood by using topological optimization of the implant. Optimal weight and mechanical characteristics of CoCrMo alloy made femoral hip stems are investigated in [19] using FEA. The final model attained not only satisfied the ISO design conditions for femoral stems but also reduced the weight by about 15% of the original model and fulfilled the mechanical expectations. Computational optimal values are attained for determining the best hip neck design for reducing the mechanical stresses and avoid stress shielding of the prosthesis in [20] for a combination of neck cross sections including elliptic, circular, oval, and trapezoidal shapes with different side profiles including circular arcs, flat, and knife edges. Trapezoid cross section combined with flat and circular arc side profiles is determined to provide outstanding stress, strain, and deformation results. The goal in [21] is to reduce stresses and deformation developed in the prosthesis by using 3D models developed with fenestrations. Slot fenestration design is shown to have the minimum deformation upon applying FEA among big loop fenestration design, design without fenestration, slot fenestration design, and many loops fenestration design models. Variational neck diameters on five hip implants are tested in order to minimize stress levels and optimize neck thickness in [22] using FEA. The best design is attained for the hip prosthesis with 9 mm neck diameter that had the maximum reduced stress. Acetabular cup's corner shape variation is analyzed using FEA in [23] for circular arc, sharp, and spline shapes interfaced with ball head at four micro separations. Reduced risks of striping wear, fracture, and fatigue in the hip prosthesis are attained for the spline-shaped corners of the acetabular cup that resulted in reduced stresses, strains, and contact pressure on the ball head interface compared to others. To optimize geometry of the implant by using bio-inspired lattice structures, FEA investigation resulted to indicate Schwarz diamond lattice structure among the three options in [24]. This structure is shown to have the best functional performance that provided the minimum level of Von Mises stresses and maximum safety factor. Impact of outer shell is investigated with the use of titanium femoral stems in [25]. FEA is used on these stems with porosities (BCC structure) of 90, 77, 63, 47, 30, and 18% and with and without outer shells of thickness 0.5, 1.0, 1.5, and 2 mm. The stems without shells are determined to have frequent fatigue failure, while the shell with porosities showed an increase in stress shielding behavior up to 28% as a result of the stress distribution behavior and fatigue strength analysis.

Physiological and implant failure mode analysis and functional recovery after THA are analyzed for surgical success. Femoral offset (FO) changes following THA can help with analysis of hip muscle activities to observe functional physiological restoration noting that FO accuracy and functional recovery are correlated [26]. Analysis of 13 hip muscles' moment arms of 18 unilateral THA patients in vivo revealed a potential improvement of abductor and external rotator function upon 2–3 mm of FO restoration; an increased FO observed to reversely correlate with length of both flexor and adductor moment arms during the gait and stance phases, respectively. A decrease of both abductor and external rotator moment arms during the whole gait and a decrease in extensor moment arms during the stance phase are correlated with a decreased FO after THA [26]. This approach can particularly help with presurgical planning for functional restoration of the hip.

Reasons for THA implantation failure are complicated and can include patient-, material-, and non-patient-related factors (such as inadequate surgical technique). Femoral head-neck interface by fretting and corrosion damage is determined as another factor contributing to THA failure [27, 28]. Determination of the exact reasons of the degradation process appears to be not possible; however, the following factors are determined to impact the implant failure:

- Body mass index [29].
- Taper length [29].
- Time in situ [30].
- Mixing of alloys [31, 32].
- Femoral head size [33, 34].
- Flexural rigidity [35].
- Female taper angle [34].
- Taper-angle mismatch [36].
- Taper diameter [37].
- Stem surface roughness [16, 30, 38–42].

Effectiveness of cemented and uncemented fixation types on the liner wear risk is analyzed theoretically by using FEA in [43]. The key intraoperative factors playing roles in determining the wear risk during surgical planning that are used in modeling included head material, head size, liner thickness, cervical-diaphyseal angle, and center of rotation positioning. Biomechanical restoration analysis was based on two types of 3D liner models' simulation of ultrahigh molecular weight polyethylene. Liner thickness and acetabular fixation techniques are determined to be significantly related to wear risk. A proper prevention technique to the cause of polyethylene liner wear is observed to be the use of a cemented fixation with a thick liner in the right center of rotation.

THA dislocation rate's exposure to cup positioning and abductor mechanism's reconstruction are evaluated on cementless THA operations of 1318 patients on the data collected in a span of 20 years in [44]. The radiological assessment of 28 or a 32 mm femoral head-sized THAs cups is based on positioning and hip rotation center, and reconstruction of the abductor mechanism is conducted by measuring the lever arm distance and the height of the greater trochanter. It is concluded for the observed 38 dislocations by using multivariate regression analysis on the implant and physiological data that these dislocations are most associated with the following:

- A greater distance to the anatomic hip rotation center.
- Acetabular inclination and version angles for hips outside two safe windows of cup position.
- Lever arm distance and height of the greater trochanter abductor mechanism.
- Hip's abductor muscle weakness.

A fixation method utilized in [45–47] is differentiation of plates that depend on plate comparisons based on the following:

- Rigidity (flexible vs. rigid).
- Formation material (titanium vs. stainless steel).

- Thickness.
- Support (use of cables, different screw types, double plating, locking, multidirectional, etc.)
- Position of plating (anterior, lateral, etc.)
- Stem design and dimensioning (long vs. short, etc.)

Upon the failure of initial rigid fixation attempt by using a polyaxial femoral plating following THA, the refracture fixation attempt was by utilizing polyaxial femoral plating as a flexible fixation method in [45]. Biomechanical effects of fixation methods using FE modeling and Vancouver type C fracture on a clinical case are compared in the study. It is observed that short bridging used for PFF rigid fixation can defeat fracture movement and prevent healing to eventually cause failure. On the contrary, non-locking plate with a longer bridging utilizing flexible fixation promoted better healing. The length of bridging appeared as the most impactful parameter on fracture location and stiffness. The path to optimum fixation construct design is conjectured to be by using a computational approach as such in [45].

Micromotion is another concern in biomechanical analysis of designed implants. For instance, in the case of cementless fixation, micromotion at the bone-implant interface has been reported to affect bone ingrowth [48]. Low micromotion, typically below 28 μm, results in bone ingrowth, while excessive micromotion that can be assumed to be above 150 μm results in the growth of fibrous tissue inhibiting biological fixation [49]. Micromotion on bone-implant interface mainly depends on the implant primary stability that relates to several factors including implant macrogeometry, elastic modulus mismatch with the bone, fixation technique, and the bone tissue quality with its defects [50].

In an attempt of optimize the dose of topical tranexamic acid for primary THA, both 1 and 2 gr. tranexamic acid are found to significantly reduce postoperative drain blood loss in [51], therefore the use of topical tranexamic acid at the end of surgery is found to be effective and safe for reducing postoperative blood loss in primary THA. Topical tranexamic acid at a dose of 1 gr. may be sufficient and cost-effective, with fewer side effects than the higher dose.

For an optimal range of motion, it is important to obtain acceptable offset and anteversion, and for the most appropriate lever arm and muscle strength around the hip [52]. In an experimental study by using sawbones with four different angles of femoral anteversion (16, 34, 47, and 59 degrees), the effectiveness of a modular femoral neck system is tested to determine optimal outcomes. The femoral neck system consisted of two neutral and four types of retroverted necks for the correction of femoral anteversion and offset in THA. Reconstruction of the preoperative anteversion and offset in the normal femur were achieved with the neutral neck. The long neck with 15 degrees of reversion was effective for the mildly or moderately anteverted femur with insufficient correction for the severely anteverted femur. An optimal value of the medial component of femoral offset in femora with anteversion of less than 47 degrees is determined to be useful by using this modular neck system for correction. Patients that have greater anteversion may find femoral necks that have a greater degree of retroversion useful which is a feature rarely seen in the clinical situations [8].

Noting that there is a wide range of choices in the selection of femur implants along with the patient-based anatomical variations, it is natural to see that there is no one-fit for all implants that can satisfy the conditions of structural strength for longer durability. Von Mises stress calculations are used for measuring the life of an implant when continuous cyclic load associated with regular day-to-day activities is applied to the implant. In [53], the trapezoidal-shaped stem with three different cross sections is considered with the femoral head size, acetabular cup thickness, backing cup thickness, and trunnion geometry varied to arrive the best possible combination. Using ANSYS R-19, the acetabular cup, backing cup, and trunnion top surface radius and femoral head sizes are varied experimentally. Trunnion interface is determined to not play a significant role with respect to the structural strength of the implant.

Patients with acetabular dysplasia were operated by circumferential acetabular medial wall displacement osteotomy in [54] to reconstruct the acetabulum during total hip arthroplasty. All patients had cementless acetabular components implanted. The authors' early recommendation was that circumferential acetabular medial wall displacement osteotomy optimizes the reconstruction of the acetabulum in patients with hip dysplasia (Fig. 2).

