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Biomechanics of the L5–S1 motion segment after total disc replacement – Influence of iatrogenic distraction, implant positioning and preoperative disc height on the range of motion and loading of facet joints

Marcel Dreischarf [a,*], Hendrik Schmidt [a], Michael Putzier [b], Thomas Zander [a]

[a] Julius Wolff Institute, Charité – Universitätsmedizin Berlin, Germany
[b] Centrum für Muskuloskeletale Chirurgie der Charité – Universitätsmedizin Berlin, Germany

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ABSTRACT

Total disc replacement has been introduced to overcome negative side effects of spinal fusion. The amount of iatrogenic distraction, preoperative disc height and implant positioning have been considered important for surgical success. However, their effect on the postoperative range of motion (RoM) and loading of the facets merits further discussion.

A validated osteoligamentous finite element model of the lumbosacral spine was employed and extended with four additional models to account for different disc heights. An artificial disc with a fixed center of rotation (CoR) was implemented in L5–S1. In 4000 simulations, the influence of distraction and the CoR's location on the RoM, facet joint forces (FJFs) and facet capsule ligament forces (FCLFs) was investigated.

Distraction substantially altered segmental kinematics in the sagittal plane by decreasing range of flexion (0.5° per 1 mm of distraction), increasing range of extension (0.7°/mm) and slightly affecting complete sagittal RoM (0.2°/mm). The distraction already strongly increased the FCLFs during surgery (up to 230 N) and in flexion (~12 N/mm), with higher values in models with larger preoperative disc heights, and increased FJFs in extension. A more anterior implant location decreased the RoM in all planes. In most loading cases, a more posterior location of the implant's CoR increased the FJFs and FCLFs, whereas a more caudal location increased the FCLFs but decreased the FJFs.

The results of this study may explain the worse clinical results in patients with overdistraction after TDR. The complete RoM in the sagittal plane appears to be insensitive to detecting surgery-related biomechanical changes.

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1. Introduction

Low back pain is a serious worldwide public health problem that affects approximately 80% of all adults at some point during their lives (Andersson, 1998). It is, among others, associated with degenerative disc diseases (DDDs; Luoma et al., 2000), which are frequently treated with spinal fusion if conservative treatment is unsuccessful. However, the treatment of lumbar DDDs with spinal fusion is highly controversial because it is associated with early and late complications, such as accelerated adjacent level degeneration (Levin et al., 2007). To avoid these negative side effects, motion-preserving technologies, such as lumbar total disc replacement (TDR), have been introduced as alternatives to spinal fusion.

Several clinical studies have demonstrated satisfactory clinical results for monosegmental TDR, but these results were demonstrated only in carefully selected patients (Freeman and Davenport, 2006; Guyer et al., 2009; Siepe et al., 2014). Various contraindications have been identified for TDR (Chin, 2007; Huang et al., 2004; McAfee, 2004; Wong et al., 2007), and the success of TDR in the clinic has fallen short of its initial high expectations. In particular, the spino-pelvic alignment ('sagittal balance') is a key factor for surgical success (Mehta et al., 2012; Pellet et al., 2011; Roussouly et al., 2005). Strube et al. (2013b) demonstrated that the sagittal profile types 1 and 4 from the classification proposed by Roussouly et al. (2005) represent a contraindication for lumbar TDR at L4-5 and L5–S1. Siepe et al. (2007, 2008) demonstrated that TDR in L4-5 is clinically superior to L5–S1 and that lumbar facet

* Corresponding author. Tel.: +49 30 2093 46143; fax: +49 30 2093 46001.
E-mail address: dreischarf@julius-wolff-institut.de (M. Dreischarf).

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and/or iliosacral-joint-pain are the most common causes of unsatisfactory clinical results following TDR (e.g., indicated by clinical scores such as the "visual analog scale" or the "Oswestry Disability Index"). They also showed that patients with a preoperative larger disc height reported significantly lower subjective patient satisfaction rates (Siepe et al., 2009). Aside from preoperative radiological parameters, in a combined clinical and computational study, Strube et al. (2013a) and Rohlmann et al. (2013) emphasized that an iatrogenic posterior translation of L5 with respect to S1 followed by an increase in the facet capsule ligament forces as well as an overdistraction followed by an increase of lordosis in L5–S1 leads to inferior clinical outcomes. However, a crucial relationship between individual preoperative disc height, iatrogenic distraction, resultant postoperative biomechanical changes (segmental range of motion (RoM); facet joint loading) and resultant clinical results remains to be established.

Finite element (FE) models of the lumbar spine have been introduced to clarify these elementary biomechanical relationships (Chen et., 2009; Chung et al., 2009; Le Huec et al., 2010; Rohlmann et al., 2009a; Rundell et al., 2012; Schmidt et al., 2012; Zander et al., 2009). These models can provide detailed insight into the segmental kinematics and loading of the facet joints (facet joint forces (FJFs) and facet capsule ligament forces (FCLFs)). Their detailed knowledge is clinically important to understand potential mechanical risk factors after TDR surgery. In several FE model studies, the biomechanical consequences of a TDR compared with the intact state were investigated and it was shown in line with *in vitro* experiments that TDR mainly increased the segmental RoM, particularly the range of extension (RoE; Chen et al., 2009; Chung et al., 2009; Goel et al., 2005; Wilke et al., 2012). The impact of surgery and patient-related factors, such as the amount of iatrogenic distraction, implant location or preoperative disc height, on the biomechanical outputs after TDR has been less frequently investigated (Le Huec et al., 2010; Schmidt et al., 2012); however, these factors may be decisive for optimal treatment and patient selection. Therefore, the specific postoperative consequence of a TDR, which is influenced by the combination of these three factors and their individual impact on the resultant RoM in all anatomical planes and loading of the facet joints, merits further discussion.

