Journal of Biomechanics 46 (2013) 1663–1669

Contents lists available at SciVerse ScienceDirect

Journal of Biomechanics

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

In vitro spine testing using a robot-based testing system: Comparison of displacement control and “hybrid control”

Kevin M. Bell [a,*], Robert A. Hartman [a], Lars G. Gilbertson [b], James D. Kang [a]

[a] Spine Research Laboratory, Department of Orthopedic Surgery, University of Pittsburgh School of Medicine, 200 Lothrop Street, C-313 PUH, Pittsburgh, 15213 PA, USA
[b] Department of Biomedical Engineering, Tulane University, New Orleans, LA, USA

ARTICLE INFO

Article history:
Accepted 8 April 2013

Keywords:
Spinal biomechanics
Osteoligamentous cervical spine
Load control
Displacement control
Hybrid control
Robotics

ABSTRACT

The two leading control algorithms for in-vitro spine biomechanical testing—“load control” and “displacement control”—are limited in their lack of adaptation to changes in the load–displacement response of a spine specimen—pointing to the need for sufficiently sophisticated control algorithms that are able to govern the application of loads/motions to a spine specimen in a more realistic, adaptive manner. A robotics-based spine testing system was programmed with a novel hybrid control algorithm combining “load control” and “displacement control” into a single, robust algorithm. Prior to in-vitro cadaveric testing, preliminary testing of the new algorithm was performed using a rigid-body-spring model with known structural properties. The present study also offers a direct comparison between “hybrid control” and “displacement control”.

The hybrid control algorithm enabled the robotics-based spine testing system to apply pure moments to an FSU (in flexion/extension, lateral bending, or axial rotation) in an unconstrained manner through active control of secondary translational/rotational degrees-of-freedom—successfully minimizing coupled forces/moments. The characteristic nonlinear S-shaped curves of the primary moment–rotation responses were consistent with previous reports of the FSU having a region of low stiffness (neutral zone) bounded by regions of increasing stiffness (elastic zone). Direct comparison of “displacement control” and “hybrid control” showed that hybrid control was able to actively minimize off-axis forces and resulted in larger neutral zone and range of motion.

1. Introduction

In vitro biomechanical testing the human cadaver cervical spine is widely used as a repeatable platform to quantify three dimensional motion of the spine in response to loads. Traditionally, kinetic parameters of the spine have been obtained through biomechanical tests based on either the flexibility method (load control) or the stiffness method (displacement control) (Panjabi, 1988). However, the inherent limitations of the two leading control algorithms have been detailed in the long-standing controversy in spine biomechanical testing, “load control vs. displacement control” (Goel et al., 1995).

In displacement control experiments, displacements are applied and the resulting loads are measured (Adams and Hutton, 1981; Goodwin et al., 1994). In load control experiments, loads (i.e., forces and moments) are applied individually (Panjabi et al., 1976a, 1976b) or in combination (Edwards et al., 1987) to the free end of a spinal specimen and the resulting unconstrained three-dimensional displacements (i.e., translations and rotations) are measured. From a control perspective, it is apparent that displacement control is less appropriate than load control in high stiffness regions such as the “elastic zone” (EZ) where small changes in applied displacement can produce large changes in load. For example, large, “unphysiological” coupled loads can result from displacement control tests when rotational displacements are prescribed about a fixed axis that is not the specimen's preferred axis of rotation (Grassmann et al., 1998). On the other hand, load control is less appropriate than displacement control in low stiffness regions of the load–displacement curve such as the “neutral zone” (NZ) where little change in applied load can produce large changes in displacement. For example, when closed-loop load control tests are performed, low stiffness of a specimen within the NZ puts high demand on the response characteristics of the control system, for efficient minimization, requiring the testing machine to respond to load control commands with large displacement steps potentially resulting in overshoot of the load targets (Kunz et al., 1994). Thus, the two leading control algorithms for in-vitro spine biomechanical testing—load control and displacement control—are both limited in their lack of adaptation to changes in the non-linear load–displacement response of a spine specimen—pointing to the need for a

---

[*] Corresponding author. Tel.: +1 412 624 2518; fax: +1 412 648 8548.
E-mail address: bellkm@upmc.edu (K.M. Bell).

0021-9290/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jbiomech.2013.04.007

sufficiently sophisticated control algorithm that is able to perform a flexibility test by governing the application of loads/motions to a spine specimen in an adaptive manner.

Goel et al. describe the requirements of flexibility tests, emphasizing the necessity of applying pure moments to specimens permitted to move in an unconstrained manner (Goel et al., 2006). Experimental designs that comply with these expectations are typically composed of adaptive loading mechanisms such as pulleys and cables, orthogonal stepper motors mounted on linear bearings, robotic arms, and Stewart platforms (Gedet et al., 2007; Wheeler et al., 2011). The unconstrained path is a function of the testing system's ability to maintain a pure moment and to permit the natural motion path of the passive subsystem throughout a spinal segment's range of motion (RoM) (Panjabi, 2007). If such testing protocols are properly executed, then motion should be uninhibited along and about each orthogonal axis. As a corollary, non-primary moments and forces should be minimal.