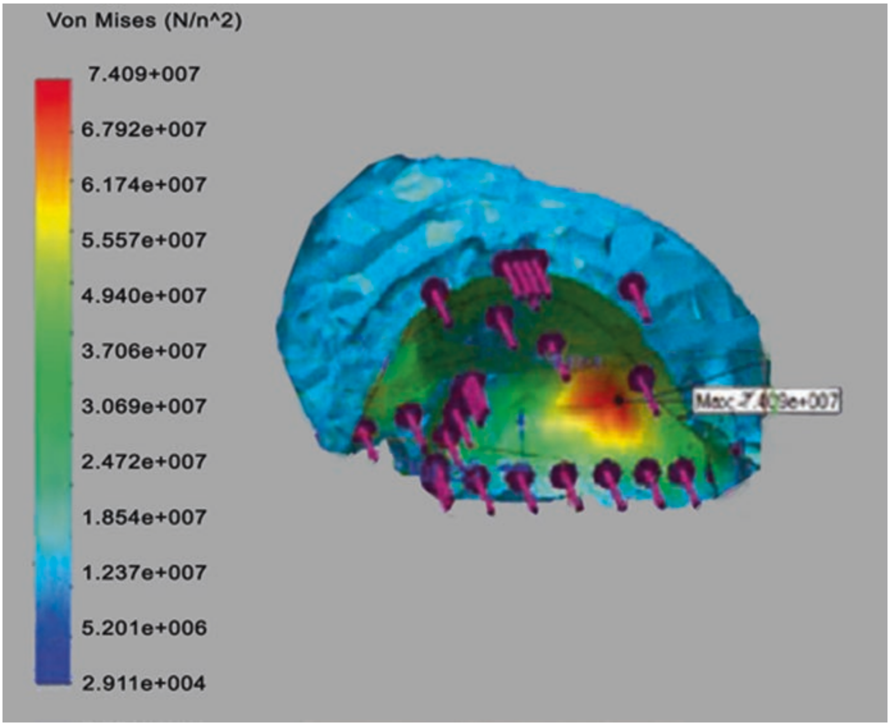

Fig. 2 An example of Von Mises stress calculations for a normal positioned cup [55]

Aseptic loosening in THA relates to optimal values used for cement mantle thickness and uniformity along with the optimal values of material mix that is patient dependent. The resultant progressive development of detrimental cement mantle defects is seen in patients upon non-optimal choices. The stresses act on cement mantle, and the associated interfaces also play primary roles in the long-term success of THA. The coverage of various surgical techniques that assist in creating an optimally thick, symmetric, and homogeneous cement mantle to control and minimize high cement stresses that initiate debonding and cement fracture is explained in [56]. Inherent properties of the cement for increased strain resistance and reduced microfractures include the following:

- Increased strength.
- Reduced brittleness.
- Improved interface adherence.

We refer to [56] for further details on how optimal application of the cementation can be achieved with the corresponding surgical details.

In an attempt to optimize risk for post-surgical operations, an evidence-based tool is used to address modifiable risk factors for adverse outcomes after primary hip surgeries in [57]. Identification, intervention, and mitigation of risk through evidence-based patient optimization are accomplished through nurses who screened patients preoperatively, identified and treated risk factors, and followed patients for 90 days postoperatively. Comparison of patients participating in the optimization program is compared to both historical and contemporary cohorts. Identification and optimization of the risk factors resulted in lower hospital length of stay and postoperative emergency department visits. Patients in the optimization cohort had a low mean value of length of stay and had significant decrease in 30- and 90-day emergency department visits. Additionally, the optimization cohort had a significant increase in the percentage of patients' discharge. There are also nonsignificant reductions in readmission rate and transfusion rate, and surgical site infections are observed.

Another evidence-based optimization attempt is made in [58] to determine the factors that play crucial roles in medical failure before THA to determine which modifiable risk factor is the most dangerous one. Factors such as smoking, abnormal body mass index (BMI), uncontrolled diabetes, and poor nutritional status are increasingly associated with complications after THA by researchers in the literature. Upon review of about 48 thousand primary THA procedures conducted in 2018, increased risk of postoperative infection, readmission, any complication, and mortality after primary THA is determined to be associated with the factors as follows:

- Low albumin.
- Elevated BMI.
- Use of tobacco.
- Diabetes.

Low albumin is determined to be the greatest risk factor among these factors. The importance of preoperative optimization and agreement of the patient and surgeon on the procedure to be applied is emphasized by the authors [58].

Empirical optimization of blood management in THA patients focusing on both hematopoiesis and hemostasis is conducted in [26]. In this large, single-center, retrospective study on 986 unilateral THA patients, the effectiveness and safety of an optimized blood management program in THA are analyzed. It is suggested by the authors that patients receiving primary unilateral THA should have multiple boluses of intravenous tranexamic acid combined with topical tranexamic acid, recombinant human erythropoietin, and iron supplements that can reduce the calculated total blood loss, hemoglobin drop, transfusion rate, and postoperative length of stay without increasing the incidence of venous thromboembolism or mortality.

Another method of optimization is through the utilization of simulation that is commonly used in wear testing and THA longevity. For instance, a hip simulator wear study was undertaken in [59] to investigate the contradiction of ex vivo studies failure to substantiate a relationship between roughness and the clinical wear factor. Five million cycles are applied to three explanted femoral heads on new acetabular liners with the simulator wear rate being five times the ex vivo value. A substantial difference is determined for the relationship of surface roughness and wear resulting from the simulation testing and unidirectional wear screening methods.

3 Mathematical Optimization for THA

Theoretical optimization by using mathematical formulation is a very rare application in THA. By theoretical optimization we mean THA-related mathematical optimization formulas generated by using the relevant constraints. For instance, topology optimization is used in [60] for having minimum compliance to ensure sufficient load-bearing capacity of the porous implant with very low thickness.

A hemispherical cup affixed to a superior flange that has an optimally graded porosity is introduced in [60] as an alternative concept for a 3D printed cage with a multifunctional fully porous layer. This model focused on 1877 computed tomography (CT) scan images of a 38-year-old male for (3D) modeling of the individual's pelvic bone. Assuming the relative density ρ as the design variable, the optimization problem can be stated as in Eq. 1 with elastic properties of the implant reducing the stiffness mismatch with the bone. This equation lowers the stress levels and micromotion at the bone-implant interface and ensures appropriate bone ingrowth while maintaining load-bearing capacity.

$$\min_{x} C(x) = \frac{1}{2} \sum_{n}^{i=1} u_i^T K_i u_i \tag{1}$$

such that

$$\sum_{n}^{i=1} v_i x_i \leq V^*$$

$$U\left(x\right)K\left(x\right) = F$$

$$0 < x_{\min} \leq x \leq x_{\max} \leq 1$$

where

- *C*: Implant compliance.
- *F*: Global force vector applied to the implant.
- *U*(*ρ*): Global nodal displacement vector.
- *K*: Global stiffness matrix of the implant.
- *P*: Vector of relative densities.
- *ρe*: Relative density of each element e.
- *V**: Prescribed volume fraction of solid material.
- *νe*: Volume of each element.
- *n*: Total number of elements.

Pelvic bone geometry and assignment of elastic properties are based on the CT scan image. Tetrahedron-based unit cell topology is used as the building block of the porous implant. This chosen topology offers load-bearing capabilities and enables bone ingrowth. Finite element analysis is used with topology optimization targeting minimum strain energy, to ensure the necessary load-bearing capacity [60]. The results are attained via analysis of the mechanics of materials with density-based topology optimization, additive manufacturing constraints, and bone ingrowth requirements integrated into the problem formulation. The micromotion is calculated as the relative sliding distance between the bone and the implant surfaces in [60]. A reduction in the maximum contact stress on the bone surface by 21.4% and a decrease in the bone-implant interface peak micromotion by 26% are attained upon numerical analysis. These numerical results indicate implant long-term stability and enhanced bone ingrowth. Even though a clinical loading case of one-legged standing is used for the analysis, the attained numerical results need to be further analyzed using different loading scenarios such as walking, running, and stair climbing.

The dislocation of the hip prosthesis is dependent of specific patient anatomy and artificial joint design. Selection of the stem model and size, the head diameter and its offset, and the acetabular cup orientation is designed at the time of preoperative planning for determining optimal geometry of the reconstructed hip. Various works had suggestions about the “optimal” acetabular cup position. In [61, 62], a larger head diameter is determined to transform a prosthetic impingement into a bone impingement. This assertion is confirmed in [63] by using a numerical model that incorporated multiple combinations of geometric examined factors including the head diameter, the acetabular cup anteversion, and its inclination. This multibody model of the hip joint implant allowed demonstrating the impact of the head size, acetabular cup inclination, and anteversion on the joint range of motion with freedom to parameterize the model to simulate other geometrical parameters of the reconstructed joint.

An optimal shape of the stem using multiple objective functions is necessary due to multiple factors causing the cement fracture. A genetic algorithm is used for multi-objective design optimization of the femoral stem of a cemented THA in [64] by focusing on failure factors of cement. The objective of the study was to determine a stem geometry considering multiple factors at the same time. Two objective functions are used for determining the largest maximum principal stress of proximal and distal sections in the cement mantle with each of the two models having boundary conditions of walking and stair climbing. A 3D finite element model of the proximal femur was developed from a composite femur. The minimization results of these four objective functions are attained by using the neighborhood cultivation genetic algorithm. Upon analysis, the geometry that leads to a decrease in the proximal cement stress and the geometry that leads to a decrease in the distal cement stress are found to be different while walking and stair climbing conditions matched. Among the five stem designs, one design is identified as the "better design" for all objective functions. In their article, the authors had shown the usefulness of multi-objective optimization through genetic algorithm use for shape optimization of the femoral stem in order to avoid cement fracture.

Inverse dual optimization is applied in [65] with an improved classical wear model and an original computational algorithm. The model was applied on titanium and cast Co-Cr alloy that are commonly used in THA applications. The classical mathematical model for wear optimization of hip implants reads,

$$W = K\frac{B \times D}{H}$$

where

- K: The wear constant specific for each material.
- B: Biomechanical load.
- D: Sliding distance of the acetabular semi-sphere of the implant (mm), measured as the number of rotations of the implant multiplied by half the distance of its circular-spherical length.
- W: Wear.
- H: The hardness of the implant material.