Thus, this FE model sensitivity study aims to determine the effect of the amount of iatrogenic segmental distraction, the individual disc height and the implant's location on the segmental RoM and facet joint loads after TDR using several different lumbar spinal geometries. The authors hypothesized that:

(1) the amount of distraction, preoperative disc height, and implant location substantially affect the segmental kinematics and
(2) an iatrogenic distraction substantially increases the facet joint loads.

2. Methods

2.1. FE models of the lumbosacral spine

A previously published symmetrical osteoligamentous FE model of the intact lumbosacral spine (L1–S1) was employed (Model 0; Fig. 1; Rohlmann et al., 2006; Zander et al., 2001). The model was extensively validated using experimental data for the RoM, intradiscal pressure and FJFs (Heuer et al., 2007; Rohlmann et al., 2001; Wilson et al., 2006); furthermore, its predictions correspond well to those of other published FE models (Dreischarf et al., 2014). Based on this model, four additional models were created using the classification proposed by Roussouly et al. (2005) to account for the large anatomical variability in the sagittal alignment

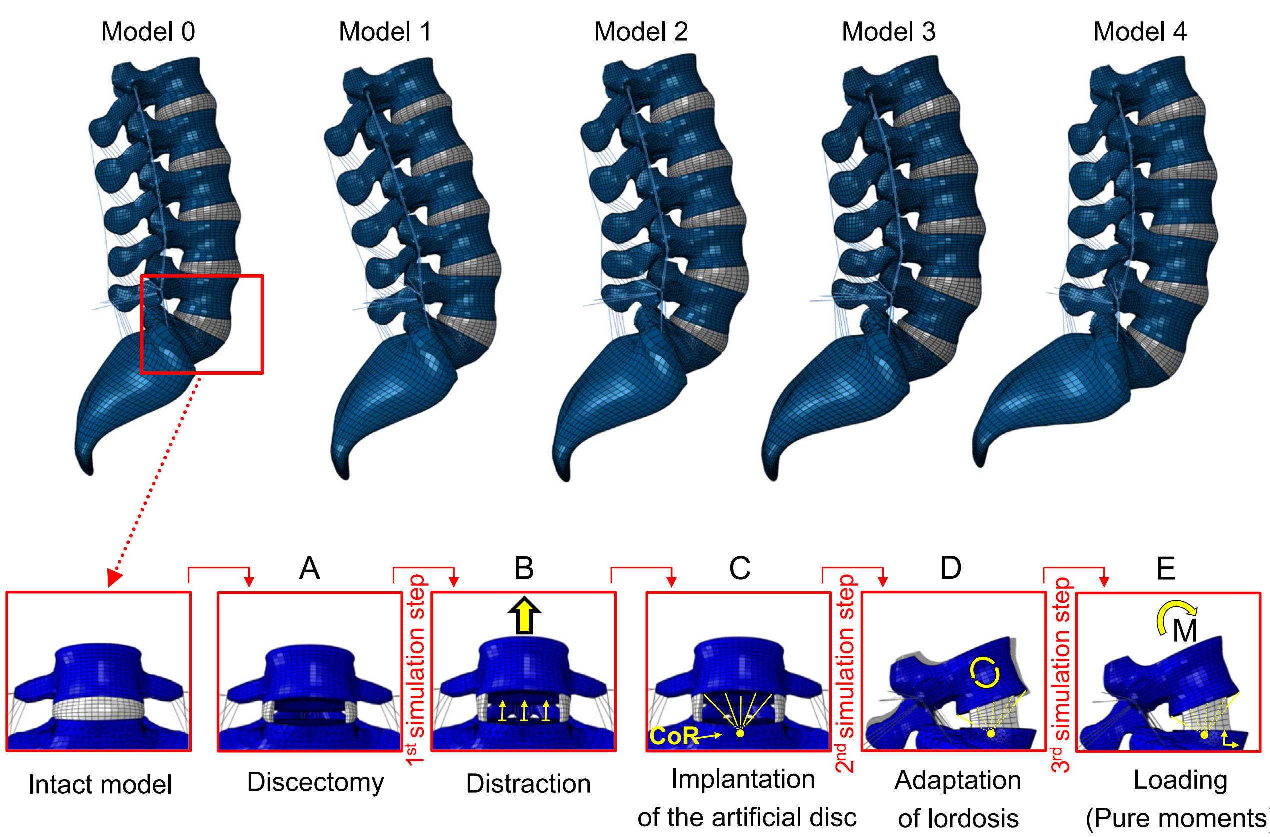

Fig. 1. Finite element models of the lumbar spine employed in the present study (top). Procedure employed in this study (bottom). (A) Resection of the central part of the intervertebral disc, anterior and posterior longitudinal ligaments and the cartilaginous endplates; (B) 1st simulation step: iatrogenic distraction and (C) subsequent insertion of the implant; (D) 2nd simulation step: adaption of the segmental lordosis and (E) subsequent simulation of flexion, extension, lateral bending and axial rotation using pure moments (3rd step).

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