Journal of Biomechanics ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Short communication

Quantification of loading in biomechanical testing: the influence of dissection sequence

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ARTICLE INFO

Article history:
Accepted 17 June 2015

Keywords:
Principle of superposition
Biomechanical test
Serial dissection
Robotics
Load-sharing

ABSTRACT

Sequential dissection is a technique used to investigate loads experienced by articular tissues. When the joint of interest is tested in an unconstrained manner, its kinematics change with each tissue removal. To address this limitation, sufficiently rigid robots are used to constrain joint kinematics. While this approach can quantify loads experienced by each tissue, it does not assure similar results when removal order is changed. Specifically, structure loading is assumed to be independent of removal order if the structure behaves linearly (i.e. principle of superposition applies), but dependent on removal order when response is affected by material and/or geometry nonlinearities and/or viscoelasticiy (e.g. biological tissues). Therefore, this experiment was conducted to evaluate if structure loading created through robotic testing is dependent on the order in which connectors are removed. Six identical models were 3D printed. Each model was composed of 2 rigid bodies and 3 connecting structures with nonlinear time-dependent behavior. To these models, pure rotations were applied about a predefined static center of rotation using a parallel robot. A unique dissection sequence was used for each of the six models and the same movements applied robotically after each dissection. When comparing the moments experienced by each structure between different removal sequences, a statistically significant difference ($p < 0.05$) was observed. These results suggest that even in an optimized environment, the sequence in which nonlinear viscoelastic structures are removed influence model loading. These findings support prior work suggesting that tissue loads obtained from robotic testing are specific to removal order.

1. Introduction

Unconstrained testing of joint segments is performed by fixing one end of an articulation and leaving the other end to move freely. Traditionally performed by servo-hydraulic machines or cables/pulleys systems to move the free end of the specimen (Crawford et al., 1995; Haher et al., 1994; Lee and Evans, 2000; Yingling and Mcgill, 1999), this approach has been used to investigate how joint loading is altered after one structure has been injured (or removed). Importantly, this technique is limited in that the resulting joint movements may change with each tissue transection as the joint moves along the path of least resistance (Lee and Evans, 2000). Alternatively, robots with sufficient rigidity and six degrees-of-freedom can reproduce identical kinematics trajectories following tissue removal (Gillespie and Dickey, 2004; Kawchuk et al., 2010). By combining this technique with serial dissection, loads experienced by each joint structure can be quantified (Gillespie and Dickey, 2004; Kawchuk et al., 2010).

However, combining robotics with serial dissection does not assure that the resulting tissue loads remain equal when the dissection sequence is changed. Although this is true for linear systems, the nature and material properties (nonlinearity, viscosity, porosity etc.) of biological structures may not result in similar loads when biomechanical tests are used with different sequences of dissection (Sasso et al., 2011; Woo et al., 2001).

Given the above, this experiment was conducted to investigate structural response to mechanical loading created through robotic testing when different sequence of structural removal is used.

2. Materials and methods

2.1. Model design and fabrication

A simple vertebral motion segment facsimile (model) was made from two rigid objects joined together by multiple, flexible connectors of different dimensions (Fig. 1). To minimize variability between copies of the model, 3D printing was used to fabricate 6 replicates. Based on the dimensional data from Panjabi (1973), the

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http://dx.doi.org/10.1016/j.jbiomech.2015.06.020
0021-9290/© 2015 Published by Elsevier Ltd.

Please cite this article as: Funabashi, M., et al., Quantification of loading in biomechanical testing: the influence of dissection sequence. Journal of Biomechanics (2015), http://dx.doi.org/10.1016/j.jbiomech.2015.06.020

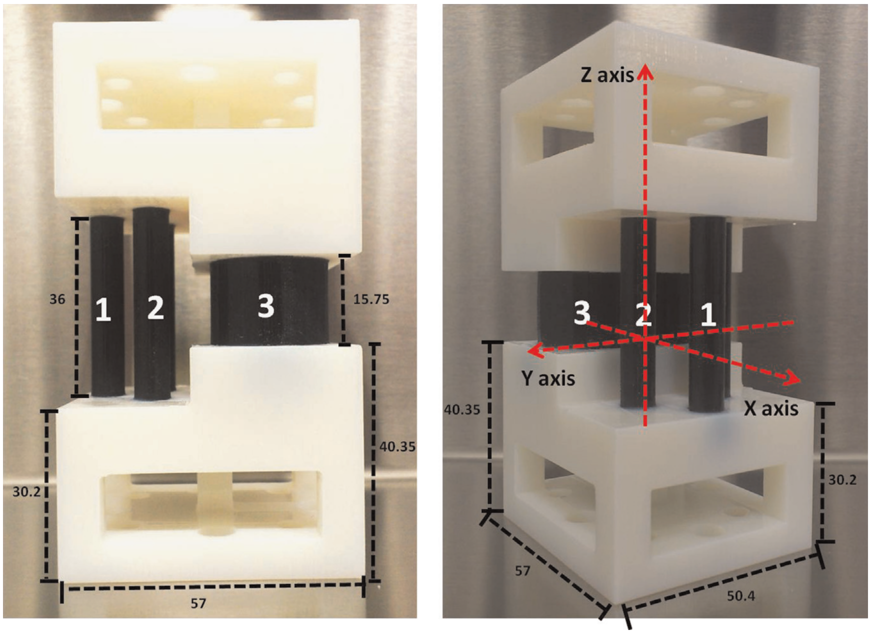

Fig. 1. Multi-material 3D print model and Cartesian axes. Numbers indicate the connector. Measures are given in millimeters.

