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Comparative evaluation of six quantitative lifting tools to estimate spine loads during static activities

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ABSTRACT

Different lifting analysis tools are commonly used to assess spinal loads and risk of injury. Distinct musculoskeletal models with various degrees of accuracy are employed in these tools affecting thus their relative accuracy in practical applications. The present study aims to compare predictions of six tools (HCBCF, LSBM, 3DSSPP, AnyBody, simple polynomial, and regression models) for the L4-L5 and L5-S1 compression and shear loads in twenty-six static activities with and without hand load. Significantly different spinal loads but relatively similar patterns for the compression ($R^2 > 0.87$) were computed. Regression models and AnyBody predicted intradiscal pressures in closer agreement with available *in vivo* measurements (RMSE ≈ 0.12 MPa). Due to the differences in predicted spinal loads, the estimated risk of injury alters depending on the tool used. Each tool is evaluated to identify its shortcomings and preferred application domains.

1. Introduction

Epidemiological studies have identified manual material handling and lifting as risk factors in occupational low back pain (LBP) (Garg and Moore, 1992; Hoogendoorn et al., 2000; Manchikanti, 2000; Thiese et al., 2014; Van Nieuwenhuyse et al., 2004). Modelling studies that predict increased compression, shear and moment loads on intervertebral discs (Arjmand and Shirazi-Adl, 2006) along with *in vivo* investigations that measure higher intradiscal pressures (Nachemson, 1981; Wilke et al., 2001), give support to and identify likely mechanisms for this association. To help manage the risk of work-related LBP, practitioners in occupational biomechanics use different tools to evaluate risk of injury to the spine during lifting activities. The 1991 NIOSH (National Institute for Occupational Safety and Health) Lifting Equation (Waters et al., 1993) recommends weight limits that almost all healthy workers may handle without an increased risk of LBP.

On the other hand, there are a number of lifting tools that directly estimate spinal loads using biomechanical modelling techniques with different degrees of complexity; the University of Michigan's 3D Static Strength Prediction Program™ (3DSSPP) software (University of Michigan Center for Ergonomics, 2014), the revised Hand-Calculation Back Compressive Force (HCBCF) equation (Merryweather et al., 2009), the Linked-Segment Biomechanical Model (LSBM) (Potvin, 1997), the simple polynomial equation of low back compression (McGill et al., 1996), the Anybody Modelling System (AnyBody Technology, Aalborg, Denmark) (Damsgaard et al., 2006), and the regression models of Arjmand et al. (2011, 2012, 2013). As expected, the underlying assumptions and simplifications made in these tools influence the accuracy of their predictions and hence their applicability in ergonomic, rehabilitation, and biomechanical applications.

For instance, modelling studies often estimate muscle forces and spinal loads based on the balance of net external moments at a single lumbar level (3DSSPP, HCBCF equation, and LSBM). Such consideration of equilibrium, however, yields results in violation of equilibrium at remaining spinal levels (especially so in more physically demanding tasks) (Arjmand et al., 2007, 2009; 2010). Also, earlier models have made simplifications (e.g., on the trunk

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geometry, muscle anatomy and line of action, passive ligamentous properties, and gravity load distribution) that could adversely influence the accuracy of predictions (Arjmand, 2006; Arjmand et al., 2006). Moreover, some tools have inherent errors due to their regression technique (assumed equations in simple polynomial, regression models, and LSBM) while others may not be as easy to use thus requiring some user training (3DSSPP and AnyBody software). No comparative investigation of the differences in the estimated spinal loads by these tools during various lifting tasks has hitherto been carried out.

Hence, the present study aims to compare predictions (L4-L5 and L5-S1 segmental compressive and anterior–posterior shear loads) of the foregoing six lifting analysis tools when applied to identical manual load holding (static lifting) activities in upright and flexed, symmetric and asymmetric, and one- and two-handed conditions. Here, we intend to: 1) assess their respective underlying assumptions, 2) determine differences in the estimated spinal loads, 3) identify the accuracy of each tool in light of the comparison of its predicted compression forces with available *in vivo* intradiscal pressure measurements, and finally 4) their preferred domains of application. It is hypothesized that the estimates of spinal loads produced by the various tools will show large differences. The current comparative study should benefit researchers in various disciplines dealing with the biomechanical modelling, assessment of risk of occupational injuries, workplace performance improvement, and rehabilitation management.