The mathematical optimization model for generating the inverse dual optimization model is designed as

$$W - K\frac{B \times D}{H} \;{}_{2} \cong \; 0$$

subject to

$$\begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \\ c_5 \end{bmatrix} \leq \begin{bmatrix} |K_j| \\ |B_j| \\ |D_j| \\ |H_j| \\ |W_j| \end{bmatrix} \leq \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \end{bmatrix}$$

Specific constraints are chosen in [65] to determine the solution for the corresponding model. Same mathematical modeling and nonlinear optimization are used in [66] on four commonly used ceramic materials for THA including ZTA Biolox, ZTA Biolox-Delta, Alumina (Al_3O_2), and Zirconium (ZrO_2). Acceptable numerical results are attained for dual optimization with low residuals. 2D graphical optimization and 3D interior multi-objective optimization are used to attain the results.

In [67], both analytical and numerical techniques are utilized to evaluate the use of a perforated, titanium funicular shell to support the proximal femoral cortex in THA. Modeling is accomplished by using beam on elastic foundations and 2D elasticity theory based on the principal interactions between the femoral cortex, the metal shell, the implant stem, and the acrylic bone cement. This model is translated into a nonlinear design optimization problem that helped to determine the dimensions of the implant and reinforcing shell that minimized an objective function by using a simplified material failure criterion. In this formulation, the five design variables used included the following:

- *L*: Implanted length of the prosthesis stem and reinforcing shell.
- *Rs*: Prosthesis stem radius.
- *Rhi*: Inner shell radii.
- *Rho*: Outer shell radii.
- *Rbi*: Reamed radius of the bone.

The effect of the design variables on dominant stresses is investigated by formulating an objective function that penalized stress concentrations. The design optimization study then consisted of minimizing this objective function for achieving the smoothest load transfer between components. The nonlinear programming problem for determining the optimum values of the design variables in the system is formulated as follows:

$$\max z = \left| \frac{d_i}{d_{yi}} \right| + w_1^{w_1} + w_2^{w_2} + w_3^{w_3} - 3$$

such that

$$w_i = 10 \times \left(|s_i| + s_i \right) + 1; i = 1, 2, 3$$

$$s_1 \equiv Rho - Rhi \geq 0.01$$

$$s_2 \equiv Rhi - Rs \geq 1$$

$$s_3 \equiv Rbi - Rho \geq 1$$

$$Rs \geq 1$$

$$50 \geq L \geq 300$$

$$10 \geq Rbi \geq 14$$

Upon determining a solution to the nonlinear optimization, an optimal design is determined between the two cases considered. This optimal design is found to be reasonable in terms of dimensions, and the boundary conditions being realistic since even perfect prosthesis-bone contact, as represented in the other case, would loosen postoperatively. Although the absolute stress levels are probably not accurate in this optimal design, the other case had doubtful boundary conditions since perfect prosthesis collar to bone contact both in tension and compression is not physically reasonable [67]. A linear programming problem is formulated as the linearization of the nonlinear programming problem above to determine linear approximation through sequential (i.e., iterative) methodology by determining repetitive linear solutions to the sequential problems. As a part of problem formulation, power series expansion of the nonlinear function can be used, and simplex algorithm can be a well suit for determining a solution.

Mathematical modeling for optimization of THA planning by incorporating joint functionalities is designed in [68]. Maximum posterior estimation is used for optimal planning to ensure the best balance of joint functionalities and bone-implant spatial relations. The training set is designed by an experienced surgeon, and a statistical model is derived from the training data sets. The mathematical model is formulated as a stochastic optimization problem by using Gaussian distribution. The solution to the optimal problem indicated two of the functionalities' improvements, while four of the functionalities to be the same as the surgeon determined planning values.

4 Conclusions and Possible Improvements

In this article we covered both computational and mathematical optimization concepts from both theoretical and practical perspectives with their relevant factors. As it can be realized from the practical standpoint, there are many factors that are difficult to incorporate into a single model with several characteristics unless it is a personalized design. There are several variables that can be incorporated into an optimization model including but not limited to the following:

- Surgeon.
- Surgery type.
- Implant modularity.
- Body mass index.
- Bone quality.
- Cement vs. cementless design.
- Cement material mix.
- Cement thickness.
- Taper length.
- Length of surgery.
- Mixing of alloys for implant design.
- Femoral head size.
- Flexural rigidity.
- Taper angle.
- Taper-angle mismatch.
- Taper diameter.
- Stem surface roughness.
- Stem surface topology design.
- Implanted length of the prosthesis stem and reinforcing shell.
- Prosthesis stem radius.
- Inner shell radii.
- Outer shell radii.
- Micromotion.
- Reamed radius of the bone.
- Bad habits (such as tobacco use, etc.)
- Additive manufacturing considerations (if applicable).
- Changing the rigidity of the connectors based on one of the following:
  - By using screws instead of cables.
  - By using cables instead of wires.
  - By using double-wrapped wires compared to single wrapped.
- Plate and strut modifications changing stiffness.
- Using longer revision stems.
- The wear constant specific for each material.
- Biomechanical load considerations.
- Sliding distance of the acetabular semi-sphere of the implant (mm), measured as the number of rotations of the implant multiplied by half the distance of its circular-spherical length.
- Wear factors.
- The hardness of the implant material.
- Implant volume.

- Interface adherence.
- Rigidity of plating (flexible vs. rigid).
- Formation material of plating (titanium vs. stainless steel).
- Thickness of plate.
- Plate support (use of cables, different screw types, double plating, locking, multidirectional).
- Position of plating (anterior, lateral, etc.)
- Stem design and dimensioning (long vs. short, etc.)
- Muscle strength.
- Nervous system conditions.
- Dose of medicine used pre-, during, and post-surgery.
- Preoperative planning methodology.

One of the challenges for using the optimization results attained for THA is the variation of the methods and analyzed outcomes. It is possible that the differentiation in the methods used for attaining measurable outcomes may not make it possible for comparative outcomes except for methods such as finite element analysis. A practical way of learning best practices from each other would be a shared platform of detailed measurements and outcomes attained. Such data along with machine/deep learning applications can help attaining predictive outcomes for varying patient conditions. This can reduce preoperative surgeon's planning time and possibly increase the implant design and surgical operation method's choice. Another method on attaining optimal results can be incorporating more factors into mathematical formulation and determining key parameters in the mathematical model through patient-specific data. This approach can be similar to the mathematical models covered in this article. Given the variability of the above-mentioned factors altogether per patient needs makes it a challenge even in the case of applying advanced techniques that take place in THA.

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Artificial Intelligence, Deep Learning, and Machine Learning Applications in Total Hip Arthroplasty

Abstract Artificial intelligence (AI) recently gained popularity in total hip arthroplasty (THA) applications due to several reasons including technological improvements such as availability of data storage, processor capabilities, AI technique developments, and surgery-related improvements including presurgical analysis techniques developed and data collected for input to algorithms (Mont, et al. J Arthroplast. 34(10):2199–200, 2019). In this work the focus will be on the research literature covering AI, deep learning (DL), and machine learning (ML) techniques that relate to only THA. This coverage excludes the combined results for total knee arthroplasty (TKA) and THA unless THA is analyzed independently from TKA. Applications determined include THA-related economic analysis and payment models, patients' well-being, risk of blood transfusion, hip fracture detection (Kim and MacKinnon. Clin Radiol. 73:439–45, 2018). Biomechanical considerations, optimal implant design, post-THA implant brand detection, hip disability upon THA, inpatient and outpatient THA surgery detection, automating and improving angle of acetabular component, text-based database search for THA-related factors, mechanical loosening detection of the transplant, patient comfort after THA, and implant failure detection. Many more applications are possible using AI, DL, and ML with few of them suggested in the conclusion section.

1 Introduction

Development of algorithms allowing to make informed decisions based on patterns learned from data and mimicking human behavior by using technology has been one of the goals of researchers for real-life applications. Impact of AI, DL, and ML applications recently (within the last 5 years) started to gain popularity even though research on deep learning applications on THA can be seen as early as 1997 [1]. One of the key aspects of THA is to be one of the most successful orthopedic procedures developed in the twentieth century, a feature that can allow to make informed judgments by using algorithms for classification and prediction noting the ability to clearly distinguish many aspects of the operational procedures. For instance, there

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are certain aspects that are clinically observed such as cement versus cementless THA procedures and reasons for implant failures that are known to train algorithms by using the corresponding data sets that can help with accurate results for testing algorithms on testing sets. Large number of features (i.e., input variables) and slowness of manual processes encourage researchers to investigate the use of AI/DL/ML algorithms to determine models that allow predictions by incorporating all the features simultaneously. Some of the challenges that we can list here with these algorithms in applications can include the small size of the sample set used for modeling that would not necessarily allow generalization (depending on conditions) and a team of interdisciplinary researchers with a broad knowledge of concepts. One other challenge is applicability of the developed models on data sets. Throughout this article, we will cover the research literature on AI, DL, and ML techniques that relate to only THA. This coverage excludes the combined results for total knee arthroplasty (TKA) and THA unless THA is analyzed independently from TKA. Applications determined include THA-related economic analysis and payment models, patients' well-being, major complication analysis, sensor-based gait analysis of THA patients, risk of blood transfusion, hip fracture detection, biomechanical considerations, optimal implant design, post-THA implant brand detection, hip disability upon THA, inpatient and outpatient THA detection, automating and improving angle of acetabular component, text-based database search for THA-related factors, mechanical loosening detection of the transplant, patient comfort after THA, and implant failure detection. Even though the following three sections are categorized into AI, DL, and ML, some of the articles have mixes of these methods. The last section is devoted to discussion and potential future research directions by using AI, DL, and ML.

