

Relationship between femoroacetabular contact areas and hip position in the normal joint: an in vitro evaluation

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Abstract

Purpose Different approaches have been proposed to diagnose femoroacetabular impingement (FAI) condition and hip instability. It is still debatable which test is the most effective to make a correct diagnosis. The true mechanics of the hip during particular physical examination manoeuvres is unknown.

Methods Eight fresh frozen hips were passively taken through 3 different commonly used positions for FAI diagnosis and hip instability: *90° Flexion-Adduction-Internal Rotation*, *Hyperextension-Adduction-External Rotation* and *Hyperextension-Neutral-External Rotation*. Kinematics and anatomical data were acquired by an optoelectronic system. The contact areas between acetabulum and femoral head were analysed to determine whether these tests are able to localize regions of the hip that may give patients pain.

Results In the hip positions where the femur was in *Hyperextension-External Rotation*, the contact area was

mainly concentrated in the posterosuperior area of the acetabulum, while during *90° Flexion-Adduction-Internal Rotation* position, there was a wider distribution of contact, not specific to the anterolateral acetabulum.

Conclusions The results confirm the ability of the *Hyperextension-External Rotation* tests to particularly analyse the posterior region of the acetabulum. Placing the hip in *90° of Flexion-Adduction-Internal Rotation* allows for testing a wider zone of the acetabulum and is not specific to abutment of the femoral head-neck region against the anterolateral acetabulum.

Keywords Hip · Instability · FAI · Contact areas · Physical examination

Introduction

Contact areas and femoral orientation in hip joint have been mostly correlated in the prospective to analyse joint impact fractures [14, 28] or load distribution during the gait cycle [15, 18]. Also during the clinical diagnosis, for hip joint pathologies, the approach of using different hip positions and the analysis of the contact areas could be helpful to identify a correlation between femoroacetabular impingement and hip joint instability.

Femoroacetabular impingement (FAI) is a condition that involves abnormal contact between proximal femur and acetabular rim [8, 10, 22, 27, 29]. The abnormal abutment between femoral head and acetabulum may result in damage to the hip joint, particularly the articular cartilage and/or the acetabular labrum [2, 12, 31].

The diagnosis of FAI and hip instability can be difficult. Further, the location of intra-articular pathology is elusive, and thus, analysing the exact biomechanics of the physical

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examination may be helpful in understanding the physical examination manoeuvres. To overcome this issue, different approaches have been proposed: computer simulation, imaging and physical examination [3, 7, 13, 16, 24, 25, 28, 30, 32].

Hip instability can be defined as the extra physiologic motion of the hip joint [9, 26], particularly symptomatic excessive motion of the femoral head relative to the acetabulum. It can have a traumatic (e.g. acetabular posterior wall fracture) or atraumatic (e.g. connective tissue disorders) aetiology. Repetitive microtrauma, such as seen in athletics, may result in capsuloligamentous laxity, potentially producing hip instability [5].

Similar to FAI, the diagnosis can be difficult to make and is based on physical examination as well as on imaging techniques (e.g. CT, MRI and MRI arthrography) [4, 6, 17, 21].

After the history, physical examination is the next step to help assess the hip joint for aetiology of groin pain. Unfortunately, scientific evidence confirms the difficulty in the physical examination in detecting the cause of hip pain [19, 20]. Moreover, in the literature there are not unambiguous and exhaustive results to define the most effective test for a complete hip diagnosis [19, 20]. Physical examination consists in testing hip range of motion in supine and prone position for both hips and comparing the two sides. Wyss et al. in 2007 [32] confirmed that, in the presence of impingement, there is a limitation of the internal rotation, and this lack of internal rotation may be more pronounced with the hip flexed at 90°. Further, the pain generated when the hip is flexed to 90°, adducted and internally rotated, is considered a sign of impingement [23]. Moreover, Audenaert et al. [1] affirmed that motions requiring high flexion in combination with adduction and/or internal rotation are most frequently affected among symptomatic patients. It is clear how the impingement test is based on this finding. Additionally, in order to detect posterior impingement or anterior instability of the hip, the most commonly performed clinical tests place the hip in hyperextension with external rotation and sometimes with adduction. This comes from the fact that moving the hip to extension and external rotation can cause anterior subluxation or dislocation leading atraumatic hip instability [9, 26].

