Medical Engineering & Physics 33 (2011) 472–478

Contents lists available at ScienceDirect

Medical Engineering & Physics

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

Spinal muscles can create compressive follower loads in the lumbar spine in a neutral standing posture

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ARTICLE INFO

Article history:
Received 22 February 2010
Received in revised form
19 November 2010
Accepted 19 November 2010

Keywords:
Spine
Follower load
Spinal muscles
Biomechanics

ABSTRACT

The ligamentous spinal column buckles under compressive loads of even less than 100 N. Experimental results showed that under the follower load constraint, the ligamentous lumbar spine can sustain large compressive loads without buckling, while at the same time maintaining its flexibility reasonably well. The purpose of this study was to investigate the feasibility of follower loads produced by spinal muscles in the lumbar spine in a quiet standing posture. A three-dimensional static model of the lumbar spine incorporating 232 back muscles was developed and utilized to perform the optimization analysis in order to find the muscle forces, and compressive follower loads (CFLs) along optimum follower load paths (FLPs). The effect of increasing external loads on CFLs was also investigated. An optimum solution was found which is feasible for muscle forces producing minimum CFLs along the FLP located 11 mm posterior to the curve connecting the geometrical centers of the vertebral bodies. Activation of 30 muscles was found to create CFLs with zero joint moments in all intervertebral joints. CFLs increased with increasing external loads including FLP deviations from the optimum location. Our results demonstrate that spinal muscles can create CFLs in the lumbar spine in a neutral standing posture *in vivo* to sustain stability. Therefore, its application in experimental and numerical studies concerning loading conditions seems to be suitable for the attainment of realistic results.

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1. Introduction

The normal functions of the lumbar spine are to support the upper body weight and other external loads without buckling *in vivo*, and to provide sufficient flexibility for normal activities [1–4]. For these normal functions, the spinal column should be strong enough to support mechanical loads, large compressive forces, and moments produced during everyday tasks [5] without failure. However, the ligamentous spinal column buckles under compressive loads of even less than 100 N, as was observed in previous studies [6,7]. Thus, the muscle forces are required *in vivo* to maintain upright posture.

Patwardhan et al. [8,9] reported interesting results of *in vitro* biomechanical tests on the lumbar spine under a compressive follower load which turns its direction in such a way as to always remain tangential to the deflection curve (lumbar lordosis). Their experimental results [8,9] showed that the ligamentous lumbar spine can sustain a large compressive load without buckling, while still maintaining its flexibility reasonably well, when the compressive load is applied in a follower force pattern. The loading configuration concept that compressive forces travel along the curvature in the lumbar spine was first proposed by Aspden [10]. It is assumed that a follower load compresses the spine and that and no intervertebral rotation occurs, and that no shear forces are acting [8,9].

Since the follower load was introduced by Patwardhan et al., it has been adapted in several experiments, or in conjunction with other loading conditions, and its successful application has been shown to simulate high physiological compressive loads on the ligamentous spine without buckling during various *in vitro* biomechanical tests of the spine [11–16]. These successful applications led to the hypothesis that the spine may indeed be subjected to the compressive follower load (CFL) *in vivo*, in order to maintain its stability while at the same time maintaining its flexibility.

Considering the follower load mechanism as a physiological motor control strategy of muscle recruitment patterns, it should however be investigated whether or not the follower load can indeed be created in the human spine by spinal musculature. Patwardhan et al. [17] carried out an analytical study using a continuum model of the spine. They simulated the spinal muscles using a hypothetical architecture involving five different muscles as did

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1350-4533/$ – see front matter. Published by Elsevier Ltd on behalf of IPEM.
doi:10.1016/j.medengphy.2010.11.014

by Crisco [7] and Panjabi [18]. They could show that trunk muscles may co-activate to generate a follower load in the coronal plane. However, their results were not sufficient to elucidate the contribution of individual muscles toward construction of the follower load. Furthermore, the investigation in the sagittal plane is missing. Because the lumbar lordosis and anatomic locations of spinal muscles are more populated in the posterior aspect of the spine, this appears to us to be more challenging.

It was believed that *in vivo*, such an inherent instability of the spinal column could be compensated by the active element, namely spinal musculature, and that this would be sufficient enough for normal *in vivo* spinal functions. Numerous investigators [7,19–23] have studied the role of spinal muscles in the stabilization of the spine analytically, experimentally, and also using a combined approach. The results of previous modelling studies have demonstrated the stabilizing roles of the spinal muscles which are possible and significant, and have at the same time provided an insight into the motor control strategy of muscle recruitment patterns. Some studies predict high shear forces in the lumbar spine [22,24–26]. Most trunk muscles run nearly parallel to the spine, and it is only a few strong muscles which were able to compensate shear forces.

As an analytical trial using a follower load mechanism, Kim and Kim [27] developed a three-dimensional (3-D) lumbar spine model including 117 pairs of the spinal muscles. However, they had to allow various degrees of shear forces in joints due to their failure in finding a perfect follower load mechanism in their model, and thus called it a modified follower load with its own limitation. For this reason, muscle forces and the joint loads incorporating the follower load mechanism have not yet been investigated.

