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Biomechanical investigation into the structural design of porous additive manufactured cages using numerical and experimental approaches

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ABSTRACT

Traditional solid cages have been widely used in posterior lumbar interbody fusion (PLIF) surgery. However, solid cages significantly affect the loading mechanism of the human spine due to their extremely high structural stiffness. Previous studies proposed and investigated porous additive manufactured (AM) cages; however, their biomechanical performances were analyzed using oversimplified bone-implant numerical models. Thus, the aim of this study was to investigate the outer shape and inner porous structure of the AM cages. The outer shape of the AM cages was discovered using a simulation-based genetic algorithm; their inner porous structure was subsequently analyzed parametrically using T10-S1 multilevel spine models. Finally, six types of the AM cages, which were manufactured using selective laser melting, were tested to validate the numerical outcomes. The subsidence resistance of the optimum design was superior to the conventional cage designs. A porous AM cage with a pillar diameter of 0.4 mm, a pillar angle of 40°, and a porosity of between 69% and 80% revealed better biomechanical performances. Both the numerical and experimental outcomes can help surgeons to understand the biomechanics of PLIF surgery combined with the use of AM cages.

1. Introduction

Posterior lumbar interbody fusion (PLIF) surgery has been used to treat spinal diseases, including degenerative disc disease and spinal stenosis [1–3]. Both a posterior screw-rod fixation system and solid intervertebral cages were selected for the PLIF surgery [4,5]. However, a traditional solid cage has extremely high structural stiffness compared with a bone graft and significantly changes the loading mechanism of the human spine [6,7]. van Dijk et al. investigated the effect of cage stiffness on the rate of lumbar interbody fusion. They concluded that the reduced stiffness of poly-(L-lactic acid) cages showed enhanced interbody fusion compared with that in titanium cages [8]. A porous structure is one possible method to reduce cage stiffness. However, this porous structure is difficult to be fabricated using computer numerical control (CNC) machining [9]. Selective laser melting is a new manufacturing technique in medical orthopedics [10,11]. This technique is an additive manufacturing (AM) process that can construct irregular and complicated three-dimensional porous metal parts by fusing fine metal powders together [12,13]. Previous studies numerically and experimentally investigated porous structural designs of AM cages and evaluated their mechanical performances [14,15]. However, those studies ignored the biomechanics of the human spine when designing the porous structure of the AM cages. Fortunately, some researchers attempted to eliminate this drawback. Lee et al. developed porous cage and lumbar L3-L4 models to investigate the biomechanics of the bone-implant constructs [16]. Additionally, Kang et al. investigated porous biodegradable fusion cages using ligamentous finite element models of mini-pig L2-L5 lumbar spine [17]. Although the bone-implant constructs developed by the previous studies could provide referable biomechanical outcomes, their numerical models may be oversimplified. Notably, numerical models with short spinal segments could not simulate more realistic loading conditions [18,19]. This model simplification may affect the evaluations of porous AM cages. In the present study, a realistic finite element model of a T10-S1 multilevel spine was developed to determine the effects of porous designs of AM cages on intersegmental rotation, cage stress, and disc stress. The mechanical tests were

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also conducted to validate the numerical outcomes. Thus, the aim of this study was evaluate the structural designs of porous AM cages numerically and experimentally.

2. Materials and methods

The outer shape and inner porous structure of AM cages were investigated in the present study in an attempt to determine their optimal parameters. The outer shape of the AM cages was optimized to enhance the subsidence resistance (Section 2.1). Then, the inner porous structure of the AM cages was parametrically analyzed to satisfy the biomechanical requirements (Section 2.2). Finally, the mechanical tests were conducted to validate the numerical outcomes (Section 2.3).

2.1. Shape optimizations for subsidence resistance of AM cages

Cage subsidence is one of the clinical complications for patients following PLIF surgery [20,21]. The subsidence resistance of the AM cages needs to be optimized before determining their porous structure. In general, an optimization problem consists of three basic components, which include design variables, constraints, and an objective function. In the present study, seven design variables were selected to define the outer shape of the AM cages (Fig. 1A). To eliminate any unfeasible designs, all AM cages needed to satisfy a geometric constraint, which was that the cross-sectional area of all cages cannot exceed an area of 300 mm^2. This specific cross-sectional area was determined in a sensitivity analysis.

