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Effects of sex, age, body height and body weight on spinal loads: Sensitivity analyses in a subject-specific trunk musculoskeletal model

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Subject-specific parameters influence spinal loads and the risk of back disorders but their relative effects are not well understood. The objective of this study is to investigate the effects of changes in age (35–60 years), sex (male, female), body height (BH: 150–190 cm) and body weight (BW: 50–120 kg) on spinal loads in a full-factorial simulation using a personalized (spine kinematics, geometry, musculature and passive properties) kinematics driven musculoskeletal trunk finite element model. Segmental weight distribution (magnitude and location along the trunk) was estimated by a novel technique to accurately represent obesity. Five symmetric sagittal loading conditions were considered, and main effect plots and analyses of variance were employed to identify influential parameters. In all 5 tasks simulated, BW (98.9% in compression and 96.1% in shear) had the greatest effect on spinal loads at the L4–L5 and L5–S1 levels followed by sex (0.7% in compression and 2.1% in shear), BH (0.4% in compression and 1.5% in shear) and finally age ($<5.4\%$). At identical BH and BW, spinal loads in females were slightly greater than those in males by $\sim$4.7% in compression and $\sim$8.7% in shear. In tasks with no loads in hands, BW-normalized spinal loads further increased with BW highlighting the exponential increase in spinal loads with BW that indicates the greater risk of back disorders especially in obese individuals. Uneven distribution of weight in obese subjects, with more BW placed at the lower trunk, further (though slightly $<7.5\%$) increased spinal loads.

1. Introduction

Back pain is a prevalent health issue worldwide (Hoy et al., 2010b; Hoy et al., 2014) with significant social and economic burdens on individuals and society (Deyo et al., 1991; Katz, 2006; Rapoport et al., 2004). Ageing (Hoy et al., 2012), obesity (Deyo and Bass, 1989) and body height (BH) (Leclerc et al., 2003) are recognized as risk factors. Ageing, for instance, increases the prevalence of back pain and alters its etiology (DePalma et al., 2011; Hoy et al., 2012; Hoy et al., 2010a). While back pain in younger individuals has often discogenic origins, it is in older individuals mainly from facets and sacroiliac joint (DePalma et al., 2011, 2012; Dionne et al., 2006). As a rising global health problem (Flegal et al., 2012; Wang et al., 2011), obesity has also been associated with back pain (Deyo and Bass, 1989; Heuch et al., 2010; Koyanagi et al., 2015; Leboeuf-Yde et al., 1999; Shiri et al., 2009, 2014; Smuck et al., 2014; Webb et al., 2003). These studies define obesity based on body mass index (BMI) whereas waist to hip ratio (Han et al., 1997; Yip et al., 2001), waist circumference (Lean et al., 1998; Shiri et al., 2013; Taanila et al., 2012) and body weight (BW) (Croft and Rigby, 1994; Heuch et al., 2015b) have also been used. As a risk factor, greater BH can also cause back pain in females (Heuch et al., 2015a; Yip et al., 2001), males (Walsh et al., 1991) or both (Hershkovich et al., 2013). Though some studies question the likely role of BH (Han et al., 1997), others suggest that taller stature could predispose individuals to back pain (Coeuret-Pellicer et al., 2010). Correlation between gender and back pain has been reported (DePalma et al., 2012; Schneider et al., 2006). Though personalized factors have been indicated in back pain, underlying mechanisms remain yet unknown.

The above factors likely alter spinal loads. To estimate loads on spine, *in vivo* studies, though valuable, are costly, limited and

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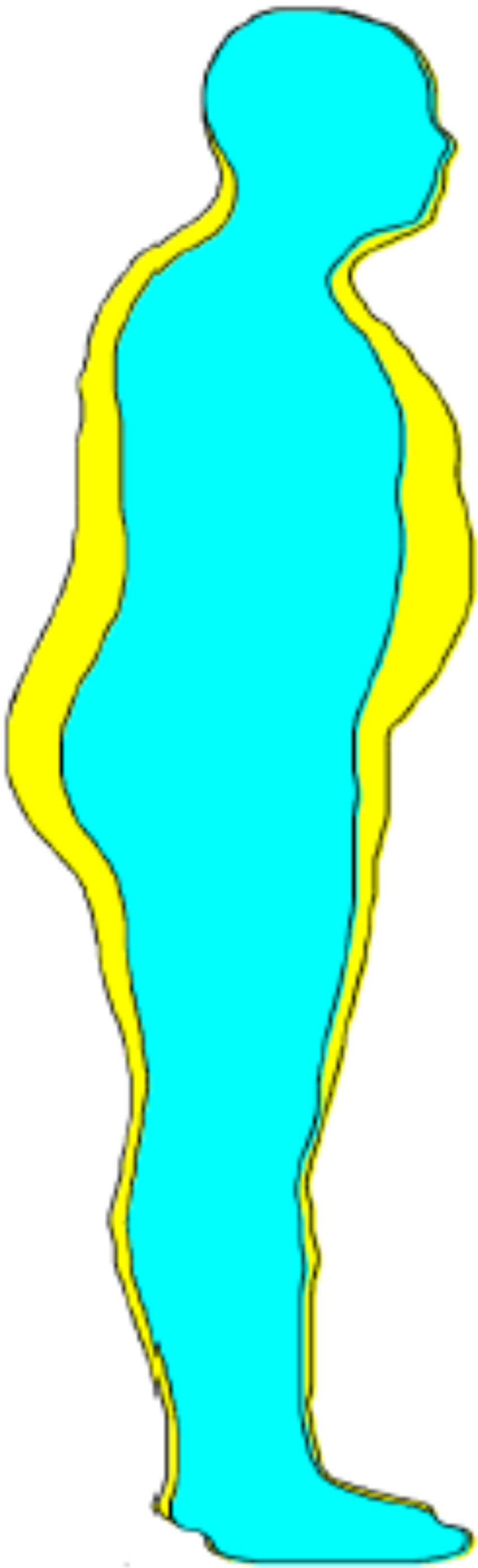

