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Current use of navigation system in ACL surgery: a historical review

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Abstract
Purpose The present review aims to analyse the available literature regarding the use of navigation systems in ACL reconstructive surgery underling the evolution during the years.
Methods A research of indexed scientific papers was performed on PubMed and Cochrane Library database. The research was performed in December 2015 with no publication year restriction. Only English-written papers and related to the terms ACL, NAVIGATION, CAOS and CAS were considered. Two reviewers independently selected only those manuscripts that presented at least the application of navigation system for ACL reconstructive surgery.
Results One hundred and forty-six of 394 articles were finally selected. In this analysis, it was possible to review the main uses of navigation system in ACL surgery including tunnel positioning for primary and revision surgery and kinematic assessment of knee laxity before and after different surgical procedures. In the early years, until 2006, navigation system was mainly used to improve tunnel positioning, but since the last decade, this tool has been principally used for kinematics evaluation. Increased accuracy of tunnel placement was observed using navigation surgery, especially, regarding femoral, 42 of 146 articles used navigation to guide tunnel positioning. During the following years, 82 of 146 articles have used navigation system to evaluate intraoperative knee kinematic. In particular, the importance of controlling rotatory laxity to achieve better surgical outcomes has been underlined.
Conlusions Several applications have been described and despite the contribution of navigation systems, its potential uses and theoretical advantages, there are still controversies about its clinical benefit. The present papers summarize the most relevant studies that have used navigation system in ACL reconstruction. In particular, the analysis identified four main applications of the navigation systems during ACL reconstructive surgery have been identified: (1) technical assistance for tunnel placement; (2) improvement in knowledge of the kinematic behaviour of ACL and other structures; (3) comparison of effectiveness of different surgical techniques in controlling laxities; (4) navigation system performance to improve the outcomes of ACL reconstruction and cost-effectiveness.
Level of evidence IV.

Keywords ACL · Computer-assisted surgery (CAS) · Navigation system · Kinematic · Tunnel placement

Introduction

There have been reports in the literature about navigation systems for ACL surgery since 1995, and Juilliard et al. were the first to describe the clinical use of computer-assisted surgery (CAS) to assess knee kinematic in ACL reconstruction [27]. Since then, many authors have used

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navigation systems for research purpose significantly improving knowledge in ACL surgery.

According to these studies about navigation system for anterior cruciate ligament (ACL) surgery reports a variety of topics and methods.

In fact, for many years, orthopaedic surgeons dealing with ligament reconstructive surgery have been focused on better understanding both the anatomy and the biomechanics of the anterior cruciate ligament (ACL) in native and injured conditions to improve clinical outcomes and to reduce failure rate in ACL reconstructive surgery.

The initial applications of the navigation systems were mostly to enhance the accuracy of tunnel position, to study graft isometry and graft orientation. Most recently it has been used to evaluate the kinematic of ACL remnants and the stability achieved by different surgical techniques [106, 119, 136].

Nowadays navigation system is a reliable and accurate system assessing both tunnel placement and knee kinematics. Moreover, it is considered the gold standard for the validation of innovative and non-invasive (skin-mounted) inertial sensors for clinical practice (e.g. KiRA, Orthokey) [48, 68, 120].

The purpose of the present manuscript is to provide a complete evidence-based overview of the past and present applications of the navigation system during ACL surgical reconstruction. They will highlight all the concepts of navigation during the years and how they evolved.

The present historic review focused on the available literature of the use of navigation systems for ACL reconstructive surgery and presents an overview of past and present applications.

Materials and methods

Search design

A systematic search of MEDLINE (PubMed) and Cochrane Library electronic database was performed for all the studies on navigated ACL reconstruction surgery. Two reviewers independently conducted the search in December 2015 with the following key words: ((ACL) OR (anterior cruciate ligament)) combined through the Boolean operator AND with ((navigation) OR (CAS) OR (CAOS) OR (computer-assisted surgery)). Such wide inclusion criteria were used to give a complete overview of the topics underling all the possible applications in the field for both clinical and research studies.

All the titles and abstracts were screened with the following inclusion criteria: (1) evidence levels 1–4 clinical studies, (2) biomechanics or clinical outcomes of navigated ACL reconstruction, (3) both cadaveric (in vitro) and clinical (in vivo) studies.

