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Effect of posterolateral disc replacement on kinematics and stress distribution in the lumbar spine: A finite element study

Wenhai Wang[a], Henry Zhang[b], Keya Sadeghipour[a], George Baran[a,*]

[a] *Temple University College of Engineering, 1947 North 12th Street, Philadelphia, PA 19104, USA*
[b] *Globus Medical, Inc., Valley Forge Business Center, Audubon, PA, USA*

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ABSTRACT

The current study aimed to compare the biomechanics of the L3–S1 spine segment treated either by fusion or total disc replacement (TDR) using the TRIUMPH® Lumbar Disc (Globus Medical, Audubon, PA). A validated three-dimensional, nonlinear finite element model (FEM) of L3–S1 was altered at L4/L5 by fusion and implantation of the TRIUMPH® Lumbar Disc. Under a hybrid testing protocol, the resultant range of motion (ROM), nucleus pressure at the adjacent levels, facet joint force, and anterior longitudinal ligament (ALL) force were analyzed. FEM predicted several changes in biomechanics when compared to the intact segment. The analyses suggest that posterolateral lumbar disc arthroplasty with the TRIUMPH® Lumbar Disc can preserve the mobility of the surgical level while not allowing excessive ROM and reducing segmental motion at the adjacent levels when compared to fusion. The current finite element model could be valuable for engineers and surgeons seeking to optimize TDR designs.

1. Introduction

The intervertebral disc plays an important role in resisting and transmitting load across a motion segment while maintaining disc height and stability. The disc commonly degenerates over time due to natural aging which can be related to lower back pain [1]. In the event that conservative treatment fails, surgical intervention may be indicated. There are two common surgical treatments for degenerative disc disease (DDD): arthrodesis (fusion) and arthroplasty (disc replacement). Spinal fusion is known to result in some loss of motion, increased stiffness, and may lead to adjacent level degeneration [2–4]. Long term results of lumbar arthrodesis are poor [5], and the incidence of complications following arthrodesis has been reported to range from 6% to 58% [6–9]. On the other hand, total disc replacement (TDR) used as an alternative surgical treatment for DDD is believed to be capable of preserving motion and restoring the normal kinematics of the spine [10,11].

Lumbar TDR has increased in popularity over the past two decades. Currently, a variety of Lumbar TDR devices are available in European and North American markets. Only a few have been FDA-approved, such as the Charité® and ProDisc®-L prostheses. While some contrary findings have been reported [12,13], it has been suggested that arthroplasty is able to preserve mobility and restore correct spinal kinematics almost to physiological levels. All currently available prostheses require an anterior surgical approach, which is similar to an open ALIF (Anterior Lumbar Interbody Fusion) procedure [14]. Complications related to anterior TDR were estimated to range from 2.0% to 29.3% [5]. Complications related to the anterior approach (*e.g.* retrograde ejaculation, vascular injury and nerve root damage) have been quoted in the range of 2.1–18.7% [5,10,15]. Disadvantages of removing the anterior longitudinal ligament (ALL) and anterior annulus were also highlighted in a finite element study by Dooris et al. [16].

Some disadvantages of the anterior approach (*e.g.* vascular injury) [17,18] may be overcome if surgeons had an option to implant posteriorly [19]. Such discs are not currently available; however, a few potential designs are either in clinical trials or under development. The aim of this study was to compare the differences in important biomechanical parameters after fusion or TDR using the TRIUMPH® Lumbar Disc (Globus Medical, Inc., Audubon, PA). TRIUMPH® is a semi-constrained metal-on-metal (Co-Cr-Mo alloy, BioDur CCM Plus^{TM}, Carpenter Technology Corporation, Wyomissing PA), ball-and-socket design that achieves at least 12° rotation in all planes (Fig. 1). The vertebral parameters investigated in this study were ROM, facet joint contact force, pressure within the nucleus, and the anterior longitudinal ligament force. These parameters were also compared to the intact and fused models. The effect

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* Corresponding author. Tel.: +1 215 204 8824; fax: +1 215 204 6936.
E-mail address: grbaran@temple.edu (G. Baran).

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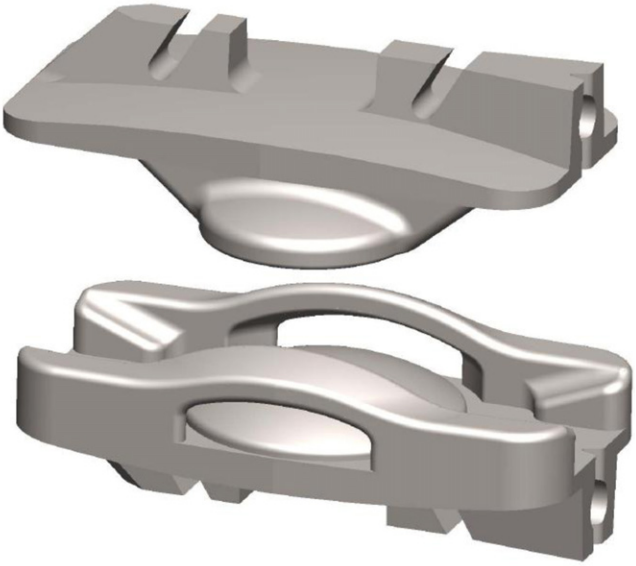

Fig. 1. The TRIUMPH® Lumbar Disc (Globus Medical, Audubon, PA).

of TDR using the TRIUMPH® Lumbar Disc on subsidence has been reported previously [20] and is not within the scope of this paper.