The hypothesis of this work was that specific clinical examination is able to highlight FAI condition and hip instability. The goal of this study was therefore to correlate some commonly performed physical examination manoeuvres to the location of contact areas between acetabulum and femoral head in order to ascertain whether these clinical tests are able to effectively emphasize the presence of FAI or hip instability [21, 26].

Materials and methods

Eight fresh frozen hips from four cadavers were tested. The cadavers were those of 1 woman and 3 men, with a mean age of 72 years (SD, 21 years) at the time of death. All the hips were screened by MRI to evaluate for evidence of any previous surgery, soft tissue pathology and arthritis—as these were exclusionary criteria. It was possible to ascertain the absence of FAI in all the evaluated hips.

The femurs were transected at the level of the knee joint to eliminate the mechanical influence of knee position on biarticular muscles. After thawing the hemicorpses for 24 h at room temperature, the specimens, positioned in supine and neutral alignment, were securely fixed to a wooden base by means of eight Steinmann pins, after which the wooden base was fastened at the end of a sturdy table to stabilize the pelvis without affecting the motion of the hips and femurs.

The hips were passively taken through the 3 different positions, hereinafter described, to study hip kinematic behaviour. The hips were manually loaded. Each test was repeated 3 consecutive times to confirm test–retest repeatability. Left and right hips were alternatively analysed for each specimen before changing the set-up. This kinematics test was performed with all the soft tissues about the hip intact.

Hip position was controlled by a navigation system. This latter is normally used for intra-operative kinematic assessment (BluIGS/KLEE, Orthokey Ltd, Delaware, DE, USA), and it also allowed for the acquisition of the anatomical data.

In order to track the relative motion between the femur and the pelvis, a tracker equipped with passive optical markers was mounted on the iliac crest (on the same side of the evaluated hip), and a corresponding tracker was fixed on the femoral diaphysis, about 100 mm distal to the lesser trochanter toward the anterolateral femur. With a tracked probe, we acquired also the anatomical structures required for the reconstruction of the anatomical surface, specifically the external acetabular surface, the internal femoral head surface and the acetabular labrum (used to define the acetabular plane). Correct kinematic analysis (limb anatomical position and orientation) was possible due the acquisition of additional anatomical landmarks, specifically bilateral anterior superior iliac spines (left and right ASIS–LASIS and RASIS), bilateral pubic tubercles for the pelvis (left and right pubic tubercles—LT and RT) and medial and lateral epicondyles of the femur (ME and LE). During real-time kinematics, the femoral head centre was functionally identified by a pivoting motion. The 3D root mean square (RMS) volumetric accuracy of the navigation system in the localization of a single passive marker is equal

to 0.35 mm [11]. According to this latter value and choosing for a more conservative estimate, our results were rounded to the first decimal place.

A 3D simplified model for each specimen was used to evaluate the contact areas between the femoral head and acetabulum, approximating the articular surfaces with different spheres. The algorithm used for the spherical approximation is a recursive method that optimizes step-by-step the parameters of the sphere equation, giving as outputs the centre and the radius of the sphere that best reproduces the anatomical surface. Additionally, we corrected the obtained radii keeping into account the dimension of probe tip (1 mm).

The error introduced with the spherical approximation was estimated as the distances between the approximated and the anatomical surfaces and was evaluated as:

$$E = \frac{\sum (D_{pc_i} - R)}{N}$$

where E is residual error expressed in mm, D_{pc_i} distance of the acquired i -point from the centre of the generated sphere, R radius of the generated sphere and N is the total number of the evaluated points for each sphere.