model consisted of two rigid blocks printed in VeroWhitePlus, a rigid material that simulated vertebral bodies. Joining these two rigid blocks were three connectors made of a rubber-like material. Connectors 1 and 2 (7.5 mm diameter and 36 mm height) were composed of A40-shore TangoBlackPlus while Connector 3 (elliptical shaped: 15.75 mm height, 22.5 mm width and 17.25 mm length) was composed of A50 shore TangoBlackPlus (Fig. 1). The resulting combination of these materials created a motion segment presumed to have a time-dependent, nonlinear behavior.

2.2. *Model preparation and mounting*

All six 3D print models were potted simultaneously with a standardized technique using dental stone (Modern Materials, South Bend, IN). A 6-axis load cell (AMTI MC3A-1000, Advanced Mechanical Technology, Inc., Watertown, MA) was used to record forces and moments generated in the models along and around each of the three Cartesian axes (*x* axis = anterior/posterior, *y*-axis = medial/lateral, *z*-axis = cranial/caudal) (Fig. 1). The load cell was mounted rigidly to the platform of a parallel robot (Parallel Robotics Systems Corp., Hampton, NH) and zeroed.

The parallel robot is comprised of a rigid platform suspended by 6 rigid struts of fixed length. Each strut is attached to an electromechanical motor that travels about a circular track. Changes in the position and orientation of the robot platform are achieved by computer-controlled movement of each motor around the track. The linear and angular resolution of the robot is approximately 1 μm and 0.001° respectively.

Both ends of the potted 3D model were then rigidly fixed: the upper end bolted to a stationary cross-beam and the lower end bolted to the load cell mounted rigidly to the parallel robotic platform. The robot was then moved until the loads and moments on the model were minimized in all axes. This was considered the starting neutral position and from this position, spatial reference points were collected from the external surface of connector 3 with an optical tracking system (NDI, Waterloo, Canada) and customized software (LabVIEW, National Instruments, Austin, TX). From these data, a static center of rotation (COR) was calculated for subsequent testing as $^1/_3$ the length of connector 3 from the posterior wall.

2.3. *Testing protocol*

Pilot testing was conducted to verify the maximum angular displacement of the 3D print models. Based on the properties of the materials used, the maximum angular displacement was considered to be the angular displacement that created relative peak moments of ± 2 Nm and was found to be $\pm 7°$ about *y*-axis, $\pm 6°$ about the *x*-axis, and $\pm 5°$ for torsion (rotation around *z*-axis). Starting from the neutral position, 3 cycles of pure rotation were applied about each axis around the same COR. In each cycle, rotations were applied first in the positive direction, returning to neutral position, followed by rotation in the negative direction. After each rotation, the model was allowed to recover for a defined period of time to allow internal forces of the materials to minimize (7 min for rotation about *y*-axis, and 5 min for rotation about both *x*- and *z*-axes as determined from pilot testing). The return of forces and moments to baseline was assured before the following test commenced. All angular displacements were applied at a rate of 1°/s and all testing was performed in a room at 23 °C with data sampling at 1 kHz.

Table 1
Sequence of connector removal for each 3D print model.

	Cut 1	Cut 2	Cut 3
Model A	Connector1	Connector2	Connector3
Model B	Connector1	Connector3	Connector2
Model C	Connector2	Connector1	Connector3
Model D	Connector2	Connector3	Connector1
Model E	Connector3	Connector1	Connector2
Model F	Connector3	Connector2	Connector1

2.4. *Sequential connector removal*

Following baseline testing, the three connectors were removed using pre-determined sequences (Table 1). After the removal of each connector, the same kinematic trajectory was performed with standardized recovery time between trials.

2.5. *Statistical analysis*

For each 3D print model, the resulting moments were plotted against time for the intact condition and following the removal of each connector. The relative mean and peak moments experienced by each connector were identified, calculated, and considered to be the primary outcome. Relative mean and peak moments were calculated as the difference between the mean and peak moments and the moments in the previous condition. The relative area between curves of the moment–rotation graph (Fig. 2), was also calculated and analyzed. The measurements of the 3 trials were averaged and considered as dependent variables.

Descriptive statistics were reported for moments around each specific axis. As measurements were taken after the removal of each connector, the resulting series of values representing the dependent variables were correlated. Therefore, a linear mixed model analysis was performed using IBM SPSS Statistics for Windows, version 22.0 (Armonk, NY: IBM Corp.) with 3 fixed factors: connector, movement, and sequence of connector removal. For all statistical tests, an α-level of 0.05 was considered.

3. Results

3.1. *Sequential connector removal*

The variance between three repeated trials was found to be negligible (analysis of variance $p = 0.805$), therefore the average of the 3 trials was used for further analysis. Fig. 2 illustrates moment–rotation curves observed about the *y*-axis. From these

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