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Sensitivity of intervertebral joint forces to center of rotation location and trends along its migration path

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ABSTRACT

Translational vertebral motion during functional tasks manifests itself in dynamic loci for center of rotation (COR). A shift of COR affects moment arms of muscles and ligaments; consequently, muscle and joint forces are altered. Based on posture- and level-specific trends of COR migration revealed by in vivo dynamic radiography during functional activities, it was postulated that the instantaneous COR location for a particular joint is optimized in order to minimize the joint reaction forces. A musculoskeletal multi-body model was employed to investigate the hypotheses that (1) a posterior COR in upright standing and (2) an anterior COR in forward flexed posture leads to optimized lumbar joint loads. Moreover, it was hypothesized that (3) lower lumbar levels benefit from a more superiorly located COR.

The COR in the model was varied from its initial position in posterior-anterior and inferior-superior direction up to ±6 mm in steps of 2 mm. Movement from upright standing to 45° forward bending and backwards was simulated for all configurations. Joint reaction forces were computed at levels L2L3 to L5S1. Results clearly confirmed hypotheses (1) and (2) and provided evidence for the validity of hypothesis (3), hence offering a biomechanical rationale behind the migration paths of CORs observed during functional flexion/extension movement. Average sensitivity of joint force magnitudes to an anterior shift of COR was +6 N/mm in upright and −21 N/mm in 30° forward flexed posture, while sensitivity to a superior shift in upright standing was +7 N/mm and −8 N/mm in 30° flexion. The relation between COR loci and joint loading in upright and flexed postures could be mainly attributed to altered muscle moment arms and consequences on muscle exertion. These findings are considered relevant for the interpretation of COR migration data, the development of numerical models, and could have an implication on clinical diagnosis and treatment or the development of spinal implants.

1. Introduction

Given the infeasibility of directly and non-invasively measuring forces within the lumbar spine in vivo, they are usually inferred from kinematics-driven biomechanical models such as *linked segment*–, *finite element*– or *multi-body models* (Abouhossein et al., 2011; Cholewicki et al., 1991; Christophy et al., 2012; Daggfeldt and Thorstensson, 2003; De Zee et al., 2007; Han et al., 2013b; Schultz et al., 1982). Since biomechanical model output is highly sensitive to kinematic inputs, a high degree of accuracy in the kinematic input is particularly imperative. One key kinematic input parameter is the definition of a so-called center of rotation (COR) between intervertebral segments around which relative segment motion can be described in terms of rotation around this center in anatomical three planes.

Several studies have shown that lumbar segments exhibit coupled translations associated with rotational movement. Mapping the migration path of the instantaneous centers of rotation (ICRs) between two adjacent vertebrae over a given motion – the centrode – has been shown to be a reasonable way to quantitatively describe such coupled motion (Aiyangar et al., 2017; Gertzbein et al., 1984; Ogston et al., 1986). More importantly, the ICR have been shown to have a biological basis linking aberrations in its location to anatomical and pathological factors (Bogduk et al., 1995; Schneider et al., 2005), based on its strong association with the center of reaction (Gracovetsky et al., 1987; Zander et al., 2016). Despite this evidence, a fixed center three-degree-of-

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freedom (DOF) rotational joint with a fixed COR that approximates an average location has been the *choice de rigueur* for representing the intervertebral disc joint (Bruno et al., 2015a; Christophy et al., 2012; De Zee et al., 2007). This compromise in using an averaged, fixed COR in biomechanical models is often forced by a lack of robust data from which migration patterns of the instantaneous centers of rotation can be extracted (De Zee et al., 2007). This shortcoming can be at least attributed to the according lack of accurate means to map these patterns during spinal movement (Crisco et al., 1994; Pearcy and Bogduk, 1988) and partly due to a lack of quantification of the biomechanical implications of simplifying a 6 DOF motion into a purely rotational one. Small changes in the presumed location of the COR and, by association, the centers of reaction (Bogduk et al., 1995; Gracovetsky et al., 1987; Schneider et al., 2005; Zander et al., 2016), can sufficiently alter estimates of muscle and ligament moment arms such as to provoke significant variations in the corresponding estimates of generated muscle force (Han et al., 2013a; Zander et al., 2016; Zhu et al., 2013). These variations in turn strongly influence estimation of net joint forces and moments, and joint reaction forces (Zander et al., 2016). Secondly, since loads in the spine are shared between the anterior components—vertebral body and intervertebral disc—and the posterior elements—the facet joint complex—, uncertainties in force estimations within the disc can lead to inaccuracies in the estimation of loads within the segment facet joints as well as the adjacent segments (Dooris et al., 2001; Han et al., 2013a; Zander et al., 2009). However, the current literature does not provide robust explanations for the observed dynamics of center of rotation during functional tasks, particularly in a manner that enables reasonable prediction of COR trajectory during a specific movement.