Moreover, the distance between the acetabulum and the femur was defined as the difference between the radius of the sphere that best approximates the femoral head (R_F)

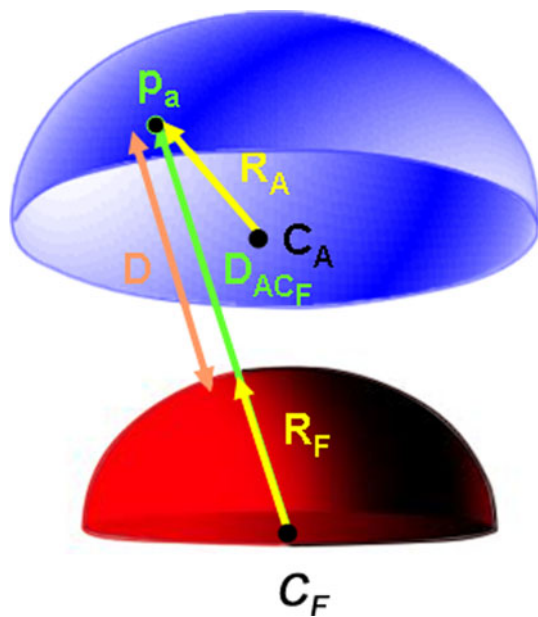


Fig. 1 Graphic representation of the model applied for calculating the distance between the acetabular and femoral head surface. R_A and R_F correspond to the acetabular and femoral radius, respectively (algorithm outputs). Analogously, C_A and C_F are the centre of the two spheres (algorithm outputs). D_{ACF} is the distance between C_F and a generic point (p_a) belonging to the acetabular surface. D is the distance between the acetabular and the femoral head surface calculated as the absolute difference $|D_{ACF} - R_F|$

and the distance of each point of the spherical acetabular surface from the centre of the femoral head (D_{ACF}). Figures 1 and 2 schematically demonstrate the method used for the calculation of the distance between femur and acetabulum.

To verify the presence of hip instability and femoro-acetabular impingement, the movements that are commonly used in the clinical practice have been analysed [1, 20, 26]; specifically, we tested the following:

- 90° Flexion-Adduction-Internal Rotation;
- Hyperextension-Adduction-External Rotation;
- Hyperextension-Neutral Abduction/Adduction-External Rotation.

Specifically, a painful feeling, particularly in the buttock region, during the last two tests may indicate the presence of posterior impingement, while anterior discomfort or apprehension often represents a positive finding of joint instability [26]. For the ease of description of contact area location, the acetabulum is represented like a clock-face (Fig. 3). The portrayal defines the 12 o'clock position as lateral or superior and is opposite the centre of the transverse acetabular ligament (12 o'clock = lateral or superior; transverse acetabular ligament = 6 o'clock), while 3 o'clock represents the most anterior point of the acetabulum (for both left and right side hips) and posterior is 9 o'clock.

Moreover, in order to give a quantitative evaluation of the contact areas and how often they occur in the tested hips, we calculated the frequency of contact. The frequency is defined as the rate of hips that show a contact area in the considered acetabular region, calculated over the total amount of the tested hips (i.e. if there are 8 hips and 4 of them are at the contact between acetabulum and femur, the frequency is equal to 50 % for that acetabular region).

Statistical analysis

In order to verify the test–retest repeatability of the performed motions, we analysed the patterns of the obtained clinical angles, evaluating interclass correlation coefficient (ICC) between the three repetitions. All the data were analysed using unique MATLAB (Mathworks Inc, Natick, MA, USA) function designed and implemented specifically for this study.

Results

The main radius calculated for the femur was 24.7 mm (SD, 1.6 mm), while for the acetabulum it measured 26.7 mm (SD, 2.1 mm). The main differences calculated between left and right sides, for the femur and acetabulum,

Fig. 2 Flow chart for the computation of the distance between acetabular surface and femoral head surface