2 Machine Learning

A machine learning algorithm is designed in [2] to propose a risk-adjusted patient-specific payment model (PSPM) that considers patient comorbidity used on preoperative big data to predict length of stay (LOS) and patient-specific inpatient payments after primary THA. The eight variables used are age group, ethnicity, gender, Charlson Comorbidity Index (based on comorbidities such as congestive heart failure renal disease and cancer documented from the 12 months before the hospitalization to 3 days after discharge), discharge disposition, type of admission, all patient refined (APR) risk of mortality, and APR severity of illness (minor, moderate, major, and extreme comorbidities). Data collected from 122,334 patients between 2012 and 2016 undergoing primary THA for osteoarthritis is used to train a naïve Bayesian model. Performance of the machine learning model is evaluated by using percentage of accuracy and area under the curve calculations. Age, race, gender, and comorbidity scores are determined to be the most important characteristics for the generated model to demonstrate validity, reliability, and responsiveness for receiver operating characteristic curve values of 87% for LOS and 71% for LOS payment. The patient complexity and error for predicting payment are determined to be correlated with 3% for moderate, 12% for major, and 32% for extreme comorbidities. The ML algorithm is determined to be good for predicting LOS and payment prior to primary THA.

Noting the financial challenges faced by the patients, authors of [3] developed logistic regression, artificial neural networks and random forest model. The database use consisted of 63,859 recorded patients from 2017 to 2018. No overnight stay in the hospital is compared to 1–3 days of stay for the models developed. Among the 40 candidate variables chosen for modeling, top 10 important features/variables included ethnicity, anesthesia type, race, BMI, age, blood urea nitrogen, year, albumin, sodium, and white blood cell count for the developed models by using artificial neural network (ANN), random forest, and multivariable regression in predicting same-day discharge patients after primary THA. Area under the curve and accuracy values are 71.5% and 65% for logistic regression, 76.2% and 73% for ANN, and 80.4% and 81% for random forest. Therefore, ANN and random forest are determined to be the outstanding classifiers for utilization in the future. These models demonstrated reliability for their future use in ambulance utilization and patient discharge. We refer to [33] for an elastic-net penalized logistic regression model developed for prediction of prolonged postoperative opioid prescriptions of THA patients.

Clinically significant outcome (CSO) for the patient-reported health state (PRHS) is modeled in [4] by using stochastic gradient boosting, random forest, support vector machine, ANN, and logistic regression. Variables used included preoperative PRHS, BMI, age, drug allergies, preoperative opioid use, smoking history, prior ipsilateral hip surgery excluding a THA, and diabetes. Data collected between 2014 and 2017 on a total of 407 patients are analyzed based on discrimination, calibration, Brier score, and decision curve analysis. Stratified splitting of 80–20 on training-testing is conducted on the data. The minimal clinically important difference (MCID) is calculated for the PRHS by using a distribution. Feature selection with random forest algorithms was used recursively to determine the subset of variables to be employed for final algorithm development. Discrimination, calibration, Brier score, and decision curve analysis indicated the random forest algorithm to perform better on predicting patient's achievement of clinically meaningful improvements for the PRHS. It is also observed that preoperative PRHS score, BMI, age, and preoperative opioid use are the most important features. Clinically meaningful improvement for the PRHS after THA is determined for 69.2% of patients.

Machine learning methods are utilized in [5] for modeling major complications of patients after THA. Approximately 90,000 THA patients of a California hospital are included in the data set with 545 patients that had major complications. Variables included in the analysis included age, gender, race, ethnicity, insurance, and medical comorbidities that are used as the variables of the developed models. AutoPrognosis, logistic regression, random forest, gradient boosting, XGBoost, and AdaBoost are compared for their accuracies. AutoPrognosis model demonstrated higher accuracy (73.2%) when compared to logistic regression that had 64.4% and other machine learning algorithms. The outcomes of the modeling resulted in classification attributes to differ for AutoPrognosis and logistic regression: Five features that appeared to be the most important in risk prediction for using AutoPrognosis are chronic obstructive pulmonary disease (COPD), dementia, malnutrition, malignancy, and Medicare coverage, while logistic regression indicated the importance of variables such as chronic atherosclerosis, renal failure, and chronic obstructive pulmonary disease. The success and discriminative ability of AutoPrognosis is due to analyzing complex nonlinear relationships and be able to capture variables that logistic regression and other machine learning algorithms could not capture. It is concluded by the authors that providing more accurate prognostic information by using AutoPrognosis can help facilitating well-versed preoperative shared decision-making.

Falling impacts the THA patients' well-being and increases the chance of post-surgical procedures due to issues that may arise. Wearable sensors can be integrated into fall risk assessment tools to collect data on patients' functional ability. Support vector machine (SVM) and linear discriminant analysis classifier are developed and tested in [6] to predict the risk of THA patients' falling by using the sensor-collected data. Research data is collected at three different stages: preoperatively, 2-week THA follow-up, and 6-week THA follow-up. Feature variables consisted of preoperational and operative trajectory data. Preoperation set consisted of sensor-derived metrics collected preoperatively, while operative trajectory set combined sensor-derived metrics from preoperative and 2-week postoperative appointments. A total of 96 patients initiated the research, and this number is reduced to 72 at the end of the data collection period. SVM demonstrated success based on the measured 87% accuracy, 97% sensitivity, 46% specificity, and 82% area under the curve (AUC) for the preoperative appointment. Upon adding 2-week postoperative data to the preoperative data, an overall improved performance of 90% accuracy, 93% sensitivity, 59% specificity, and 88% AUC is achieved by using the linear discriminant analysis classifier. The importance of the high accuracy of the fall risk prediction models is emphasized for THA patients.

Logistic regression is compared to six machine learning algorithms in [7] for predicting the risk of blood transfusion in both THA and TKA by using long short-term memory networks (LSTM), RF, decision tree (DT), k-nearest neighbors (KNN), SVM, and naïve Bayes classifier. Here we report only the results attained for THA; the postoperative transfusion rate of 22.79% for THA of the 12,642 patients is observed. The variables considered included age, sex, BMI, hemoglobin, type 2 diabetes, operation time, tranexamic acid use, interoperative blood loss, and hypertension. A tenfold cross-validation strategy is used to quantify the predictive ability of each model defined as the AUC of the receiver operating characteristic. Both LSTM and RF models had significantly better accuracies than LR, Naïve Bayes, KNN, SVM, and DT. Hypertension is determined to be a risk factor for transfusion.

24 statistical models are designed in [8] for prediction of hip fractures over time in 4722 women and 717 men with 5 years of follow-up. AUC values of 92% by using the bootstrap aggregated flexible discriminant analysis and 89% by using Extreme Gradient Boosting (GB) are determined to be the best "female model" and

best "male model," respectively. Identifying features of the model included bone mineral density, glucose measurements, and osteoarthritis diagnosis. ML demonstrated improvement on hip fracture prediction beyond logistic regression.

Length of stay and cost of THA patients' predictive modeling are conducted in [9] by using naïve Bayes machine learning algorithm. Feature selection included age, sex, ethnicity, race, type of admission, risk of mortality, and severity of illness. Accuracies of 76.5% for length of stay and 79% for cost are attained with performances of 88% and 89% for length of stay and cost, respectively. Model error and risk of mortality are determined to be positively correlated indicating validity of increase in risk-adjusted payment for each risk of mortality. Due to the cost of delivery of hip fracture care depending on non-modifiable patient-specific factors, the bundled care is concluded to be an inconvenient payment model for hip fractures in [9].

Biomechanical and bone quality data attained from CT, electromyography, and gait analysis are used in [10] for making a THA surgical decision prosthesis adaptation to the bone by using the BMD of the proximal and the distal region of the femur and cementation. Feature selection for RF included base of support, BMD of the proximal region of femur, and start and stop of the electromyographic signals. Feature selection for GB included base of support, toe in/out operated, velocity, healthy leg BMD, and start and stop of the electromyographic signals. Random forests (RF) and gradient boosted tree are performed as classifiers on 51 patients' data based on the splitting of the data into 75% training and 25% testing sets. RF method had the best results utilizing the training set, while GB on the test set demonstrated good results including 92.9% accuracy, 100% specificity, and 85.7% value of under the curve of receiver operator characteristic. Features playing key roles in the choice of cemented or uncemented prosthesis selection are determined to be the skeletal muscle parameters such as the start and stop of muscle contraction from EMG signals and temporal and spatial gait parameters. The usefulness of the regression analysis for predicting the BMD of the distal and proximal parts of the operated femur after 1 year from the surgery is also demonstrated to be useful by the authors as a part of the patient follow-up.

Optimal implant design parameter characteristics are structured in [11] by integrating biomechanical analysis into machine learning techniques. 3D finite element analysis is integrated into ANN and SVM with the selected implant geometric features including stem length, lateral thickness, medial thickness, and the distance between the implant neck and the central stem surface. The output is designed to be the strain reduced by the presence of the hip implant. A pattern-search minimization algorithm is used to identify the optimal geometry of the implant by exploring new values of the input parameters in an iterative fashion. The optimization algorithm explored unseen values of the selected parameters of the hip implant geometry to minimize the function. Four geometrical ranges are explored for the dimensions of the bone by considering a clinically admissible shape. ANN and SVM techniques had similar pattern to the pattern-search minimization algorithm; optimizing parameters of the SVM had better prediction of the lower random errors; therefore, it had better results than ANN. An optimized implant that had reduced stress shielding is observed to need a decreased stem length and a reduced implant surface contact with the bone. In the case of thinner stems, the two radiuses associated with the stem width at the distal cross section in contact with the bone played a role for better stress shielding results.