The longstanding limitations regarding lacking data is being overcome with recent developments in direct measurement of bone kinematics using dynamic radiographic techniques, particularly during in vivo load bearing functional activities (Ahmadi et al., 2009; Aiyangar et al., 2014; Anderst et al., 2008; Wu et al., 2014). Very recently, Aiyangar et al. mapped the migration patterns of the instantaneous COR during a lifting task using dynamic stereo radiography (DSX) to show that the COR generally migrates from an anterior-most location towards a posterior location during a progressive extension movement from a forward flexed to an upright position (Aiyangar et al., 2017). Further they also demonstrated that the average COR superior-inferior (SI) location is level-specific, with the average SI coordinates tending to be located in an increasingly superior location as one moves inferiorly from L2L3 toward the lowest anatomical segment (L5S1).

Given these recent insights into COR migration patterns during specific functional lifting activity, we postulated that the instantaneous COR location for a specific joint is optimized to minimize the joint reaction forces within the intervertebral disc of that particular joint. We designed the current study to test the following hypotheses:

1. In a flexed position, an anterior location of COR results in the lowest magnitude joint reaction force.
2. In an upright position, a posteriorly located COR results in lowest magnitude joint reaction force.
3. In inferior lumbar segments the lowest joint reaction forces result from more superior locations of COR as compared to upper segments.

2. Methods

The effect of COR location on joint reaction forces was investigated using a recently described and publicly available kinematics driven upper body musculoskeletal model (Senteler et al., 2016) for OpenSim® (Delp et al., 2007). The model represents a generic human male with a height of 170 cm and 71 kg body weight. It includes the body segments from the femur bones upwards. The lumbar spine is implemented using six body segments from the first lumbar level to the sacrum. The pelvis and sacrum are treated as a single rigid construct, as is the thorax consisting of the thoracic vertebrae and ribcage. Additional bodies for cervical spine, head, upper and lower arms, and hands complement the model. Mass and inertia properties are assigned to all body segments based on the literature (Pearsall et al., 1996; Shan and Bohn, 2003). The geometric representation of bones were adopted from previous models (Christophy et al., 2012; Holzbaur et al., 2005; Vasavada et al., 1998). Each body within the model included its own coordinate system which could be selected as local reference frames to express simulation results such as joint forces or body kinematics. Vertebrae-specific coordinate system origins were located in the middle of the corresponding vertebral body's posterior edge as shown in Fig. 1. The x-axes are aligned with the bisector of upper and lower endplate. The muscle architecture and force generating capacity of individual muscles was directly adopted from the lumbar spine model of Christophy et al. (2012).

Muscle moment arms were obtained as outputs from the OpenSim (Delp et al., 2007) software. Briefly, muscle moment arms are defined in OpenSim as follows:

$$r_\theta = \frac{\tau_\theta}{s} \tag{1}$$

with the equivalent definition based on the "tendon-excursion method" as:

$$r_\theta = \frac{dl}{d\theta} \tag{2}$$

where

r_θ = muscle moment arm specific to a joint-associated kinematic quantity, "θ"

τ_θ = scalar quantity representing the effective torque acting about "θ" due to the scalar tension force, "*s*" generated by muscle activation.

$dl/d\theta$ = change in length (dl) of the muscle effected by a small displacement ($d\theta$).

The algorithm implemented in OpenSim version 3.0 and beyond uses a Generalized Force Method to directly satisfy the definition of moment arm according to Eq. (1) rather than the perturbation method to compute muscle moment arms based on the tendon excursion method. See (Sherman et al., 2013) for further details.

The model included joint bushings for each of the lumbar levels, with assigned stiffness being individually calibrated based on load controlled *in vitro* experiments to account for influence of the intervertebral disc as well as passive elements such as ligaments and joint capsules. In a neutral position of the lumbar spine represented by upright standing, the bushing forces were zero. All details on model implementation and extensive corroboration of model predictions against joint reaction forces from the literature are described elsewhere (Senteler et al., 2014, 2016, 2017).

To investigate the effects of COR on generated joint forces, a sinusoidal lumbar extension motion from 45° forward flexed posture to upright standing was simulated. Motion was restricted to the sagittal plane and did not include vertebral translations; pure rotation was simulated around the fixed COR of each vertebra. Rotational range of motion was distributed among vertebral levels as described in the original lumbar spine model (Christophy et al., 2012; Senteler et al., 2016). A static optimization algorithm minimizing squared muscle activation (OpenSim default) was employed to predict the muscle forces best matching the

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