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A finite element study on the mechanical response of the head-neck interface of hip implants under realistic forces and moments of daily activities: Part 1, level walking

Hamidreza Farhoudi, Khosro Fallahnezhad, Reza H. Oskouei*, Mark Taylor

The Medical Device Research Institute, Flinders University, Adelaide, Australia

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ABSTRACT

This paper investigates the mechanical response of a modular head-neck interface of hip joint implants under realistic loads of level walking. The realistic loads of the walking activity consist of three dimensional gait forces and the associated frictional moments. These forces and moments were extracted for a 32 mm metal-on-metal bearing couple. A previously reported geometry of a modular CoCr/CoCr head-neck interface with a proximal contact was used for this investigation. An explicit finite element analysis was performed to investigate the interface mechanical responses. To study the level of contribution and also the effect of superposition of the load components, three different scenarios of loading were studied: gait forces only, frictional moments only, and combined gait forces and frictional moments. Stress field, micro-motions, shear stresses and fretting work at the contacting nodes of the interface were analysed. Gait forces only were found to significantly influence the mechanical environment of the head-neck interface by temporarily extending the contacting area (8.43% of initially non-contacting surface nodes temporarily came into contact), and therefore changing the stress field and resultant micro-motions during the gait cycle. The frictional moments only did not cause considerable changes in the mechanical response of the interface (only 0.27% of the non-contacting surface nodes temporarily came into contact). However, when superposed with the gait forces, the mechanical response of the interface, particularly micro-motions and fretting work, changed compared to the forces only case. The normal contact stresses and micro-motions obtained from this realistic load-controlled study were typically in the range of 0–275 MPa and 0–38 μm, respectively. These ranges were found comparable to previous experimental displacement-controlled pin/cylinder-on-disk fretting corrosion studies.

1. Introduction

Contemporary modular designs of Total Hip Replacement (THR) is a successful solution for surgeons to cope with various anatomies of different patients. Modular THRs also offer the option of replacing only the failed components and keeping the others in place during revision surgeries (Krishnan et al., 2013). In spite of these advantages, modular THRs have suffered from an increasing number of failures which in part are caused by adverse local tissue reaction from metallosis and pseudotumors (Hussenbocus et al., 2015; Korovessis et al., 2006). Histological studies have shown the presence of corrosion products and metal ions in the local tissues surrounding metallic modular junctions (Hart et al., 2010, 2009; Huber et al., 2009). Fretting corrosion is known to occur at the head-neck taper junction of THRs and has been identified as the main cause of metal ion release to the surrounding tissues (Cooper et al., 2012; Higgs et al., 2013a). Fretting corrosion is understood to be a function of a range of parameters such as loading condition, contact geometry, stress field at the interface, relative micro-motion, characteristics of the contacting materials and corrosivity of the environment (Bryant, 2013). Fretting is identified as the initiator of the fretting corrosion phenomenon also termed as mechanically assisted crevice corrosion in modular junctions (Swaminathan and Gilbert, 2012). Fretting itself is a function of a variety of parameters, in particular stress field, micro-motion amplitude, frequency and number of cycles (Berthier et al., 1989).

The mechanical environment at the head-neck junction is complex and is subjected to forces and frictional moments. These vary with time, type of physical activity, characteristics of the patient and implant geometric and material properties (Bergmann et al., 2010; Bishop et al., 2008; Farhoudi et al., 2015). Due to its complexity, *in vitro* studies mostly apply the loads in a simplified, two degree of freedom (DoF) system, commonly sliding tests with a representative vertical load as

* Corresponding author.
E-mail address: reza.oskouei@flinders.edu.au (R.H. Oskouei).

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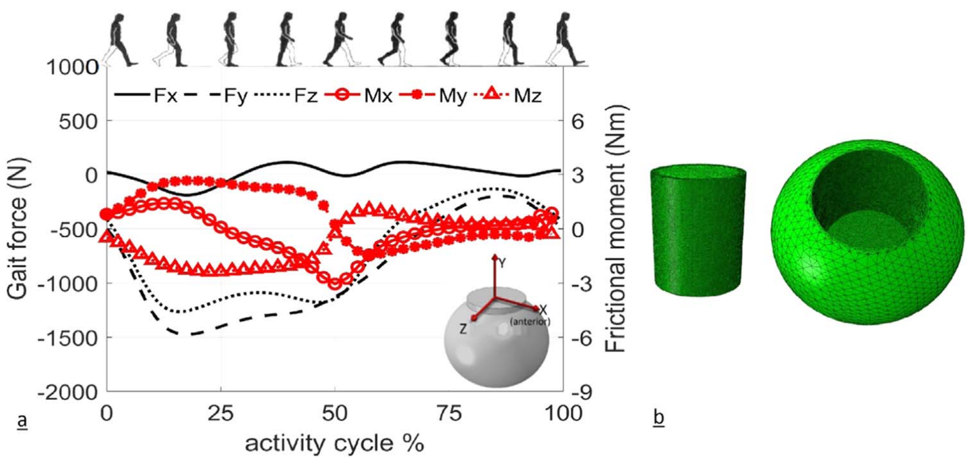

Fig. 1. (a) Input gait forces and frictional moments for a normalized walking gait cycle presented in a coordinate system at the bottom face of the neck (end-of-neck coordinate system) for right hip, and (b) finite element models of head and neck with a meshing structure gradually refined towards the contact interface.

the most important component of the resultant load (Gilbert et al., 2009; Goldberg and Gilbert, 2003; Panagiotidou et al., 2015).