3 Deep Learning

A deep learning application by using ANN on a network that learns and predicts LOS, inpatient charges, and discharge disposition by using 78,335 primary THA is implemented in [12]. The 15 preoperative attributes included age, gender, ethnicity, race, type of admission, location of admission (emergency department or not), patient code, risk of mortality (minor, moderate, major, severe), patient's severity of illness, number of associated chronic conditions and diagnoses, comorbidity status, weekend or weekday admission, hospital type, patient's income quartile, and internal or external (i.e., transfer) patient. All patient refined risk (i.e., minor, moderate, major, severe) is a composite disease-specific (i.e., minor 25% uncomplicated diabetes, moderate 25% diabetes with kidney disease, major 25% prior ketoacidosis, extreme 25% prior diabetic coma) measure accounting for the number and severity of underlying comorbidities. These attributes are used for generation of four hidden layers with 112, 56, 28, and 14 nodes from the input to the final layer that are heuristically chosen. Glorot normalization algorithm is used for initialization of each hidden layer node, and rectified linear activation function is applied by using a kernel constraint. Softmax activation function is used for the output layer consisting of the number of classes to determine the probabilities. Metrics used for validity included accuracy and area under the receiver operating characteristic curve. ANN learning in the first 30 training rounds resulted area under the curve values of 82% for LOS, 83.4% for charges, and 79.4% for disposition. Patient-specific payment model introduced established a risk increase of 2.5% for moderate, 8.9% for major, and 17.3% for severe comorbidities. These results are found to be reliable and valid for using the tier-based patient-specific payment model for future purposes.

A hip implant recognition algorithm is designed in [13] to detect implantation on 170 postoperative hip anteroposterior x-rays collected from 5 hospitals that incorporated 29 implant brands. Images are manually labeled, and they are successfully trained for the stem detection model. A six-layered convolutional neural network (CNN) in Keras deep learning platform is developed. 224 × 224 grayscale image inputs are used that had two layers of convolution and one max pooling layer to generate a feature map that is fed into two fully connected layers that generated 29 class outputs. Validation on 25% of training set is conducted based on the recognition model that had detection and clustering. 99% area under the curve value is attained from the receiver operating characteristic curve generated from a test set containing 25% of all stem-cropped images. The generated CNN showed usefulness in predicting stem detection in THA applications.

Classification of the quality (e.g., the staying length in hospital) after THA procedure in Taiwan is modeled in [14]. The proposed approach incorporated expert knowledge, global discretization, imbalanced bootstrap technique, reduct and core methods, rough sets, rule induction, and rule filter. Logistic regression, SVM, and multilayer perceptron (MLP) are utilized for modeling. The second version of Learning from examples module (LEM2) algorithm is applied for symbolic attributes in their work. The LEM2 algorithm calculates a single local covering for each concept from a decision table to generate decision rules. Calculation of each rule's quality index is based on a specific rule quality function that depends on the measure of support, consistency, and coverage to determine the strength of the rules [35]. Another application used in [14] is rough set theory (RST) approach that is introduced for AI applications. RST is a soft computing technique first proposed by Pawlak [15] that uses mathematical modeling to address class data classification problems and identified to be a very useful tool for decision support systems, especially in cases in which hybrid data, vague concepts, and uncertain data are involved in the decision process [16]. In conclusion, RST is found to be the best model among all considerations as a feasible choice for classification learning of imbalanced class data and combination of core attributes. Comparison of accuracy of different methods for both options of all 17 attributes and 7 core attributes in the THA data set had strong outcomes with a minimum of 85% accuracy calculation.

Prediction of the dependent variable hip disability and osteoarthritis outcome score (HOOS) is the primary outcome of [17] by utilizing THA results. A total of 160 patients with 44% female population is included in the study. The authors used the least absolute shrinkage selection operator (LASSO) [18] as the machine learning algorithm for predictive analysis. LASSO can reduce overfitting through penalization of the regression coefficients by sometimes reducing to zero resulting in excluding a predictor entirely so that the out-of-sample prediction accuracy is maximized. The main objective of LASSO is to minimize the mean squared error by reducing the coefficients. Post-surgery and 3-month follow-up data for analysis of HOOS is collected. In total a 23-item rating scale is designed with 25 coefficients utilized in the model. Independent variables included the following:

- Clinical and demographic variables such as such as age, gender, race, Hispanic ethnicity, marital status, level of education categorized into less than a college degree, college degree, or advanced degree, employment status, number of hours worked per week, planned legal action, and worker's compensation status.
- Patient-reported health and health habits, smoking status (smoked vs. never smoked), BMI, and exercise of number of days per week of mild, moderate, and strenuous.
- Cognitive appraisal processes using Brief Appraisal Inventory© [19].
- Surgical approaches including direct lateral, anterolateral, and direct anterior methods.

LASSO is determined to be a weak predictor that failed to include several important variables that are often considered important in predictive modeling in surgical outcomes such as smoking, age, level of education, and frequency of exercise. Diagnostic plots revealed at most moderate difficulties with the final model that utilized the 2-month postsurgical collected data. The most predictive independent variables of postoperative HOOS are determined to be cognitive appraisal processes. Variables predicting a worse HOOS are anterior surgical approach, increased BMI, thoughts of work, frequent comparison to healthier peers, and increased medical comorbidities. Variables that predicted a better HOOS consisted of thoughts related to family interaction, trying not to complain, employment at the time of surgery, and helping others. In conclusion, authors pointed out the need of an accurate predictive model need due to limited ability to identify patients at risk of having a mismatch in outcome following THA based on the models generated.

THA patient designation using machine learning for inpatient and outpatient classification is implemented in [20]. Of the 1409 medicare patients included in the study by using the data between 2017 and 2019, 77.4% of the patients experienced THA. 80% of the data is used for training and 20% for testing. Extreme Gradient Boosting (XGBoost) is a machine learning tool building predictive models utilizing gradient boosting framework. Inpatient/outpatient are predicted target variables used for the XGBoost method as the training data. Input variables used in the model included the following:

- Patient demographics such as age, gender, and BMI.
- Diagnosis leading to joint pain such as rheumatoid arthritis, osteoarthritis, and avascular necrosis.
- Past medical history such as cardiac history, history of a venous thromboembolic event [VTE], diabetes mellitus [DM], and other rheumatologic disease.
- Charlson Comorbidity Index (CCI).
- American Society of Anesthesiologists' Physical Status Classification (ASA).
- Revised Cardiac Risk Index.
- Modified Frailty Index (mFI).
- Preoperative functional scores.
- Hip disability and osteoarthritis outcome score (HOOSJR).
- VR12 physical component.
- VR12 mental component (mcs) scores.

The XGBoost model demonstrated 78.7% accuracy for predicting an inpatient or outpatient stay with 81.5% that is observed to be the area under the receiver operating characteristic curve. The most influential features in the predictive model included BMI, age, functional scores, and ASA Physical Status Classification.

Angular position of the acetabular component is observed to be a risk factor in implant dislocation following THA. A deep learning approach is undertaken in [21] to automate the angle measurement with the goal of increasing accuracy in measurements, reducing human error, and speeding up the measurement process. The data consisted of 600 anteroposterior (AP) radiographs taken from equal number of male and female THA patients from 2000 to 2017 with 300 of the cases ultimately dislocated and 300 cases without dislocation. Among these cases, 200 had osteoarthritis, 200 had rheumatoid arthritis, and 200 had other indications. Manual annotation, augmentation, and random splitting for 80% training, 10% validation, and 10% testing data sets are applied. Training of the models based on sex, underlying pathology, and ultimate dislocation status are critical considerations in the models generated. Two U-Net CNN models are formed to segment AP pelvis and cross-table lateral hip images independently. The encoders of both models had the VGG-16 architecture, and initial weights were pooled from a model pretrained on the ImageNet database. Well-known Adam optimizer is used after training the network's decoder layers for 50 epochs with a batch size of 8. Model performance is evaluated on independent test data sets that were not used for training and validation. The inclination angle model had performance values of 91.3% for acetabular component and 84.3% for ischial tuberosity. The anteversion angle model had performance value of 90.3% only for acetabular component. Less than 2.5% of the cases had differences of 5° or more when human and deep learning measurements are compared. The high accuracy of the CNN models showed their effectiveness in automating the measurement of angular position of acetabular components.

Deep learning and machine learning models are developed in [22] as a part of natural language processing for efficient and accurate hip dislocation detection following primary THA by using standard (radiology notes) and non-standard (follow-up telephone notes) free-text medical narratives. After preprocessing, 105 out of 1890 patients had a dislocation sustained that resulted in a total of 380 radiology and 174 telephone notes. No indication of a dislocation is found in 2634 radiology and 609 telephone notes. Traditional machine learning models used included generalized linear model, KNN, random forest, SVM, and shallow neural network. The deep learning models included long short-term memory (LSTM) model and a CNN model. The classification of both deep and machine learning models is tuned to detect radiology notes that relate to three categories: (1) current dislocation, (2) evidence of previous dislocation, and (3) no dislocation. The proposed CNN model achieved the best overall performance for classification of both the radiology and telephone notes into the above-mentioned three categories. Therefore, the developed CNN model in [22] can be used for accurate and efficient hip dislocation detection from free-text medical narratives.

Mechanical loosening detection of THA implants is analyzed in [23] by using a deep learning algorithm and two different methods that utilize saliency maps and activation maximization [8]. Saliency map identifies the pixels most significantly affect the CNN classification output by ranking all the pixels of an input image based on their relative influence on a specific class score. An input image is generated by activation maximization for each filter that maximizes that filter's output [8]. 40 patients' image-specific saliency maps are used in [23] for training a CNN with 17 mechanically loose and 23 with well-fixed THA for detecting mechanical loosening of THA implants by classifying the input x-rays into categories of "loose" and "well-fixed." The first layer of CNN that looks directly at the x-ray image learns to detect very simple patterns such as horizontal and vertical lines in the image, while deeper layers that consist of middle and last convolutional layers learned more complex filters. The usefulness of combining saliency maps and activation maximization is shown for accurate mechanical loosening detection that can be used by decision-makers for revision surgeries.

