Assessment of Congruence and Impingement of the Hip Joint in Professional Ballet Dancers

A Motion Capture Study

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Background: Early hip osteoarthritis in dancers could be explained by femoroacetabular impingements. However, there is a lack of validated non-invasive methods and dynamic studies to ascertain impingement during motion. Moreover, it is unknown whether the femoral head and acetabulum are congruent in typical dancing positions.

Hypothesis: The practice of some dancing movements could cause a loss of hip joint congruence and recurrent impingements, which could lead to early osteoarthritis.

Study Design: Descriptive Laboratory Study.

Methods: 11 pairs of female dancer's hips were motion captured with an optical tracking system while performing 6 different dancing movements. The resulting computed motions were applied to patient-specific hip joint 3D models based upon MR images. While visualizing the dancer's hip in motion, impingements were detected and located using computer-assisted techniques. The range of motion and congruence of the hip joint were also quantified in those 6 recorded dancing movements.

Results: The frequency of impingement and subluxation varied with the type of movement. Four dancing movements (développé à la seconde, grand écart facial, grand écart latéral and grand plié) seem to induce significant stress in the hip joint, according to the observed high frequency of impingement and amount of subluxation. The femoroacetabular translations were high (range: 0.93 - 6.35 mm). For almost all movements, the computed zones of impingement were mainly located in the superior or posterosuperior quadrant of the acetabulum, and this was relevant with respect to radiologically diagnosed damaged zones in the labrum. All dancers' hips were morphologically normal.

Conclusion: Impingements and subluxations are frequently observed in typical ballet movements, causing cartilage hyper compression. These movements should be hence limited in frequency.

Clinical Relevance: The present study indicates that some dancing movements could be damageable for the hip joint, which could lead to early osteoarthritis.

Keywords: motion capture; early hip osteoarthritis; impingements; dancing

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Professional ballet dancers are subject to develop hip osteoarthritis (OA) due to repetitive and extreme movements performed during their daily dancing activities.[3,12,19,20] In the nondysplastic hip, early OA could be explained by femoroacetabular impingements (FAI) which occur when there is an abutment conflict between the proximal femur and the acetabular rim. Two types of FAI have been distinguished: the cam FAI caused by a non-spherical head at the femoral head-neck junction[2,14,16,17,24,30] and the pincer FAI due to acetabular overcoverage[2,9,16,17,24,30] or acetabular retroversion.[25] FAI induces early chondrolabral damages typically described as located in the anterosuperior quadrant of the acetabulum.[1,2,28,30]

FAI of the cam/ pincer type cannot explain observed OA in hips with normal morphology. However, repetitive microtrauma is believed to be one of the causes of the development of early OA in the young active adult.[20,22] Indeed, sporting activities that require repetitive external rotation[3,8,12,20,21,22] or hyperabduction[12,26] such as ballet, have been thought to result in labral tears. Nevertheless, the arthrogenous movements (i.e., the movements that could lead to OA) have not yet been clearly identified. It is also unclear whether the femoral head and acetabulum are congruent in extreme positions (e.g., split position). Lack of joint congruency could be another potential cause of early OA.

According to Tannast et al[30] and to the FAI theory, hip damage occurs at the zone of femoroacetabular impingement. However, the concurrence of the actual impingement zone and resulting joint damage in the same patient has not yet been confirmed. Moreover, there is a lack of validated non-invasive methods to ascertain impingement during motion. Existing imaging methods only include a static interpretation of the joint damage (e.g., computed tomography (CT)[1], magnetic resonance imaging (MRI)[18]), while dynamic imaging protocols are affected by technical limitations (e.g., trade-off between acquisition speed and image quality, confined area of measurement). Thus, a dynamic study of the hip joint in extreme positions, such as the ones regularly assumed by the dancers, has never been performed.

Our hypothesis was that the practice of some dancing movements could expose the dancer's hip to a loss of joint congruence and to recurrent impingements, which could lead to early OA. In this paper, we present the results of a descriptive study conducted with female professional ballet dancers. The purpose of this research is to visualize and simulate in 3D extreme ranges of motion of the hip and to detect and locate potential FAI, using optical motion capture and computer-assisted techniques. Moreover, this study aims at quantifying in-vivo the range of motion (ROM) and congruence of the hip joint in typical dancing positions.

MATERIALS AND METHODS

Motion capture of the hip joint was carried out on 11 female dancers (22 hips) aged between 18 and 38 years (mean, 25.36 years). The volunteers were either advanced students at higher schools of dance or professional dancers. They all performed classical ballet and contemporary dance. They had all been dancing for more than 10 years and practiced for more than 12 hours per week. The study was approved by the local ethics committees and the volunteers gave written informed consent. The exclusion criterion was a history of hip surgery or injury.

MR Imaging and 3D Reconstruction

Before motion capturing, each dancer was MRI scanned with a 1.5-T system (Avanto; Siemens Medical Solutions, Erlangen, Germany). The images were acquired in the supine position.

Two musculoskeletal radiologists performed a consensus reading. For each subject, acetabular cartilage lesions and labral lesions were assessed and documented, including locations and extents. The presence of subchondral acetabular or femoral bony abnormalities (e.g., cysts) and the presence of a herniation pit (a round cystic lesion at the anterior aspect of the femoral neck) were also reported. The normality of both the femoral head and the acetabulum was measured according to radiographic criteria: femoral alpha neck angle[23], acetabular depth[24] and acetabular version.[25]

Using the MR images, a virtual 3D model of the hip joint was reconstructed thanks to a validated segmentation software.[11,27] Thus, for each dancer, patient-specific 3D models of the pelvis, femur, including cartilage surfaces and labrum were obtained. The average (standard deviation) accuracy of this recontruction was 1.25 mm (1 mm).[11,27]

Motion Capture

The motion of the 11 dancers were optically captured within a 45.3 m^3 measurement volume (3.6 x 4.2 x 3 m) using 8 infrared cameras (Vicon MX 13i, Oxford Metrics, UK), sampling at 120 Hz. The volunteers were equipped with two clusters of six 7 mm spherical markers affixed onto the lateral and frontal parts of both thighs. Six markers were also stuck on pelvic anatomical landmarks (e.g., anterior superior iliac spines). The skin markers were arranged to ensure their visibility to the cameras throughout the range of motion. Additional reflective markers were distributed over the body to confer a more complete visualization from general to detailed.

