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Analyzing Bony Constraints as a Key Stone of an Integrated Approach towards Functional THA Planning

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Abstract

Both, prosthetic design and implantation have a great influence on the impingement and dislocation risk after total hip arthroplasty (THA). Potential impingement risks should be analyzed during THA planning. In order to analyze bony impingement, often 3D meshes of the bony structures have to be transformed and collision between the 3D meshes is calculated which might be complex and time consuming. This work introduces a simplified collision calculation algorithm based on 2D mapping. Possible impingement points on the femur and the pelvis, which are points on a sphere, are extracted and mapped into a 2D plane. Impingement can be calculated using a 2D distance map.

The method was applied for analysing a dislocation case. A 38-year-old female THA patient had a dislocation 3 months after the surgery. The hip dislocated anteriorly in the standing positon while carrying a load in the front (a child) and turning the upper body slightly towards the contralateral side. The cup orientation was within the so called Lewinnek safe zone. The pelvis in standing position was tilted by 11° posteriorly. The impingement analysis revealed that maximal external hip rotation was less than 15° and even less than 10° when the pelvis is tilted more posteriorly which might have been the case during the dislocation. Considering additional soft-tissue involvement, a minor external rotation could in fact be a potential cause for dislocation.

Using the previously introduced prosthetic ROM-based target zone calculation algorithm, optimized THA parameters were determined. This include changing the CCD angle and the stem or neck antetorsion. Using the modified parameters, external rotation of at least 20° would have been possible without bony impingement. The dislocation could have been avoided.

1 Introduction

Both, prosthetic design and implantation have a great influence on the impingement and dislocation risk after total hip arthroplasty (THA) [Kessler et al. 2008; Kurtz et al. 2010; Bunn et al. 2012]. Potential impingement risks should, therefore, be analyzed during THA planning. Different algorithms considering prosthetic impingement had been introduced in literature [Jaramaz et al. 1998; Widmer & Zurfluh 2004; Yoshimine 2006]. Since the geometry of implant components and its correlation can be described by simple mathematical equations, the calculation of impingement points can be done quite fast and is therefore feasible in clinical routine planning sessions. However, these algorithms do not consider bony motion constraints ("bony impingement") which also pose a dislocation risk (e.g. [Renkawitz et al. 2012]). Although soft tissue impingement normally prevents direct impingement of bone, bone collision analysis is used as an approximation of ROM constraints. In order to analyze bony impingement, often 3D meshes of the bony structures have to be transformed and collision between the 3D meshes need to be calculated [DiGioia III et al. 2000; Kessler et al. 2008; Renkawitz et al. 2012] which might be complex and time consuming. In this work, a simplified collision calculation algorithm based on a 2D mapping is presented and demonstrated on a case study of a dislocation case.

2 Material and Methods

In our previous work, a method for range of motion (ROM)-based target zone calculation had been introduced [Hsu et al. 2017]. The pre-defined ROM of the femur is converted to the ROM of the femoral neck axis. This ROM is then compared to the limits of the cup (with consideration of the head-neck-ratio) and a target zone containing all impingement-free cup orientations were determined. We extended this method for bony impingement detection.

In order to incorporate the bony anatomy of the patient, a 3D reconstruction of the adjacent bony structures of the hip is needed. The bony surfaces of the pelvis and the femur are segmented from CT data using thresholding and manual post-processing. In our study, an initial alignment with a functional pelvic tilt has been derived from standing EOS data. The femur is orientated with the mechanical axis parallel to the vertical axis (in standing position) and the line connecting the posterior condyle parallel to the mediolateral axis.

The hip joint is modelled as a spherical joint, translations in all three directions are neglected. Then, any point on the femur which has a distance R to the centre of rotation can only impinge with a point on the pelvis which has the same distance (see Figure 1(a)). These possible impinging points on pelvis and femur can be all determined by calculating the intersections between a sphere and the bones (see Figure 1 (b)-(c)). Instead of analysing impingement in 3D space, the contours are mapped onto a 2D plane (see Figure 1 (d) similar to the cup limits and neck axis in our previous study [Hsu et al. 2017]). On the 2D plane, the angular distances to the bony limits (shown in green) are calculated. The area inside the bone has a negative value, the area outside has a positive value.

The pelvis is fixed to the world coordinate system. Therefore, the limits of the pelvis and the distance map have to be calculated only once for a given radius R. Arbitrary motion can be applied and tested with this method. The limits of the femur are transformed for each femur orientation and mapped into 2D. Figure 1 (e)-(g) show an example for a flexion/extension motion. For each point on the femur contour, the minimal distance to impingement for all motions is stored and can be displayed as a colour map as shown in Figure 1 (h). It can be seen, which part of the femur causes impingement or is close to an impingement for the given desired ROM.