AI, DL, and ML are also used for research on hip fractures that relate to THA; we cover only one research article in this area of interest as an example of an application; however, this area of interest is not a direct application of THA; therefore, it is not covered here extensively. Detection of hip fractures by using a deep convolutional neural network (DCNN) on plain pelvic radiographs upon THA is designed in [24]; 25,505 limb radiographs collected between the beginning of 2012 and end of 2017 are used with the retraining of 3605 frontal pelvic radiographs. Some of the deep learning research evaluating medical images use cropped images to avoid "black box" mechanisms such as [25] and enhance the accuracy of final validation, while authors of [24] reduced the image matrix size to 512 × 512 pixels instead. DenseNet-121 is used as the architecture of the designed neural network by using pixel values from the digital images as inputs using convolution and pooling techniques on each layer and to adjust the weights in the neural network according to the difference between the output and true label. Designed DCNN yield to strong results including 91% accuracy, 98% sensitivity, 2% false-negative rate, and 98% area under the receiver operating characteristic curve (AUC) when tested on 100 additional images collected during 2017. Gradient-weighted class activation mapping (Grad-CAM) is used by the authors to confirm the validity of the model, and 95.9% accuracy is attained by using the visualization algorithm for lesion identification (Figs. 1 and 2).

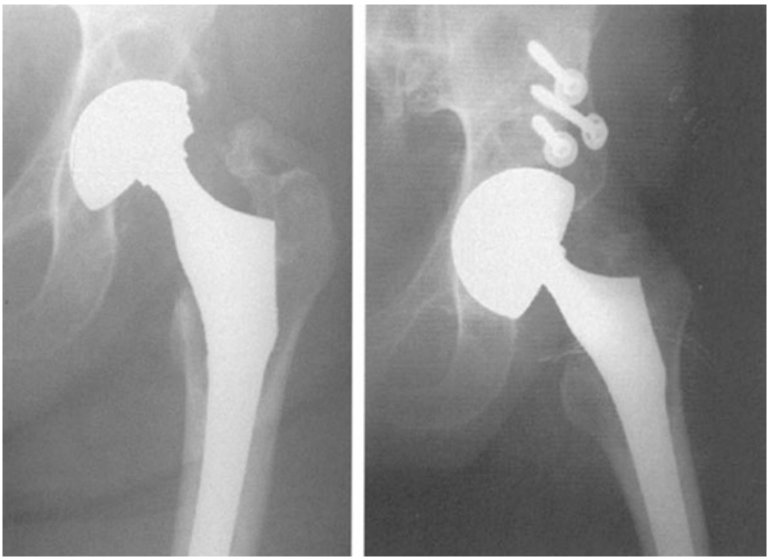

Fig. 1 An image that can be detected easily using DL of polyethylene wear on a radiograph [26]

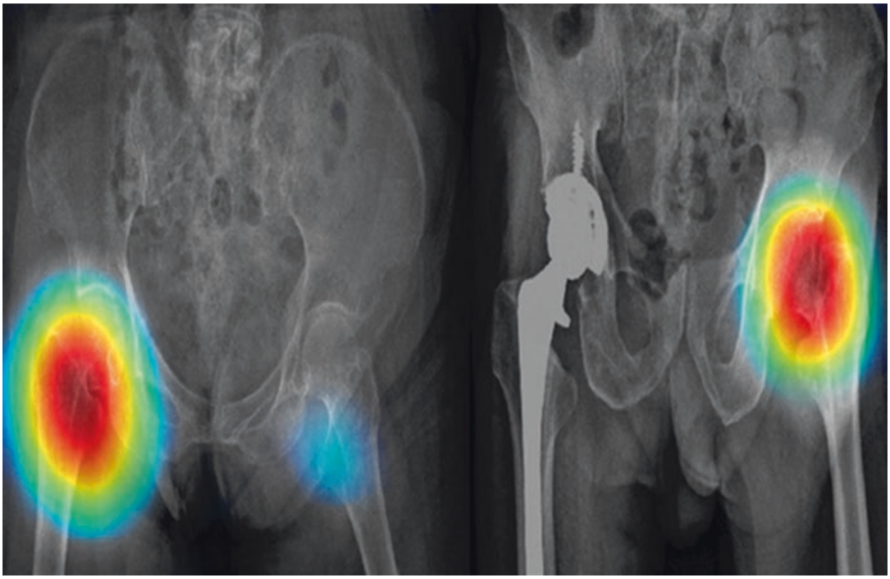

Fig. 2 Two images of gradient-weighted class activation mapping used for visualizing the class of discriminative regions for DL applications [24]

4 Artificial Intelligence

One of the earliest applications of ANN on THA is focused on patient comfort after THA based on bodily pain reduction in [1]. A total of 221 patients' survey data on 14 variables included gender, race, income, education, age at surgery, BMI, marital status, availability of help at home, preoperative effect of pain on physical function, preoperative support requirements, preoperative reported change in health over the year prior to surgery, pain-limiting activities' frequency, effect of pain on work, and preoperative SF-36 pain score. The ANN designed is trained by using 26 input nodes to predict the relative success of THA surgery using the presurgical patient survey information and a backpropagation feedforward neural network training to predict the output variable using the jackknife method. The best ANN achieved 83% of total percentage correctness and 62% of weighted percentage correctness. Area under the receiver operating characteristic curve is determined to be 79%. In conclusion, authors pointed out the success of neural networks to predict the success of THA accurately. Such an approach found to be feasible for predicting patients at greatest risk of poor outcomes based on their reported surveys.

The usefulness of ANN for failed implant identification is investigated in [27]. A total of 2116 AP hip radiographs capturing femoral stem implantation following THA from 2002 to 2019 are analyzed. Training is conducted on 1410 AP hip radiographs with an additional 706 used for validation and a unique consecutive series of 324 radiographs used for testing accuracy. The neural network architecture performance is trained, validated, and tested by using AlexNet, DenseNet, GoogLeNet, Inception-ResNet-v2, Inception-v3, ResNet-101, ResNet-50, ResNet-18, SqueezeNet, VGG-19, and VGG-16. Among all the options, Dense-Net 201 architecture attained 100% accuracy in training data, 95.15% accuracy on validation data, and 91.16% accuracy that outperformed the other options. The ANN utilization in iPhone 6 cellular phone application resulted in approximately 1-second runtime. Therefore, the ANN designed is determined to be a strong predictor for failed implant identification.

It is important to determine the manufacturer and the model of the hip implant upon hip arthroplasty. Radiographs are used for implant classification by experts specialized in the subject matter. Delays in care, increased morbidity, and additional economic burden are consequences of unidentifiable hip implants. A CNN algorithm is designed in [28] for differentiating and detecting 18 different hip implants by Zimmer, DePuy, Stryker, and Smith & Nephew manufacturers based on plain radiographs. 1972 AP plain radiographs from 4 sites are collected with 1559 used for training, 207 used for validation, and 206 used for external testing of the CNN. Input images are rescaled to 299 × 299 pixels. After preprocessing, inception V3 network is utilized with pixel normalization to the range of −1 to 1. The network is trained by using all training images for a total of 1000 epochs. Accuracy, sensitivity, specificity, and area under the receiver operating characteristics curve of the model are calculated for determining model performance in predicting the correct implant during both validation and external testing sets. Designed CNN demonstrated progressive "learning" through the 1000 epochs by improving validation accuracy and decreasing validation loss function values. CNN achieved 99.6% accuracy, 94.3% sensitivity, 99.8% specificity, and a value of 99.9% for area under the receiver operating characteristics curve as the average of all 18 manufacturers' implant identification. Implant stem designs for all of accuracy, sensitivity, and specificity included the following:

- 100% for Zimmer Biomet Arcos, Zimmer Biomet Taperloc, DePuy Corail, DePuy SROM, Smith & Nephew Birmingham, Smith & Nephew Synergy, Stryker ABG, and Stryker Exeter
- At least 99.5% for DePuy AML, DePuy Summit, Stryker PCA, and Stryker Restoration Modular.

The other six brands also had strong results with a minimum of 98.1% accuracy and a minimum value of 98.3% specificity, except with two minimum values of 66.7% sensitivity attained for two brands. Hence the CNN generated in [28] for differentiating the 18 hip arthroplasty implant models from four industry leading manufacturers demonstrated its effectiveness (Fig. 3).