2. Methods

2.1. Simulated tasks

Twenty-six static activities in upright and flexed postures during symmetric and asymmetric loads and postures using one- and two-handed lifting techniques are considered. Spine loads at the L4-L5 and L5-S1 levels are estimated by lifting analysis tools while assuming an identical body weight of 68.4 kg and height of 174.5 cm of a healthy male subject (Arjmand et al., 2009, 2010). These include 16 symmetric and 6 asymmetric static activities as follows (Fig. 1): 1) relaxed upright posture with no load in the hands located at ~15 cm anterior to the L5-S1 disc, 2–3) holding 19.8 kg at 25 cm or 55 cm anterior to the L5-S1 disc in the upright posture, 4) flexing forward by 50° with hands at ~25 cm anterior to the L5-S1 disc, 5) flexing forward by 70° while holding 19.8 kg in hands at 32 cm anterior to the L5-S1 disc, 6) peak voluntary flexion at 110° with hands 40 cm anterior to the L5-S1 disc, 7–8) asymmetric one-handed lifts of 19.8 kg once on the left and then on the right side at ~34 cm lateral and 0 cm posterior to the L5-S1 disc in the upright posture, 9–12) holding symmetrically a total of 19.8 kg (9.9 kg in each hand) with arms on sides and hands at 0 cm anterior to and ~34, 70, 85, and 81 cm lateral to the L5-S1 disc (corresponding to ~13, 50, 90, and 110° abduction of arms, respectively), 13–18) holding 17 kg symmetrically at a constant horizontal distance of 23 cm and vertical distances of respectively 25, 53, 81, 108, 137, and 165 cm to the ankle (corresponding to anterior load positions of ~38, 44, 30, 30, 30, and 30 cm to the L5-S1 disc and forward trunk flexion angles of ~80, 40, 13, 0, 0, and 0°) (Russell et al., 2007), 19–20) twisting the trunk by 30° to the right and to the left while holding 19.8 kg at 42 cm anterior and 21 cm lateral to the L5-S1, 21) flexing symmetrically forward by 70° while holding a load of 19.8 kg asymmetrically at 41 cm anterior and 33 cm right lateral to the L5-S1 disc, and finally 22) bending forward by 70° and laterally to the right by 20° while holding a load of 19.8 kg asymmetrically at 38 cm anterior and 47 cm right lateral to the L5-S1 disc. In addition, in order to investigate the sensitivity of each tool's response to variations in the magnitude of the hand load, simulations of task 2 (load handling symmetrically at 25 cm anterior to the L5-S1 disc in the upright posture) are repeated with 0, 25, 50, and 75% of 19.8 kg in hands (i.e., 0, 4.95, 9.9, 14.85 kg).

Corresponding body postures, i.e., trunk and pelvis rotations for a given load position, are determined based either on our previous *in vivo* measurements (Arjmand et al., 2009, 2010) when available or on the posture prediction algorithm of the 3DSSPP software. In tasks 1 to 7, intradiscal pressures (IDP) are initially estimated based on computed compression forces at the L4-L5 disc and are subsequently compared to *in vivo* measurements reported by Wilke et al. (2001) whose male subject had body weight of 72 kg and height of 173.9 cm similar to those considered in our model. The axial compression-IDP relations computed at the L2-L3 for various flexion angles (Shirazi-Adl and Drouin, 1988) are used to estimate L4-L5 disc pressures based on predicted L4-L5 compression forces at different flexion moments.

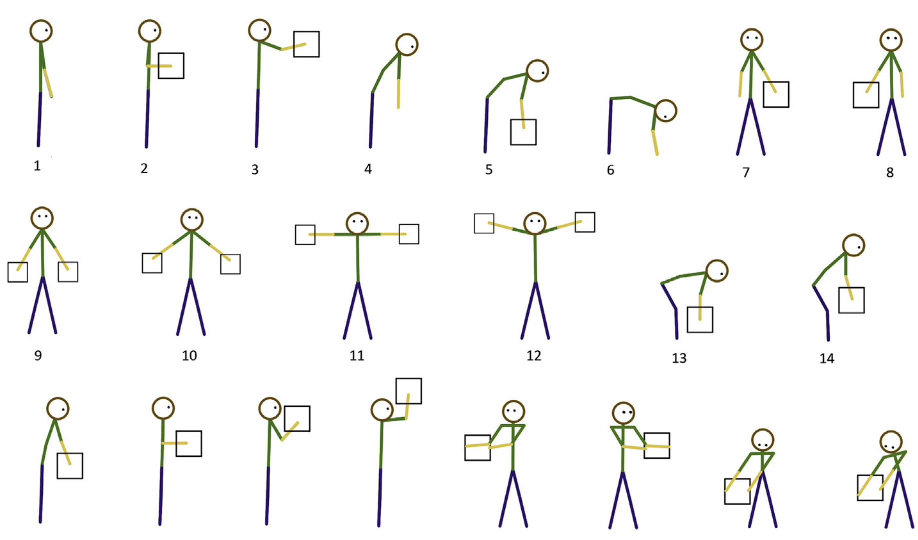

Fig. 1. Schematics of the simulated tasks for prediction of spinal loads by different lifting analysis tools.