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Influence of varying compressive loading methods on physiologic motion patterns in the cervical spine

Kevin M. Bell [a,*], Yiguo Yan [a], Richard E. Debski [b], Gwendolyn A. Sowa [c], James D. Kang [a], Scott Tashman [a]

[a] Ferguson Laboratory for Spine Research, Department of Orthopaedic Surgery, University of Pittsburgh School of Medicine, Pittsburgh, PA, USA
[b] Department of Bioengineering, University of Pittsburgh School of Medicine, Pittsburgh, PA, USA
[c] Department of Physical Medicine and Rehabilitation, University of Pittsburgh School of Medicine, Pittsburgh, PA, USA

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ABSTRACT

The human cervical spine supports substantial compressive load in-vivo arising from muscle forces and the weight of the head. However, the traditional in-vitro testing methods rarely include compressive loads, especially in investigations of multi-segment cervical spine constructs. Various methods of modeling physiologic loading have been reported in the literature including axial forces produced with inclined loading plates, eccentric axial force application, follower load, as well as attempts to individually apply/model muscle forces in-vitro. The importance of proper compressive loading to recreate the segmental motion patterns exhibited in-vivo has been highlighted in previous studies. However, appropriate methods of representing the weight of head and muscle loading are currently unknown.

Therefore, a systematic comparison of standard pure moment with no compressive loading versus published and novel compressive loading techniques (follower load – FL, axial load – AL, and combined load – CL) was performed. The present study is unique in that a direct comparison to continuous cervical kinematics over the entire extension to flexion motion path was possible through an ongoing intra-institutional collaboration. The pure moment testing protocol without compression or with the application of follower load was not able to replicate the typical in-vivo segmental motion patterns throughout the entire motion path. Axial load or a combination of axial and follower load was necessary to mimic the in-vivo segmental contributions at the extremes of the extension-flexion motion path. It is hypothesized that dynamically altering the compressive loading throughout the motion path is necessary to mimic the segmental contribution patterns exhibited in-vivo.

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1. Background

In-vitro biomechanical testing has been critical in the design and evaluation of surgical instrumentation. Determination of realistic physiologic loading levels for the cervical spine has, however, proven difficult outside of the in-vivo setting. Unconstrained pure moment testing combined with the hybrid testing method is currently the gold standard test protocol for evaluation of motion preservation technology and adjacent level effects. Pure moment testing was specifically designed to apply uniform loading at each cross section throughout the length of a spinal construct, permitting irregularities to be identified (Panjabi, 1988). Pure moment testing is well suited for making relative comparisons between treatments, but is currently not based on or representative of in-vivo motion (Panjabi, 2007).

Additionally, the human cervical spine supports substantial compressive load in-vivo arising from muscle forces and the weight of the head. However, the traditional in-vitro testing methods rarely include compressive loads; especially in investigations of multi-segment cervical spine constructs. Various methods of modeling physiologic loading have been reported in the literature including axial forces produced with inclined loading plates, eccentric axial forces application, follower load, as well as attempts to individually apply/model muscle forces in-vitro (Adams and Dolan, 2005; Cook, 2009; Cripton et al., 2000; DiAngelo and Foley, 2004; Goel et al., 2006; Miura et al., 2002; Panjabi, 1988, 2007; Panjabi et al., 2001; Patwardhan et al., 2000; Wilke et al., 1994, 2001, 1998).

Miura et al. (2002) and DiAngelo and Foley (2004) published articles directly aimed at determining the most appropriate loading mechanism to produce physiologic motion patterns. Miura et al. (2002) presented pure moment testing combined with follower load and, through adjusting moment targets, was able to

* Corresponding author. Tel.: +1 412 657 7857; fax: +1 412 648 8548.
E-mail address: kmb7@pitt.edu (K.M. Bell).

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achieve ~20% agreement with segmental range of motion reported in literature, however typical segmental motion patterns were not observed with this technique. DiAngelo and Foley utilized an eccentric axial compressive method in attempt to mimic the weight of the head. DiAngelo and Foley (2004) was able to show reasonable agreement with the segmental motion patterns, but the magnitudes dramatically underestimated the average in-vivo segmental kinematics.

The objective of this project is to identify and verify the appropriate in-vitro loading conditions that would replicate the in-vivo kinematics of the cervical spine, with the overall goal of improving the biofidelity of the experimental platform. A systematic comparison of standard pure moment with no compressive loading versus published and novel compressive loading techniques (follower load – FL, axial load – AL, and combined load – CL) was performed. It is hypothesized that an optimized follower load, passing through the segmental centers of rotation, will add stability to the system but will not dramatically affect the segmental motion patterns observed throughout the extension to flexion motion path. In contrast, axial load applied perpendicular to superior most vertebral body, will not maintain the pure moment assumption, whereby enabling the segmental motion patterns to be altered.