Data from the subjects were acquired during 6 dancing movements (Figure 1): arabesque, développé devant, développé à la seconde, grand écart facial, grand écart latéral and grand plié. These movements were chosen, because they combined extreme hip flexion and/ or abduction with rotation. Moreover, they seemed to create significant stress in the hip joint, according to the dancers' experience.

Figure 1. Recorded dancing movements: A) Left arabesque B) Left développé devant C) Left développé à la seconde D) Grand écart facial E) Right grand écart latéral F) Grand plié.

The hip joint kinematics was computed from the recorded surface markers' trajectories. The major drawback with optical motion capture systems is the soft tissue deformation due to muscle contractions, causing parasitic marker movements with respect to the underlying bones (e.g., 20 mm for a marker stuck on the thigh[4]). Thus, rigid motion of the innominate bone and femur cannot be robustly estimated. To solve this issue, we used a previously developed and validated optimized fitting algorithm which accounted for skin motion artifacts and anatomical constraints.[5,6,7] Its accuracy was 0.4, 0.59, 0.24 mm for medio-lateral, anteroposterior and proximo-distal translations, and 0.55°, 2.86°, 1.71° for flexion/ extension, abduction/ adduction and internal/ external rotation, respectively. From these results, the soft tissue artifacts were hence successfully minimized by the use of this algorithm.

The resulting computed motions were applied to the dancer's hip joint 3D models reconstructed from MRI data. Figure 2 shows examples of computed dancing postures. A ball and stick representation of the overall skeleton was also added to improve the analysis and visualization of the motion.

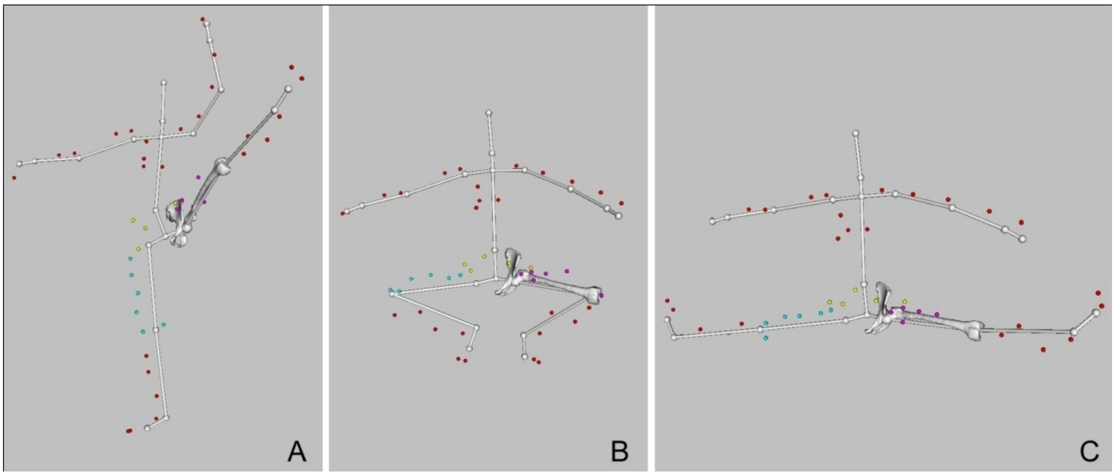

Figure 2. Examples of computed dancing postures (here the left hip), showing the markers setup (small colored spheres) and the virtual skeleton: A) Left développé à la seconde B) Grand plié C) Grand écart facial.

ROM and Joint Congruency Computation

The ROM and congruency of the hip joint were quantified for each dancer and for the 6 recorded dancing movements. This was calculated using the dancer's bony 3D models and two coordinate systems (one for the femur and one for the pelvis). We used the definitions proposed by the Standardization and Terminology Committee of the International Society of Biomechanics[32] to report joint motion in an intra- and inter-subject repeatable way. The local axis system in each articulating bone was first generated. This was achieved by setting a geometric rule that constructed the pelvic and femoral coordinate systems using selected anatomical landmarks defined on the reconstructed surface of the innominate and femur bones. These axes then standardized the joint coordinate system (Figure 3A). In the neutral position and orientation, the pelvic and femoral frames were aligned. Thus, given the computed bone positions from the motion capture data, the relative orientation between the innominate bone and femur was determined at each point of the movement by computing the relative orientation of the femoral frame to the pelvic frame (Figure 3B). This was finally expressed in clinically recognizable terms (flex/ ext, abd/ add and IR/ ER) by decomposing the relative orientation into three successive rotations. It is important to note that the measurements were performed independently of the major anatomical planes (i.e., sagittal, transverse, frontal planes).

