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Study of the friction-induced vibration and contact mechanics of artificial hip joints

Ehsan Askari [a,b,*], Paulo Flores [b], Danè Dabirrahmani [a], Richard Appleyard [a]

[a] Australian School of Advanced Medicine, Macquarie University, Sydney

[b] Department of Mechanical Engineering, School of Engineering, University of Minho, Portugal

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ABSTRACT

The main objective of this work is to study the effect of friction-induced vibration and contact mechanics on the maximum contact pressure and moment of artificial hip implants. For this purpose, a quasi-static analysis and a multibody dynamic approach are considered. It is shown that the multibody dynamic model is effective at predicting contact pressure distribution and moment of hip implants from both accuracy and time-consuming points of view. Finally, from the computational simulations performed, it can be observed that the friction-induced vibration influences the contact pressure and the moment in hip implants by introducing an oscillating behaviour in the system dynamics.

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1. Introduction

It has been recognised by a good number of researchers that the computation of the pressure distribution and contact area of artificial hip joints during daily activities can play a key role in predicting prosthetic implant wear [1–4]. The Hertzian contact theory has been considered to evaluate the contact parameters, namely the maximum contact pressure and contact area by using the finite element method [1,2]. Mak and his co-workers [1] studied the contact mechanics in ceramic-on-ceramic (CoC) hip implants subjected to micro-separation and it was shown that contact stress increased due to edge loading and it was mainly dependent on the magnitude of cup-liner separation, the radial clearance and the cup inclination angle [3,4]. In fact, Hertzian contact theory can captured slope and curvature trends associated with contact patch geometry subjected to the applied load to predict the contact dimensions accurately in edge-loaded ceramic-on-ceramic hips [5]. Although the finite element analysis is a popular approach for investigating contact mechanics, discrete element technique has also been employed to predict contact pressure in hip joints [6]. As computational instability can occur when the contact nodes move near the edges of the contact elements, a contact smoothing approach by applying Gregory patches was suggested [7]. Moreover, the contributions of individual muscles and the effect of different gait patterns on hip contact forces are of interest, which can be determined by using optimisation techniques and inverse dynamic analyses [8,9]. In addition, contact stress and local temperature at the contact region of dry-sliding couples during wear tests of CoC femoral heads can experimentally be assessed by applying fluorescence microprobe spectroscopy [10]. The contact pressure distribution on the joint bearing surfaces can be used to determine the heat generated by friction and the volumetric wear of artificial hip joints [11,12]. Artificial hip joint moment due to friction and the kinetics of hip implant components may cause prosthetic implant components to loosen, which is one of the main causes of failure of hip replacements. Knee and hip joints' moment values during stair up and sit-to-stand motions can be evaluated computationally [13]. The effect of both body-weight-support level and walking speed was investigated on mean peak internal joint moments at ankle, knee and hip [14]. However, in-vivo study of the friction moments acting on the hip demands more research in order to assess whether those findings could be generalised was carried out [15].

The hypothesis of the present study is that friction-induced vibration and stick/slip friction could affect maximum contact pressure and moment of artificial hip joints. This desideratum is achieved by developing a multibody dynamic model that is able to cope with the usual difficulties of available models due to the presence of muscles, tendons and ligaments, proposing a simple dynamic body diagram of hip implant. For this purpose, a cross section through the interface of ball, stem and lateral soft and stiff tissues is considered to provide the free body diagram of the hip joint. In this approach, the ball is moving, while the cup is

* Corresponding author at: Australian School of Advanced Medicine, Macquarie University, Sydney. Tel.: +61 241 607 3601.

E-mail address: ehsanaskary@gmail.com (E. Askari).

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considered to be stationary. Furthermore, the multibody dynamic motion of the ball is formulated, taking the friction-induced vibration and the contact forces developed during the interaction with cup surface. In this study, the model utilises available information of forces acting at the ball centre, as well as angular rotation of the ball as functions of time during a normal walking cycle. Since the rotation angle of the femoral head and their first and second derivatives are known, the equation of angular momentum could be solved to compute external joint moment acting at the ball centre. The nonlinear governing equations of motion are solved by employing the adaptive Runge–Kutta–Fehlberg method, which allows for the discretisation of the time interval of interest. The influence of initial position of ball with respect to cup centre on both maximum contact pressure and the corresponding ball trajectory of hip implants during a normal walking cycle are investigated. Moreover, the effects of clearance size, initial conditions and friction on the system dynamic response are analysed and discussed throughout this work.