AM cages have irregular and complicated geometries, and there is no way to get an exact solution for them. In the present study, a mathematical formula was not an objective function because there are currently no useful mathematical formulae that represent the subsidence resistance of AM cages. Therefore, three-dimensional finite element models were developed and used as an objective function. The finite element models consisted of an AM cage and one osteoporotic vertebra (Fig. 1B). The materials of both the AM cage and the osteoporotic vertebra were assumed to be elastic isotropic (Table 1). The AM cage and the vertebra were map-meshed with high-order 20-node elements of SOLID 186. To reach

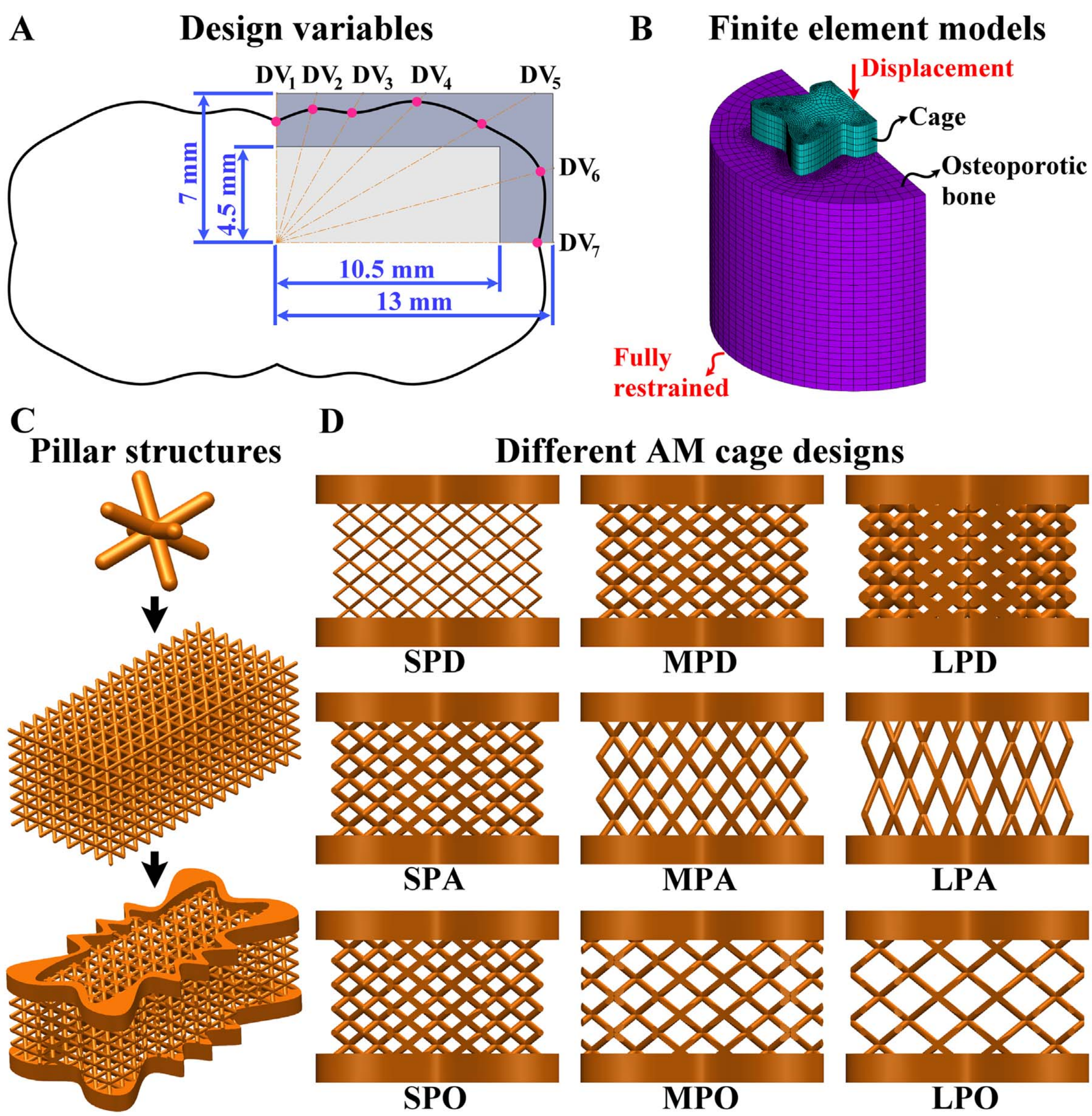

Fig. 1. (A) Design variables of the shape optimization; (B) Finite element model of the shape optimization; (C) The designs of the pillar structures of the AM cages; and (D) Different AM cage designs.