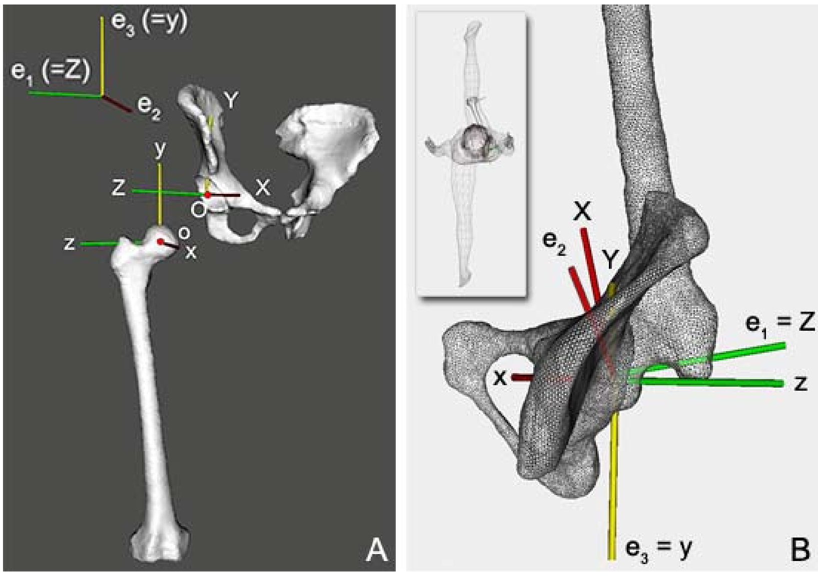

Figure 3. A) The pelvic coordinate system (*XYZ*), the femoral coordinate system (*xyz*), and the joint coordinate system (*e1e2e3*) for the right hip joint. Flexion/ extension is about the pelvic body fixed axis (*e1*). Internal/ external rotation is about the femoral body fixed axis (*e3*) and abduction/ adduction is about the floating axis (*e2*). B) Representation of the relative orientation between the innominate bone and femur using the pelvic and femoral coordinate systems, while the subject is performing, e.g., a grand écart latéral (top view).

The relative position between the innominate bone and femur was described by making reference to a vector ($\mathbf{D_{HJC}}$) joining a point defined in each of the pelvic and the femoral frames. This vector provided numerical information about the congruency of the joint, where non-null value for this vector denoted a subluxation representing a loss of joint congruence, as demonstrated in Figure 4. For the sake of the already-mentioned repeatability issue, these reference points were chosen so as to coincide with the origins of the two frames, namely the hip joint center (HJC). To determine its position, a functional method[10] was used. This entailed the simulation of hip joint 3D models during a circumduction motion pattern, while enforcing a constant inter-articular distance corresponding to the reference distance in the neutral posture. For this simulated motion (involving rotations and translations), the HJC was estimated as the least moving femoral point in the pelvic frame.

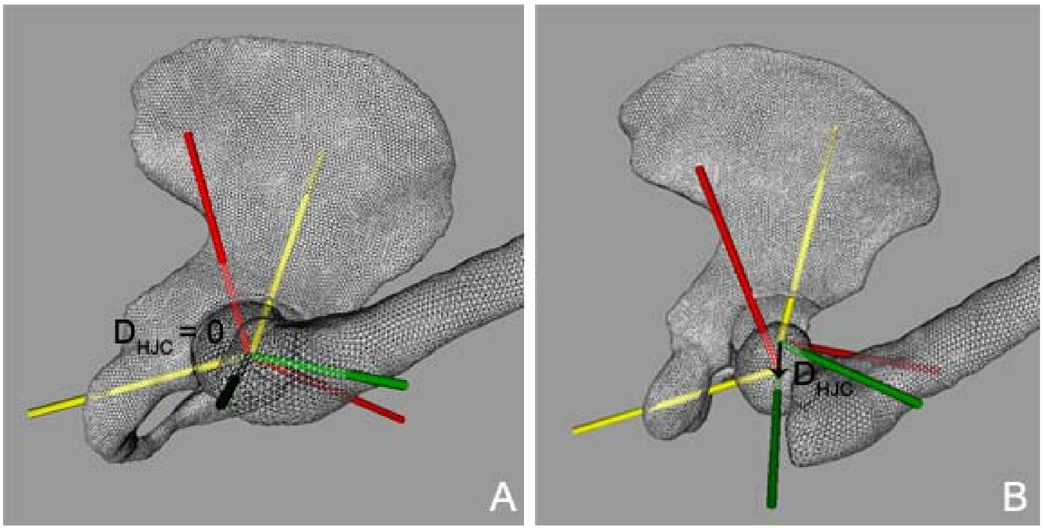

Figure 4. The vector $\mathbf{D_{HJC}}$ used to quantify the congruency of the hip joint. Left: the vector is null and the joint is thus congruent. Right: the vector denotes a subluxation (i.e., a loss of joint congruence).

FAI Detection and Localization

Individual impingement zones were automatically detected and calculated in real-time over the full range of motion. The 6 recorded dancing movements were investigated. While visualizing the dancer's hip joint in motion, a collision detection algorithm was used to virtually locate abnormal contacts between the proximal femur and the labrum.[5,6,7] Moreover, the surface-to-surface distance (i.e., penetration depth) was computed in order to estimate the overall FAI (Figure 5). This distance represented the topographic extent of the labrum compression and was reported in millimeters.

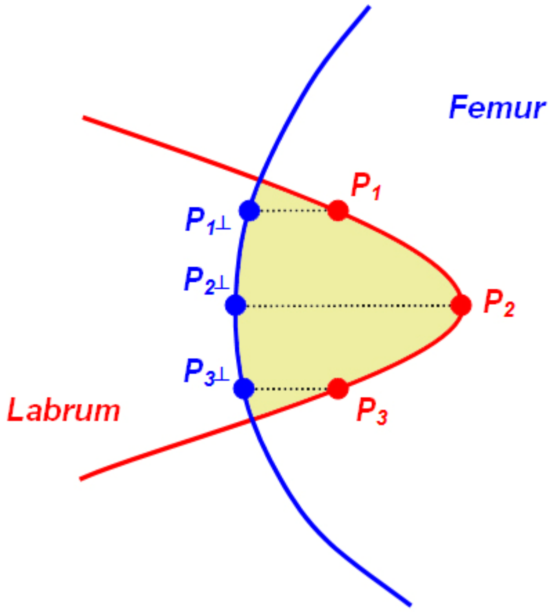

Figure 5. 2D schematic view of the impingement zone (yellow area). The surface-to-surface distance (i.e., penetration depth, dotted line) is defined for each P_i of the labrum's surface by the norm of the vector $\mathbf{P_i P_{i\perp}}$., where $\mathbf{P_{i\perp}}$.is the projected point $\mathbf{P_i}$ onto the femur's surface. This distance represents the topographic extent of the labrum compression.

