Medical Engineering and Physics 000 (2016) 1–6

Contents lists available at ScienceDirect

Medical Engineering and Physics

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

Influence of lumbar spine rhythms and intra-abdominal pressure on spinal loads and trunk muscle forces during upper body inclination

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ARTICLE INFO

Article history:
Received 29 September 2015
Revised 19 January 2016
Accepted 31 January 2016
Available online xxx

Keywords:
Spine rhythm
Intra-abdominal pressure
Inverse quasi-static
Anybody
Spinal loads
MiSpEx

ABSTRACT

Improved knowledge on spinal loads and trunk muscle forces may clarify the mechanical causes of various spinal diseases and has the potential to improve the current treatment options. Using an inverse dynamic musculoskeletal model, this sensitivity analysis was aimed to investigate the influence of lumbar spine rhythms and intra-abdominal pressure on the compressive and shear forces in L4-L5 disc and the trunk muscle forces during upper body inclination.

Based on in vivo data, three different spine rhythms (SRs) were used along with alternative settings (with/without) of intra-abdominal pressure (IAP). Compressive and shear forces in L4-L5 disc as well as trunk muscle forces were predicted by inverse static simulations from standing upright to 55° of intermediate trunk inclination.

Alternate model settings of intra-abdominal pressure and different spine rhythms resulted in significant variation of compression (763 N) and shear forces (195 N) in the L4-L5 disc and in global (454 N) and local (156 N) trunk muscle forces at maximum flexed position. During upper body inclination, the compression forces at L4-L5 disc were mostly released by IAP and increased for larger intervertebral rotation in a lumbar spine rhythm.

This study demonstrated that with various possible assumptions of lumbar spine rhythm and intra-abdominal pressure, variation in predicted loads and muscles forces increase with larger flexion. It is therefore, essential to adapt these model parameters for accurate prediction of spinal loads and trunk muscle forces.

1. Introduction

Detailed knowledge of the spinal loads and trunk muscle forces may help to understand the causes of various spinal diseases and in developing viable treatment options. Due to the inherent complexity of the spinal column, morphologically and mechanically, direct non-invasive measurement of the spinal loads, such as forces and moments, is impossible. Also, measurement of the muscle forces, particularly in deeper regions is difficult due to complex multi layered structure which are inaccessible for many measuring devices. Therefore, an inverse musculoskeletal rigid body model provides an alternative for load assessment by the prediction of joint reactions and muscle forces. However, several model parameters, such as the lumbar spine rhythm i.e. the relative distribution of lumbar flexion at different lumbar levels and intra-abdominal pressure may have a substantial influence on the model outcome but this has never been investigated before.

Several in vivo studies measured lumbar intervertebral rotations and the corresponding range of motion [1–5]. In a radiological study, Pearcy measured the intervertebral rotations of each lumbar segment in 11 healthy volunteers while they performed maximal upper body flexion with no motion in hip and pelvis [2]. Some volunteers showed higher intervertebral rotations at the lower lumbar levels while others at the upper or middle levels. Wong et al. investigated healthy volunteers for upper body flexion [1] and found less segmental rotations at the lower levels of the lumbar spine as well as a linear relationship between segmental rotations and upper body flexion.

In upper body inclination, the contribution of the lumbar flexion and pelvis rotation were also investigated [6–12]. Most of the studies developed a consensus for the simultaneous lumbo-pelvic relationship [7,8,11,12]. These studies showed that the initial phase of the upper body inclination is predominated by the lumbar flexion and at later phases by the pelvic rotation resulting in a variable lumbo-pelvic (L/P) ratio which is the ratio of total lumbar flexion over pelvic rotation. Tafazzol et al. showed that the L/P ratio decreased ranging from a mean value of 2.51 for 0–30° of upper body inclination to 1.34 for a range of 90–120° [13].

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http://dx.doi.org/10.1016/j.medengphy.2016.01.013

In addition, the influence of intra-abdominal pressure (IAP) on the mechanics of lumbar spine had been reported in several studies [14–24] which supported the idea of lumbar unloading and stabilization due to IAP. Hodges et al. found that IAP increases spinal stiffness and stability and results in lumbar unloading [17,20].

The aim of the present sensitivity study was to show how different lumbar spine rhythms and intra-abdominal pressures influence the compressive and shear forces in the L4-L5 disc and the trunk muscle forces during upper body flexion. It was hypothesized that the reasons for the controversial results of the in vivo intradiscal pressure measurements [25–28] are related to the variable lumbar spine kinematics and spinal loading during upper body flexion.

