Medical Engineering and Physics 38 (2016) 297–301

Contents lists available at ScienceDirect

Medical Engineering and Physics

journal homepage: www.elsevier.com/locate/medengphy

Technical note

Sensitivity analysis of the position of the intervertebral centres of reaction in upright standing – a musculoskeletal model investigation of the lumbar spine

Thomas Zander*, Marcel Dreischarf, Hendrik Schmidt

Julius Wolff Institute, Charité – Universitätsmedizin, Augustenburger Platz 1, D-13353 Berlin, Germany

ARTICLE INFO

Article history:
Received 15 July 2015
Revised 20 October 2015
Accepted 8 December 2015

Keywords:
Musculoskeletal model
Centre of reaction
Centre of rotation
Static equilibrium
Standing

ABSTRACT

The loads between adjacent vertebrae can be generalised as a single spatial force acting at the intervertebral centre of reaction. The exact position *in vivo* is unknown. However, in rigid body musculoskeletal models that simulate upright standing, the position is generally assumed to be located at the discs' centres of rotation. The influence of the antero-posterior position of the centre of reaction on muscle activity and joint loads remains unknown. Thus, by using an inverse dynamic model, we varied the position of the centre of reaction at L4/L5 (i), simultaneously at all lumbar levels (ii), and by optimisation at all lumbar levels (iii). Variation of the centres of reaction can considerably influence the activities of lumbar muscles and the joint forces between vertebrae. The optimisation of the position of the centre of reaction reduced the maximum lumbar muscle activity and axial joint forces at L4/L5 from 17.5% to 1.5% of the muscle strength and from 490 N to 390 N, respectively. Thus, when studying individual postures, such as for therapeutic or preventive evaluations, potential differences between the centre of reaction and the centre of rotation might influence the study results. These differences could be taken into account by sensitivity analyses.

1. Introduction

The loads transferred between adjacent vertebrae consist of stresses in the intervertebral discs, ligaments and facet joints. Assuming rigid vertebrae, the loads can be generalised to a single, spatial force acting at a distinct point. This point is termed the intervertebral centre of reaction [1] (or reaction centre, RC). Applying the equivalent force at this point would result in the same static equilibrium. Upright standing is overlaid with postural sway but is considered a reproducible static posture [2], and standing is typically regarded as a posture for which there are no remarkable ligament or facet joint forces or bending in the intervertebral discs [3,4]. Because of these assumptions, the complete load transfer is placed on the intervertebral disc in rigid body musculoskeletal models simulating standing and is modelled primarily by a spherical joint [e.g., 5–8] unless more sophisticated approaches are used [9,10]. Due to their nature, spherical joints cannot transfer moments and thus, represent the intervertebral RC. The exact position *in vivo* is unknown. In models, however, spherical joints (and thus, the RCs) are assumed to be locally fixed at the centre of rotation (CoR) for certain motions [11]. However, contrary to these model assumptions, the position of the RC is *not* fixed and is dependent on the subject and the activity [12–14]. The position is controlled by the muscle activation pattern and is influenced by pre-tension in passive structures such as ligaments, facet joints, and different regions of the intervertebral discs. Furthermore, the position is dependent on the spinal profile and level, on body weight and its distribution, and on ageing and degeneration; essentially, the position is dependent on the morphology, material properties, and stress state of the intervertebral discs. Consequently, there are generally deviations in the positions of the RC and CoR.

Several findings show that pre-tension in passive structures occurs and is variable between standing subjects. When considering the sagittal plane, an additional force between adjacent vertebrae from ligaments acts at a lever arm to the CoR and can create a flexion or extension moment. In rigid body mechanics, moments are equivalent to a shift of the resultant force (geometrical sum of all forces). This shift expresses the distance between RC and CoR, assuming the CoR is locally fixed. *In vitro* measurements show pre-tension in lumbar ligaments even at neutral positions [15,16]. Moreover, the neural arch might support loads during normal posture [17]. The appearance of facet joint forces after prolonged standing is also indicated by *in vivo* measurements on

* Corresponding author at: Julius Wolff Institute, Augustenburger Platz 1, D-13353 Berlin, Germany. Tel.: +49 30 209 346 142; fax: +49 30 209 346 001.
E-mail address: thomas.zander@charite.de (T. Zander).

http://dx.doi.org/10.1016/j.medengphy.2015.12.003

subjects without spinal disorders, which show a significant correlation between lordosis and pain [18]. The commonly used term 'hanging on the ligaments' [19–22] describes a distinct way of standing and implies that passive structures assume part of the load. Thus, it is not clear whether the simplifying assumption of a local coincidence of RC and CoR, which is a common assumption of musculoskeletal models, is reasonable. Several studies emphasise the importance of muscle moment arms (lever arm of a muscle to the CoR) on mechanical equilibrium [e.g., 23–27] but have not studied their sensitivity to muscle activities and joint loads in detail or distinguished between RC and CoR. The influence of the antero-posterior position of the RC on muscle activity and joint load remains unknown. This sensitivity analysis aimed to determine the effect of the lumbar RC positions on the joint and muscle forces during upright standing with an inverse dynamic rigid body musculoskeletal model to determine whether it is acceptable to assume negligible deviations between the positions of the intervertebral RC and CoR.