Fig. 1. Schematic body shape of an obese person (outer contour) *versus* a lean person (inner contour) in the sagittal plane (BMI Visualizer, Perceiving Systems Department, Max Planck Institute for Intelligent Systems, Germany). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

invasive (Dreischarf et al., 2015; Rohlmann et al., 2013; Sato et al., 1999). Musculoskeletal models have emerged as robust and relatively accurate alternatives. Hajihosseinali et al. (2015) applied an image-based anisotropic scaling method to modify musculature morphology in a musculoskeletal trunk model while investigating the effects of changes in BW on spinal loads. They reported that BW substantially influences spinal loads particularly at flexed postures. Using a linear and isotropic scaling scheme in AnyBody Modeling System (Damsgaard et al., 2006), Han et al. (2013) found that the spinal shear and compression forces change linearly with BH and BW though the effect of BW is more pronounced. To investigated age-related hyperkyphosis by a static model of the spine, Bruno et al. (2012) considered three spinal configurations (hyperkyphosis alone, with pelvic tilt or with increased lordosis) and reported that changes in both kyphosis and spinal posture affect spinal loads. Nevertheless, to-date no study has comprehensively investigated the likely effects of all subject-specific parameters of age, sex, BH and BW on spinal loads.

Computing spinal forces by multi-joint trunk musculoskeletal models, especially when BW changes, requires an accurate segmental weight distribution along the spine (T1–L5). Pearsall et al. (Pearsall, 1994; Pearsall et al., 1996) evaluated this distribution in lean individuals using CT imaging. For overweight and obese individuals, however, available studies have estimated only the total trunk mass center by MR images (Matrangola et al., 2008), X-ray absorptiometry scans (Chambers et al., 2010) and 3D body scans (Pryce and Kriellaars, 2014). Consequently, the required segmental weight distribution in overweight and obese individuals has not yet been estimated.

We aim to comprehensively investigate the effects of alterations in age, sex, BH and BW on spinal loads. To adequately account for the overweight and obese individuals, we initially develop a novel technique to estimate segmental weight distribution along the trunk (T1–L5) as BW alters. Moreover, using an updated validated nonlinear finite element (FE) subject-specific trunk musculoskeletal model (Ghezelbash et al., 2016) in conjunction with personalized spinal kinematics (with respect to age and sex) (Pries et al., 2015), we evaluate spinal loads and sensitivities therein as individual parameters alter in a full-factorial simulation (90 cases) taking 4 independent factors (age, sex, BH and BW) in five sagittally symmetric tasks. In accordance with earlier studies, we hypothesize that spinal loads are much more sensitive to variations in BW than in sex, BH and age.

2. Methods

2.1. Musculoskeletal model of trunk

The development and validation of a nonlinear FE, subject-specific, musculoskeletal model of the trunk for symmetric–asymmetric tasks are reported elsewhere (Ghezelbash et al., 2016). The model includes a comprehensive sagittally-symmetric muscle architecture (126 muscle fascicles) and spinal motion segments (T11–T12 to L5–S1) that are simulated as shear-deformable beam elements with nonlinear properties (Shahvarpour et al., 2016; Shirazi-Adl, 2006). To estimate muscle forces, the musculoskeletal trunk model is driven by measured kinematics while minimizing sum of squared muscle stresses (Arjmand et al., 2010; Arjmand and Shirazi-Adl, 2006). Moreover, to adjust the model in accordance with subject's personal parameters (age, sex, BH and BW), we use a physiological-based scaling method that modifies both muscle architecture (geometry and area of muscles) and