To document areas of increazed labral compression, the penetration depth distribution on the surface of the labrum was represented using a color scale (Figure 6A). The blue color was assigned when no collisions were detected (penetration depth=0), while other colors showed the impingement zone. The red color denoted the area with the highest labral compression (penetration depth=max).

To describe and report the exact location of the impingement zone, the acetabulum was divided into 8 sectors (position 1, anterior; position 2, anterosuperior; position 3, superior; position 4, posterosuperior; position 5, posterior; position 6, posteroinferior; position 7, inferior; position 8, anteroinferior), as depicted in Figure 6B. The impingement zones were hence assigned numbers correlating with their position.

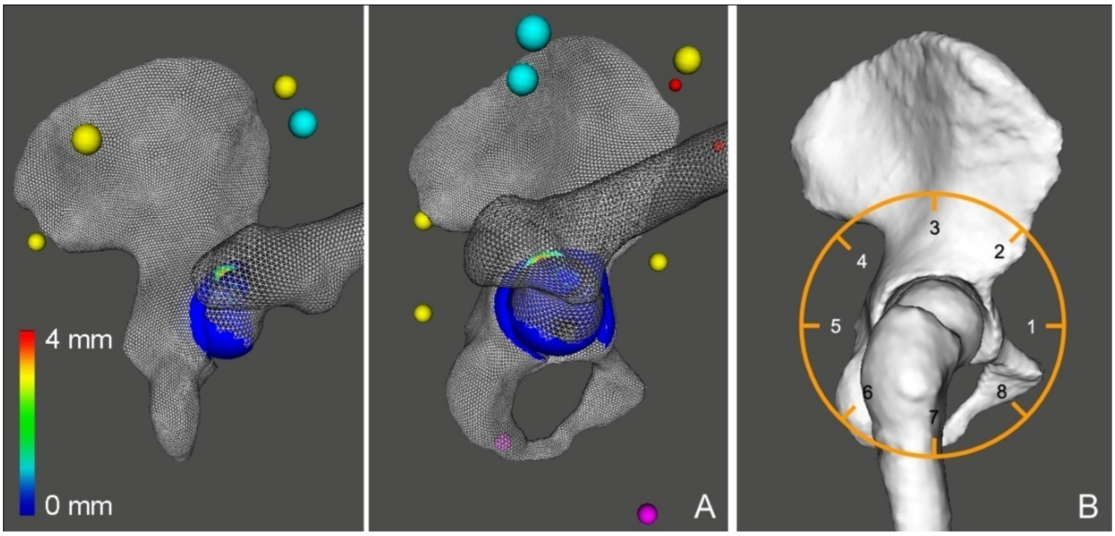

Figure 6. A) Visualization of the FAI region during extreme motion (posterior and lateral views). The colors represent the penetration depth distribution: the blue color is assigned when no collisions are detected (penetration depth=0), while other colors show the impingement zone. The red color denotes the area with the highest labral compression (penetration depth=max). B) Acetabulum divided into 8 sectors (position 1, anterior; position 2, anterosuperior; position 3, superior; position 4, posterosuperior; position 5, posterior; position 6, posteroinferior; position 7, inferior; position 8, anteroinferior) to report the location of the impingement zone.

Statistical Analysis

A statistical analysis was conducted for each of the 6 dancing movements. We calculated the frequency of impingement, subluxation and created histograms displaying the frequency of distribution of the zone of impingement. We computed the mean values and the standard deviations (SD) of the penetration depth, subluxation and range of motion according to the three standard anatomical angles. We finally computed the frequency of distribution of the location of diagnosed MRI lesions.

RESULTS

As shown in Table 1, dancing involves intensive hip flexion and abduction (except the arabesque where the hip is in extension and the grand écart latéral where one hip is in extension). For all movements, no significant left-right differences were noted.

Globally, the angles showed low standard deviations (range: 5.2 - 29.9), suggesting that movements were repeated similarly across dancers.

Findings concerning impingement and subluxation are presented and discussed below for each recorded dancing movement. The following two criteria were applied: (1) Whenever there is subluxation, there is loss of hip joint congruence. Thus, any femoroacetabular translation can be considered detrimental to the joint; (2) Increased penetration depth results in increased labral compression. Thus, when performed repetitively, the greater the penetration depth is, the more potentially damageable for the joint the impingement can be.

Table 2 summarizes for the reader mean values and standard deviations of computed penetration depths and subluxations by movement. For all movements, no privileged direction of femoroacetabular translations was observed.

Arabesque

For the 11 dancers analyzed, neither FAI nor subluxation were detected, while performing this movement. We believe this may have a kinematical interpretation: since only low amplitude angles are required to reproduce this motion, this does not create significant stress in the hip joint.

Développé Devant

Impingements were observed for 24% of the dancers' hips. The mean penetration depth (SD) was 2.5 mm (1.2 mm). The computed zones of impingement were variably distributed between the anterior and posterior quadrant of the acetabulum (position 2 to 5 according to our documentation), as depicted in Figure 7A. No subluxations were noted.