2. Materials and methods

Three-dimensional models of the lumbar spine were implemented using the finite element modeling software ABAQUS/Standard 6.7 (SIMULIA, Providence, RI). Three different configurations of the models were considered: (1) an intact L3–S1 lumbar spine model employed as a reference with parameters applicable to a healthy adult; (2) a 'fused model' with fusion at L4/L5; (3) a TDR model with the L4/L5 level implanted with the TRIUMPH® Lumbar Disc.

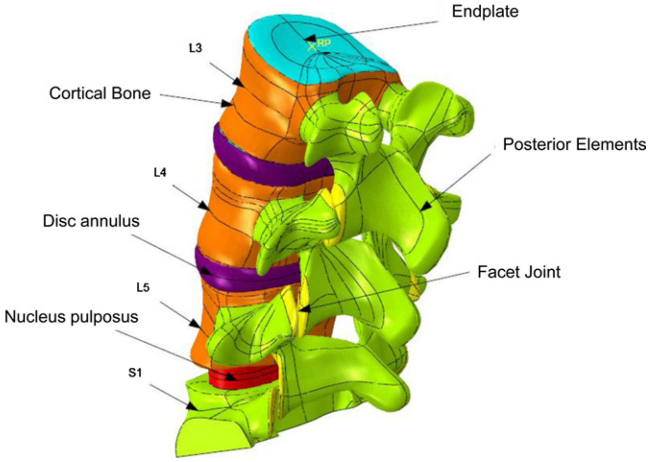

Fig. 2. 3D geometry of L3–S1 segments. (L5 disc annulus was removed for viewing the nucleus pulposus.)

2.1. Intact model

The L3–S1 human lumbar spine geometry was obtained from a CAD model (Digimation, Inc., Lake Mary, FL) (Fig. 2). For purposes of computational efficiency, most of S1 was removed. The cancellous core, posterior elements of the vertebrae, the annulus fibrosus, and the nucleus were modeled as three-dimensional isotropic four-node tetrahedral solid elements (C3D4). Thin shell elements (S3R) with thicknesses of 0.5 mm and 0.3 mm were used to model the cortical shell and endplate, respectively [12,21]. The entire model consists of approximately 230,000 elements, with 85,000 elements used for the implant alone (Fig. 5).

Material properties were obtained from several references and listed in Table 1 [22–25]. The annulus fibrosus was modeled by a hyperelastic constitutive law for the ground substance and by nonlinear springs oriented at ±30° to the horizontal for the annulus fibers [26]. Coefficients of the 5th order Ogden hyperelastic formulation were determined from experimental data [24] and used

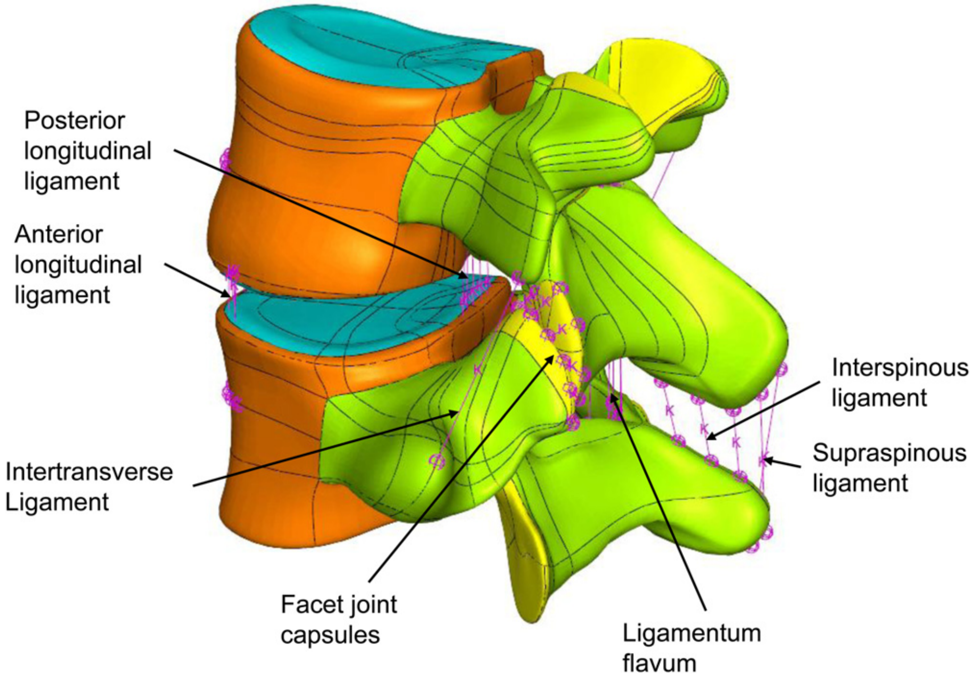

Fig. 3. Representation of ligaments at L4/L5.