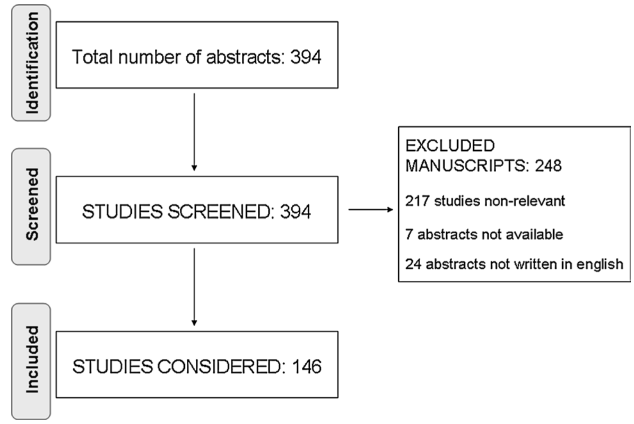

Fig. 1 Flow chart of study

The full text of all the relevant papers were obtained and further by screened to confirm the eligibility. Papers were excluded in case of: (1) incomplete\inappropriate description of navigation system application, (2) unclear description of population and setting, (3) conference proceedings, (4) non-English language. The references of all included studies were screened to further search for any other relevant scientific manuscripts.

Discrepancies in the papers evaluation were resolved by discussion and consensus decision.

A total of 394 articles were identified on the initial literature search. Of these, 248 were excluded. In particular, 217 were not relevant according to the purpose of the present systematic review, 7 abstracts were not available, and 24 papers were not written in English. This means that a total of 146 papers met all the inclusion criteria (Fig. 1).

From the selected 146 studies, details were extracted on study characteristics and design, demographic parameters, navigation system application and cadaveric (in vitro) or clinical (in vivo) study.

Data extraction

An excel sheet was prepared including the following information: authors names and year of publication, cadaveric (in vitro) or clinical (in vivo) setting, total number of knee evaluated through navigation and main purpose of the navigation use (e.g. kinematic assessment or tunnel placement).

Articles using navigation system for kinematic evaluation were reorganized in another table describing anatomical structures evaluated, such as native anterior cruciate ligament and its antero-medial and postero-lateral bundles (AMB–PLB), postero-lateral corner (PLC), postero-medial corner (PMC) or surgical reconstruction techniques used to achieve stability: ASB anatomical single bundle; ADB, anatomical double bundle; SB, single bundle; DB, double bundle; AE, all epiphyseal; TT, trans-tibial; ITB, ileotibial band. In the same group,

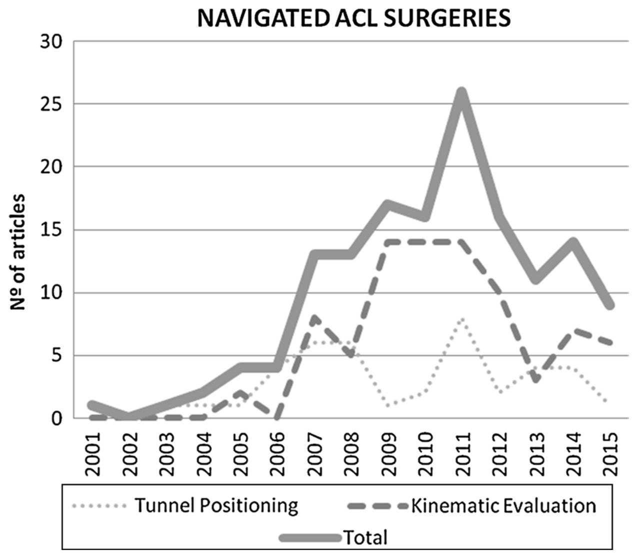

Fig. 2 Trend of publication concerning navigated ACL surgery (*thick line*). During the early years navigation systems were mainly used to improve tunnel positioning (*dotted line*) from 2007 they have been mainly used for kinematics evaluation (*dashed line*)

evaluated parameters were also included: ATT, anterior tibial translation; IE, internal\external rotation; VV, varus\valgus vest; PST, pivot-shift test; ACC, acceleration) and anatomical structure or reconstruction technique evaluated through the navigation system (ACL, anterior cruciate ligament; PMC, postero-medial corner; PLC, postero-Lateral Corner; AMB, antero-medial bundle; PLB, postero-lateral bundle.

All the papers were therefore summarized and discussed based on main aims and purposes, delineating the areas of research for navigated ACL reconstruction. All the aspects will be covered in the manuscript, from anatomical and surgical analysis to kinematics and laxity considerations, from clinical to research aspects.

