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Computer-based estimation of the hip joint reaction force and hip flexion angle in three different sitting configurations

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ABSTRACT

Sitting is part of our daily work and leisure activities and can be performed in different configurations. To date, the impact of different sitting configurations on hip joint loading has not been studied. We therefore evaluated the hip joint reaction force (HJRF) and hip flexion angle in a virtual representative male Caucasian population by means of musculoskeletal modelling of three distinct sitting configurations: a simple chair, a car seat and a kneeling chair configuration. The observed median HJRF in relation to body weight and hip flexion angle, respectively, was 22.3% body weight (%BW) and 63° for the simple chair, 22.5%BW and 79° for the car seat and 8.7%BW and 50° for the kneeling chair. Even though the absolute values of HJRF are low compared to the forces generated during dynamic activities, a relative reduction of over 50% in HJRF was observed in the kneeling chair configuration. Second, the hip flexion angles were both in the kneeling chair (−29°) and simple chair configuration (−16°) lower compared to the car seat and, as such, did not reach the threshold value for femoroacetabular conflict. In conclusion, the kneeling chair appears to hold the greatest potential as an ergonomic sitting configuration for the hip joint.

1. Introduction

Throughout history, mankind has gradually evolved from an active hunter-gatherer lifestyle to a sedentary lifestyle (Redman, 1978; Scarre, 2005). In the current western society, this sedentary evolution has led to self-reported median sitting times of approximately 5 h per day (Loyen et al., 2016). Sitting is performed in different configurations, often for long periods of time and in the context of both occupational and leisure activities. Prolonged sitting is thought to be associated with a high risk of developing self-reported musculoskeletal disorders (Hallman et al., 2015; Szeto and Lam, 2007). The annual prevalence of self-reported musculoskeletal discomfort in office workers amounts to 63% with mostly spinal complaints but also hip symptoms in up to 6% (Janwantanakul et al., 2008). While the impact of sitting has been studied in detail on loading and kinematics of the spine, the hip has not previously been the subject of such analysis.

High hip flexion sitting, such as in a car seat, is a challenging position in which the proximal femur is pushed towards the acetabulum (Ganz et al., 2008; Parvizi et al., 2007; Philippon et al., 2007b). In some hips with morphology exhibiting a prominent anterolateral head-neck transition, it has been shown that femoroacetabular contact occurs as early as 79.8° of hip flexion (Audenaert et al., 2011). Prominent shape of the proximal femur and/or acetabulum resulting in early collisions is a pathomechanical condition known as femoroacetabular impingement (FAI). Finite element analysis of the hip joint from standing to sitting has revealed up to three times higher shear stress in cam type FAI hip joints compared to controls (Chegini et al., 2009). The repetitive and persistent nature of this mechanical conflict and the associated higher stress in FAI lead to cartilage and labral damage (Ganz et al., 2008). The resulting intra-articular damage is responsible for hip pain of which FAI patients often complain during prolonged sitting, especially in low car seats (Larson and Giveans, 2008; Parvizi et al., 2007; Philippon et al., 2007a). With a reported radiographic prevalence of FAI at-risk signs of 30–70% in the Caucasian population (Frank et al., 2015; Jung et al., 2011; Kapron et al., 2011; Van Houcke

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et al., 2015) and a likely association with hip osteoarthritis development (Ganz et al., 2003, 2008; Reid et al., 2010), FAI represents a relevant disease burden (Agricola and Weinans, 2016).

To date, ergonomic studies of sitting configurations have mainly focused on lumbar posture and sitting comfort in general (Amick et al., 2003; Bettany-Saltikov et al., 2008; Ijmker et al., 2007; Schmidt et al., 2014). Up untill now, the hip joint has not been the subject of such analysis. Therefore, the aim of this article was to provide initial insight into hip joint loading and kinematics in three distinct sitting configurations that are relevant to daily life situations and that represent the full hip flexion spectrum. First, we evaluated the resulting hip joint reaction force (HJRF) in standard kneeling chair, simple chair and car seat configuration. Secondly, we analyzed the hip flexion angle that is required to maintain each of the three sitting configuration. Third, this study aimed to validate three musculoskeletal models that were built to evaluate the loading and kinematics of the hip joint during sitting. We hypothesize that the kneeling chair configuration would result in the lowest hip flexion and HJRF.