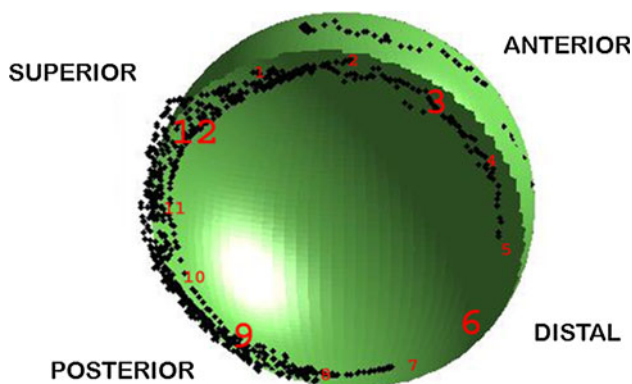
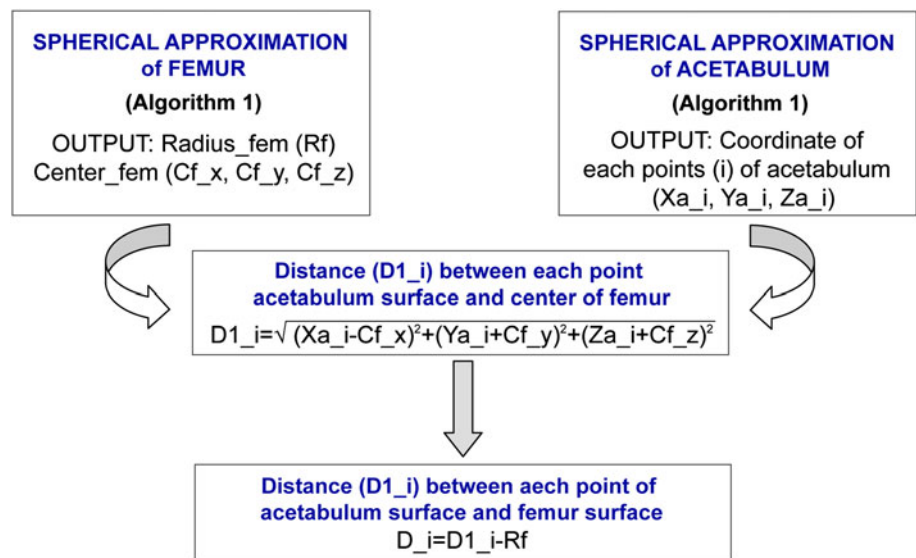


Fig. 3 Clock-face representation of the acetabulum. The green sphere represents a generic acetabular surface, while the black points reproduce an acetabular labrum surface. The numbers define the clock-scheme of the acetabulum. As shown by the figure, 6 o'clock corresponds to the incision of the transverse acetabular ligament

were 0.3 mm (SD, 0.2 mm) and 0.8 m (SD, 0.5 mm), respectively. The error as a result of the spherical approximation was 1.4 mm (SD, 0.2 mm) for the acetabulum and 0.6 mm (SD, 0.2 mm) for the femoral head.

Table 1 reports the ICC calculated between the three repetitions of the tests analysed.

Figure 4a–c show up the frequency (and its location) of the contact areas between acetabulum and femur for all the tested hip positions. In order to discern between systemic contact areas (attributable to the movement) and contact areas attributable to change events, the frequency threshold was set to a high value of percentage over the total amount of the hips. We choose to fix it at the 70 % of the total.

Figure 4a reports the condition where the hip is hold in Hyperextension-Adduction-External Rotation. Considering the clock-face scheme of the acetabulum, we found a contact area mainly confined between 8 and 12 o'clock that

corresponds to the posterosuperior area of the acetabulum. While in the anterior acetabular region (2–4 o'clock), no hips showed contact areas in this configuration. An analogous condition was found during the Hyperextension-Neutral-External Rotation test (Fig. 4b). During this latter test, we found a slightly more extended contact area than the previous one. In fact, the frequency of contact exceeded the threshold value (70 %) at 8–11 o'clock, while between 2 and 6 o'clock there was no contact. Figure 4c reports the results achieved during the 90° Flexion-Adduction-Internal Rotation test. An almost uniform dislocation of the contact areas over the whole clock-scheme was identified. Furthermore, at this location there are no higher-than-threshold and null frequency values.

Table 2 summarizes the regions of the acetabulum (using the clock-face representation system) that demonstrated the area with the highest frequency of contact.

Discussion

The most important finding of the present study was the exact localization of the contact areas during diagnostic movements normally used in the clinical practice.