Due to the wide range of the treated topics, it resulted impossible to pool the results in a meta-analytic manner.

The analysis of all the collected manuscripts in relation to the year of publication made possible to appreciate an increased interest, and during the last decade, in using navigation systems for ACL reconstructive surgery, this is correlated with Lopomo et al. [69] (Fig. 2).

Results

Temporal trend of navigated ACL studies

The selected manuscripts have been organized according to the main aim of the study. Such selection underlined a trend of the navigation system application as the time pass by. In fact, during the initials years, until 2006, ACL surgeries were navigated with the main purpose to optimize the positioning of both graft and tunnels. Anatomical references and graft isometry during the range of motion were acquired intraoperatively and in real time, ensuring the desired orientation of the tunnels and graft [15, 29, 38, 51, 57, 82, 92, 103, 109, 111, 139, 143, 144]. Subsequently, navigation system were also used to measure knee laxity in 3D conditions making it possible to improve the knowledge of ACL surgery outcomes and biomechanics, as well [5–8, 10–12, 16–18, 20, 21, 24, 25, 30–33, 39–44, 46, 48–50, 53, 56, 59–67, 70, 71, 76, 78, 80, 81, 84–89, 91, 93, 95, 96, 99, 100, 102, 104, 105, 108, 112–114, 117, 118, 122, 126–129, 133–135, 137, 138, 146–151, 154, 156, 157] (Fig. 2).

Main areas of research in navigation in ACL surgery

In addition to systematic reviews or meta-analysis manuscripts [13, 14, 19, 28, 47, 52, 55, 83, 90, 152, 155], four main fields of application for navigation system in ACL reconstruction have been identified:

1. Technical assistance for tunnel placement: studies that use the navigation system to perform tibial and/or femoral tunnels drilling.
2. Kinematic evaluation of ACL: studies that use the navigation system to analyse the biomechanical behaviour of the ACL and peripheral structures with the aim to better reproduce the native behaviour by the reconstructive surgery.
3. Comparison of effectiveness of different surgical techniques: studies that use the navigation system to perform laxity measurement to compare the outcome of different surgical
4. Ability of navigation to improve the outcomes of ACL reconstruction and cost-effectiveness: studies that analyse the clinical and economical efficacy of the navigation system for ACL reconstruction.

All these topics will be debated in depth in the discussion section.

Discussion

Navigation and tunnel placement

During the past years several different techniques have been described in order to decrease the failure rate due to mistakes in such procedures [22, 72, 98, 121]. Many studies have showed that CAS may improve the accuracy of anatomical tunnel orientation and position during ACL reconstructive surgery [15, 29, 38, 51, 57, 82, 92, 103, 109, 111, 139, 143, 144].

Shafizadeh [131] in a cadaveric set-up analysed the variability of tunnel positioning. Thirteen experienced surgeons were asked to identify arthroscopically both the femoral and the tibial tunnels for two times. The selected positions were recorded using an image-based navigation system. As a result it has been found an intraobserver variability of 1.7–3.6 mm and an interobserver variability of 2.3–3.9 mm, and the standard deviations of data were up to 7.8 and 13.2 mm (depth and height, respectively) for the femur and up to 9.6 and 18.3 mm (antero-posterior and lateral, respectively) for the tibia. These findings confirmed the variability of tunnel positioning described several years ago by Kohn et al [58]. Shafizadeh et al. [130] also analysed the variability in landmarks acquisition asking thirteen experienced surgeons to identify the bony landmark required for image-free ACL navigation in the same cadaver knee. The mean variability (SD) was 3.0 mm for the tibial landmark positions and 2.9 mm for the femoral one. The study suggested that there exists an inter- and intraobserver variability in intra-articular landmark identification that can lead to a miscalculation of tunnel position in image-free ACL reconstruction.

On the other hand, Angelini et al. [3] in 2010 have compared the accuracy of tunnel placement and graft isometry for ACL reconstruction with and without CAS in a 36 cadavers study. No statistically significant differences in tunnel positioning were observed even if the CAS group obtained a better isometry (less variation of the distance between the femoral and tibial tunnel during flexion–extension) when compared to the control group.

Several studies have compared the precision achieved using navigation with normal arthroscopic tunnel placement. Maak et al. [75] in an in vitro study investigated the effect of different tibial and femoral tunnel placement on ACL graft impingement. In particular, 16 cadaveric knee joints underwent ACL reconstruction: the tibial tunnel was positioned in the footprint of AM bundle while the femoral tunnel was placed either on the antero-medial (AM) bundle footprint, in the centre of footprint or in the posterolateral (PL) bundle footprint.