An ANN non-parametric metamodel is used as a tool for sensitivity analysis in a cost-effectiveness model in [29]. The decision analytical model used is developed in [30] to investigate the effectiveness and cost-effectiveness of alternative hip prostheses. The metamodels are developed in two stages with the first screening phase emphasizing a nonlinear factor screening for importance analysis to reduce the number of variables attained from the simulation and second phase employing an

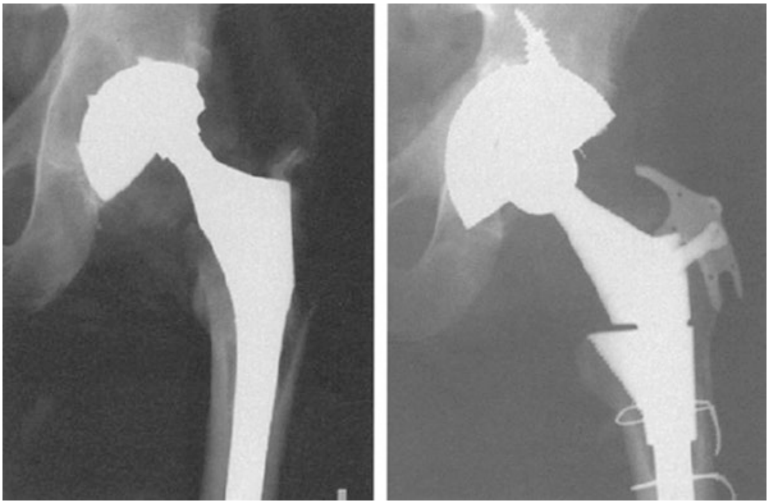

Fig. 3 An image of DePuy anatomic medullary locking cup with acetabular cup system liner [26]

ANN to structure an input-output relationship of the cost-effectiveness model [29]. The performance of the resulting ANN is compared with multiple linear regression and Gaussian process based on Charnley and Spectron prosthesis. 12 of the 31 features are selected from the simulation. Mean square error of prediction and mean absolute percentage deviation of the ANN meta models displayed the best performance measures for predicting both costs and quality-adjusted life years for the two prostheses. Overall, both ANN and linear regression models predicted the quality-adjusted life years highly accurately while ANN showing the best predictive capability for costs in THA model. ANN model is determined to be a good predictive modeling technique for health economic simulations.

Automated record search for text detection by using ANN in comparison to classic record search by two manual reviewers is investigated in [31]. Manual patient record analysis included hospitalization report, surgery report, and postoperative outpatient clinical report and excluded radiographic, laboratory, and pathology reports that were not reviewed. Surgery and implant characteristics such as implant size and implant articulation were extracted with any reported adverse events, and their respective treatments were recorded. The purpose of ANN development is to establish ease of access and increasing quality of accurate monitoring of the THA patients' records. A text mining engine utilizing a natural language processing technology and machine learning for extracting key concepts from electronic medical records are the two key components of the algorithm. Recall, precision, accuracy, and F-values are used as the statistical measures for the data collected from 532 patients and 613 hips. As a result, the comparison of manual and ANN search for implant characteristics resulted in significantly higher accuracy of the algorithm with 94.8% than the accuracy of the reviewer with 93.4%. ANN algorithm demonstrated better results than the manual process even in the case of existing clear pattern for implant sizes with low-level training. Overall performance of the algorithm is measured as 96% for recall, 88% for precision, and an F-value of 0.89 for all adverse events. The automated ANN search algorithm is determined to be capable of analyzing and interpreting large quantities of electronic medical records faster than the manual search with a performance level equivalent of comparable or slightly better than a human reviewer.

5 Conclusion and Possible Improvements

In this work applications of AI, DL, and ML that relate to THA in the research literature are covered. A variety of research results are covered throughout this article with implant design and failure, post-THA patient satisfaction, database search and text detection, and biomechanical considerations. Deep learning results attained for the THA applications covered in this work particularly have strong results for the most part. Current applications of the algorithms have limited scope; however, more advanced results can be attained. Such applications can include parallel computing, integration of DL directly into hardware applications used in THA, and integrating optimization algorithms into AI/DL/ML algorithms. Supervised learning methods can be particularly helpful in applications. Adaptive learning approaches can also be included based on multiple surgeries on same patient types. There are many more AI/DL/ML applications that can be integrated into other advanced technologies that can guide surgeons during THA. We must note the results of the reviewed articles in this work are particular instances of applications of the AI theory; therefore, they may not be able to yield good results in other collected data sets necessarily; there are many factors that play in such research results.

To the best of our knowledge, utilization of AI, DL, and ML on psychological treatment of patients to prevent them go through THAs has not been investigated in the research literature. Such research requires specific data collection from THA candidates who go through psychological treatment; after such a therapy, patients' decision to pursue or not pursue with THA treatment can be determined. The current practice in elective orthopedics does not routinely include psychological interventions despite evidence that psychological factors such as personality, anxiety, depression, and negative thinking styles can influence outcomes and recovery from surgery [32]. In fact, there is very limited research and investment on impact of psychological treatment on patients to prevent going through THA, and the majority of the literature focuses on the impact of psychological treatment based on pre- and post-THA outcomes. The application of AI theory with the corresponding feature (i.e., variable) selection during psychological treatment and analyzed along with the success of the treatment for declining occurrence of THA appears as a brand-new research area. Noting that the average age of THA patients is getting younger over the years, effectiveness of psychological treatment can be investigated for declining the increase in THA over the years. This idea leaves us with a brand-new THA research area application from a psychological standpoint that can also be applied in other surgical procedures: Can we use AI, DL, and ML effectively to determine features that help THA candidates prevent going through THA after psychological treatments and help them to heal naturally? If the answer is yes, then these features can help to decline the increase in THA procedures by the help of psychologists focusing on helping the patients.

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Advancing Engineering of Total Hip Arthroplasty

Abstract There are many engineering techniques utilized in addition to the effectiveness testing of the surgical techniques of THA. These considerations start all the way from the materials that are supplied for the physical structure of the implant along with the implant design that would allow an implant to be structured for the patient. Looking through the articles that can be seen in the literature of THA, majority of the researchers focused on specific needs of THA improvement rather than a holistic approach; what might be missing in this "localized" approach is the error term that the previous step brings into the success of THA. In this article, a discussion on potential advancement methods that can be utilized along with the pros and cons that take place in THA all the way from the supplier of the manufacturer along with the post-surgical treatments. We also raise an important psychology-related research question to be investigated: Can we prevent patients go through THA by using psychological treatments?

1 Introduction

The typical phrase that can be seen in published THA research is "THA is one of the most successful surgeries in the history of mankind." We don't even see a need for referencing any research to this phrase due to its frequency of occurrence. The major question that this brings is "What is causing the error that does not result in 100% accuracy?" There are two sides to the response of this question. First response can be based on factors that would not allow a successful THA; under these conditions, we do not have any control over the THA outcomes such as some physiological factors that may arise, and we do not have any control on these issues for implant failure. The other response is based on those factors that we can have control over and be able to design the needs of a successful THA accordingly. These considerations can include the following:

- Supplier and quality of material used.
- Manufactured parts with their materials used.

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- Implant design.
- Preoperative planning.
- Surgical technique choice.
- Post-surgical technique for healing.
- Psychological factors to prevent THA.

The next sections are designated to explain improvement opportunities and ideas that relate to the above-mentioned bullet points. What follows would be the conclusion on the use of technology for near future potential technological improvements on the success of THA along with the importance of psychological treatment to prevent patients go through THA and heal naturally.

2 Suppliers' Quality of Materials and Manufacturers' Production

This first step of implant's journey is one of the most basic steps of THA success but yet could be the most important one. One typical challenge that needs to be recognized is the quality of the material provided by the supplier and the mixed of metals (if applicable) to get to the level of desired strength and stiffness. Including statistical factors such as the metal mix which have plus/minus certain attributes may result in significant changes in biomechanical testing even for the same brand of implant. In the biomechanical testing of implants, the basic question would be whether the same manufactured implant would fail at the same number of loadings or not under equivalent conditions. High success of THA mainly shows reliable and good quality products by manufacturers. Robotics use can further improve the success of implant production [2].

One of the most recent trends in implant production is personalized printing of the implants based on the specific needs of patients. This approach also aligns with the results attained in the literature that makes sense due to anatomical differences of patients. One improvement aspect in this approach would be use of robotics that can result in improvements of THA procedures [2]. Another aspect is determining the best implant design. One way of achieving this goal would be sharing resources based on completed THA surgical procedures with agreed characteristics that play a role in decision-making. AI/DL/ML can be then utilized for detecting the best THA outcomes attained based on the changing patient parameters that resulted in the corresponding successes. DL algorithms can be particularly useful in such applications that require further testing on such data sets [5]. A detailed patient record is crucial in this case. There needs to be consensus on the record keeping among all data sharing resources for declining errors; the best way to minimize error is developing a single data resource that is accomplished by several branches of hospitals that belong to the same patient care provider. Such data sets are likely to require big data analysis, and minimizing the record error is a critical element of such data collection. Optimization techniques will need to be used for determining best practices along with the design needs of such implantation search [4]. Biomechanical analysis during optimization is also essential in the developed implant.

3 Implant Design Improvement Opportunities

Not surprisingly, implant design has been the most attention paid in the literature for THA implant development. Modularity, cementation, material utilization, stem length, and cup design are all impactful on the implant's design. As mentioned in the previous section, data sharing along different resources, even maybe globally, can help researchers identify the best practices for specific THA needs. Another challenge in the design aspect is researchers using different methods of analysis that are incompatible for comparison purposes. One simple example is the number of screws, plates, and wires used. Optimal designs are attempted to be attained by many practitioners [1]; however, varying patient characteristics would always be hidden, and underlying reasons for best practices are patient specific, and there are many changing parameters for sharing outcomes. Noting the factors mentioned in [4] for optimal implant design, a mathematical nonlinear optimization model with constraints can be designed by determining underlying parameters from such data. This takes us back to the idea of resource sharing and utilization of patient records with hidden names for identifying best practices. Such approach with personalized implant design and 3D printing can result in improving THA outcomes; however, the complexity of the data still plays an important role in applications. The improvement role of 4D printing in THA applications can also be investigated as a part of the implant design.

