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An enhanced and validated generic thoraco-lumbar spine model for prediction of muscle forces

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ABSTRACT

A direct measurement of the complete loads in the spine continues to remain elusive. Analytical musculoskeletal models to predict the internal loading conditions generally neglect or strongly simplify passive soft tissue structures. However, during large intervertebral motions, passive structures such as ligaments and the stiffness of the intervertebral discs are thought to play a critical role on the muscle forces required for equilibrium. The objective of the present study was to add the short segmental muscles, lumbar ligaments and disc stiffnesses to an existing base musculoskeletal model of the spine in order to establish what role passive soft tissue structures play in spinal loading, but also validate these results against experimentally determined load data.

The long trunk muscles not included in previous models, short segmental muscles, lumbar ligaments and disc stiffnesses were implemented into a commercially available musculoskeletal spine model construct. For several activities of daily living, the loads acting on the vertebral bodies were then calculated relative to the value for standing, and then compared to the corresponding values measured *in vivo*.

Good agreement between calculated and measured results could be achieved in all cases, with a maximum difference of 9%. The highest muscle forces were predicted in the m. longissimus (146 N) for flexion, in the m. rectus abdominis (363 N) for extension, and in the m. psoas major (144 N and 81 N) for lateral bending and axial rotation.

This study has demonstrated that the inclusion of the complete set of muscle and ligament structures into musculoskeletal models of the spine is essential before accurate spinal forces can be determined. For the first time, trend validation of spinal loading has been achieved, thus allowing confidence in the precise prediction of muscle forces for a range of activities of daily living.

1. Introduction

Gaining access to the loading conditions in the spine is highly complex, where the loads can currently be measured *in vivo* only in very few components. Analytical musculoskeletal spine models [1–4] have therefore been introduced to investigate the biomechanical behaviour of the spine and allow an understanding of the internal loading conditions where *in vivo* experiments are not yet possible. Until now, however, modelling of the passive soft tissue structures has not been included in spinal musculoskeletal models due to the complexity of anatomy and lack of information regarding the material properties of the different structures. For example, all known spine models [1–4] miss one or several of the following components: some long muscles, intrinsic short segmental muscles, disc stiffnesses or ligaments, but these spine models were generally developed for understanding specific situations. However, before a more general knowledge of loading in the spine can be gained during activities with a wide range of motion, inclusion of these passive soft tissue structures becomes essential.

De Zee et al. [5] recently introduced a detailed base spine model using commercially available software (AnyBody Technology, Aalborg, DK). However, their validation was limited to the maximum extension moments during upright standing postures. While good results were achieved for this activity, their model did not include short segmental muscles, which stabilise the spine [6], ligaments, which are loaded during large intervertebral rotations [7], disc stiffness, which affects the muscle forces required for equilibrium in certain positions, or intra-abdominal pressure (IAP), which affects the global stiffness of the spine [8]. The exclusion of these structures, which play a mechanical role in loading the spine, is therefore likely to play a critical role on the joint intersegmental reaction and muscle forces during large spinal motions, and could therefore

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limit the use of this base model to investigate the biomechanical behaviour of the spine during activities of daily living.

Recently, Abouhossein et al. [9] demonstrated a clear load distribution between the passive elements and the intervertebral disc during the application of flexion and extension moments in their 3D multi-body lumbar spine model. Although the important role of passive elements for load sharing was confirmed, the effect of passive elements on the muscle forces and the spinal loads could not be investigated. Therefore, the development of a spine model that includes these additional musculoskeletal components is therefore essential for predicting realistic muscle forces in positions other than upright standing.

Before models can reliably predict realistic spinal loads, particularly in cases of spinal disorders, it is critical to undertake extensive validation, but this is often not easy to perform due to lack of experimental data regarding spinal loads and muscle forces *in vivo*. Although few groups have measured the intradiscal pressure (IDP) in the lumbar spine *in vivo* [10–13], it has become clear that relationships exist between disc pressure, cross-sectional area of the disc, and the force applied [14–16]. However, it seems likely that these relationships are non-linear, or at least require a correction factor, since the fibres of the annulus are only able to transfer tensile forces, and almost exclusively tensile stresses occur in the outer shell of the annulus [17]. To this aim, a correction factor of between 1.3 and 1.8 has been suggested [17]. Therefore, it is only relative values – e.g. those related to standing as a reference – that are appropriate for a comparison between the *in vivo* intradiscal pressure and the calculated forces on a vertebral body.

The loads acting on spinal implants such as internal spinal fixation devices [18] or vertebral body replacement (VBR) [19] have also been measured *in vivo*. Since these implants measure only a part of the spinal loads, their results cannot be used directly for comparing spinal loads in a variety of poses. However, when the results are determined relative to those during standing, they can indeed be considered for validation of analytical models.