TABLE 1

Range of motion (deg) of the hip joint by movement, according to our referential (the neutral orientation of the hip joint is taken as reference)

Movements	**Left hip**		**Right hip**	
	Mean	**SD**	**Mean**	**SD**
Left arabesque				
Flex / Ext	0 / 28.4	10.2	-	-
Abduction	18.7	7.8		
IR / ER	0 / 27.7	13.6		
Right arabesque				
Flex / Ext	-	-	0 / 23.4	11.0
Abduction			21.5	7.7
IR / ER			0 / 22.7	20
Left développé devant				
Flex / Ext	88.4 / 0	14.5	-	-
Abduction	24.9	14.9		
IR / ER	0 / 2.7	29.9		
Right développé devant				
Flex / Ext	-	-	92.5 / 0	15.2
Abduction			24.2	10.3
IR / ER			0 / 0.7	11.7
Left développé à la seconde				
Flex / Ext	84.9 / 0	18.6	-	-
Abduction	49.9	5.2		
IR / ER	18.3 / 0	17.6		
Right développé à la seconde				
Flex / Ext	-	-	95.2 / 0	16.6
Abduction			49.2	6
IR / ER			22.1 / 0	15
Grand écart facial				
Flex / Ext	62.2 / 0	23.4	72.8 / 0	18.5
Abduction	73.1	6	71.5	8.4
IR / ER	0 / 2.3	25.1	9.9 / 0	24.5
Left grand écart latéral				
Flex / Ext	116.4 / 0	18.4	0 / 42.8	13.3
Abduction	38.8	13.5	29.8	8.4
IR / ER	35.7 / 0	15	0 / 28.1	18.2
Right grand écart latéral				
Flex / Ext	0 / 31.2	6.6	117 / 0	5.8
Abduction	25.8	5.7	34.6	14
IR / ER	0 / 27.3	13.8	37.9 / 0	8.9
Grand plié				
Flex / Ext	52.9 / 0	13.3	62.1 / 0	18.3
Abduction	68.2	7.6	64.9	8
IR / ER	0 / 10.2	11.3	0 / 11.2	18.4

Développé à la Seconde

FAI were detected for 45% of the dancers' hips. 78% of the contacts were located in the superior or posterosuperior area of the acetabular rim (Figure 7B). The penetration depths were intense (mean: 3.25 mm; SD: 1.91 mm), with a peak value of 6.22 mm. Subluxations were observed in 25% of the cases, but the femoroacetabular translations were significant (mean: 4.56 mm) for all hips, as suggested by the low standard deviation (1.14 mm). Furthermore, when a subluxation occurred, it was always correlated to an impingement.

TABLE 2
Computed penetration depths and subluxations by movement

Movements	Penetration depth (mm) Mean ± SD (range)	Subluxation (mm) Mean ± SD (range)
Arabesque	0	0
Développé devant	2.5 ± 1.2 (1.12 – 4.01)	0
Développé à la seconde	3.25 ± 1.91 (0.89 – 6.22)	4.56 ± 1.14 (3.16 – 5.57)
Grand écart facial	3.63 ± 2.55 (0.77 – 6.88)	3.42 ± 1.6 (0.93 – 5.67)
Grand écart latéral (front leg)	2.22 ± 1.83 (0.32 – 5.84)	5.14 ± 1.28 (3.33 – 6.35)
Grand écart latéral (back leg)	1.11 ± 1.33 (0.17 – 2.05)	3.15 ± 0
Grand plié	2.47 ± 1.76 (0.37 – 4.93)	3.77 ± 2.08 (1.4 – 5.29)

Grand Ecart Facial

While executing this movement, impingements were often observed (61% of the dancers' hips). All computed impingement zones were located in the superior or posterosuperior quadrant of the acetabulum (Figure 7C). The mean penetration depth (SD) was 3.63 mm (2.55 mm). Moreover, this is the movement with the highest frequency of subluxation (39%) with a mean value (SD) of 3.42 mm (1.6 mm). All subluxations were associated with an impingement.