Studies have reported that frictional moment can also contribute to the fretting corrosion of modular head-neck interface. Panagiotidou et al. (2015) reported that increasing the unidirectional frictional torque on the neck axis (0 Nm, 9 Nm, 14 Nm, and 18 Nm) increases the depassivation current of the interface significantly. Jauch et al. (2014) monitored the disruption of the passive oxide layer due to the applied torque about the head-neck axis; and therefore, initiation of fretting corrosion. They reported that with an increase in the assembly force of the taper junction from 4.5 to 6 kN, the fretting corrosion initiation torque increased from 3.92 ± 0.97 Nm to 7.23 ± 0.55 Nm. In another study, Jauch et al. (2016) investigated the overall micro-motion in different head-neck combinations subjected to a unidirectional sinusoidal loading with a maximum magnitude occurring during walking (2.3 kN), stair climbing (4.3 kN) and stumbling (5.3 kN). The micro-motions varied between 3.3 μm and 33.4 μm and increased with rising the peak forces.

To better understand fretting at the head-neck junction, the mechanical environment of the junction needs to be studied in terms of contact pressure, contact length and relative micro-motions. Finite element analysis (FEA) is found to be a cost effective method for this purpose (English et al., 2015; Donaldson et al., 2014). Fallahnezhad et al. (2016) developed a three dimensional finite element (FE) model to investigate the torsional strength of a head-neck taper junction with different material combinations. They reported that under the same assembly force, a greater contact length shapes between a CoCr head and titanium neck compared to a CoCr head and CoCr neck, and consequently the CoCr/Ti combination had a higher torsional strength. Donaldson et al. (2014) developed a stochastic FEA to evaluate the effective parameters on the frictional work over a cycle (fretting work) in a head-neck taper junction based on the forces of level gait. They concluded that the major parameters that effectively contribute to the value of fretting work are taper angle mismatch, centre offset and body weight. It was also reported that every 0.1° increase in the mismatch angle can increase the contact pressure by 85 MPa. To verify their model, they applied an assembly force at 45° off-axis to two sets of head-neck junction made of Al 6061 at a 3:1 size scale. As raised in their paper, for a single case study (not stochastic) a more accurate validation is required for realistic predictions. Dyrkacz et al. (2015) developed a 3D FE model to seek the parameters that can affect relative micro-motions in the taper junction. Their study revealed that assembly force, taper size and materials combination play an important role in changing the micro-motion values. However, in their model, the angular mismatch between the head and neck components was neglected while it has a significant effect on the contact pressure and micro-motions (Donaldson et al., 2014).

In addition to the previously available contact forces (Bergmann et al., 2010, 1993; English and Kilvington, 1979), head-cup frictional moments have recently become available for walking activity (Farhoudi et al., 2016; Damm et al., 2013). This provides 6 DoF load inputs including three force components and three moment components (Farhoudi et al., 2016). However, the contribution of the frictional moments to the stress field, relative displacements between the contacting surfaces and consequently fretting wear behaviour has not been reported yet.

Benefiting from the available 6 DoF load inputs, in this study, a finite element analysis of a head-neck taper junction of an implant was conducted in three different loading conditions which include level walking gait forces only (F only), level walking frictional moments only (M only) and combined gait forces and frictional moments (F & M). This was to carefully evaluate the contribution of frictional moments to the fretting wear related parameters at the interface. The results of this study present a perspective of dynamic stress field and micro-motion at the head-neck interface of the modelled geometry and materials during level gait.

2. Methods

A previously established and verified three dimensional (3D) finite element model of an isolated head-neck junction (Fallahnezhad et al., 2016) was further developed to simulate and apply currently available 6 DoF load inputs of level gait. The model consisted of a 12/14 taper design having a 32 mm diameter CoCr head and a CoCr neck with a proximal angular mismatch (head taper angle = 2.858°, neck taper angle = 2.834°, angular mismatch = 0.024° (Rehmer et al., 2012)). The nodes located at the external surface of the head were constrained in all directions. The assembly force (4 kN) and the load components of level gait were applied to the bottom face of the neck. The forces were obtained from Hip98 software (Bergmann et al., 2010) and the frictional moments were calculated from a previous study for a 32 mm metal-on-metal bearing couple (Farhoudi et al., 2016), as shown in Fig. 1a. The maximum magnitude of the frictional moments in this 32 mm metal-on-metal bearing (with a friction coefficient of 0.20) was found to be 3.68 Nm. For comparison purposes, the average of maximum frictional moments from 10 patients with a 32 mm ceramic-on-polyethylene bearing was reported as 2.15 Nm with a maximum friction coefficient of 0.19. The highest individual moment was also reported as 4.28 Nm (Damm et al., 2017). This indicates that the frictional moments used in the present work are comparable to the available *in-vivo* measurements with similar maximum friction coefficients; however, material combination for the head-neck interface can of course influence the fretting wear related parameters in the junction.

Both the gait force and frictional moment components were sampled over 100% of a normalized gate cycle (0 for initial contact and 100 for terminal swing) and were applied to the end-of-neck coordinate system.