Medical Engineering & Physics 34 (2012) 498–505

Contents lists available at SciVerse ScienceDirect

Medical Engineering & Physics

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

Concave polyethylene component improves biomechanical performance in lumbar total disc replacement—Modified compressive-shearing test by finite element analysis

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ARTICLE INFO

Article history:
Received 14 June 2011
Accepted 18 August 2011

Keywords:
Lumbar spine
Total disc replacement
Ultra-high molecular weight polyethylene
Concave articulating surface
Nonlinear finite element analysis

ABSTRACT

Failure of ultra-high molecular weight polyethylene components after total disc replacements in the lumbar spine has been reported in several retrieval studies, but immediate biomechanical evidence for those mechanical failures remained unclear. Current study aimed to investigate the failure mechanisms of commercial lumbar disc prostheses and to enhance the biomechanical performances of polyethylene components by modifying the articulating surface into a convex geometry. Modified compressive-shearing tests were utilized in finite element analyses for comparing the contact, tensile, and shearing stresses on two commercial disc prostheses and on a concave polyethylene design. The influence of radial clearance on stress distributions and prosthetic stability were considered. The modified compressive-shearing test revealed the possible mechanisms for transverse and radial cracks of polyethylene components, and would be helpful in observing the mechanical risks in the early design stage. Additionally, the concave polyethylene component exhibited lower contact and shearing stresses and more acceptable implant stability when compared with the convex polyethylene design through all radial clearances. Use of a concave polyethylene component in lumbar disc replacements decreased the risk of transverse and radial cracks, and also helped to maintain adequate stability. This design concept should be considered in lumbar disc implant designs in the future.

1. Introduction

With the advantage of superior mechanical properties and biocompatibility, ultra-high molecular weight polyethylene (UHMWPE) has been widely utilized as weight-bearing material in total joint replacement components [1,2]. The ball-and-socket styled articulating mechanism for total disc replacement (TDR) is commonly adopted, particularly in lumbar TDRs such as the SB Charité III (DePuy Spine, Raynham, MA, USA), and ProDisc-L (Synthes-Stratec Inc., Oberdorf, Switzerland), with a dome-shaped (convex) PE component articulating against metallic (cobalt–chrome alloy) endplates. Previous reports demonstrated that high postoperative satisfactions (up to 83–99%) [3–5] have been achieved with TDRs in the treatment of lumbar intervertebral disc degeneration, and they also efficiently improved the clinical outcomes in both Visual Analogue Scales and Oswestry Scores [3,6–8]. Compared to conventional spinal fusion surgeries, the TDR technique with preserved segmental mobility allowed better long-term survivorship and lower complication rates from adjacent disease [9–11]. Nevertheless, from experience of general joint replacement techniques, it is clear that the problem of PE component failure remains unsolved.

The features of failure and wearing patterns of PE components in lumbar TDRs have been focused on in previous studies. Kurtz et al. characterized the transverse cracks on the PE core of a retrieved SB Charité III disc using micro-computed-tomography imaging [12], and several studies with larger numbers of retrievals for failure styles including radial cracks, rim fractures, and wearing patterns were published thereafter [13–15]. Severe wear of PE components in lumbar disc implants has been correlated to asymmetric motion patterns [16], and the consequences of failure of PE components in lumbar TDRs have been well investigated. Several mathematical models and finite element studies have been performed to investigate the biomechanical behaviors of different lumbar TDR designs

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doi:10.1016/j.medengphy.2011.08.010

[17] and the effects of design features on PE components. To the premise that the articulating mechanism of the ball-and-socket joint is preserved, in the modification of lumbar TDR designs it is most feasible to only adjust the radial clearance between articulating surfaces. The effects of radial clearance on wearing patterns and contact stresses have been investigated [18,19]. However, with general loading conditions applied in previous numerical studies, immediate biomechanical evidence for mechanical failure of PE components remained unclear due to limited understanding of the failure mechanisms.

Nowadays, the prevailing PE components in major joint prostheses, such as knee and hip joints, are designed with concave geometries as the physiological imitations. However, PE component applied to articulating surface of lumbar TDR is generally with a convex geometry, while the feasibility of concave PE for lumbar TDR has not been evaluated. As an articulating component in TDR, failure of the PE component would influence the motion pattern and mechanical stability of the spinal segment. Therefore, improvement of the PE component design is necessary, as well as establishing more completed testing techniques for examining the possible mechanical failures of PE components. The purpose of this study was then to improve the mechanical performance of PE components of lumbar TDR by changing the general convex articulating surface into a concave shape. Additionally, a modified compressive-shearing test was utilized in nonlinear finite element analyses to distinguish the failure mechanism of PE components with various geometries and radial clearances.