Even if the impingement was observed in all femoral tunnel positions (mean impingement angle were 42.8° for the AM, 19.4° for the central, 16.7° for the PL positions), the anatomical femoral socket position in the centre of the footprint may reduce the risk and magnitude of socket impingement when compared with an AM bundle position.

In 2001 Picard et al. [110], in an in vitro set-up, using foam knees, found statistical significant differences between the ideal tunnel and the performed tunnels using radiograhic measurements.

More recently, Hart et al. [37] performed a clinical, radiological and functional comparison between computer-assisted and conventional ACL surgery. A total of 80 patients were evaluated (40 in each group). Regarding the achieved tunnel position, after radiological evaluation, they only found an increased accuracy in the femoral tunnel placement using the navigation systems than traditional arthroscopic technique. However, they did not find any significant difference in tibial tunnel positioning, and more importantly no differences were found in functional and clinical outcomes.

Others studies have shown improved positioning especially of the femoral tunnel placement under computer assistance [73, 74, 132].

Gerber et al. [35] used the navigation system in order to assess the tibial and femoral geometry, including precise mapping of the intercondilar notch for balancing the risk of impingement and isometry. They advocate that the real-time analysis allowed by the navigation system could be helpful in avoiding unnecessary notchplasties in ACL reconstruction even with less flexible biological graft fixation.

Moreover, there are studies that underlined how the use of the navigation system in ACL reconstruction could be useful for inexperienced surgeons to avoid poor tunnel orientation and positioning [4, 159].

Schep et al. [124] studied inter-surgeon variance during computer-assisted planning of ACL reconstruction and showed that the tunnel position was not associated with the surgeon experience when using the CAS.

Taketomi et al. [142] investigated whether in the anatomical double-bundle ACL reconstruction surgery the order of the execution of AM and PL femoral tunnel could affect the results in terms of anatomical placement. Thirty-four patients were divided into two groups depending on the sequence of preparation of the two femoral tunnels. The ACL reconstruction was performed using a three-dimensional fluoroscopy-based navigation system. The PL-tunnel first group showed a more anatomical tunnel placement combined with a higher risk of socket communication when compared with the AM-tunnel first group.

Non-assisted tunnel positioning or traditional arthroscopic technique is based on a good visualization of the anatomical landmarks to place correctly the guide wires for tunnel drilling. Despite biomechanical properties of the ACL remnants (proprioception, stability, improved revascularization and cell proliferation), these may affect a good visualization of the footprints, making it necessary to clean the footprint to achieve an tunnel positioning [1, 2, 34, 101, 125].

In such situations, navigation systems might be used to confirm the ACL footprint position on the intercondylar lateral wall and to create an adequate tunnel using the native ACL footprint as a landmark [145]. Taketomi et al. [141] using 3D fluoroscopy-based navigation systems treated 47 patients with remnant-preserving ACL reconstruction, 28 using a rectangular bone–patellar tendon–bone (BTB graft) and 29 using double-bundle ACL reconstruction with Hamstrings. After surgery, they evaluated the tunnel placement using a 3D computer tomography. They showed that femoral socket locations were considered to be on the anatomical footprint in accordance with previous cadaveric studies in remnant-preserving ACL reconstruction.

Furthermore, revision ACL surgery is considered to be a challenging procedure, because of several issues orthopaedics surgeons have to deal with, including bone defects, primary tunnel malposition and pre-existing fixation devices, making adequate new tunnel positions fundamental for surgery outcomes.

In the present research, three studies [97, 115, 140] described the use of navigation system to increase the possibilities of creating a correct position avoiding pre existent problems.

Taketomi et al. [140] treated 12 patients with one-stage ACL revision surgery. After surgery CT scan was performed to confirm correct tunnel position in each patient.

More recently Plaweski et al. [115] have used CAS in 52 revision surgeries for tunnel positioning and kinematic evaluation. Navigation system allowed an optimal position with a mean (std) isometry of 3.2 (0.7) mm, and no tunnel malpositioning was observed.