The hypothesis of this study was that specific hip positions are able to highlight FAI condition and hip instability. The aim of this study was therefore to correlate the location of femoroacetabular contact areas and hip positions. This

Table 1 Mean ICC value for clinical angles, among three repetitions of the movements for all the specimens

90Flex-Add-IntRot	HypExt-Add-ExtRot	HypExt-Neu-ExtRot
0.7	0.8	0.8

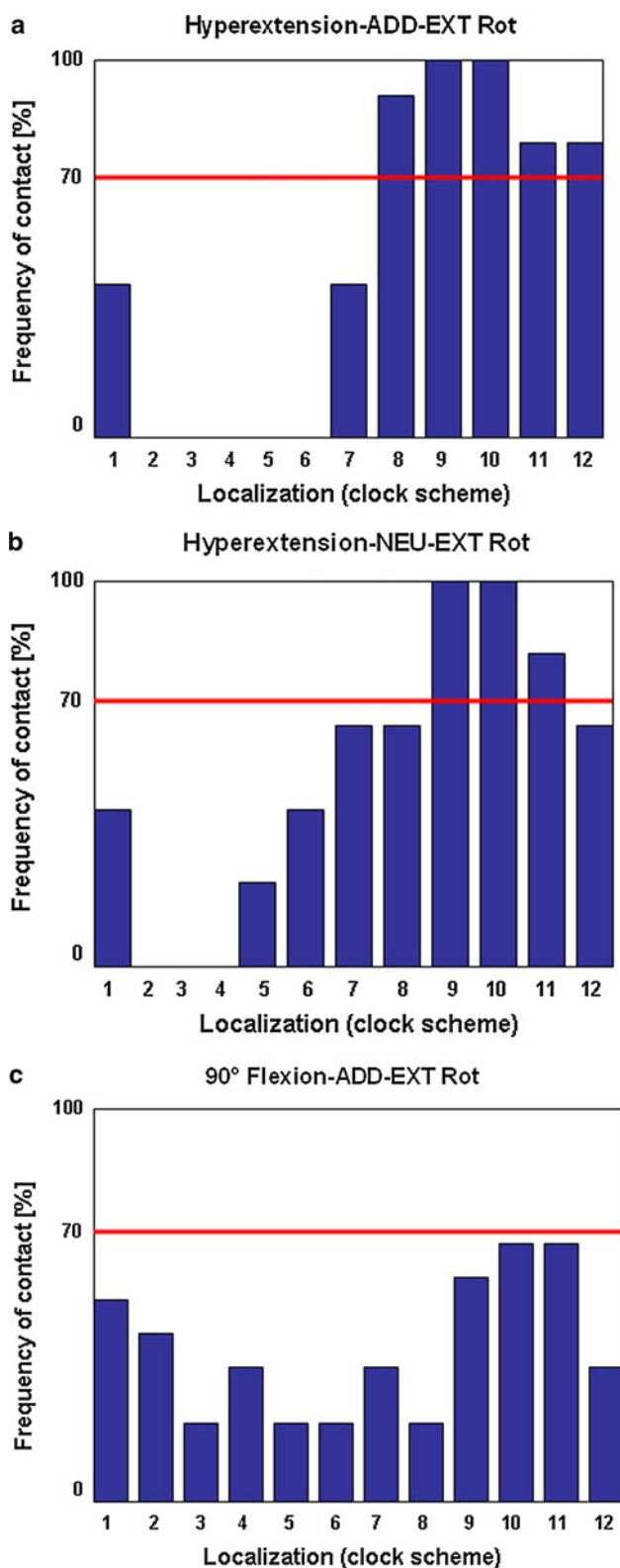


Fig. 4 **a** Contact areas during Hyperextension-Adduction-External Rotation test. **b** Contact areas during Hyperextension-Neutral Abduction-Adduction, and external rotation test. **c** Distribution of contact areas for all the evaluated hips during 90° of hip flexion with adduction and internal rotation

Table 2 Distribution of contact areas in the three different hip positions analysed

90Flex-Add-IntRot	HypExt-Add-ExtRot	HypExt-Neu-ExtRot
No frequency over 70 %	8–12	9–11

was done taking the hip through those tests considered *posterior impingement* and *instability* tests, while a navigation system was recording kinematics as well as anatomical data for our analysis.