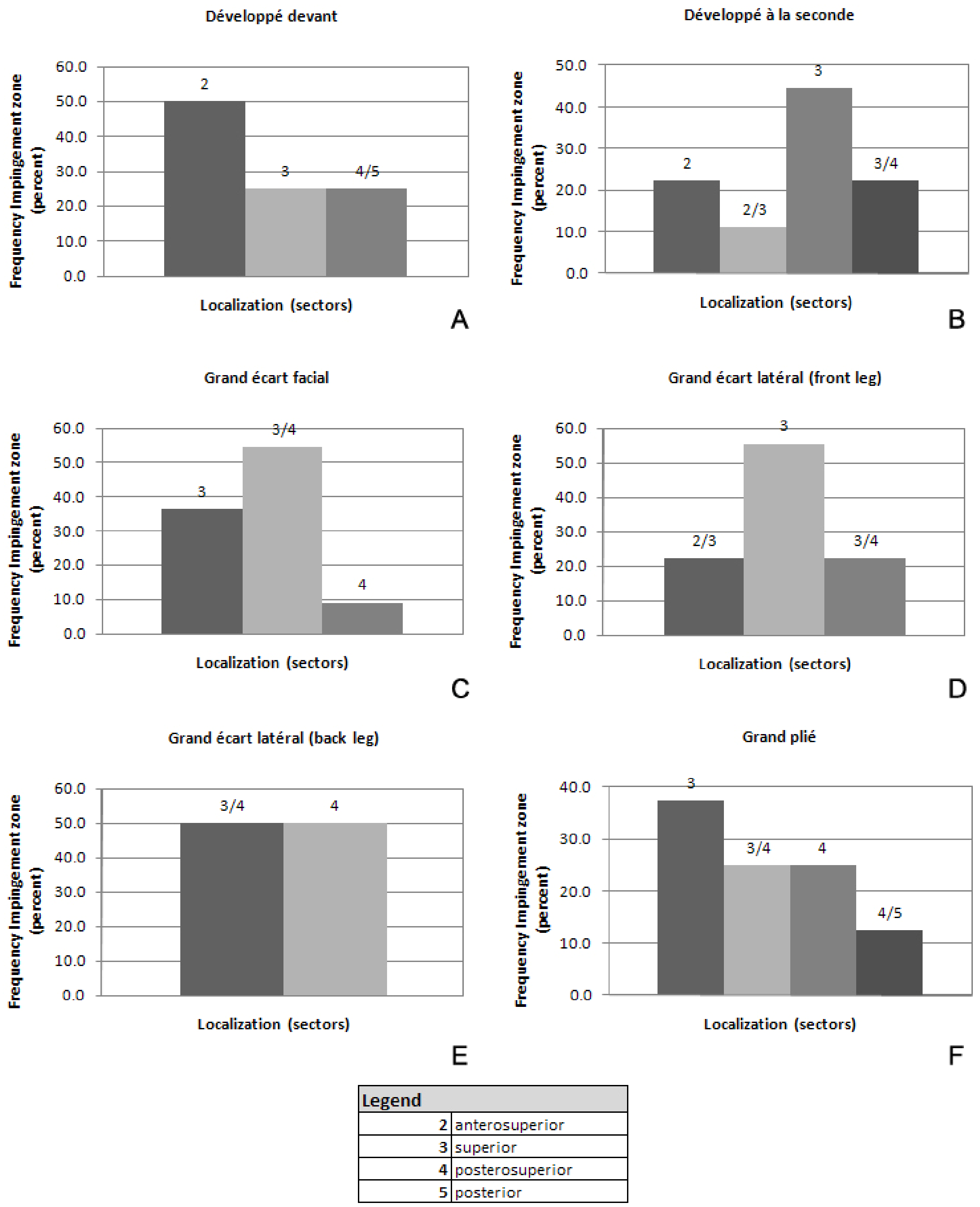

Figure 7. Histograms showing the distribution of frequency of the computed impingement zones for each movement: A) Développé devant B) Développé à la seconde C) Grand écart facial D) Grand écart latéral (front leg) E) Grand écart latéral (back leg) F) Grand plié.

Grand Ecart Latéral

For the leg in flexion (front leg), the highest frequency of FAI (70% of the dancers' hips) was noted. The mean penetration depth (SD) was 2.22 mm (1.83 mm). The simulation showed that all collisions occurred at the superior or posterosuperior acetabular rim (Figure 7D). We also found strong femoroacetabular translations (mean: 5.14 mm; SD: 1.28 mm) in 31% of the cases that were correlated to impingements.

For the leg in extension (back leg), the frequency of impingement was low (22% of the dancers' hips), as well as the penetration depths (mean: 1.11 mm; SD: 1.33 mm). The contacts were all located in the superior or posterosuperior quadrant of the acetabulum (Figure 7E). Only one subluxation was detected.

Grand Plié

Impingements were observed for 44% of the dancers' hips. The mean penetration depth (SD) was 2.47 mm (1.76 mm). All computed impingement zones were located in the superior or posterosuperior area of the acetabular rim, as shown in Figure 7F. The frequency of subluxation was low (17%) with a mean value (SD) of 3.77 mm (2.08 mm). However, all femoroacetabular translations were correlated to an impingement.

MRI Findings

According to the morphological analysis, the hips of the 11 dancers did not present any cam or pincer morphology. It was concluded that all 22 measured hips have a normal anteversion, alpha angle and acetabular depth (see Appendix A).

Based on the assessment of the MRI scans, three types of lesions were found: 1) degenerative labral lesions, 2) cartilage thinning associated with subchondral cysts and 3) herniation pits in superior position. For more than 80% of the dancers' hips, the degenerative labral lesions and acetabular damages were diagnosed in the superior (61% and 77%, respectively) and posterosuperior parts (22% and 8%, respectively) of the acetabular rim. Fibrocystic changes (herniation pits) were found in 11 hips, 9 being located in a superior or posterosuperior position (81%).

Interestingly, the computed zones of impingement were relevant with respect to the MRI findings. Indeed, both the degenerative labral lesions and computed zones of impingement were located in the superior or posterosuperior quadrant of the acetabulum (position 3 and 4).

DISCUSSION

As previously mentioned in the introduction, there is a lack of validated non-invasive methods to ascertain impingement during motion. Moreover, little is know about the congruency of the hip joint. In this study, we have therefore presented a methodology to perform functional simulations of the hip joint in extreme positions. FAI and joint congruency were actively assessed and demonstrated in-vivo. With the use of motion capture, the active ROM of the hip joint could be accurately determined, which is clinically not possible. The results of this study clearly showed that the detected FAI were located in the superior or posterosuperior quadrant of the acetabulum, and that subluxations occurred in dancing movements. As far as we know, this is the first in-vivo study of the hip joint in extreme dancing positions.

According to the literature[13,15,29], the passive hip ROM of dancers is normal compared to the general population, with a trend to increased flexion, abduction and external rotation. However, only trained subjects are able to assume dancing movements, such as the ones performed in ballet. As expected, this extreme motion is thus possible thanks to a combination of three articular motion patterns. This is also confirmed by the active ROM reported in this study, showing that dancing requires intensive hip flexion and abduction combined with rotation.

