A Multibody Predictive Dynamic Model to Optimize Acetabular Cup Orientation in Total Hip Arthroplasty Surgery Considering Different Spine Stiffness

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EXTENDED ABSTRACT

1 Introduction

Clinical evaluations of patients who have had Total Hip Arthroplasty (THA) have revealed increased dissatisfaction, suggesting that the traditional Lewinnek safe zone may not be suitable for all [1]. Different spinal conditions and stiffness have a direct effect on THA surgery; if the spine is too stiff or rigid, the prosthetic implant may not be properly positioned, leading to joint instability, pain, and even implant failure. Therefore, it is important to assess spine stiffness pre-THA to ensure optimal outcome. Surgeons should consider different spine types and their effect on lower limb motion. Currently, X-ray images are used to plan the surgery but fail to evaluate stiffness; thus, we propose a predictive multibody dynamic simulation, including spine stiffness evaluation, as an alternative to static X-ray analysis. While there are some recommendations for patients with stiff spines in the clinical literature [1], there is no model-based cup orientation analysis for different spinal conditions. We introduced a multibody predictive dynamic approach that can provide subject-specific cup orientation, which ultimately can improve THA outcome.

2 Materials and Methods

A functional lumbar spine unit, with nonlinear ligaments and intervertebral disks (Figure 1), was developed and validated using in-vitro experiments from the literature [3]. This unit was used to develop a 10 degree of freedom multibody sagittal human skeletal model using MapleSim software, featuring 7 DOF for the spine and 3 DOF for the lower limbs (hip, knee, and ankle).

Trajectory optimization was utilized to develop a predictive sit-to-stand human motion simulation that was able to simulate the relative orientations of femur and pelvis for different spinopelvic stiffness and mobility.

$$\min_{x(t),\, u(t)} J_B\left(t_0,\, t_f,\, x(t_0)\,,\, x\left(t_f\right)\right) + \int_{t_0}^{t_f} J_P\left(\tau, x(\tau)\,, u(\tau)\right) d\tau \tag{1}$$

$$J_P = \sum_{i=1}^{n} \int_{t_0}^{t_f} \left(\frac{u_i}{u_i^{max}}\right)^2 + \sum_{i=1}^{n} \int_{t_0}^{t_f} w_i \dddot{x}_i^{\,2}, \tag{2}$$

where J_B are the boundary conditions including kinematics and dynamic constraints, and the integral part (J_P) represents the cost function for this optimization along the motion. Also, u_i are joint torques, $\dddot{x_i}$ are joint jerks, and w_i are weights. We have found that this cost function has the lowest error in the predicted joint angles compared to a motion capture experiment. Angular Distance to Impingement (AID) criteria [2] was employed to optimize the acetabulum implant component anteversion angle (Ant) to prevent impingement by maximizing the AID value at every instance of the motion.

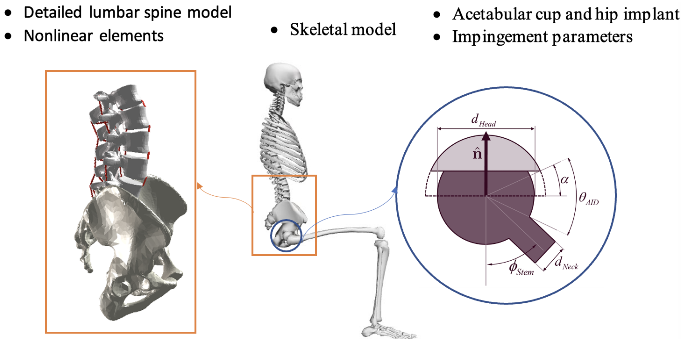

Figure 1: Human skeletal model including a detailed spinopelvic elements and the impingement parameters and AID components.

$$\theta_{\mathrm{AID}} = \frac{\pi}{2} + \alpha - sin^{-1}\left(\frac{d_{neck}}{d_{head}}\right) - \phi_{stem} \tag{3}$$

$$\underset{\beta_{Ant},\beta_{Inc}}{\operatorname{argmax}}\left(\min_{t_0<t<t_f}\theta_{AID}\left(t,\beta_{Ant},\beta_{Inc}\right)\right) \tag{4}$$

where the α, d_{neck}, d_{head}, and ϕ_{stem} are defined in Fig. 1, and β_{Ant}, β_{Inc} are the radiographic cup anteversion and inclination angles respectively. The lower the AID value, the greater the risk of impingement (i.e., $AID \leq 0$ means the impingement accrued).

3 Results

The impingement analysis results for a sit-to-stand motion are shown in Figure 2. The farther away the trajectories are from the red impingement area (higher AID values), the safer the patient is from impingement. This figure shows how treating patients with the clinically recommended values for different categories of patients, rather than patient-specific optimized values, increases impingement risk. Patient-specific cup anteversion is optimized for various spinal conditions and compared to clinical literature [2] (Table 1). The last two columns in the table indicate a lower risk of impingement if surgeons use optimized values.

Table 1: Optimized model cup anteversion values and corresponding calculated AID for different spinopelvic mobilities/stiffnesses in sit-to-stand motion vesus clinically recommended anteversion values [1] and calculated AID.

Spinal type	**Anteversion**			**Inclination**	**AID**	
	model°	mean° [SD](lit)	target° (lit)	target° (lit)	model	lit
Normal spine	23	23 [19-25]	20-25	40-45	26.7	26.4
Anatomical Stiff	28.8	28 [25-33]	25-30	45	20.9	19.8
Long fusion (S1-L5-L4)	34	29 [21-34]	20-30	40-45	27	19.3
Short fusion (S1-L5)	32				26	16.5
Fused-stiff spine (S1-L5-L4)	38	32 [22-40]	25-35	45	28.5	20.3

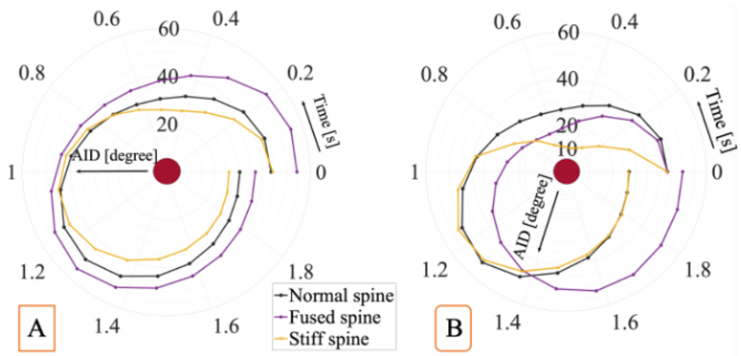

Figure 2: Implant impingement analysis using A: Patient-specific optimized values of anteversion for each spinal condition; B: Mean anteversion values that are clinically recommended for different categories of patients.

4 Discussion and Conclusions

A novel approach is proposed for THA surgery planning using a multibody predictive model. The results are in line with the literature [2]. In addition, the effect of different levels of spine fusion on implant orientation is evaluated (i.e., long or short fusion). The advantage of the predictive model is optimal anteversion values based on subject-specific predictions instead of a wide range of clinical suggestions. Also, the impingement analysis clarified that considering spine stiffness in THA is necessary.

Acknowledgments

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