2. Methods

2.1. Reference model

The musculoskeletal standing human body model (Fig. 1a) of the AnyBody modeling system (ver. 5.3, AnyBody Technology, Aalborg, Denmark, model version 1.5) was used. The reference model includes several body parts, i.e. the skull, arms, spine, pelvis, and legs. The spine composed of rigid vertebral bodies such as the cervical, lumped thorax, five lumbar vertebrae and sacrum. All major muscles were included in the model related to the trunk, arms and legs. A total of 188 muscle fascicles were used to represent the muscular architecture of the lumbar spine model. A detailed overview of the model and lumbar spine were given in the literature [29]. The body height (173.9 cm) and body weight (72 kg) were adapted in the musculoskeletal model similar to the volunteer participated in the study of Wilke et al. [25]. Upper body flexion from standing upright to 55° (Fig. 1a) was performed three times with different lumbar spine rhythms. The range of upper body flexion was selected that can be validated with in vivo measurements for lumbar flexion (35.9°). Here, 55° of upper body inclination was reconstructed with thoracic flexion (4°), lumbar flexion (35°) and pelvis rotation (16°).

2.2. Spine rhythms

Though several spine rhythms exist, three lumbar spine rhythms (SRs) were selected (Fig. 1b) from the studies of Pearcy [2] and Wong et al. [1]. Spine rhythm SR 1 allowed more rotation at the lower levels of the lumbar spine whereas SR 2 and SR 3 provided more rotations at the upper and middle levels, respectively. The relative distributions of the lumbar flexion at the lumbar levels were given in Fig. 1b. In addition, the lumbo-pelvic ratio was based on the calculated median values of the normalized lumbar flexion and pelvis rotation relative to their peak values, that were adapted from the study of Tafazzol et al. [13]. The flexion in the thoracic spine is limited due to ribcage attachment and has small contribution in upper body inclination. The current model consists of a lumped thoracic spine and thoracic flexion was assumed as a rotation at T12-L1 joint. To predict the rotation at T12-L1 joint, a linear regression model was fitted to the data between (T5-L1) thoracic flexion and total lumbar flexion [13].

2.3. Joint stiffness

The intervertebral discs in the AnyBody model were assumed to be spherical joints having three rotational degrees of freedom. The joint stiffness was modeled as differentiated ligaments and disc stiffness [30]. Here, lumbar ligaments such as anterior longitudinal, posterior longitudinal, supraspinous, interspinous and ligamentum flavum were included separately with stiffness from the works of Chazal et al. and Pintar et al. [31,32]. The disc stiffness coefficient (fraction of lumbar joint rotational stiffness [33] to represent disc rotational stiffness) was found to be 0.3 [30]. At zero inclination, the predefined values of slack lengths were considered for these ligaments and ligament forces at this initial position were zero.

2.4. Intra-abdominal pressure

During upper body flexion, the IAP increases almost linearly ranging from approximately 1 to 4.4 kPa, similar to the IAP

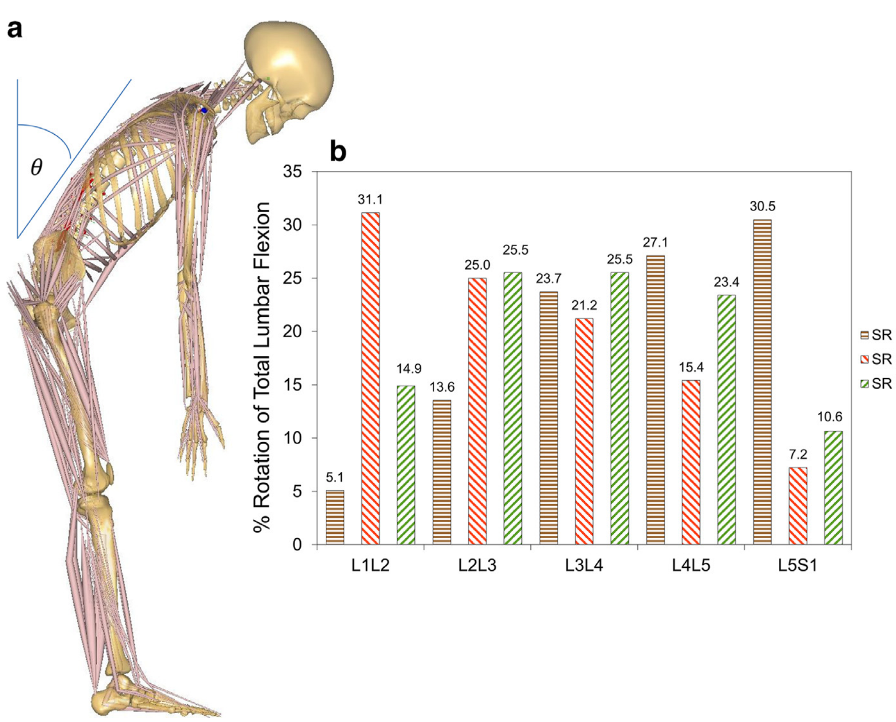

Fig. 1. (a) AnyBody musculoskeletal model during intermediate upper body inclination (θ) (left). (b) Lumbar spine rhythms from the studies of Pearcy [2] and Wong et al. [1].