The results have been reported for 11 dancers, presenting no morphological abnormalities. The computed FAI can therefore not be imputed to any cam or pincer morphology. This already reveals that motion seems to have a direct influence on the physiology of the hip joint. For all dancers' hips, FAI and subluxations occurred at the maximal hip ROM and were frequently observed. Moreover, the subluxations were always visually correlated to impingements, suggesting that a subluxation would occur in response to the collision between the proximal femur and the acetabular rim. These findings corroborate the fact that the hip joint undergoes a high stress during extreme motion, as it was also pointed out in previous studies.[3,8,12,20,21,22,26]

Based on our statistical analysis, the frequency of impingement and subluxation varied with the types of movement. However, four dancing movements seem to be potentially harmful for the hip joint: the grand écart facial where the highest frequency of subluxation (39%) was observed, the grand écart latéral (front leg) where the highest frequency of FAI (70%) was noted, the développé à la seconde and the grand plié where high penetration depths (mean: 3.25 mm and 2.47 mm, respectively) and femoroacetabular translations (mean: 4.56 mm and 3.77 mm, respectively) were quantified. These results do not mean that the dancers should stop executing these movements, but rather they should limit them in frequency during dancing class. We suppose that, in that way, the hip joint would be better preserved.

In a previous work[10], a MRI-based assessment of the congruence of the hip joint in lateral split position was conducted. Compared with our study, the femoroacetabular translations were similar (mean: 2.05 ± 0.74 mm; range: 0.63 – 3.56 mm), but slightly lower to those we computed. One explanation could be that the hip joint kinematics computation is less accurate in motion capture than in MRI scanning. In fact, our translation errors were in the order of magnitude of the reported MRI bone motion tracking accuracy (~ 0.5 mm), and they thus cannot explain the discrepancies in the results. However, in the MRI study, the assessment was limited to a single static posture and did not account for joint dynamics. It is therefore understandable to obtain a higher amount of subluxation when analyzing the hip joint in active motion.

Substantial penetration depths were computed for all extreme movements (range: 0.17 – 6.88 mm). Knowing that the labrum has superiorly and posteriorly an average height of 6-7 mm[31], our results indicate that the labrum is highly compressed during extreme motion. However, the true extent of compression cannot be determined without a more advanced simulation. Indeed, our simulation ignores soft tissue and potential bone deformation under loads. Taking into account the mechanical properties of the bones, cartilages and labrum could lead to slightly different results. Future work should hence include a physically-based simulation of the bony and chondrolabral structures. Nevertheless, according to our data, there is little doubt that the labrum is exposed to high mechanical stress.

For almost all movements, the computed zones of impingement were mainly located in the superior or posterosuperior quadrant of the acetabulum and this was relevant with respect to the MRI findings. In fact, the detected lesions were typical lesions of femoroacetabular conflicts, but they were located in superior or posterosuperior position. This is unusual because the resulting chondrolabral damages in the cam or pincer hip are generally located in the anterosuperior position, as reported by different authors.[1,2,28,30] Consequently, we think that dancing implies a new superior/ posterosuperior FAI.

There are potential limitations to the accuracy of the global set-up. Indeed, errors in our methodology could originate from two different sources: the first source of error could be the segmentation and modeling of 3D models from MRI data (error

≈ 1.25 mm). While CT provides a better evaluation of the bones than MRI, it is not truly appropriate for soft tissue imaging. We therefore decided to use MRI, because it was less invasive and allowed to evaluate both soft and bony structures at the same time. The second source of error could be the kinematics computation from motion capture data (translational error ≈ 0.5 mm, rotational error < 3°). Since the measurements are external (no direct access to the joint), motion capture is generally subject to greater errors (especially in rotation) than dynamic RSA or MRI. However, this modality is not harmful and allows for the recording of large ranges of motion. It was thus more suitable for a study involving professional ballet dancers volunteers. Despite these two possible sources of error, our methodology was still accurate and valid. In particular, we do believe that the error values of the global set-up did not call into question the conclusion of this study.

In summary, the findings validate our hypothesis. From our data, we conclude that (1) the practice of some dancing movements could expose the dancer's hip to recurrent impingements located in the superior or posterosuperior quadrant of the acetabulum, and (2) the femoral head and acetabulum do not seem to be always congruent in typical dancing positions. Based on the evidence, we believe that FAI and subluxation could lead to cartilage hyper compression and therefore could be potential factors for the developement of early hip OA.

APPENDIX A

Results of the morphological analysis of the 11 dancers' hips according to radiographic criteria (Table 3). The femoral alpha neck angle was measured in eight positions aorund the femoral neck in accordance with the method described by Nötzli et al.[23] The acetabular depth was evaluated according to the method detailed by

Pfirrmann et al.[25], and the acetabular version according to the method detailed by Reynolds and al.[24] For the alpha angles, only the measures in anterior and anterosuperior positions are reported, since they are the more significant.

TABLE 3
Morphological analysis

Measures	Min	Mean ± SD	Max
Femoral alpha neck angle (anterior)	36.52	45.32 ± 4.13	53.85
Femoral alpha neck angle (anterosuperior)	34.88	45.14 ± 6.02	55.0
Acetabular depth	4.64	8.14 ± 1.27	10.26
Acetabular version	0.34	7.02 ± 3.41	15.67

REFERENCES

1. Beaulé PE, Zaragoza E, Motamedi K, Copelan N, Dorey FJ. Three-dimensional computed tomography of the hip in the assessment of femoroacetabular impingement. J Orthop Res. 2005;23(6):1286-1292.
2. Beck M, Kalhor M, Leunig M, Ganz R. Hip morphology influences the pattern of damage to the acetabular cartilage: femoroacetabular impingement as a cause of early osteoarthritis of the hip. J Bone Joint Surg Br. 2005;87:1012-1018.
3. Binningsley D. Tear of the acetabular labrum in an elite athlete. Br J Sports Med, 2003;37:84-88.
4. Cappozzo A, Catani F, Leardini A, Benedetti M, Croce UD. Position and orientation in space of bones during movement: experimental artefacts. Clin Biomech. 1996;11(2):90-100.