Muscle forces are known to play a critical role in generating the spinal reaction forces [1–4]. A further opportunity to validate musculoskeletal predictions of loading conditions in the spine could be to assess the trends of the reaction forces for various activities as an indirect analysis of muscle activation patterns.

The goals of this study were therefore to (1) implement the mechanical action of the following musculoskeletal components: previously neglected long muscles, short segmental muscles, ligaments, disc stiffnesses, and intra-abdominal pressure activation in an existing base musculoskeletal spine model, (2) validate the enhanced spine model using *in vivo* measured data, and (3) present the highest muscle forces for standard loading cases of flexion, extension, lateral bending and axial rotation.

2. Materials and methods

The geometry of the segments and the muscle architecture were selected from a base spine structure in a three-dimensional full body model available in the repository version 1.1 accompanied by Anybody Modelling System version 4.2 (AnyBody Technology, Aalborg, Denmark).

2.1. The base spine model

In the full body base model, the following body components were included: skull, arms, legs, pelvis and spine (Fig. 1, left). The spine consisted of the cervical, thoracic and lumbar region, as well as the sacrum. The cervical and thoracic spine was modelled as a single lumped segment while the lumbar spine consisted of five rigid bodies and 198 muscle fascicles. Long muscles were connected over several wrapping sites on the segments between insertion and origin, to allow the curvature of the spine to be followed during body movements. The mass of the body segments was distributed according to the literature [20], and mass-inertia properties were calculated and applied to the rigid body segments.

The muscles and their attachment sites were identified from previous anatomical works [21–24] and incorporated into the base spine model (10 latissimus dorsi, 6 external oblique, 6 internal oblique, 34 longissimus, 24 iliocostalis, 22 psoas major, 10 quadratus lumbarum, 1 rectus abdominis, 5 transversus, 18 simispinalis, 38 lumbar multifidi, 24 thoracic multifidi). All muscles were modelled as single force components [5] and were able to exert only tensile forces. No tendons or passive element properties were modelled in the base model and no muscle dynamics such as force–length and force–velocity relationships were considered.

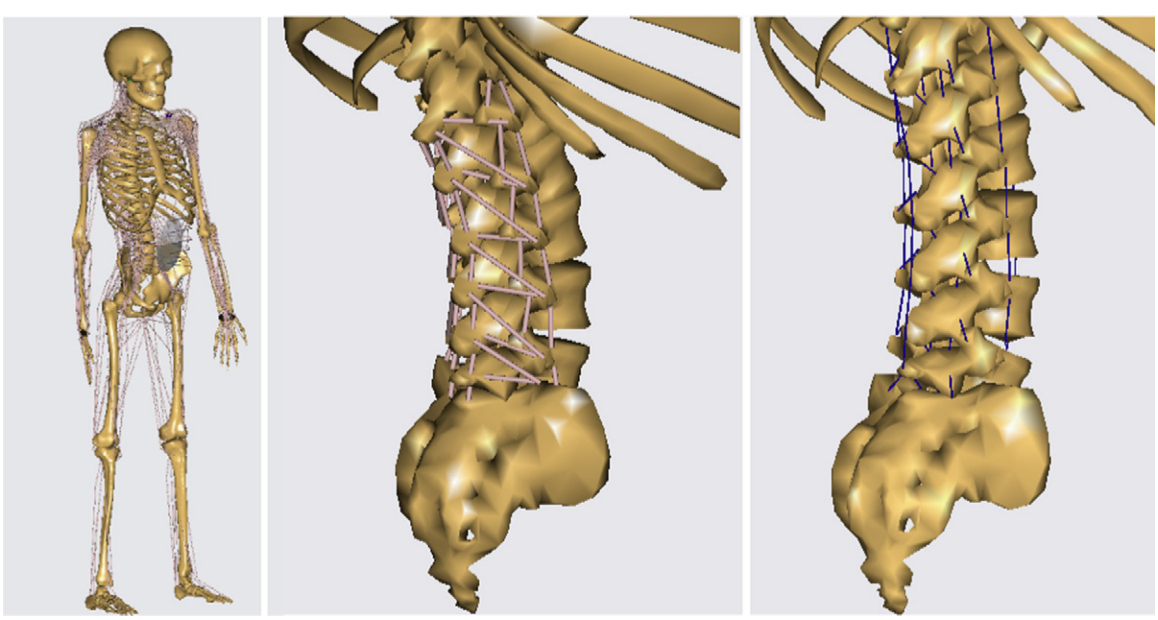

Fig. 1. Full body musculoskeletal model (left), spine model that includes short segmental muscles (centre) and model with ligaments implemented (right).