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Optimal acetabular component orientation estimated using edge-loading and impingement risk in patients with metal-on-metal hip resurfacing arthroplasty

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ABSTRACT

Edge-loading in patients with metal-on-metal resurfaced hips can cause high serum metal ion levels, the development of soft-tissue reactions local to the joint called pseudotumours and ultimately, failure of the implant. Primary edge-loading is where contact between the femoral and acetabular components occurs at the edge/rim of the acetabular component whereas impingement of the femoral neck on the acetabular component's edge causes secondary or contrecoup edge-loading. Although the relationship between the orientation of the acetabular component and primary edge-loading has been identified, the contribution of acetabular component orientation to impingement and secondary edge-loading is less clear. Our aim was to estimate the optimal acetabular component orientation for 16 metal-on-metal hip resurfacing arthroplasty (MoMHRA) subjects with known serum metal ion levels. Data from motion analysis, subject-specific musculoskeletal modelling and Computed Tomography (CT) measurements were used to calculate the dynamic contact patch to rim (CPR) distance and impingement risk for 3416 different acetabular component orientations during gait, sit-to-stand, stair descent and static standing. For each subject, safe zones free from impingement and edge-loading (CPR $<10\%$) were defined and, consequently, an optimal acetabular component orientation was determined (mean inclination 39.7° (SD 6.6°) mean anteversion 14.9° (SD 9.0°)). The results of this study suggest that the optimal acetabular component orientation can be determined from a patient's motion and anatomy. However, 'safe' zones of acetabular component orientation associated with reduced risk of dislocation and pseudotumour are also associated with a reduced risk of edge-loading and impingement.

1. Introduction

Metal-on-metal hip resurfacing arthroplasty (MoMHRA) became an established surgical option in the late 1990 s/early 2000 s, particularly for the young active patient with end-stage hip disease. In England and Wales in 2006, 10% of all primary total hip replacements performed were MoMHRA. However, subsequent concerns about high revision rates and soft tissue reactions meant that by 2012 usage had fallen to 1%.

Occurrence of soft tissue or fluidic masses local to the hip joint (pseudotumour (Pandit et al., 2008a), adverse reaction to metal debris (Langton et al., 2010)), aseptic lymphocytic vasculitis associated lesions (Willert et al., 2005), adverse local tissue reaction (Schmalzried, 2009)) are associated with high blood, serum and hip aspirate levels of cobalt (Co) and chromium (Cr); the principal elements of the metal alloy used to manufacture MoMHRA implants (De Smet et al., 2008a; Kwon et al., 2009; Langton et al., 2009a). This indicates these reactions are associated with increased levels of wear. Retrieval studies have confirmed that implants revised for pseudotumour have higher wear than implants revised for other reasons (Kwon et al., 2010). Retrieval studies have also shown that implants revised for pseudotumour are more likely to have experienced edge-loading (Kwon et al., 2010; Langton et al., 2011).

Primary edge-loading is the result of contact between the femoral and acetabular components at the edge of the acetabular component while contact between the femoral neck and the cup edge causes secondary or contrecoup edge-loading. The occurrence of primary edge-loading has shown an association with acetabular component orientation (De Haan et al., 2008b). The risk of pseudotumour is reduced for an acetabular component orientation of 45° (±10°)

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inclination and 20° (±10°) anteversion (Grammatopoulos et al., 2011). This relationship between acetabular component orientation and risk of edge-loading has been further highlighted by studies that have calculated the distance of the hip contact force vector from the edge of the acetabular component (contact patch to rim distance). This has been carried out using two methods: by using the average hip contact force (HCF) vector of four subjects with instrumented prostheses standing (Bergmann et al., 2001) and calculating the 3D position of the acetabular component from Computed Tomography (CT) scans or radiographs (Langton et al., 2009b; Matthies et al., 2014; Yoon et al., 2013) or by carrying out motion analysis and CT scans of subjects and musculoskeletal modelling to define the HCF vector for activities of daily living (Mellon et al., 2013).

The contribution of secondary edge-loading (impingement) to wear of metal-on-metal hip resurfacing arthroplasty (MoMHRA) is more difficult to determine and consequently fewer studies have investigated this. Radiographic signs of impingement have been shown to have an association with elevated serum ion levels of cobalt and chromium but only in combination with poor acetabular component orientation (Le Duff et al., 2014).

The relationship between component positioning and the occurrence of high metal ion levels and/or pseudotumours is not clear-cut. Subjects with "well-placed" components have developed pseudotumours, albeit it in small numbers (Donell et al., 2010; Grammatopoulos et al., 2011; Kwon et al., 2011; Matthies et al., 2012) and some patients with mal-positioned components avoid high metal ion levels (Grammatopoulos et al., 2011; Matthies et al., 2012). The reasons for this are unclear although it has been suggested that high wear and/or the occurrence of pseudotumours are associated with other factors such as implant design, metal hypersensitivity (Pandit et al., 2008b), or an individual's motion patterns (Mellon et al., 2013).