4 Preoperative Planning Improvement Opportunities

The impact of preoperative THA planning using technology and designed surgical experiments has been determined to be successful [2]. The use of advanced imaging modalities of the body parts and integration to the robotic-assisted surgery is a way of potentially improving THA outcomes with limitations. Development of a convolutional neural network for integrating DL into robotic-assisted THA surgery along with an appropriate use of optimization methodology can make a big impact on the surgical procedure. This needs to be pre-planned in order to determine the success of the surgery. This approach can be also used for implant sizing for the patient. Another preoperative planning improvement can be 3D simulation of different THA implant designs that demonstrates biomechanical consequences of the patient prior to surgery by using virtual reality (VR) that is gaining popularity in surgeon training. Incorporating a robot into such a system would be also a way to design a robotic-assisted surgical procedure (with biomechanical features) that is shown to be successful in THA applications [3].

5 THA Surgical Technique Improvement Opportunities

Incorporating robotics into THA procedure to assist a surgeon is a value-adding activity as long as it is implemented right [2]. THA surgical data sharing on THA outcomes by using consensus on variables for data collection would be one way to explore this option. AI/DL/ML can be then used for detecting the best method of results attained. A large data set that can be used for determining the successes of robots for ever-changing patient circumstances can be a strong factor for using the right technology when available. Even in the case when a robot is not used, the right choice of surgical procedure through the collected data with patients' surgery-related characteristics can be factors in designing a successful THA surgery with limitations.

6 Post-surgical Technique for Healing

The utilization of robotics and VR during the healing process of THA is shown to be successful in speed of recovery and patient satisfaction [2]. This healing process is particularly crucial for early discharge of patient and speed of recovery overall. Determining the patients' characteristics that benefit from such approach can be also possible though shared resources of information for patients' economic benefits. Analysis of such data can be used for 3D simulation of patient recovery with the time expected to recovery calculated for practitioners with limitations.

7 Advancing Analysis of THA Outcomes

Considering the multiple negative effects of comorbidities that could potentially have on the outcomes of THA procedure, a careful examination of such conditions is crucial to ensure the achievement of successful THA outcomes based on the information collected through the instruments utilized to evaluate the comorbidities presented by the patients [6]. Among the most commonly used indices, Charlson Comorbidity Index (CCI), Elixhauser Comorbidity Method (ECM), and the modified Frailty Index (mFI) are most commonly used [6]. The CCI allows for the prediction of the future health status of patients presenting multiple comorbidities, as well as the incidence of mortality following hospital admission and potential rehospitalization [7]. The mFI, instead, is related to both aging and the presence of comorbidities, to aid in the recognition of patients at high risk of complications following the procedure. Finally, the ECM comprises 30 variables, each corresponding to a specific disease identified with an ICD (International Statistical Classification of Diseases and Related Health Problems) code, which facilitates the collection of data. The analysis of data can focus on the life quality, functionality, and mortality, complications, overall length of stay in the hospital, readmission, reintervention, satisfaction, and transfusion of blood in such a data set. The American Society of Anesthesiologists physical status classification (ASA) and the CCI are the most widely employed comorbidity evaluations in patients undergoing THA. These tools provide a reliable prediction of the outcomes of the surgical procedure, including life quality, functionality, fatality rates, length of hospital stay, and readmissions; however, the ASA resulted more accurate in the prognosis of adverse events, as well as the length of stay, dismissal, and health status of the patients following THA. Nonetheless, this tool could display inconsistency in the analyzed outcomes because of its subjective character [8], thus implicating the need for additional instruments to ensure accurate prediction of the results. The ECM is useful in the prediction of severe complications and can provide more accurate results than ASA in the anticipation of THA outcomes [9]. However, due to the high quantity of variables, the collection of data is particularly complex.

One of the main obstacles faced by the investigators when analyzing the quality of life of patients in randomized trials is the determination of the relevance of any of the discovered differences. For this reason, the use of patient-reported outcome measures (PROM) to achieve postoperative assessments is significantly increasing, as they appear to be extremely helpful in the provision of scores regarding the status of the patients to be later examined by clinicians. PROMs not only assess the functional outcomes of the procedure including the physical, social, and cognitive capabilities of the patient but also examine the adverse events correlated to the surgery such as tiredness, uneasiness, and pain and multidimensional constructs that specifically encompass the health-related life quality [7]. A wide variety of PROMs are used to assess the perceived health gains of the patients undergoing THA, among which the Harris Hip Score (HSS), the Oxford Hip Score (OHS), the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC), the modified d'Aubigne and Postel Method, and the EQ-5D-3L questionnaire are some that can be listed.

Deep and machine learning methodologies can be used on the data collected by using the instruments mentioned above for further detailed analysis on the comorbidities and their correlations to the outcomes of THA surgeries. These techniques can be used on both qualitative and quantitative data analysis [5]. Analysis of PROMs by including textual and numerical data not only can be particularly time saving but also can yield valuable outcomes of patients' opinions on the THA outcomes; however, this type of analysis also has limitations that may not be necessarily applicable to all data sets.

8 Psychological Factors to Prevent THA

Elective surgery represents a considerable source on stress for the patients [10]. Noting that implants are prone to failure eventually, "Can we help patients to not go through THA and heal naturally?" is an important question to ask. Many attempts have been made to prepare patients before surgery with the aim of reducing stress and improving outcomes [11]. This stress alone could be impacting patient in a negative way and increase the level of dissatisfaction. It would be ideal to prevent THA and provide psychological support to the patients on better living and healing naturally. In [12], based on THA patients wait listed for 1–26 months with a median of 6 months of the surgery, it is shown that those waiting longest were no worse on any of the outcome measures and their mental health was better. In fact, it is concluded that mental disorders are common in patients waiting for hip replacements and are not directly related to hip function and their origins are unknown, but they require clinical assessment and treatment. It is concluded that there is no evidence that physical or social function or mental health is worse in those waiting longer for THA. The current practice in elective orthopedics does not routinely include psychological interventions despite evidence that psychological factors such as personality, anxiety, depression, and negative thinking styles can influence outcomes and recovery from surgery [13]. In fact, there is very limited research and investment on impact of psychological treatment on patients to prevent going through THA, and majority of the literature focuses on the impact of psychological treatment either pre- or post-THA outcomes. This is likely to leave us with the most important advancement in THA research: Can we prevent potential THA patients to go through THA by using psychological treatments? The clinical literature doesn't seem to investigate on this matter to the best of our knowledge which leaves an important gap that should be investigated. It could be possible to reduce pain and help patients have better mental state. Additionally, the impact of religious believes and their impact on preventing patients going through THA can be investigated for the best interest of the patients.

9 Conclusions

Improvement opportunities for THA starting with the supplier all the way to the end of the healing process are covered in this work along with the importance of psychological factors to not go through THA. It is important to note the extensive nature of the suggestions with the integration of the robotics, VR, and big data analytics techniques. Similar to the probability calculations in [2] for success of using robotics in THA, multiplication of success probabilities of all factors would play a crucial role in the outcomes of THA. The review of THA literature theoretically suggests the highest THA success rate attainment to be possible through implementation of the following altogether:

- Shared data resource utilization to generate a large data set for determining best possible practices dependent of patient characteristics.
- Right use of deep learning (or possible AI or ML) techniques for data analysis to determine best possible THA needs of the patient.
- Right use of robotics during the implant production stage and during surgery.

- Use of highly accurate 3D imaging modality, VR, and robotics during presurgical planning.
- Optimization of all possible parameters for determining patient-specific surgical needs (such as type of surgery, biomechanical behavior, etc.) by using data.
- Personalized implant 3D printing.
- Use of robotics for post-surgical healing.

There are many more THA advancement techniques that can be tested that are not mentioned in this article; however, the abovementioned steps are initial futuristic steps that can be taken toward attaining better THA outcomes with limitations. As the final note, psychological treatment might be the key to prevent patients go through THAs and have a better and happy life. This is likely to leave us with the most important advancement in THA research from a psychological standpoint: Can we prevent THA candidates from going through THA by using psychological treatments and help them to heal naturally? Given the literature information above and personal experiences, the answer appears to be a "yes."

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Correction to: Total Hip Arthroplasty

Emre Tokgöz

Correction to: E. Tokgöz in *Total Hip Arthroplasty*, https://doi.org/10.1007/978-3-031-08927-5

The original version of the FM was published without including the acknowledgment line "Contributions by Alessia Truden" in title page and front cover. Now, the suggested change is updated in FM and front cover.

The updated original version of this book can be found at
https://doi.org/10.1007/978-3-031-08927-5

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Epilogue

There is a cumulative percentage increase in the number of total hip arthroplasty (THA) patients over the years [1]. It appears important for looking into alternative ways to prevent occurrences of THA procedures such as psychological treatments and promoting better life. It is shown in the literature that psychological factors such as personality, anxiety, depression, and negative thinking styles can influence outcomes and recovery from surgery [2]. This raises the question of whether these factors might be causing the surgery itself depending on the patient's conditions. Noting the physiological structure of a person as an interconnected network with everything stemming from the brain and ruling the body through the nervous system, the ultimate interest of healthcare is to help people have a happy and healthy life. Unless a person has to go through THA, we recommend doctors to act early and recommend their patients to receive psychological help along with structuring healthier living conditions through healthier eating, a less stressful life, and declining negative thinking. Even though THA is known to be a successful surgery, the hurdles that THA patients going through THA journey from the beginning to the end not only impact them but also impact their families and friends. Recommendations for better living can include the following:

- Reducing stress
- Eating healthy (by this we don't necessarily mean a strict diet that enforces a person to eat strictly designed by a dietitian; we mean eating healthy food in a controlled way that the patient wants to eat since our bodies tell us what they need)
- Helping needy by donating money (even if it is a small amount)
- Finding inner piece
- Declining negative thinking (by getting professional help if needed)
- Looking into ways to find the truth about God depending on person's religious interests (if there is any)

Acting early and helping patients through such considerations can help patients to have a better and healthier lives.

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