2. Methods

2.1. Protocol

$N=12$ fresh-frozen human (C3-7) cervical cadaveric specimens (51.8 years ± 7.3) were pre-screened with CT and dissected, preserving osteoligamentous structures. Specimens were mounted in a robot-based spine testing system, consisting of a serial linkage robotic manipulator (Staubli RX90, Staubli Inc., Duncan, SC) with an on-board six-axis load cell (UFS Model 90M38A-150, JR3 Inc., Woodland, CA) and custom specimen-mounting fixtures (Bell et al., 2007; Gilbertson et al., 1999; Hartman et al., 2009). Four clinical lateral mass screws were used to secure the specimens to the mounting fixtures (one in each pedicle and two in the anterior portion of the vertebral body). After mounting, specimens were wrapped in 0.9% saline soaked gauze and periodically sprayed with saline in order to prevent dehydration. The robot was controlled via MATLAB (Mathworks, Inc.) and operates under adaptive displacement control to a pure moment target of 2.0 N m for flexion and extension (FE) for each state in a randomized order (no compression (Fig. 1A), follower load, axial rotation, combined loading). Due to the quasi-static nature of the adaptive displacement control algorithm the system operated at a rate of 0.067 ± 0.0014°/s. Two consecutive full extension to flexion loops were performed with the data from the second cycle being presented to account for preconditioning (Cripton et al., 2000). Segmental motion was recorded using a five camera VICON system tracking passive reflective markers rigidly attached as a marker group to each vertebral body. A hand held VICON digitizer was utilized to digitize the anatomical coordinate system for each vertebral body relative to the marker group and the Euler angle rotations of C34, C45, C56, and C67 were determined and reported.

2.2. Follower load

Follower load application was accomplished by loading the specimen with bilateral cables passing through cable guides inserted into the vertebral bodies and over pulleys attached to the base (Fig. 1B). A novel active system was implemented in our laboratory using linear actuators coupled with load cells. Control of the system was integrated with the custom-built PC-based control program written in MATLAB that is currently used to control the robot testing system, and enabled active control of the loading throughout the motion path. The follower load system (Fig. 1B) consists of two independently controlled 24 V servo motor linear actuators (Ultramotion – 3-B.125-DC426_24-4-/4) and compression/tension load cells (Transducer Techniques – MLP-100). A Galil Motion Controller (DMC-4183-BOX8 (-16BIT)-D3040-D4040) controlled this system using on-board closed loop Proportional-Integral-Derivative (PID) load control. The 3/64" diameter stainless steel wire rope lanyard was threaded through a custom designed adjustable cable guide system attached with clinical pedicle screws to enable the follower load cable to interface with the specimen in a manner consistent with the design criterion: (a) tangent to the curvature of the spine and (b) pass through the specimen's center of rotation (COR). Optimization of the follower load path to align with the specimen's COR was accomplished through an offline iterative feedback process using the moment output of the testing system's on-board six-axis load cell. With the specimen in the neutral position, 100 N of follower load was applied to the specimen and resulting change in moments was recorded.

Follower load magnitude of 100 N was chosen as it is representative of the most common follower load magnitude presented in literature (Cho et al., 2010; Finn et al., 2009, 2011; Lee et al., 2011; Martin et al., 2011; Paxinos et al., 2009; Snyder et al., 2007). The position of the cable guide was then adjusted to counteract the moment change and the process was repeated until less than 0.1 N m change in moment was observed. Preliminary testing of the described optimization process was performed ensuring that the previously described maintenance of segmental curvature angle criteria was upheld (Patwardhan et al., 2003).

2.3. Axial load

Although less popular than follower load as a method to apply compressive load due to published instability issues with this testing method, some authors believe axial loading to be the most physiologic loading scheme—mimicking head weight (DiAngelo and Foley, 2004). Axial loading can be applied along an axis locally fixed to the specimen or globally fixed to the world coordinate system. Previous reports have shown that the cervical spine buckles at very low loads when an axial load is applied globally, therefore for this study the axial load was applied along an axis locally fixed to the specimen (perpendicular to the robot end effector – Fig. 1C). The axial load was applied using the robotic arm to a load target of 50 N (DiAngelo and Foley, 2004), representative of the approximate weight of the head, using the adaptive displacement control algorithm enabling the load to be applied purely in the axial direction and be maintained throughout the flexion–extension rotation path.

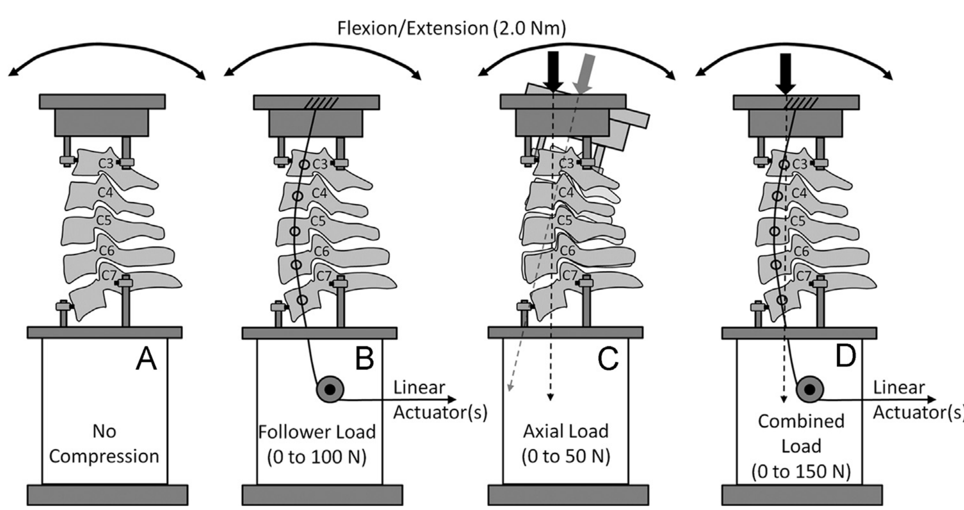

Fig. 1. Schematic of the four loading states implemented in this study, (A) no compression, (B) follower load, (C) axial load rotated state showing perpendicular line of action depicted for clarity and (D) combined load.