The aim of this study was to identify the optimal acetabular component orientation for a group of MoMHRA patients based on primary edge-loading and impingement (secondary edge-loading) risk calculated dynamically for four activities of daily living.

2. Method: patients

In an on-going study, a cohort of 158 (201 hips) MoMHRA patients has their serum metal ion levels measured regularly. Sixteen subjects (seven females and nine males) from this 158 with unilateral MoMHRA with metal ion levels that represented the range of the whole cohort responded to a written request and agreed to participate in the current IRB approved study. The subjects had either a Birmingham Hip Resurfacing (BHR) (Smith and Nephew, Birmingham, UK) ($n=8$) or a Conserve Plus (Wright Medical Technology, Memphis, TN, USA) hip resurfacing ($n=8$). The Laboratory of Clinical Biology, University Hospital Ghent, Belgium used inductively-coupled plasma mass spectrometry (ELAN DRC II, PerkinElmer Life and Analytical Sciences, Shelton, CT, USA) to determine the subjects' serum levels of cobalt and chromium (De Smet et al., 2008b).

3. Method: motion analysis

A laboratory equipped with 12 camera Vicon MX system (Oxford Metrics Ltd., Oxford, UK) and three force platforms (2 × OR6 AMTI R6–6–1000, 1 × OR6 AMTI R6–7–1000, Advanced Medical Technology Inc., MA, USA) was used to conduct motion analysis. An established (Kadaba et al., 1990) marker configuration with extra markers on the medial femoral condyles, the tibial tuberosities, the medial malleoli, the distal 5th and 1st metatarsals was used (25 markers total).

The subjects' motion was measured during four activities of daily living (ADL): walking, sit-to-stand, static standing and stair descent. Kinematic and force plate data were collected with a sampling rate of 100 Hz and 1000 Hz, respectively.

4. Method: computed tomography (CT) scans

Immediately following motion analysis, retro-reflective motion analysis markers were removed and replaced with radio-opaque markers and CT scans (Siemens Somatom, Siemens Medical Solutions USA, Inc., NY, USA) of each subject's pelvis and lower limbs were obtained. The 3D coordinates of the markers, the anatomical pelvic landmarks, the MoMHRA components, the points around the femoral neck and hip joint centre were determined (SliceOmatic, V4.2, TomoVision, Virtual Magic Inc., Montreal, Canada).

5. Method: musculoskeletal modeling

Subjects were modeled performing static standing, gait, sit-to-stand and stair descent in the AnyBody Modeling System (v.5.0, AnyBody Technology A/S, Aalborg, Denmark). Each model incorporated subject-specific hip joint centres (HJC) derived from the individual CT scans, as well as nonlinear scaling methods to adapt the lower limb model to a given geometry. The musculoskeletal model used a three-stage procedure. Firstly, the patient-specific joint kinematics were estimated based on a stick-figure model constructed from the standing reference frame and the estimated HJCs. Secondly, the Twente Lower Extremity Model (TLEM) (Klein Horsman et al., 2007) implemented in the AnyBody Managed Model Repository v.1.2 was non-linearly morphed using Radial Basis Functions (RBF) (Lund, 2011) to match the segment lengths, joint parameters of the stick-figure model and subject-specific pelvis bony landmarks (ASIS and PSI) and estimated hip joint centres estimated from the CT scan. Inverse dynamic analysis was performed for the morphed TLEM model with the measured ground reaction forces as external loads and polynomial muscle recruitment criterion of power 3 to estimate muscle and joint contact forces (Klein Horsman et al., 2007). The capsular ligaments were not included in the model.

6. Method: edge-loading & impingement risk

Edge-loading and impingement risk was determined for all possible cup orientations, in 1° intervals, between 20° and 80° inclination and -15° and 40° anteversion (3,416 orientations). The edge-loading risk for every orientation was determined using the Contact Patch to Rim (CPR) distance. The CPR distance is the location of the intersection of the HCF with the inner surface of the acetabular component relative to the edge/rim of the component. The point of intersection is assumed to be the centre of the contact patch between the two components. All CON implants were modeled with an acetabular component with a coverage angle (α) of 170° and a diametrical clearance of 173 μm (Campbell et al., 2006). The coverage angle for the BHR acetabular component was dependent on the size of the implant and varied from 159.1° to 166.2° (Board and Walter, 2010).

The CPR distance was calculated for each subject for gait, stair descent, static standing and sit-to-stand. The analysis was limited to the periods during the dynamic activities when loads were highest, that is, stance phase during gait and stair descent and after seat-off for sit-to-stand. CPR distance was calculated as a percentage of half the inner circumference of the acetabular component to allow comparison between subjects with different sized components. At each acetabular component orientation, the lowest CPR distance out of the three ADLs was recorded.