An alternative method to achieve the specified flexibility test lies in traditional robotic hybrid control. Hybrid control methods, combining aspects of load control and displacement control, are readily found in the classical robotics literature (Raibert and Craig, 1981). Industrial robots are inherently displacement controlled devices and are designed for relatively simple pick-and-place operations such as spot-welding, spray painting, etc. However, in recent years robots have begun to be utilized increasingly for assembly tasks such as part-mating which requires high precision manipulation. Hybrid control gives the manipulator the ability to measure and respond to contact forces—extending the effective precision of a manipulation and enabling precise control despite the uncertainties and variations of the work environment. Previously, hybrid control methods adapted from literature have been successfully applied to the multi-DOF (degree-of-freedom) biomechanical testing of musculoskeletal joints such as the knee using a robotic/UFS (universal force–moment sensor) testing system (Carlin et al., 1996; Fujie et al., 1993; Livesay et al., 1995; Rudy et al., 1996)—suggesting the possibility that hybrid control approaches might be appropriate for the spine as well.

In the present paper, the alternative hybrid control method was directly compared to traditional displacement control using a robot-based spine testing system to test intact cervical motion segments operating under both methods. This study design was chosen in order to confirm or deny the efficacy of utilizing an inherently displacement controlled robotic manipulator for the highly uncertain task of spine flexibility testing. The results were also analyzed in an effort to corroborate the emerging opinions regarding flexibility and stiffness testing and to directly delineate the differences between hybrid control and displacement control.

2. Materials and methods

2.1. Device description

The experimental platform consisted of specimen, robotic manipulator, and robotic controller. The serial linkage robotic manipulator (Staubli RX90, Staubli Inc., Duncan, SC) was equipped with an on-board six-axis load cell (UFS Model 90M38A-150, JR3 Inc., Woodland, CA) and custom specimen-mounting fixtures (Fig. 1A). Clinical pedicle screws (three per vertebra) were used to secure spinal specimens within the mounting fixtures. Upon insertion the pedicle screw was manually tested for rigidity and augmented with bone cement if necessary to ensure sufficient fixation was achieved. Following testing the rigidity of the pedicle screw fixation was also manually confirmed to ensure loosening did not occur during the testing procedure.

The robot was controlled via a custom-built PC-based control program written in MATLAB software. Prior to in-vitro cadaveric testing, preliminary testing of the PC-based controller was performed using a rigid-body-spring model (Fig. 1B) which was custom designed to mimic the stiffness and range of motion of a spinal segment. The hybrid control algorithm uploaded onto the PC-based controller contained an iterative “displacement control” loop with embedded “load control” loop to minimize undesired coupled forces/moments induced by motions applied during displacement control (Fig. 2).

2.2. Development of hybrid control algorithm

Two different displacement control modules (basic displacement control–BDC and adaptive displacement control–ADC) and three different load control modules (stiffness-based, PID-proportional/integral/derivative, and fuzzy logic) were implemented and compared (Fig. 3).

The stiffness-based load control algorithm minimized coupled forces and moments using data from previous steps, calculating stiffness and inverting the diagonal stiffness to find the displacements needed to minimize the coupled loads. To avoid overshoot and oscillations, step-size limitations were imposed. The PID controller used the same concept, but regulated the error output to systematically step back to a force-minimized position in small increments. The basic concept of fuzzy logic load control is that the “states” of the system are used to derive an output. In the present application, the difference in the measured loads and targeted loads (“error”), and the rate of change of the “error” were used to prescribe movements of the robot end-effector to minimize the coupled forces/moments. Generally, a number of iterations within the fuzzy logic load control module were required to minimize the coupled loads within an acceptable range. Comparison of the performance of the three load control modules was performed by experiments with the physical model, examining the ability of each module to minimize undesired coupled loads without “overshoot”. Direct comparison of the three load control modules was performed in the superior/inferior degree of freedom with a consistent starting load of −33 N and the resulting minimization response was recorded and plotted versus the iteration step number.

The BDC module instructed the robot to incrementally rotate the superior vertebra of the specimen about a user-specified axis of rotation (AOR). The location of the AOR was selected based on the mean location of the instantaneous axis of rotation of typical cervical spine motion segments reported in literature (Bogduk and Mercer, 2000). This was accomplished by creating a local coordinate system aligned with the specimens anatomy with the origin defined as a point on the midline at the posterior 1/3 of the vertebral body's depth in the anterior posterior

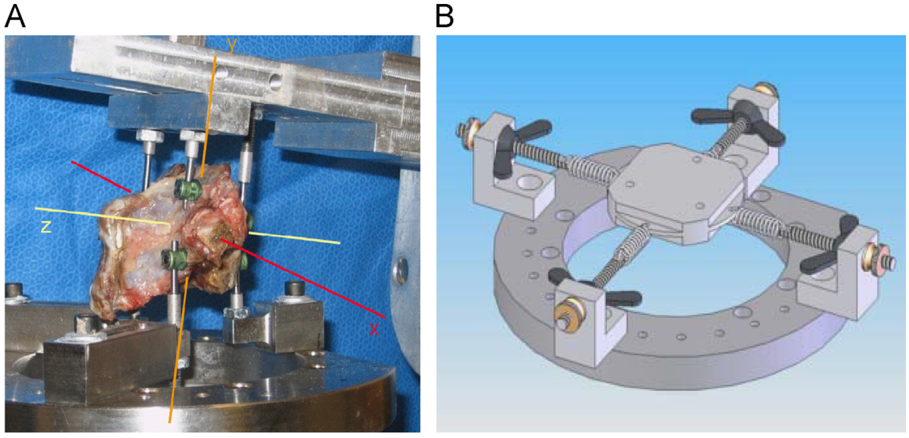

Fig. 1. Robotics-based spine testing system with (A) human cervical functional spinal unit (FSU), mounted within testing system using pedicle screws (three per vertebra). Rx = Flexion/Extension (FE), Ry = Axial Rotation (AR), Rz = Lateral Bending (LB). (B) Schematic of the rigid-body-spring model used for experimental testing of the hybrid control algorithm.