Kinematic evaluation

Kinematic assessment has become the main feature of navigation systems in anterior cruciate ligament reconstruction (Table 1). Currently, [5–8, 10–12, 16–18, 20, 21, 24, 25, 30–33, 39–44, 46, 48–50, 53, 56, 59–67, 70, 71, 76, 78, 80, 81, 84–89, 91, 93, 95, 96, 99, 100, 102, 104, 105, 108, 112–114, 117, 118, 122, 126–129, 133–135, 137, 138, 146–151, 154, 156, 157] 56 % of all the selected articles have used navigation system to evaluate static and/or dynamic laxity. Among those there were more in vivo studies than in vitro studies. Using different set-ups, researchers have studied the effect of different structures including the antero-medial bundle (AMB) and the posterolateral bundle (PLB) of the ACL and the secondary restraints of the knee including the menisci, the lateral capsule, and also, the stability achieved after different surgical techniques.

In particular, navigation system has demonstrated to be an important tool for laxity evaluation and for better understanding the effect of combined injuries on knee kinematics. Musahl et al. [93] and Petrigliano et al. [108], studied in vitro the effect of meniscectomy after ACL reconstruction showing loss in rotational stability after meniscal removal.

Martelli et al. [79] in an in vitro study and Zaffagnini et al. [153] during an in vivo analysis proposed and validated an innovative protocol in order to evaluate multidirectional knee joint laxities during ACL reconstructive surgery.

Since then, with the development of new and more user-friendly navigation systems, the interest in computer-assisted procedures for clinical outcomes and research purpose increased and many studies have been published to describe knee joint kinematics. The ACL remnant preservation has also been studied. Nakamae et al. [99] and Nakase et al. [100] evaluated the contribution of ACL remnants on knee laxity. They found that remnants bridged to the posterior cruciate ligament and to the intercondilar notch contributed to the antero-posterior laxity at 30º of flexion.

The assessment of extra-articular compartment has represented another interesting field of study related to pre-operative and post-operative degrees of laxity. In fact, during the most recent years the interest of the scientific community has moved to the extra-articular components of the knee stability, highlighting the biomechanical role of the antero-lateral ligament in controlling the tibial rotation and the knee dynamic laxity [21, 86, 158].

Navigation system has been also used to assess the influence pre-to-post-operative laxity. Signorelli et al. [133] in 2013 have shown the importance of preoperative measurements, in order to suspect secondary restraint lesions. In fact, higher level of pre-operative laxities can underline complex injuries, where additional procedures to ACL reconstruction may be performed to gain a better stabilization.

Since the joint laxity level is highly patient specific, comparison with contralateral knee remains of primary importance for a complete evaluation. Despite the invasiveness of the navigation system, Miura et al. [84] and Imbert et al. [42] were the first to perform an in vivo study comparing contralateral uninjured knee to ACL-deficient knee.

Currently, the main clinical assessment evaluating dynamic laxity of the knee is the pivot-shift (PS) test [68]. According to this, interest in navigating such test was increased during the last years. In fact, PS test has been decomposed in many parameters; the most important are related with the translation, rotation and acceleration of the lateral tibial plateau [70].

According to Musahl et al. [94] the navigation system is helpful for the surgeon during the evaluation under anaesthesia, in detecting high-grade laxity in order to customize the ACL reconstruction technique. In the same study it has been also proposed a treatment algorithm based on the type and degree of pathological laxity.

Navigation system and surgical procedures comparison

Several authors have evaluated and compared knee kinematics after different ACL reconstruction procedures using

Table 1 Summary of the manuscripts that use the navigation system for kinematic evaluation in ACL surgery

