Validation of a Novel Technique for Estimation of the In-vivo Loads on the Lumbar Intervertebral Disc

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Introduction

Evaluation of the loads on the lumbar intervertebral discs (IVDs) is critically important since it is closely related to biomechanics, pathology, prosthesis design and tissue engineering. Non-invasive estimation of the in-vivo loads on the IVD remains a challenge. Using our previously established dual fluoroscopic imaging system (DFIS) [1], in-vivo kinematics of the vertebrae can be accurately obtained. In this study we proposed a new technique to estimate in-vivo loads on the IVD using a subject-specific finite element (FE) model of the IVD and its kinematics from DFIS as input boundary conditions. The objective of this study was to validate the technique by comparing the FE analysis results to the in-vitro experiment measurements using three lumbar IVDs.

Materials and Methods

Three fresh-frozen cadaveric lumbar spinal motion segmental units (two L2/3 and one L4/5, 23 to 44 years old) with healthy IVDs were selected from 3 donors. Each specimen was carefully dissected to remove the muscles, ligaments and posterior elements to focus only on the force-displacement behaviors of the IVD. The vertebral bodies were potted in bone cement for fixation on the testing system. 3D geometric models of the specimens were reconstructed from CT scans.

Each specimen was then installed on a 6DOF robot [2] with 6DOF load cell (Fig 1a). The inferior and superior endplates were fixed to the ground and the robot end effector, respectively. The center of the IVD and 3 principal directions were determined using a digitization platform and recorded in a local coordinate system. 7 loading cases: 400 N compression and 5 Nm moments in 3 principal directions were applied by the robot. Each loading case included 10 incremental steps that under custom written robot control optimization algorithm [2]. At each step, resultant forces and moments at the center of the IVD were recorded by the load cell. Fluoroscopic images of the specimens were captured and the kinematics of the vertebrae were measured using the DFIS [1] (Fig 1b).

A subject specific FE IVD model was built from the 3D geometric information of the IVD endplates from CT scan (Fig 2). The model consisted of four parts: nucleus pulposus (hydro-fluid elements), annulus ground substance (hyper-elastic hexahedral elements), annulus fibrosi (tension only truss elements) and superior and inferior endplates (rigid elements). Material properties and constructions of the FE models were adopted from the published literatures [3]. The obtained kinematics from DFIS were used as inputs in the FE analysis. Forces and moments were calculated and compared with those measured in the experiments from the load cell in the same local coordinate system.

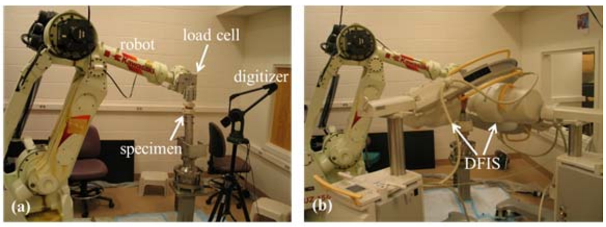
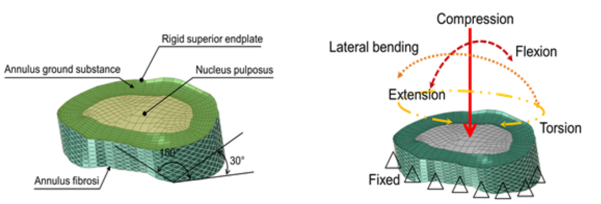


Fig. 1: Experimental setup of the 6DOF robot and DFIS system.



(a) (b)

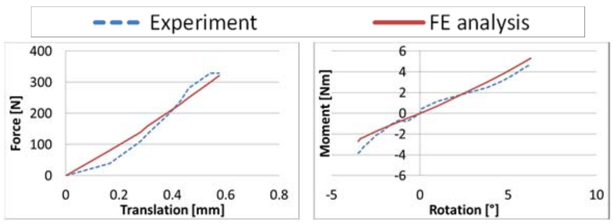
Fig. 2: (a) FE models of the IVD and (b) boundary conditions for FE analysis

Results

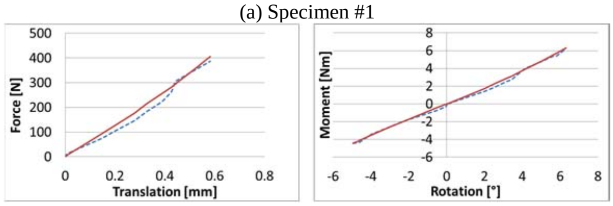
The forces and moments calculated from the subject specific IVD FE model had good agreements with those recorded in the in vitro test (Fig. 3). Comparing the FE analysis results with the experiment results of various loading cases, the average difference between the forces at the end steps were 18% and the average difference between the overall areas under the force-displacement curve were 17%.

Discussion and Conclusion

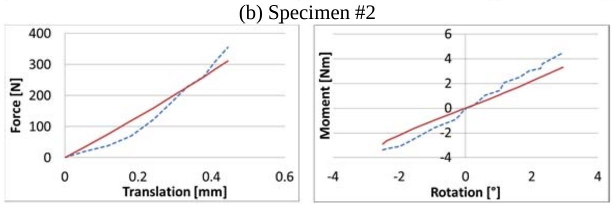
Traditional FE analyses of the lumbar spine were usually performed under controlled external loads. Alternatively in the proposed technique, kinematics of the IVD endplates was used as input boundary conditions to calculate the loads on the IVDs. We validated the force responses of the FE models by directly comparing those with the in-vitro experiment results of the same IVDs, and the accuracy was within 20% of the applied load. Upon validation, the same approach can be extended to the estimation of in vivo spinal forces. It could be a promising tool to study spine biomechanics as well as help understand pathologies and develop surgical techniques in living human subjects.



(a) Specimen #1



(b) Specimen #2



(c) Specimen #3

Fig. 3: Force-displacement curve (left) under compressive force and moment-displacement curve (right) under flexion/extension moment from in-vitro experiment and FE analysis

Acknowledgement

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References

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