2. Methods

2.1. Inverse dynamic model

This sensitivity analysis was performed using the inverse dynamic musculoskeletal model from AnyBody Technology A/S (Aalborg, Denmark), version AMMR 1.6.4 (Fig. 1). The model consists of 64 rigid segments and more than 800 muscle fascicles. The original intra-abdominal pressure mechanism was modified such that extension would not occur during standing. The reaction force of the abdominal muscles was evenly distributed throughout the lumbar vertebrae. By default, the model simulated upright standing with no ligaments or facet joints directly modelled in the lumbar region. The plumb line of the upper body's centre of mass ran nearly through the centre of the hip joints. The plantar centre of pressure was located directly below the ankle joint.

For model validation, the calculated increases in lumbar joint force caused by different weights carried in the hand, were recently compared with *in vivo* forces generated from implant loads during upright standing [28]. The comparison showed good agreement between the measurements and predictions. The spherical intervertebral joints between the thorax and sacrum were originally located at the CoR measured by Pearcy and Bogduk [11]. However, their kinematic motion capabilities were not needed here because the simulations were static. A more detailed description of the model and muscle recruitment can be found in the literature [8,28,29].

2.2. Sensitivity analyses

The joint positions in the model represent the RC and were varied in the antero-posterior (ap) direction with respect to the original joint positions in different ways (Fig. 1):

(i) Only the ap-position of the L4/L5 joint was varied ±10 mm anterior and posterior.
(ii) All of the joint positions between the thorax and sacrum were simultaneously varied by ± 20 mm anterior and posterior.
(iii) All of the joint positions were optimised because the anatomical differences of the intervertebral levels do not require the RCs at the same relative ap-position. This optimisation was based on the same objective function G used for inverse dynamic muscle recruitment (Eq. 1) except only the lumbar muscles were considered (M. iliocostalis, M. longissimus, Mm. multifidi, M. psoas major, M. semispinalis, M. spinalis, and M. transversus abdominis).

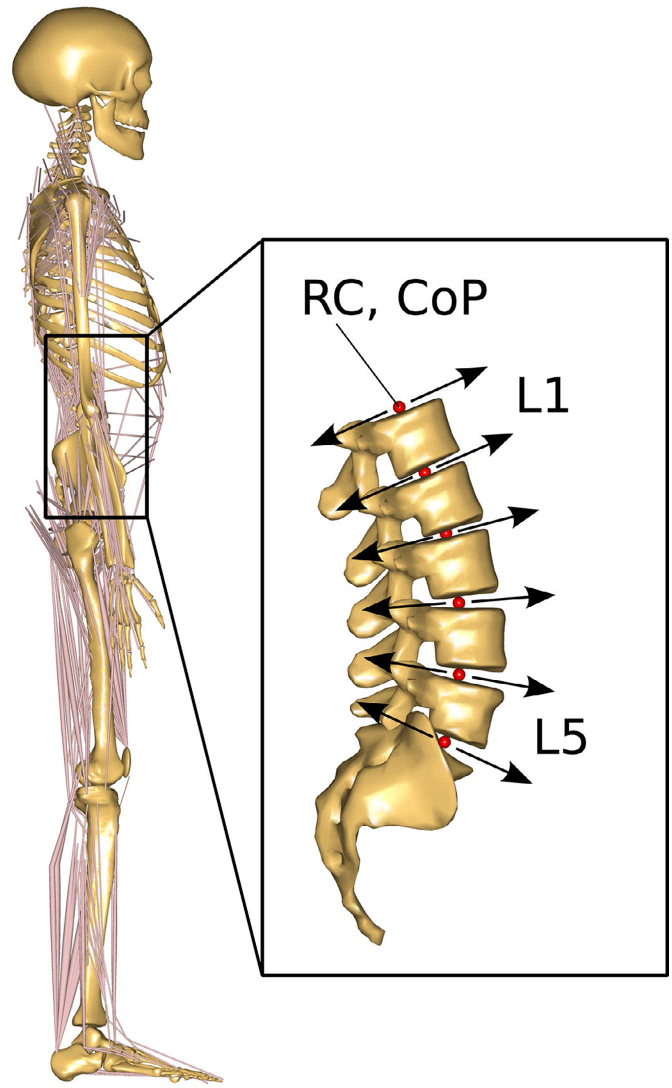

Fig. 1. Inverse dynamic musculoskeletal model during standing and an enlarged view of the lumbar region with pre-defined position for the intervertebral centres of rotation (CoR) and of reaction (RC). Arrows show the direction of the RC shifts for the sensitivity analyses.

$$\text{minimise}\, G = \sum_{i=1}^{N} \sigma_i^3 \quad (1)$$

$$\text{subject to}\, f(RC_{T12L1}, \ldots, RC_{L5Sa}, F_1, \ldots, F_N) = 0 \quad (2)$$

$$F_i = \sigma_i \cdot \text{PCSA}_i \quad (3)$$

$$F_{\max,i} = \sigma_{\max,i} \cdot \text{PCSA}_i \quad (4)$$

$$0 \le F_i \le F_{\max,i};\ i = 1, \ldots, N \quad (5)$$

in which G is the objective function; σ is the muscle activity; i is the muscle number; N is the total number of (lumbar) muscles; f corresponds to the equilibrium equation and depends on the RC positions; F are the muscle forces, which can only be positive; PCSA are the physiological cross-sectional areas and $\sigma_{\max}$ are the muscle strengths. In simple terms, the objective function attempts to reduce the activity of highly loaded muscles in particular. This