Studies that have used navigation system for kinematic evaluation in ACL surgery					
First author	Year	Set-up	Number of Knees	Evaluated parameters	Analysed structures/technique
Saiegh et al.	2015	Vitro	14	ATT/PST/IE rot	All
Sena et al.	2015	Vitro	6	ATT/PST/IE rot	Mechanized pivot-shift
Bonanzinga et al.	2015	Vitro	7	ATT/IE rot	PLC
Imbert et al.	2015	Vivo	32	ATT/PST/IE rot/VV	ACL + LT
Christino et al.	2015	Vivo	30	ATT/IE rot	ACL paediatric
Usman et al.	2015	Vivo	14	ATT/IE rot	OTT versus SB
Feng et al.	2014	Vitro	7	IE rot	PLC/PMC/ACL & PCL
Porte et al.	2014	Vivo	20	ATT/PST/IE rot	ASB and contralateral intact knee
Kopf et al.	2014	Vivo	15	ATT/PST/IE rot/VV	DB/PLB
Imbert et al.	2014	Vivo	32	ATT/PST/IE rot/VV	ACL-deficient and intact knees
Monaco et al.	2014	Vivo	20	ATT/PST/IE rot	ACL + LT
Zaffagnini et al.	2014	Vivo	26	ATT/PST/IE rot	ADB versus NADB
Lopomo et al.	2014	Vivo	40	ATT/ACC	Pre-op and post-op status
Komzák et al.	2013	Vitro	30	ATT/IE rot	PLB and AMB
Signorelli et al.	2013	Vivo	100	ATT/PST/IE rot/VV	Pre-op and post-op status
Sena et Al	2013	Vitro	6	ATT/IE rot vel.	ITB versus TT versus AE
Verhelt et al.	2012	N/A	N/A	ATT/IE rot	SB versus DB
Lim et al.	2012	Vitro	7	ATT/IE rot	ASB versus NASB
Nakase et al.	2012	Vivo	50	ATT/IE rot	ACL remnants
Komzák et al.	2012	Vivo	60	ATT/IE rot	ASB and ADB (PL and AM)
Ettinger et al.	2012	Vitro	10	ATT/IE rot	DB
Dawson et al.	2012	Vitro	26	ATT	Pivot versus Lachman test
Lee et al.	2012	Vivo	42	ATT/IE rot	Kin evaluation of tunnel placement
Van der Brachtet al.	2012	Vitro	5	ATT/IE rot	Lateral tibial tunnel in Rev. ACL
Lee et al.	2012	Vivo	42	ATT/IE rot	ASB versus ADB
Ohkawa et al.	2012	Vivo	125	ATT/IE rot	CAS and clinical outcomes
Voos et al.	2011	Vitro	11	ATT/PST	Effect of Tibial Slope
Koga et al.	2011	Vitro	11	ATT/IE rot	Effect of graft angles fixation
Citak et al.	2011	Vitro	6	ATT/IE rot	Valgus force in the PST
Cross et al.	2011	Vitro	12	ATT/PST	AM SB versus CTR SB
Plaweski et al.	2011	Vivo	46	ATT/IE rot/PST	ASB versus ADB
Monaco et al.	2011	Vitro	10	ATT/IE rot	ACL + LT
Maeda et al.	2011	Vivo	83	ATT/IE rot	ACL remnants
Zaffagnini et al.	2011	Vivo	35	ATT/PST/IE rot/VV	ACL + LT versus ADB
Petrigliano et al.	2011	Vitro	10	PST	ACL and menisectomy
Seon et al.	2011	Vivo	62	ATT/IE rot	High versus low femoral tunnel
Musahl et al.	2011	Vitro	5	ATT/PST	ASB versus ADB with meniscal lesion
Plaweski et al.	2011	Vivo	63	ATT/IE rot/PST	ASB versus ADB
Colombet et al.	2011	Vivo	20	ATT/IE rot/PST	ACL + LT
Bedi et al.	2011	Vitro	20	ATT/PST	Effect of tunnel position
Plaweski et al.	2011	Vivo	63	ATT/IE rot/PST	ASB versus ADB
Colombet et al.	2011	Vivo	20	ATT/IE rot/PST	ACL + LT
Bignozzi et al.	2010	Vivo	18	ATT/PST	ADB
Lopomo et al.	2010	Vivo	18	ATT/PST	PST decomposition
Hofbauer et al.	2010	Vivo	55	ATT/IE rot	ASB versus ADB
Musahl et al.	2010	Vitro	16	ATT/PST	ACL and menisectomy
Lombach et al.	2010	Vitro	20	IE rot	PL and AM bundles