5. Charbonnier C, Assassi L, Volino P, Magnenat-Thalmann N. Motion study of the hip joint in extreme postures. Vis Comput, Springer-Verlag, 2009;25(9):873-882.
6. Charbonnier C, Lyard E, Magnenat-Thalmann N. Analysis of extreme hip motion in professional ballet dancers. In Proc of the 10th International Symposium on 3D Analysis of Human Movement, Amsterdam, Netherlands, October 2008.
7. Charbonnier C, Schmid J, Kolo FC, Magnenat-Thalmann N, Becker C, Hoffmeyer P. Virtual Hip Joint: from Computer Graphics to Computer-Assisted Diagnosis. Eurographics 2009 - First Medical Prize, Eurographics Association, Munich, Germany, pp. 1-4, 2009.
8. Clohisy JC, Knaus ER, Hunt DM, Lesher JM, Harris-Hayes M, Prather H. Clinical presentation of patients with symptomatic anterior hip impingement. Clin Orthop Relat Res. 2009;467:638-644.
9. Ganz R, Parvizi J, Beck M, Leunig M, Nötzli H, Siebenrock KA. Femoroacetabular impingement: a cause for osteoarthritis of the hip. Clin Orthop Relat Res. 2003;417:112-120.
10. Gilles B, Kolo FC, Magnenat-Thalmann N, Becker C, Duc S, Menetrey J, Hoffmeyer P. MRI-based assessment of hip joint translations. J Biomech. 2009;42(9):1201-1205.
11. Gilles B, Moccozet L, Magnenat-Thalmann N. Anatomical modelling of the musculoskeletal system from MRI. MICCAI '06, Part II. LNCS, Springer Berlin / Heidelberg, 4190, pp. 289-296, 2006.
12. Groh MM, Herrera J. A comprehensive review of hip labral tears. Curr Rev Musculoskelet Med. 2009;2:105-117.
13. Gupta A, Fernihough B, Bailey G, Bombeck P, Clarke A, Hopper D. An evaluation of differences in hip external rotation strength and range of motion between female dancers and non-dancers. Br J Sports Med. 2004;38(6):778-783.
14. Ito K, Minka MA 2nd, Leunig M, Werlen S, Ganz R. Femoroacetabular impingement and the cam-effect: a MRI based quantitative anatomical study of the femoral head–neck offset. J Bone Joint Surg Br. 2001;83:171-176.

15. Khan K, Roberts P, Nattrass C, Bennell K, Mayers S, Way S, Brown J, McMeeken J, Wark J. Hip and ankle range of motion in elite classical ballet dancers and controls. Clin J Sport Med. 1997;7(3):174-179.
16. Lavigne M, Parvizi J, Beck M, Siebenrock KA, Ganz R, Leunig M. Anterior femoroacetabular impingement: Part I: Techniques of joint preserving surgery. Clin Orthop Relat Res. 2004;418:61-66.
17. Leunig M, Beaulé PE, Ganz R. The concept of femoroacetabular impingement. Clin Orthop Relat Res. 2009;467:616-622.
18. Leunig M, Podeszwa D, Beck M, Werlen S, Ganz R. Magnetic resonance arthrography of labral disorders in hips with dysplasia and impingement. Clin Orthop Relat Res. 2004;418:74-80.
19. Lewis CR, Sahrmann SA. Acetabular labral tears. Phys Ther, 2006;86:110-121.
20. Mason JB. Acetabular labral tears in the athlete. Clin Sports Med, 2001;20:779-790.
21. McCarthy J, Noble P, Aluisio FV, et al. Anatomy, pathologic features, and treatment of acetabular labral tears. Clin Orthop. 2003;406:38-47.
22. McCarthy J, Noble P, Schuck M, et al. The Otto E. Aufranc Award: the role of labral lesions to development of early degenerative hip disease. Clin Orthop. 2001;393:25-37.
23. Nötzli HP, Wyss TF, Stöcklin CH, Schmid MR, Treiber K, Hodler J. The contour of the femoral head–neck-junction as a predictor for the risk of anterior impingement. J Bone Joint Surg Br. 2002;84:556-560.
24. Pfirrmann CWA, Mengiardi B, Dora C, Kalberer F, Zanetti M, Hodler J. Cam and pincer femoroacetabular impingement: Characteristic MR arthrographic findings in 50 patients. J Radiol, 2006;240(3):778-785.
25. Reynolds D, Lucac J, Klaue K. Retroversion of the acetabulum: a cause of hip pain. J Bone Joint Surg Br. 1999;81:281-288.
26. Santori N, Villar RN. Acetabular labral tears: result of arthroscopic partial limbectomy. Arthroscopy. 2000;16:11-15.

27. Schmid J, Magnenat-Thalmann N. MRI Bone Segmentation using Deformable Models and Shape Priors. MICCAI '08, Part I. LNCS, Springer Berlin / Heidelberg, 5241, pp. 119-126, 2008.

28. Siebenrock KA, Schöniger R, Ganz R. Anterior femoro-acetabular impingement due to acetabular retroversion and its treatment by periacetabular osteotomy. J Bone Joint Surg Am. 2003;85:278-286.

29. Steinberg N, Hershkovitz I, Peleg S, Dar G, Masharawi Y, Heim M, Siev-Ner I. Range of joint movement in female dancers and nondancers aged 8 to 16 years: anatomical and clinical implications. Am J Sports Med. 2006;34(5):814-823.

30. Tannast M, Goricki D, Beck M, Murphy SB, Siebenrock KA. Hip damage occurs at the zone of femoroacetabular impingement. Clin Orthop Relat Res, 2008;466:273-280.

31. Won YY, Chung IH, Chung NS, Song KH. Morphological study on the acetebular labrum. Yonsei Med J, 2003;44(5):855-862.

32. Wu G, Siegler S, Allard P, Kirtley C, Leardini A, Rosenbaum D, Whittle M, D'Lima D, Cristofolini L, Witte H, Schmid O, Strokes I. ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion - part I: Ankle, hip and spine. J Biomech. 2002;35(4):543-548.