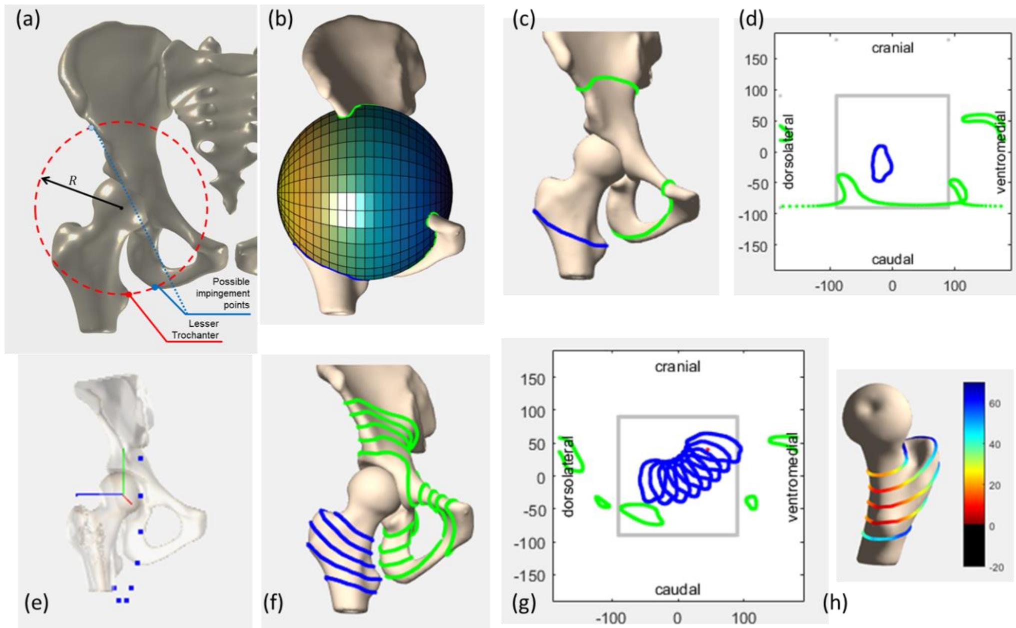

Figure 1: Calculation steps for bony impingement analysis.

Implantations parameters such as cup position (medialization, cranialization, anterior/posterior position), stem orientation and design (antetorsion, offset, neck angle) have an influence on the prevalence of bony impingement [Kurtz et al. 2010] and can be analysed and adapted to the individual case.

The method was applied for analysing a dislocation case. A 38-year-old female THA patient had a dislocation 3 months after the surgery. The hip dislocated anteriorly in the standing positon while carrying a load in the front (a child) and turning the upper body slightly towards the contralateral side. Post-operative CT as well as post-operative standing EOS images have been used for bony impingement analysis. For deriving the pelvic tilt during dislocation, the post-operative EOS was used. Due to the fact that the patient was carrying a load, additional posterior tilt was simulated (-5° and -10° were added to the pelvic tilt measured from EOS images). External hip rotation from 0° to 30° in 5° increments was tested.

In a second step, we analysed the post-operative implant placement and ROM (according to [Hsu et al. 2017]) and analysed options for optimization. The cup orientation was kept unchanged, but the stem antetorsion and neck angle were varied and bone impingement analysis was performed.

3 Results

The post-operative pelvic tilt in standing position was -11° (posterior tilt). Therefore, -11°, -16°, and -21° were used for simulating pelvic tilt situation during child carrying. The calculated minimal distances to impingement are listed in Table 1. It can be seen that for a pelvic tilt of -11°, the maximum amount of external rotation is less than 15° before bony impingement (without additional soft tissue impingement!). When the pelvis is tilted even more posteriorly, the maximum external rotation decreases to less than 10°. Considering additional soft-tissue involvement, a minor external rotation could in fact be a potential cause for dislocation.

The cup and stem orientation was measured in the reconstructed 3D model. The values were: inclination = 44°, anteversion = 19°, antetorsion = 35°, stem adduction = 7° and stem flexion = 3°. The femoral component had a neck angle of 135°. After ROM-based target zone calculation, we found, that for placing the actual cup orientation inside the target zone, the antetorsion had to be reduced by 10° (or using a prosthesis with a neck-to-stem antetorsion of -10°) and the stem adduction had to be increased by 5° (or decreasing the neck angle by 5°). Using this optimized parameters, the initial alignment of the femur were changed accordingly and the resulting minimal distances to impingement are listed in Table 1. It can be seen that for even larger posterior pelvic tilt, external rotation of 20° is possible before bony impingement. This might have prevented the dislocation.

	External rotation [°] / Pelvic tilt[°]	0	-5	-10	-15	-20	-25	-30
post-operative situation	**-11**	5	4	1	0	-1	-3	-5
	-16	3	1	-1	-2	-4	-5	-7
	-21	2	1	-1	-3	-5	-7	-8
optimized situation	**-11**	10	8	6	4	2	0	-1
	-16	8	6	4	2	0	-1	-3
	-21	7	6	4	2	0	-2	-4

Table 1: Minimal distance to impingement for various parameters. Negative values means that impingement occurred.

4 Discussion

The proposed method reduces the problem of collision detection between the femur and the pelvis during THA planning from a complex 3D to a simpler 2D problem. Any arbitrary motion of the hip can be evaluated by transforming points from the femur contour and looking up the distance to impingement on the 2D distance map. The case study showed the relevance of incorporating the bony impingement analysis into the THA planning process. Parameter set with high risk for bony impingement can be determined and should be avoided.

Calculating bony impingement as such is, however, misleading, since in practice, soft tissue will always impinge prior to any contact between bony structures. Therefore, the distance to bony impingement can only be seen as an estimate for actual impingement phenomena involving soft tissues. Instead of evaluating the minimal distance to impingement, another measure could be the relative change of distance to impingement from neutral to any position or the change of minimal distance to impingement between pre- and post-operative alignment.

The definition of a related target zone requires further investigations. What minimum distance to impingement is acceptable? How this should be related to the general clinical status and level of activity of the specific patient? Should the surgeon adapt these target zone on a case by case basis?

Whereas this work addresses the problem of impingement, further aspects have to be considered for implant design and placement. This includes the resulting hip force orientation representing other causes of dislocation [Pedersen et al. 2005; Hsu et al. 2017]. Moreover, patient-specific musculoskeletal conditions influence the amplitude and orientation of the resulting hip force, edge loading and implant wear and thus should be considered for the definition of an optimal patient-specific implant design and placement. The development of methods for including all relevant criteria for patient-specific target zone estimation is part of our ongoing work.

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Disclosures

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