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Dynamic evaluation of THA components by Prosthesis Impingement Software (PIS)

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Abstract. *Background and aim of the work:* Implant dislocation in total hip arthroplasties (THA) is a common concern amongst the orthopedic surgeons and represents the most frequent complication after primary implant. Several causes could be responsible for the dislocation, including the malpositioning of the components. Conventional imaging techniques frequently fail to detect the mechanical source of dislocation mainly because they could not reproduce a dynamic evaluation of the components. The purpose of this study was to elaborate a diagnostic tool capable to virtually assess if the range of movement (ROM) of a THA is free from anterior and/or superior mechanical impingement. The ultimate aim is to give the surgeon the possibility to weigh the mechanical contribution in a THA dislocation. *Methods:* A group of patients who underwent THA revision for acute dislocation was compared to a group of non-dislocating THA. CT scans and a virtual model of each patient was obtained. A software called “Prosthesis Impingement Simulator (PIS)” was developed for simulating the (ROM) of the prosthetic hip. The ROM free of mechanical impingement was compared between the two groups. *Results:* The PIS test could detect the dislocations with a sensitivity of 71,4%, and a specificity of 85,7%. The Fisher’s exact test showed a p-value of 0,02. *Conclusion:* The PIS seems to be an effective tool for the determination of hip prosthetic impingement, as the main aid of the software is the exclusion of mechanical causes in the event of a dislocation.

Key words: total hip arthroplasty, THA, dislocation, software, revision surgery, range of motion, impingement

Introduction

The number of primary total hip arthroplasties (THA) over the last decades has constantly increased (1). Dislocation is the most common complication after primary THA and has an estimated incidence between 0.3% to 10% (2).

Approximately 50% of the dislocations occur within the first 3 months after surgery, and more than 75% occur within the first year (3). Within the first 2 years postoperatively, dislocation is the most common cause for revision surgery (4).

Prosthetic dislocation is defined as the complete loss of articulation contact between the artificial joint components. In the THA there is an ideal biomechanical system that must be recreated, and a stable implant is obtained through optimal cup inclination and anteversion, stem antetorsion, reconstruction of the rotational center of the hip, offset, and leg length (5).

It is of utter importance to distinguish whether the THA dislocation is due to a sufficient traumatic event or it is secondary to implant instability. The latter is suggestive of inadequate tissue tension or component malpositioning (5).

THA dislocation has been described to be caused by several mechanisms and classified according to the displacement direction. The dislocation cause may be supposed according to dislocation direction and the specific inducing movement. An insufficient anteversion or a retroversion of the cup, a lack of soft tissue tension, and a primary or secondary impingement may produce a dorsal dislocation, which is the most common pattern observed (5). The most common dislocation movement is combined internal rotation and adduction of the flexed hip joint. If a cranial dislocation is observed, a lack of coverage of the cup, an abductor insufficiency, or a polyethylene wear may be suspected. The possible causes for an anterior prosthetic dislocation could be excessive combined antetorsion of the stem and the cup, joint hyperlaxity, primary or secondary impingement. In those cases dislocation may be produced by external rotation and adduction of the extended hip joint (5). In every case the malpositioning of the components enters into the differential diagnosis.

The most significant pre-surgery risk factors for dislocation include anatomical variations of the hip, often occurring along with congenital hip dysplasia or metabolic bone disorders, rapidly progressive and inflammatory arthropathies, as well as necrosis of the femoral head (6). Moreover, previous fractures or surgical procedures of the hip could significantly increase the chance of prosthetic dislocations (5). Procedure-specific risk factors can be identified in the surgical approach, the positioning of the components, the soft-tissues conditions, and the surgeon's experience (5).

The correct alignment of the implants during hip replacement surgery has been demonstrated to be of utter importance for the stability of the artificial joint. Both acetabular and femoral cup positioning is guided by individual anatomic requirements. In their famous study Lewinnek et al. proposed a "safe zone" of cup inclination of $40^\circ \pm 10^\circ$ and anteversion of $15^\circ \pm 10^\circ$ to minimize dislocation risk after primary THA (7). These parameters have guided the hip surgeons for decades, and still do it. However, it has been extensively demonstrated that even if the implants are placed in this safe zone, dislocations can still occur (8,9).