2. Materials and methods

2.1. Approach

The study was designed as a theoretical experimental study with computational analysis of the resulting hip flexion angle and HJRF during static sitting configurations. Three commonly used sitting configurations were evaluated: simple chair, car seat and kneeling chair. In each configuration, the HJRF and hip flexion angle in the right hip were calculated in a virtual representative adult male Caucasian population based on anthropometric measurements from the United States NHANES survey (CDC, 2016). (Table 1).

The Anybody Modelling system (Anybody Technology, version 6.0, Aalborg, Denmark), which has been validated for estimating HJRF (Manders et al., 2008), was chosen for this purpose.

2.2. The Anybody Modelling system

The Anybody Modelling system is a multibody dynamics model consisting of rigid bodies, joints, drivers and force-moment actuators (muscles) that have to be determined. The system can solve the associated equilibrium equations with an *inverse dynamics* approach: the external forces and motions are known and the internal forces have to be computed (Damsgaard et al., 2006).

2.3. Seated anybody model

The seated application model, previously developed by Rasmussen et al. (2009b). to provide a rational basis for the development of ergonomic chairs, was used as a starting point for modelling three different sitting configurations. The application model works with the AAUHuman body model, composed of validated sub-models (de Zee et al., 2007a; de Zee et al., 2007b; Klein Horsman, 2007; Van der Helm, 1994). This computational seated human model has been validated to reliably predict reaction forces with change in seated posture (Olesen et al., 2009). All model segments are defined as rigid bodies with mass properties corresponding to both bone mass and the proportional soft tissue mas. Body weight and height were used as input variables. The distribution of body weight per segment was calculated according to Winter (Winter, 2009). The joints are frictionless and link segments using a spherical joint for the hip and hinge joints for knee and ankle. The muscles are defined isometrically as strings through “via points” wrapping over surfaces.

The chair is located in the environment of the application model, and depending on the desired sitting configuration, the backrest, leg rest and/or footrest are included. The seated body model automatically follows the chair components due to kinematic links made between the chair and the human model. The thorax is linked to the backrest, the pelvis is linked to the seat pan and both feet are linked to the footrest.

Table 1
Percentile scaled anthropometric measurements of the US male Caucasian population according to the NHANES anthropometric data report 2011–2014 (CDC, 2016).

Percentile	Weight (kg)	Height (m)
5	78.9	1.66
10	81.3	1.68
15	82.9	1.70
25	85.3	1.72
50	90.0	1.77
75	95.1	1.82
85	98.0	1.85
90	100.0	1.86
95	102.8	1.89

2.3.1. Muscle recruitment criterion

Muscle recruitment in inverse dynamics is the process of determining which set of muscle forces will balance a given external load. However, the computation of individual muscle forces is hampered by the *muscle redundancy problem*, because there are more muscles available than are strictly necessary to drive motion in a certain joint. As such, there are not enough equilibrium equations available to calculate the individual muscle forces. Hypothetically, among the possible muscle recruitment solutions, the one with the least amount of muscle forces necessary would be preferred. The equation is therefore approached with an optimization based on muscle recruitment. In this case, the quadratic muscle recruitment criterion was chosen because of its good performance in calculating joint reaction forces in static configurations (Rasmussen et al., 2009a):

Minimize function:

$$G\left(f^{(M)}\right) = \sum_{i=1}^{n^{(M)}} \left(\frac{f_i^{(M)}}{N_i}\right)^2 \tag{1}$$

Subjected to the following constraints:

$$Cf = d \tag{2}$$

$$f_i^{(M)} \geq 0, \quad i \in \left\{1, \ldots, n^{(M)}\right\} \tag{3}$$

The objective function G describes the minimization of a quadratic combination of muscle forces $f_i^{(M)}$ involved, where N_i is the strength of muscle number $_i$. The quadratic criterion penalizes large terms in the sum of all muscle forces and as such distributes the load over several muscles instead of favouring one muscle to generate all the force (Eq. (1)). Eq. (2) defines the dynamic equilibrium equations where C is the coefficient matrix for the unknown forces f, whereas d represents all known applied loads and inertia forces. The condition in Eq. (3) states that muscles can only pull, not push. The quadratic criterion does not take overloading of the muscles into account. Since muscles physiologically cannot reach activity levels above 100%, an additional constraint is defined preventing the activation of the muscles from exceeding 100%.

2.3.2. Contact definition - friction

In real life, the body is supported by the chair generating