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Biomechanical comparison between concentrated, follower, and muscular loads of the lumbar column

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ABSTRACT

Experimental and numerical methods have been extensively used to simulate the lumbar kinematics and mechanics. One of the basic parameters is the lumbar loads. In the literature, both concentrated and distributed loads have been assumed to simulate the *in vivo* lumbar loads. However, the inconsistent loads between those studies exist and make the comparison of their results controversial. Using finite-element method, this study aimed to numerically compare the effects of the concentrated, follower, and muscular loads on the lumbar biomechanics during flexion. Two conditions of equivalent and simple constraints were simulated. The equivalent condition assumes the identical flexion at the L1 level and loads at the L5 level for the three types of loads. Another condition is to remove such kinematic and mechanical constraints on the lumbar. The comparison indices were flexed profile, distributed stress, and transferred loads of the discs and vertebrae at the different levels. The results showed that the three modes in the equivalent condition show the nearly same flexed profiles. In the simple condition, however, the L1 vertebra of the concentrated mode anteriorly translates about 3 and 5 times that of the follower and muscular mode, respectively. By contrast, the flexion profiles of the follower and muscular are comparable. In the equivalent condition, all modes consistently show the gradually increasing stress and loads toward the caudal levels. The results of both concentrated and muscular modes exhibit the quite comparable trends and even magnitudes. In the simple condition, however, the removal of flexion and load constraints makes the results of the concentrated mode significantly different from its counterparts. In both conditions, the predicted

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indices of the follower mode are more uniform along the lumbar. In conclusion, the kinematic and mechanical constraints significantly affect the profile, stress, and loads of the three modes. In the equivalent condition, the concentrated mode can simulate the similar results to the muscular mode and top-loading fashion seems to be more practicable for experimental setup. In the simple condition, the follower mode can serve as the alternative to avoid the unreasonably higher flexion at the L1 level and shear at the L5 level. In the future, the detailed studies about the load-related effects on both load-transferring mechanism and failure mode of the lumbar-implant construct should be conducted.

1. Introduction

Lumbar column is a structure that is composed of five vertebral bodies interconnected with discs, ligaments, and muscles. Its functions are to protect organs, maintain postures, and perform motions. Degenerative, traumatic, and tumorous problems often induce the lumbar instability and eventually lead to neurological symptoms. There have been a great number of the implants used to treat various kinds of lumbar diseases. For the clinicians and bioengineers, the *in vivo* performances of the implants are often evaluated by means of the experimental evaluation or numerical simulation [1–4]. For experimental evaluation, the cadaveric or synthetic lumbar specimens are controlled by the testing jigs to constrain the applied loads or the induced motion. Using medical images and computer graphics, the three-dimensional configuration of lumbar tissues can be established for numerical simulation. Prior to simulation, the biomechanical characteristics of the lumbar construct are defined by some basic parameters: material properties, lumbar loads, and boundary constraints [5].

In general, the lumbar loads consist of body weight and muscular contractions. Historically, the various types of experimental setups and numerical methods have been used to apply the loads onto the intact and instrumented lumbar columns [6–8]. The application of the lumbar loads can be divided into three modes: concentrated, follower, and muscular. The first is the top-loading fashion that transforms body weight and muscular contraction into compression, shear, moment, and torque, and applies them at the lumbar top [9,10]. The other modes (*i.e.* follower and muscular loads) are to distribute the loads along the lumbar column. For the follower mode, the compressive loads are exerted at the two sides of each vertebral body by the tube–cable mechanisms [11–13]. The muscular mode simulates the muscles as the three-dimensional network of the cable-like structures that attach to the peripheries of all vertebral levels [14–16].

From a technical viewpoint, with the concentrated mode it is comparatively easier to design the experimental setup that can locally constrain the lumbar top and transmit the loads to the caudal levels. However, the excessive motion at lumbar top and the unreasonable shear along the lumbar are the major concerns for the top-loading fashion [9,17,18]. Although the muscular mode can be considered more similar to the physiological loads, the three-dimensional contractions of the lumbar muscles are technically more difficult to be experimentally reconstructed or numerically simulated. Accordingly, the advocates of the follower mode claim that the tube–cable mechanism can apply the compressive preload and reasonable shear along the lumbar [9,15]. The current authors postulated that the three loads might lead to the different load-transferring path, lumbar-deforming profile, and stress-distributing patterns along the lumbar. Consequently, the inconsistent applied loads in the reported studies potentially make their results difficult to be compared and this constitutes as the motive of the current study.

Using finite-element method, this study aimed to evaluate the load-induced effects on the lumbar biomechanics. A five-segment lumbar model with seven ligaments and five muscle groups was developed. The flexion was simulated by the exertion of concentrated, follower, and muscular loads. The flexion at the L1 level and the resultant loads at the L5 level were systematically controlled as the equivalent and simple conditions. In the equivalent condition, the flexion at the L1 top and the loads at the L5 bottom were elaborately adjusted the same to constrain the three loaded lumbar columns. In the simple condition, two kinematic and mechanical constraints were removed. The model was validated against the cadaveric data and the deformed discs and loaded vertebrae were chosen as the comparison indices. The results are expected to provide further insight into the effects of the concentrated and distributed loads on the lumbar biomechanics.

2. Methods

2.1. Five-segment models of lumbar column

A five-segment lumbar was established from the scans of the computed tomography (CT) of a 25-year-old male volunteer without any lumbar disease. The CT-scanning images of the lumbar with 1-mm slice separation were three-dimensionally reconstructed as a lumbar model with triangular surface meshes using the software BioFit-Image, Ed. 1.0 (BioFit Co. Ltd., Taiwan). The surface model of the lumbar was further transformed into a solid model with smooth and seamless surfaces by the software SolidWorks, Ed. 2015 (SolidWorks Corporation, Concord, MA, USA). As shown in Fig. 1, the lumbar model consists of four motion units (vertebral bone, endplate, and intervertebral disc) and surrounding soft tissues (ligaments and muscles). Each vertebral bone includes a vertebral body and a posterior element. A vertebral body is composed of a cortical shell and a cancellous core and an intervertebral disc consists of the annular fibrosis and the nucleus pulposus. The endplate was simulated as a 1-mm plate sandwiched between the vertebral body and intervertebral disc. There were seven