Moreover, the precise identification of the subsequent cause for an implant dislocation is often really challenging. The most recent CT metal suppression protocols have improved the visualization of the

components and the comprehension of their orientation, however it is actually impossible to understand the cup and stem interactions through the entire range of motion, when looking only at the static reconstructions. The mechanisms responsible for the dislocation affect the entire decision making process that leads to a potential revision surgery, so the assessment of the mechanical status seems to be crucial.

The purpose of this study was to elaborate a diagnostic tool capable to virtually evaluate if the range of movement of a total hip arthroplasty is free from anterior and/or superior mechanical impingement. The aim is to give the surgeon the possibility to weigh the mechanical contribution in a THA dislocation, in order to optimize the treatment choice.

Materials and methods

A retrospective case-control study was conducted. Patients selected as cases underwent a THA revision surgery for a history of acute dislocation between 2011 and 2017. All the patients were treated through a standard postero-lateral approach for both the primary implant and the revision. Exclusion criteria were anterior dislocation, clear mobilization or wear of the components, high-energy traumas, previous revision surgery and severe sarcopenia. Clear mobilization was considered if any radiological sign of components mobilization and/or progressive osteolysis was present at the last follow up. Sarcopenia was contemplated if patients presented with reported significant low muscle mass and performance at physical examination. The patients selected as controls were chosen between type A, B1 or C periprosthetic fracture, without a previous history of dislocation, or patients with a well-functioning THA who underwent a CT scan for other reasons. Patients with unstable periprosthetic fracture were excluded because of the altered components relative position after the trauma. All the patients must have had a high-resolution CT scan of the hip with metal suppression protocol.

In cooperation with Politecnico of Turin a software called "Prosthesis Impingement Simulator (PIS)" was developed in order to simulate the conditions that leads to THA dislocation.

The workflow was divided into three distinct phases. For the initial segmentation we started from

a standard series of DICOM images of each patient's CT scan; with the aid of *3D Slicer* software (Slicer, Brigham and Women's Hospital, Harvard University, NIH) we created the 3D models of patient's hip bones and prosthetic components. The second phase was the preparation of the 3D models previously obtained for the subsequent motion analysis. We developed a tailored algorithm for the identification of the hip centre of rotation, with a process called "sphere fitting" process. Once the 3D models were correctly set, they were eventually processed with the PIS. This software allows to visualize the patient's 3D model and to simulate a complete hip motion around its center of rotation.

For this study we set the parameters for the simulation of a posterior dislocation. We put the modeled hip in flexed position at both 90° and 60°, with a following continuous simulated intra-rotation. The software could then calculate at each degree of flexion the maximum intra-rotation values before the manifestation of any sort of impingement, both between the bones or the components. The impingement area was then highlighted in red.

Then we observed the models behavior with different cut-offs for normal prosthetic hip range of motion: i.e. at 60° and 90° of flexion, respectively 40° and 20° of intra-rotation were set.

PIS was used as a test both for cases and controls. This test was considered as positive if at least one out of two simulations found an impingement below 40° and 20°. As a consequence, the test was considered as negative when the values of simulations were both above the established thresholds.

To conduct the statistical analysis Sofastats (Paton-Simpson & Associates Ltd) software was used. Fisher's exact test was used for the analysis of the contingency tables. Positive and negative predictive values were also calculated.

Results

According to inclusion and exclusion criteria, a total of 21 patients were selected from an initial cohort of 54 patients. 7 were identified as cases and 14 as controls. In the two groups the mean age was respectively 77,5 (SD = 5.8) and 79 years (SD = 7.3), (P value 0.60). 37,5 % of the cases were male, compared to the 43 % of the controls. (P value 0.806). Right THA was observed in 75% of the cases and in 43% of the controls (P value 0.145).

The ROM analysis of the two groups is shown in table 1.

Table1. Comparisons between cases and controls. Variables are shown as degrees.

THA re-dislocation patients			THA non re-dislocation patients		
Patient	Intrarotation at 60° of flexion (°)	Intrarotation at 90° of flexion (°)	Patient	Intrarotation at 60° of flexion (°)	Intrarotation at 90° of flexion (°)
A	40,5	20,5	A ₁	48,5	24,5
B	23,0	4,5	B ₁	52,5	34,5
C	48,5	24,5	C ₁	70,0	36,5
D	16,5	< 0	D ₁	48,0	40,5
E	32,5	16,5	E ₁	59,5	24,5
F	24,5	21,0	F ₁	44,5	24,5
G	34,5	< 0	G ₁	56,5	24,5
			H ₁	57,5	28,5
			I ₁	48,5	24,5
			L ₁	55,0	32,5
			M ₁	44,5	24,5
			N ₁	48,5	22,5
			O ₁	30,5	11,5
			P ₁	35,0	12,5

Table 2. Contingency table of the administered impingement test.