We hypothesized that the compressive follower load mechanism (no intersegmental rotation and no shear forces in the intervertebral joints) is also feasible *in vivo* by the muscle forces. Complete proof of this hypothesis would be a very challenging task, and this requires a series of comprehensive studies. As a start, static analyses using a geometrical model incorporating all thoracolumbar spinal muscles reported in the literature on anatomy were performed in this study. The aim here is to investigate the feasibility of a follower load mechanism and its muscle activation patterns which create the follower load in the lumbar spine in a neutral standing posture with a given physiological muscle force capacity (MFC).

2. Methods

A 3-D surface model of the lumbosacral spine in the standing posture consisting of the eight rigid bodies including trunk (rib cage and T12), five lumbar vertebrae, sacrum-pelvis was developed. The dimension of vertebrae and the disc height were obtained from Zhou's CT scan measurements [28]. The disc height was assumed to be about 10 mm in all levels since the range varied from minimum 5 mm to maximum 16.1 mm in L3–L4 to L5–S1 levels [28]. The length from the top of trunk to sacrum was 470 mm in this model. The lordosis of 50° (Cobb angle measured between the top of L1 and the sacrum) was simulated in this study.

In this 3-D model (Fig. 1), the trunk and head were considered to be one rigid body which is connected to the L1 vertebra through the T12–L1 intervertebral joint. All lumbar vertebrae were also assumed to be rigid bodies connected to one another with similar intervertebral joints. For modelling purposes, the sacrum-pelvis was assumed to be rigid and fixed in the sagittal plane. Since the posture was assumed to be the post-deformed static state, further deformation of the discs – as assumed in another study [26] – was not considered in the present model.

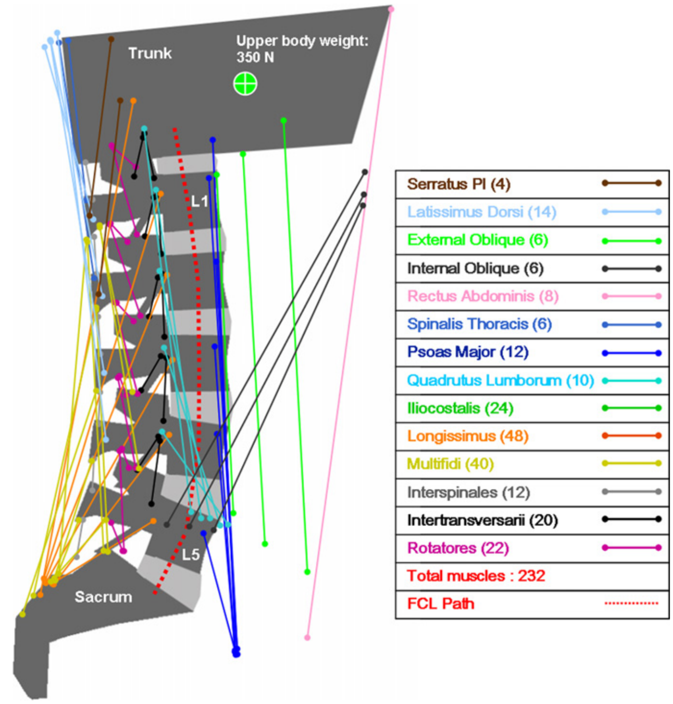

Fig. 1. A schematic illustration of the muscles selected for the 3-D static model. Numbers in parentheses indicate the number of each muscle included.

2.1. A 3-D muscle modelling of the lumbar spine

A full spine orthopaedic sawbone model was used to estimate the attachment points of muscles according to the previous anatomical studies [29–39]. The geometry of the spine was reconstructed based on the sawbone model using a commercial CAD software and the 3-D coordinate of attachment points were obtained. A total of 232 spinal muscle components were identified and incorporated into this rigid body model (4 serratus posterior inferior, 14 latissimus dorsi, 6 external oblique, 6 internal oblique, 48 longissimus, 24 iliocostalis, 12 psoas major, 10 quadratus lumbarum, 8 rectus abdominis, 6 spinalis thoracis, 40 multifidi, 12 interspinales, 20 intertransversarii, and 22 rotatores).

2.2. Formulation and optimization analysis

A static equilibrium analysis was performed so that we could predict the muscle forces required for creating compressive follower loads (CFLs) in the intervertebral joints in a quiet standing posture. This was done as follows: the external loads on the lumbar spine included the weight of the upper body of 350 N located at the center of gravity of the trunk [27,40]. Since the position of the upper body weight varies widely in the literature, the trunk was assumed to produce a flexion moment of 3.5 Nm around the geometrical center (GC) of T12 vertebral body [27]. A total of six free body diagrams were drawn to analyse the force and moment equilibriums at the trunk and five lumbar vertebrae. For example, Fig. 2 shows the free-body diagram at L3 vertebra in static equilibrium with 18 external muscle forces directly affecting the L3 vertebra and internal joint reaction forces and moments. In order to make the internal joint reaction forces a compressive follower load (CFL), the direction of joint reaction forces at L2–L3 and L3–L4 were assumed to run parallel to the lines connecting the geometrical centers (GCs) of L2 and L3 vertebral bodies and L3 and L4 vertebral bodies [15], respectively, while their magnitudes and locations (r) remained unknown. This is depicted in Fig. 2.