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An open source lower limb model: Hip joint validation

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ABSTRACT

Musculoskeletal lower limb models have been shown to be able to predict hip contact forces (HCFs) that are comparable to *in vivo* measurements obtained from instrumented prostheses. However, the muscle recruitment predicted by these models does not necessarily compare well to measured electromyographic (EMG) signals.

In order to verify if it is possible to accurately estimate HCFs from muscle force patterns consistent with EMG measurements, a lower limb model based on a published anatomical dataset (Klein Horsman et al., 2007. Clinical Biomechanics. 22, 239–247) has been implemented in the open source software OpenSim. A cycle-to-cycle hip joint validation was conducted against HCFs recorded during gait and stair climbing trials of four arthroplasty patients (Bergmann et al., 2001. Journal of Biomechanics. 34, 859–871). Hip joint muscle tensions were estimated by minimizing a polynomial function of the muscle forces. The resulting muscle activation patterns obtained by assessing multiple powers of the objective function were compared against EMG profiles from the literature. Calculated HCFs denoted a tendency to monotonically increase their magnitude when raising the power of the objective function; the best estimation obtained from muscle forces consistent with experimental EMG profiles was found when a quadratic objective function was minimized (average overestimation at experimental peak frame: 10.1% for walking, 7.8% for stair climbing).

The lower limb model can produce appropriate balanced sets of muscle forces and joint contact forces that can be used in a range of applications requiring accurate quantification of both. The developed model is available at the website https://simtk.org/home/low_limb_london.

1. Introduction

Musculoskeletal models of the lower limb have been developed and used to investigate the biomechanics of the hip (Crowninshield et al., 1978), muscle architecture with respect to force generation (Arnold et al., 2010) and to aid in surgical considerations (Delp et al., 1990) including preclinical implant testing (Heller et al., 2001). The geometrical data used to implement these models have generally been inferred from anatomy books e.g. Seireg and Arvikar (1973) or cadaveric measurements e.g. Brand et al. (1982). Recently a new set of anatomical data was collected by Klein Horsman et al. (2007) on a single specimen. They applied the criterion of mechanical equivalence proposed by Van der Helm and Veenbaas (1991) to muscle discretization and reported muscle attachment positions. Joint kinematics and muscle contraction parameters were also measured, making this dataset particularly suitable for musculoskeletal model implementation. Models derived from this data have already been used and published (Klein Horsman, 2007; Cleather and Bull, 2010) although to the authors' knowledge only qualitative validation of the resulting models has so far been conducted (Koopman and Klein Horsman, 2008).

Two standard forms of validation are used in these models: the first is a direct measure of hip contact forces (HCFs), the internal forces transferred between the femoral head and the acetabulum of the pelvis, from instrumented implants taking measurements at the femoral head (Rydell, 1966; Davy et al., 1988; Bergmann et al., 2001) and the second is the use of electromyographic signals (EMGs) as a surrogate for muscle force and activation patterns (Seireg and Arvikar, 1975; Pedersen et al., 1987; Glitsch and Baumann, 1997; Lenaerts et al., 2008).

Several investigators in the literature calculated HCFs (Paul, 1965; Seireg and Arvikar, 1975; Crowninshield et al., 1978; Hardt, 1978; Röhrle et al., 1984; Pedersen et al., 1987; Glitsch and Baumann, 1997; Lenaerts et al., 2008) but only a few of them (Brand et al., 1994; Lu et al., 1997; Heller et al., 2001; Stansfield et al., 2003) validated their model against experimental measurements obtained through instrumented prostheses. Considering just the studies based on hip joint instrumented prostheses, Brand et al. (1994) validated their model using a nonlinear optimization approach but the

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