2. Multibody dynamic model of the artificial hip joint

The multibody dynamic model originaly proposed by Askari et al. [16] has been considered here to address the problem of evaluating the contact pressure and moment of hip implants. A cross section *A-A* of a generic configuration of a hip joint is depicted in the diagram of in Fig. 1, which represents a total hip replacement. Fig. 1 also shows the head and cup placed inside of the pelvis and separated from stem and neck. The forces developed along the interface of the ball and stem are considered to act in such a way that leads to a reaction moment, *M*. This moment can be determined by satisfying the angular motion of the ball centre during a walking cycle. The available data reported by Bergmann et al. [17] is used to define the forces that act at the ball centre. This data was experimentally obtained by employing a force transducer located inside the hip neck of a live patient. The information provided deals with the angular rotation and forces developed at the hip joint. Thus, the necessary angular velocities and accelerations can be obtained by time differentiating the angular rotation. Besides the 3D nature of the global motion of the hip joint, in the present work a simple 2D approach is presented, which takes into account the most significant hip action, i.e. the flexion-extension motion. With regard to Fig. 2 the translational and rotational equation of motion of the head, for both free flight mode and contact mode, can be written by employing the Newton–Euler's equations [18,19], yielding

$$\sum M_O \mathbf{k} = I\ddot{\theta}\mathbf{k}, \quad \sum \mathbf{M}_O = \begin{cases} M\mathbf{k} - (R_j)\mathbf{n} \times \mathbf{F}^t_{P_j} & \delta > 0 \\ M\mathbf{k} & \delta \le 0 \end{cases} \tag{1}$$

$$\sum F_X = m\ddot{x}, \quad \sum F_X = \begin{cases} f_x + (\mathbf{F}^t_{P_j} + \mathbf{F}^n_{P_j}) \cdot \mathbf{i} & \delta > 0 \\ f_x & \delta \le 0 \end{cases} \tag{2}$$

$$\sum F_Y = m\ddot{y}, \quad \sum F_Y = \begin{cases} f_y + (\mathbf{F}^n_{P_j} + \mathbf{F}^t_{P_j}) \cdot \mathbf{j} - mg & \delta > 0 \\ f_y & \delta \le 0 \end{cases} \tag{3}$$

where $\mathbf{F}^n_{P_j}$ and $\mathbf{F}^t_{P_j}$ denote the normal and tangential contact forces developed during the contact between the ball and cup, as it is represented in the diagram of Fig. 3. In Eqs. (1)–(3), x, y and θ are the generalised coordinates used to define the system's configuration. In turn, variable m and I are the mass and moment of inertia of ball, respectively. The external generalised forces are denoted by f_x, f_y and M and they act at the centre of the ball as it is shown in Fig. 3. The gravitational acceleration is represented by parameter g, R_j is the ball radius and δ represents relative penetration depth between the ball and cup surfaces.

The penetration depth can be expressed as [20]

$$\delta = r - (R_b - R_j) \tag{4}$$

in which R_b denotes the cup radius and $(R_b - R_j)$ represents the joint radial clearance, which is a parameter specified by user.

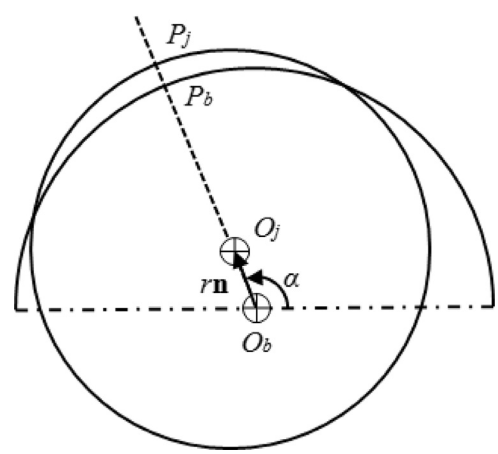

Fig. 2. A schematic of the head and cup interaction observed in the Sagittal plane.

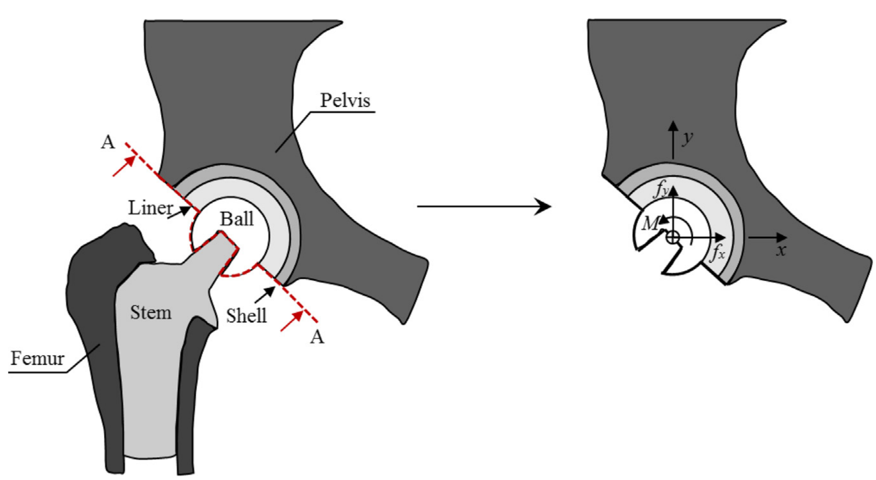

Fig. 1. A schematic of the artificial hip implant with the cross section *A-A* (Left figure), and the head and cup separated from the neck and stem through the cross section *A-A* (Right figure).

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