To the best of our knowledge, this is the first study to localize the dislocation of the hip joint contact areas in a controlled configuration with specific physical examination manoeuvres.

The overall results of this study confirm the thinking associated with the examination in relation to clinical practice. In fact, especially concerning the first two clinical tests, we obtained a femoroacetabular contact area mostly localized in the posterior region of the acetabulum, as we originally hypothesized. In particular, this study demonstrates that the Hyperextension-External Rotation clinical tests (with and without adduction) do stress the posterior acetabulum. Thus, this manoeuvre can help detect an anatomical lesion localized primarily in the posterior region of the acetabulum. This study found the highest frequency of contact between acetabulum and femur in the posterior regions of the acetabulum, suggesting that it is this region that is most stressed by hyperextension positioning of the hip with external rotation.

On the other hand, the relative infrequency of contact with the anterior region of the acetabulum in the hyperextension position seems to call into question as to whether this position is appropriate to evaluate for anterior hip instability. Moreover, the large distribution of contact areas during the hip impingement test position, “90° Flexion-Adduction-Internal Rotation”, being throughout the acetabulum, suggests that this test is not specific to anterolateral impingement or assessment of anterolateral pathology in the hip. Of course, these specimens did not have FAI anatomy, and thus, the results may differ in subjects or specimens with FAI.

Thus, the hypothesis that the *Hyperextension* and *External Rotation* positions are specific to the diagnosis of posterior acetabular impingement does hold true. But, placing the hip in 90° of flexion, adduction and internal rotation, a wider zone of the acetabulum is stressed and thus tested and is not specific to anterolateral or lateral pathology. Hence, it may be sensitive to intra-articular pathology, but not specific to location of damage.

This study does have some limitations. First is use of cadaveric specimens, which, by necessity, lacks muscular

forces, and thus joint reactional forces, which likely influence these results. However, these examination manoeuvres are done with the patient supine and relaxed and the examiner moving the hip, so the internally generated forces by the patient normally do not exist. It is just the resting tone that is missing, and the effect of that is unknown. Secondly, there are only a limited number of specimens that were measured while passively taking in different position. Lastly, there was no objective measure of load control. However, the high degree of repeatability noted on the test–retest suggests that this lack of objective force measurement did not significantly affect our results.

However, with all these limitations, we can conclude that this study provides the greatest detail to date about the areas of contact during particular physical examination manoeuvres of the hip joint.

Based on the data presented, the Hyperextension-External Rotation tests (with or without adduction) are more specific to posterior acetabular pathology. The impingement test, with the hip in 90° of flexion, adduction and internal rotation, is not specific to anterolateral pathology, but has a wide distribution of contact area of the acetabulum.

The study confirms the validity of a novel method to obtain objective information about hip kinematics in the in vitro setting.

The information obtained from this study could also be applied under in vivo conditions. Replacing the acquisition of the anatomical surface with clinical images (i.e. MRI) may allow for the quantification of the predisposition to or the presence of FAI.

Further, mapping the entire acetabulum may be useful in the clinical situation. By matching each single movement to its area of contact, it may be possible to determine the most appropriate test to evaluate a specific condition and possibly to predict treatment. In fact, knowing which portion of the acetabulum is subjected to the most stress during a specific manoeuvre may help to predict more precisely the specific location of damage.

From the clinical point of view, this study may allow for better understanding the applicability of the analysed physical examination manoeuvres in assessing hip instability and FAI conditions, as well.

Conclusion

This work is the first study that provides comprehensive contact areas data analysing the whole acetabular surface and femoral head, as well. We have seen that holding the hip in *Hyperextension* and *External Rotation*, the main contact was at the posterior acetabulum. This makes that tests suitable for a posterior impingement evaluation. While detecting a more uniform contact areas dislocation

during the “90° Flexion-Adduction-Internal Rotation”, we took into discussion its ability to test an anterolateral (or lateral) pathology and this comes in contrast to what it was supposed to do.

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