Table 1 continued

Studies that have used navigation system for kinematic evaluation in ACL surgery					
First author	Year	Set-up	Number of Knees	Evaluated parameters	Analysed structures/technique
Voos et al.	2010	Vitro	12	ATT/IE rot	High versus low femoral tunnel
Bedi et al.	2010	Vitro	N/A	ATT/PST	PST and lateral tibial translation
Bedi et al.	2010	Vitro	20	ATT/PST	ASB versus ADB
Monaco et al.	2010	Vitro	6	ATT/IE rot	ACL and two restraints PLB AMB ALL
Park et al.	2010	Vivo	70	ATT/IE rot	High versus low femoral tunnel
Yamamoto et al.	2010	Vivo	150	ATT/IE rot/PST	Clinical grading versus Kinematic values
Nakamae et al.	2010	Vivo	30	ATT/IE rot	ACL remnants
Musahl et al.	2010	Vitro	12	ATT	Two SB techniques and DB techniques
Miura et al.	2010	Vivo	10	ATT/IE rot	AMB and PLB versus contralateral intact knee
Seon et al.	2009	Vivo	40	ATT/IE rot	ASB versus ADB
Pearl et al.	2009	N/A	N/A	ATT/PST	PST in ACL-deficient knee
Lopomo et al.	2009	Vivo	60	ATT	CAS reliability
Monaco et al.	2009	Vivo	30	ATT	Validation KT 1000
Kanaya et al.	2009	Vivo	26	ATT/IE rot	Oblique ASB versus ADB
Brophy et al.	2009	Vitro	5	ATT/IE rot	Oblique versus central SB
Song et al.	2009	Vivo	85	ATT/IE rot	Stable versus unstable ACL knee
Musahl et al.	2009	Vitro	12	ATT/IE rot	Mechanized pivot-shift
HO et al.	2009	Vitro	16	ATT/IE rot	ASB versus ADB
Song et al.	2009	Vivo	40	ATT/IE rot	ASB versus ADB
Ferreti et al.	2009	Vivo	10	ATT/IE rot	ADB (PL and AM bundle)
Ishibashi et al.	2009	Vivo	90	PST	PST and DB
Steiner et al.	2009	Vitro	20	ATT/IE rot	Independent versus trans-tibial tunnel
Jenny et al.	2009	Vitro	N/A	ATT	CAS versus STRESS RX
Zaffagnini et al.	2008	Vitro	6	ATT/IE rot	Effect of tunnel position
Lane et al.	2008	Vivo	12	ATT/IE rot/ACC/p angle	In vivo analysis of PST
Ishibashi et al.	2008	N/A	N/A	N/A	SB versus DB
Brophy et al.	2008	Vitro	5	ATT/IE rot	Intact ACL versus SB reconstruction
Ishibashi et al.	2008	Vivo	80	N/A	ASB versus ADB
Martelli et al.	2007	Vivo	80	ATT/IE rot/VV	CAS for kinematic assessment
Robinson et al.	2007	Vivo	21	ATT/PST	PL and AM bundles
Steckel et al.	2007	Vitro	5	ATT/IE rot	Intact ACL versus SB/DB reconstruction
Ferreti et al.	2007	Vivo	20	ATT/IE rot	SB versus DB
Monaco et al.	2007	Vivo	20	ATT/IE rot	ACL + LT versus ADB
Martelli et al.	2007	Vivo	79	ATT/IE rot/VV	CAS for kinematic assessment
Kendoff et al.	2007	Vitro	N/A	ATT/IE rot	CAS versus KT1000 and goniometer
Colombet et al.	2007	Vitro	4	ATT/IE rot	Unstable, AMB and PLB
Martelli et al.	2005	Vitro	3	ATT/IE rot/VV	New protocol for kinematic assessment
Ishibashi et al.	2005	Vivo	32	ATT/IE rot	ADB (PLB and AMB)

For each manuscript it has been reported: name of the first author, year of publication, set-up (in vivo/in vitro), number of knees included, evaluated parameters and the analysed structures/technique

CAS computer-assisted surgery, *ATT* aterior tibial translation, *ACL* anterior cruciate ligament, *PCL* posterior cruciate ligament, *IE rot* internal/external rotation, *SB* single bundle, *ASB* anatomical single bundle, *VV* varus/valgus, *DB* double bundle, *ADB* anatomical double bundle, *ACC* acceleration, *ALL* antero-lateral ligament, *LT* lateral tenodesis, *PST* pivot-shift test, *AMB* antero-medial bundle, *PLB* postero-lateral bundle, *PLC* postero-lateral corner, *PMC* postero-medial corner, *N/A* non available information, *AE* all epiphyseal, *ITB* Ileotibial band, *TT* trans-tibial

the navigation systems for quantitative evaluation. Most of the studies compared the stabilizing effect of double-bundle (DB) ACL with the single-bundle (SB) ACL reconstruction. Several articles have compared two ACL reconstruction techniques under the kinematic point of view [9, 32, 43, 45, 50, 54, 84, 96, 112, 129, 137, 148].