	Case	Control	Total
PIS test +	5	2	7
PIS test -	2	12	14
	7	14	21

In table 2 the contingency table for the PIS test is shown. The test sensitivity was 71,4%, the test specificity was 85,7%. The positive predictive value was 71,4%, and the negative predictive value was 85,7%. The Fisher's exact test showed a p-value of 0,02.

Discussion

Our results analysis shows that PIS could identify the THAs at risk for dislocation with a sensitivity of 71,4% and a specificity of 85,7%. It is possible to state that it is a satisfactory performance with statistical significance because the main aid of the software is the exclusion of mechanical causes in the event of a dislocation. If the software couldn't find any impingement, we should consider that other reasons except for malpositioning could be involved. This is a crucial aspect for the planning of the subsequent treatment. Along with that, the discharge of a malpositioning case could also positively affect the possible related medico-legal issues.

The optimal components location has been debated for decades, and the historical concept of the "safe zones" proposed by Lewinnek has been questioned by many authors (10). The problem is intricate and it has a double face. From one side the optimal positioning is influenced by the hip anatomy, the spino-pelvic angles and the dynamic changes that occur during motion; on the other hand, it was demonstrated that the prosthetic definitive orientation by sight alone could widely deviate from the surgeon's intra-operative estimation. (11). If we consider all these variables, it becomes clear how hard it is to perform a conclusive analysis on prosthetic stability only on the basis of the x-rays or even a CT scan, for they provide static images and could not give a thorough evaluation of the ROM. From this perspective a dynamic analysis as the one given by the PIS appears to be a precious tool for the surgeon.

Two THAs out of seven were identified as non-impinging on the software results if they had clinically dislocated, this could be explained by the software impossibility to take into account the soft tissues, as they reasonably have a significant role in the ROM limitation. Woerner et al. state that frequently only bony and prosthetic impingement are taken into account when analyzing dislocations, but the soft tissues could also be relevant (12). In their study they measured the maximum intra-operative ROM with a navigation computed system, then all the patients underwent a 3D-CT post-operatively; with the aid of a collision-detection algorithm, the ideal ROM free from bony and/or prosthetic impingement was calculated. They found out that the intra-operative ROM was significantly reduced if compared to the one calculated with the software, concluding that soft tissues impingement had a role in the ROM reduction. Regarding flexion, extension, abduction and adduction the ROM was found to be reduced by over 20°, whereas in external rotation by over 10°. On the contrary, the soft tissue impingement was found to have little less impact on internal rotation at 90° of flexion. The soft tissues play also a crucial function in determining the tension of the implant, which is in the end the only constraint that keeps the prosthetic ball and socket coupled.

Our study has some limitations, starting from the small case series analyzed. We also didn't analyze other specific movements that could produce dislocations except the reported ones. The analysis may be limited as we considered a common normal ROM as the specific target of the analysis and we decided to focus only on the posterior dislocation for its higher incidence (13). In this context, Ghaffari et al. (14) studied the relations between prosthesis components and patients' dislocation-prone activities by developing a 3D model simulation. They found that specific activities produce peculiar hip motions which bring the components more or less near to their ROM limits and thus closer to dislocate. It seems that the sit-to-stand and standing while bending at the waist are the most prone to dislocation activities. A possible interesting implementation of the PIS could be the inclusion in the simulation of the real critical patients' movements.

We have also to mention the struggle to standardize the patients' position in the CT scan, thus

influencing the relative position of the components in the virtual model. In order to solve it, a prospective study should be designed with an associated CT torsional study of the femur.

Conclusion

The PIS seems to be an effective tool for the determination of hip prosthetic impingement. Its leading convenience could be the exclusion of mechanical causes for recurrent dislocations, due to the malpositioning of the components. Some criticism still exists for the extension of its versatility, especially for the account of the soft tissues. Future implementations will concentrate on the accuracy of the movements simulations and the standardization of the imaging protocols.

Conflicts of interest: Each author declares that he or she has no commercial associations (e.g. consultancies, stock ownership, equity interest, patent/licensing arrangement etc.) that might pose a conflict of interest in connection with the submitted article.

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