2. Materials and methods

2.1. Modeling of TDR implants

Commercial TDRs [SB Charité III (SBC) and ProDisc-L (PDL)] were reconstructed into three-dimensional solid models using SolidWorks 2007 (SolidWorks Corp., USA), referring to the published parameters of the products. The modified TDR with concave PE component (CVP) design was also modeled (Fig. 1). The SBC model includes two concave metallic endplates and one dual-convex mobile PE component. The PDL model includes a superior metallic endplate with concave articulating surface against a single convex PE component, with the flat base positioned against the inferior metallic endplate. The CVP model was derived from the PDL model. The articulating surface of the superior metallic endplate in the CVP model was changed from a concave into a convex shape, whereas the PE component was modified into a concave shape. Radii for articulating surfaces of all PE components in the three TDR models were considered as 14.0 mm [18,19]. Thicknesses of the PE components were respectively 7.5, 6.5, and 4 mm for the distance of SBC between the superior and inferior apexes, PDL between the apex and the flat base, and the CVP between the base of the concave groove and the flat base (Fig. 2). For realizing the effect of radial clearances on biomechanical responses of PE components, radial clearances of 0.1, 0.3, and 0.5 mm were respectively assigned to articulating surfaces of metallic endplates in the three TDR models. All solid TDR models were meshed with ABAQUS 6.9 (SIMULIA Inc., USA). Eight-node solid block elements were applied to mesh the PE components. According to convergence tests, numbers of elements contained within PE components were respectively 11,960, 10,344, and 10,854 for SBC, PDL, and CVP models. The metallic endplates in all models were assumed as rigid bodies because the elastic modulus of metal is substantially greater than that of PE. For mimicking the true deformation, material properties of PE components were nonlinearly applied with a Poisson's ratio of 0.45, referring to the true stress/strain curve for elastoplastic PE model [1].

2.2. Boundary and loading conditions

Contact characteristics between metallic and PE articulating surfaces were defined by finite sliding with hard contact, and a penalty friction with 0.05 of friction coefficient was specified [19]. In order to observe the biomechanical behaviors between the articulating surfaces, bases of PE components for PDL and CVP models were assumed to be fixed with subjacent metallic endplates to prevent possible dislocations. Superior metallic endplates in all models were restricted in three rotational degrees of freedom to avoid paradoxical revolutions, while all inferior metallic endplates were completely fixed at their bases. PE components in SBC models were left unconstrained in all degrees of freedom. Vertical compressive preloads of 500 N [20] were initially applied at the superior metallic endplates, and lasted to the end of simulation to ensure solid contact between articulating surfaces. Thereafter, incremental anterior shearing loads of 10 N per step were applied at superior endplates until maximal values of 200 N were achieved.

2.3. Criteria of evaluation

The maximal contact, tensile and shearing stresses on PE components, and horizontal translations of superior metallic endplates were recorded in each loading step to investigate the influence of convex/concave geometries and radial clearances. Stress values were used for evaluating the failure mechanism of PE components, referring to experimental data [2,21]. The sensitivity of TDR models can be gauged through the observed stress changes for each incremental load. The critical values of shearing loads, defined as the loads resulted in a greater than 10% increase in all types of stresses when compared to the previous load step, were recorded.

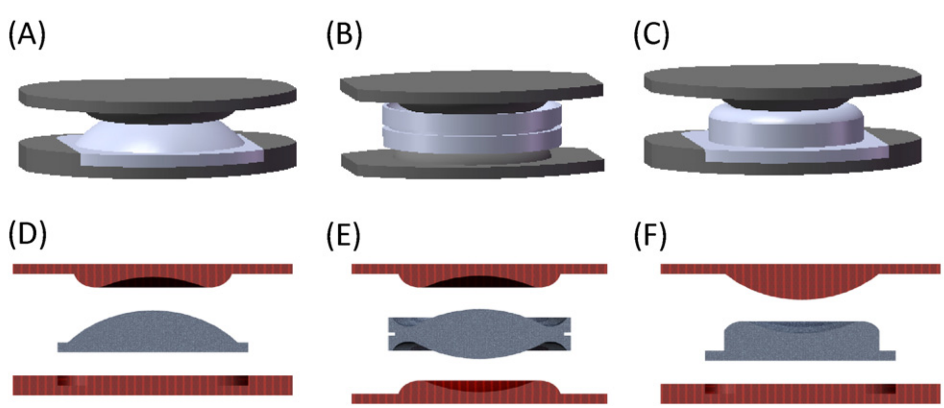

Fig. 1. Three models of lumbar TDR implants: (A) PDL, (B) SBC, (C) CVP, and cross-sectional views: (D) PDL, (E) SBC, and (F) CVP.