Generally, the most evaluated parameters were the anterior tibial translation (ATT) and the internal external rotation (IE rot) at different degrees of flexion. Others studies also have used the PS test and the varus/valgus (VV) laxity assessment. Considering the ATT, most of the studies do not show significant differences in controlling the drawer and Lachman tests when comparing SB vs DB technique. However, the double-bundle technique seems more effective in controlling both IE rotation and the PS test [9, 26].

To add more rotational control to the SB technique, navigation system has been used to assess different tunnel positions during reconstructive surgery as well as the impact on the post-operative laxity. Studies have shown that a more oblique intra-articular configuration by a lower femoral tunnel can decrease rotatory instability [11, 104, 128] but has inferior control on rotation when compared to the DB technique.

The effect of the addition of a lateral tenodesis (LT) to the SB ACL surgery has also been studied. Many authors, in an in vivo set-up, have measured translation and rotation at different times: before ligament reconstruction, between the fixation of the intra-articular graft and the LT, and finally after the surgery was completed. These studies have shown that, analogously to SB reconstruction, the SB + LT technique allows a good ATT control showing also great rotatory control [23, 41, 88].

Monaco et al. [86] and Zaffagnini et al. [158] in two different studies compared a SB plus extra-articular tenodesis to a DB reconstruction.

They both found a better control on internal rotation at 90° of knee flexion with the SB plus extra-articular tenodesis, while Zaffagnini et al. underlined superior results also for external rotation at 90° of knee flexion.

Navigation system performance, clinical outcomes and cost-effectiveness

Concerning the technical performance of the navigation systems in 1997, Pearle et al. [107] studied the reliability and precision of navigation systems by comparing an image-free navigation system to robotic/UFS testing system in an in vitro set-up for the first time. He demonstrated an accuracy of ±0.1 mm for linear measurements and ±0.1° for angular measurements.

Among the selected papers, there are also some evaluations concerning the economical aspects of the use of navigation systems. In the aforementioned manuscripts, it has been shown how the navigation system can improve tunnel positioning and how it helps to control both preoperative laxity deficiency and postoperative outcomes. Such considerations enhance clinical outcomes and decrease the failure rate of ACL reconstruction.

However, there are also manuscripts that do not indicate any improvement in clinical outcome when using navigation systems [15, 29, 116, 123]. Recently, Margier et al. [77] in a prospective multicentre open controlled study evaluated 214 patients who underwent ACL reconstruction surgery with and without computer assistance. They found that ACL reconstruction using a computer-assisted navigation system is more expensive than conventional surgery, it adds extra time to the surgery and it is not mitigated by better clinical outcomes. However, the major limitations for this study are small sample size and short-term follow-up (2 years). In fact, the principal goal in ACL surgery is the long-term stability and prevention of osteoarthritis. It is known that a more anatomical placement of the tunnels and a correct diagnose of additional lesions may show some benefits of its use at a longer follow-up [36]. Despite these advantages, comparative studies of ACL reconstruction with and without navigation systems have shown that the clinical outcomes at short-term follow-up are similar. This combined with costs and invasiveness has limited the use of the navigation system to research-related cases.

The most important findings of the performed analysis are that navigation system during ACL reconstruction offers a wide range of applications. Anyway the common final goal, which is also the greatest challenge, is the accurate tracking of the knee kinematics in order to benefit the surgical strategy. This, inevitably, involves technical consideration about the required technology. In fact, the navigation system still remains an invasive device adding potential risks to the surgery and limiting the possibility to perform contralateral limb evaluation or follow-up examination.

The fact that the majority of the laxity evaluations were performed in in vivo condition could be correlated to the fat that the navigation systems, more than others CAS devices, were specifically developed for surgery preferring an easy-to-use set-up and ensuring more realistic studies.

Navigation system has proven to be highly precise and reliable for tunnel positioning and for quantifying knee laxity during ACL reconstructive surgery.

The introduction of the navigation system made possible the evaluation of the specific patient laxity at time zero after surgery making available to the surgeon a series of information which support the optimization of both the customization of the procedures and also consideration about different surgical strategies and their outcomes.

Currently, navigation system is considered the gold standard for laxity quantification and validation of new non-invasive devices for clinical practice. Additionally, navigation is useful for the measurement of knee laxity and kinematics of pre- and post-operative surgery, thus allowing a precise comparison of different techniques.

Conclusions

What the present historical review has highlighted is that there is a wide range of applications for the navigation system in the field of ACL reconstructive surgery and its interest during the years is increasing for both clinical and experimental studies.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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