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In Vitro Spine Testing Using a Robot-Based Testing System: Comparison of Displacement Control and “Hybrid Control”

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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.

Keywords

Spinal biomechanics; osteoligamentous cervical spine; load control; displacement control; hybrid control; robotics

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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, b) 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 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.

Materials and Methods

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 (Figure 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 (Figure 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 (Figure 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 (Figure 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 direction and superior edge of the inferior vertebral body (Figure 1A). This axis was kept unchanged throughout the test. For the ADC module the user-specified AOR was also utilized for the first displacement step—which usually resulted in undesired coupled forces/moments to be minimized by the embedded load control loop as described above. After the incremental rotation step the fuzzy logic load control module was implemented to minimize off axis forces and moments below the .5 N and .25Nm threshold respectively (no compressive loading). Additionally, after load minimization, the actual axis of rotation was calculated based on the current and previous spinal position, replacing the initial user-specified axis for the next displacement control iteration. In this way, the ADC algorithm was able to adapt to the specimen’s preferred axis of rotation.

Comparison of BDC and “Hybrid Control”

For direct comparison of BDC and hybrid control, six fresh frozen human cervical specimens were cleaned of musculature, producing osteoligamentous structures that were sectioned into functional spinal units (FSUs: C4-5 (n=6) and C6-7 (n=6)). Each FSU (n=12) was subjected to flexion-extension bending (FE), lateral bending (LB) and axial rotation (AR) testing for each control method. The specimens were preconditioned with three cycles of BDC loading and the BDC and hybrid control tests were performed during the fourth or fifth cycles in a pairwise randomized order. All testing, including preconditioning, was performed to a load target of ± 2.5 Nm with 10N compressive preload (Wilke et al., 1998). BDC was achieved on the robot-based spine testing system by silencing the load control inner loop and rotating about a rigid (non-updating) axis until the load target was achieved. Conversely, ADC and fuzzy logic load control were combined to perform hybrid control, wherein the helical axis of motion (HAM) was calculated and all off-axis forces and moments were minimized at each step in the quasi-static movement. In BDC the system operated at a rate of 0.35 ± 0.0053 degrees/second and whereas the active minimization process of the hybrid control algorithm decreased the rate to $0.067 \pm .0014$ degrees/second. The testing rates for BDC and hybrid control were consistent for all degrees of freedom.

The quality of motion is described by off-axis load measurements and the HAM. Off-axis forces and moments were quantified as root mean squared error from minimization target (zero for all non-primary axis except $f_y=10$ N) throughout the motion path. A single (overall) HAM was calculated based on the (+/-) maximum rotation positions for each motion path. The change in HAM was also quantified as the change in orientation of the overall HAM and the point through which the HAM passed through the primary plane of motion. The quantity of motion is displayed as the range of motion (ROM) and the width of the NZ exhibited for each primary motion. The width of the NZ was determined using the method presented by Smit et al, wherein the boundaries of the NZ were determined based on the second derivative of a double sigmoidal curve fit to the moment vs. rotation (Schmidt et al.,

2008; Smit et al., 2011). Results were summarized and expressed in bar graphs representing median $\pm$ standard deviations and a non-parametric Wilcoxon signed-rank test for paired design was used to determine significance (* $p < 0.05$).

Results

Hybrid Control Algorithm Performance—Physical and Computational Models

Comparison of the performance of the three load control modules by experiments with the rigid-body-spring model showed that the fuzzy logic controller minimized undesired coupled loads without the characteristic “overshoot” of the stiffness controller (Figure 4). The response of the PID and the fuzzy logic controllers were very similar, although the PID controller did exhibit minimal overshoot. The slight overshoot exhibited by the PID controller could have been reduced/eliminated with further tuning, however the fuzzy logic controller offers the practical advantage of approximate logic (as opposed to exact) enabling it to adapt to the specimen’s stiffness without the need for specimen-specific tuning. However, a potential drawback of the fuzzy logic controller (and also the PID controller) was the increased number of iterations needed to minimize the forces; the stiffness-based load control module achieved force minimization in approximately half the number of iterations. Considering the relative advantages and disadvantages of the three load control systems the fuzzy logic load control module was selected and used for all subsequent testing in this study.

Comparison of the performance of the BDC and ADC modules using the rigid-body-spring model demonstrated that the ADC module automatically adapted to the specimen’s natural axis of motion—as evidenced by the smaller coupled forces to be minimized by the ADC after the initial move (Figure 5). The BDC module failed to adapt—hence each applied rotation repeatedly produced a characteristic, large force spike.

Comparison of BDC and “Hybrid Control”

The hybrid control algorithm (with ADC module and fuzzy logic load control module) enabled the robot-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 DOF—successfully minimizing coupled forces/moments. These parameters can be observed qualitatively in Figure 6 wherein representative raw data from one FE experiment is displayed and are quantified in Figure 7. 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 (NZ) bounded by regions of increasing stiffness (EZ).

Comparing BDC and hybrid control in terms of quality of motion, the off-axis forces generated in displacement control are larger. The median RMSE for off-axis forces/moments was reduced from $10.77 \pm 3.98\text{N} / 0.34 \pm 0.13\text{Nm}$ for BDC to $1.71 \pm 0.72\text{N} / 0.11 \pm 0.04\text{Nm}$ under hybrid control (Figure 7). The adaptation of the hybrid control system to the specimen specific rotation parameters can be seen in Figure 8 wherein the HAM shifts by an average of $6.30 \pm 4.23\text{mm}$ and 12.82 ± 10.65 degrees as opposed to BDC in which the axes were fixed. Also of note is that the smallest change in axes was observed during FE ($5.73 \pm 3.00\text{mm} / 4.91 \pm 3.40$ degrees) and the largest change was observed during AR ($7.70 \pm 4.06\text{mm} / 22.21 \pm 7.34$ degrees).

To assess the quantity of motion, the ROM data for each primary motion from each specimen were averaged together. Median rotation extrema for BDC and hybrid tests are compared in Figure 9. For all primary rotations, hybrid control ROM (FE = 18.17 ± 6.11 degrees, AR = 14.52 ± 6.78 degrees, LB = 10.77 ± 4.28 degrees) was significantly larger

than BDC ROM ($FE = 17.50 \pm 6.20$ degrees, $AR = 10.25 \pm 4.19$ degrees, $LB = 9.00 \pm 3.46$ degrees). Similar results were found for the width of the NZ, with hybrid control resulting in a wider NZ than BDC for both AR (hybrid = 5.38 ± 3.41 degrees, BDC = 3.25 ± 1.42 degrees) and LB (hybrid = 4.90 ± 2.19 degrees, BDC = 4.00 ± 1.71 degrees) however no difference was detected for FE (hybrid = 6.93 ± 4.06 degrees, BDC = 7.25 ± 2.77 degrees).

Discussion

In the present study, biomechanical testing of human cervical FSUs using a robot-based spine testing system in a hybrid control mode successfully elicited nonlinear kinetic behavior from the specimens similar to that reported by others in studies using traditional control methods. In particular, the characteristic “S-shaped” curves of the moment-rotation response obtained in this study were consistent with previous reports of the FSU having a region of low stiffness (NZ) bounded by regions of increasing stiffness (EZ) (Panjabi, 1988). Notably, coupled forces and moments were successfully minimized by the hybrid control algorithm, thus the hybrid control algorithm was able to successfully perform a “flexibility test”—previously the province of load control approaches. Notwithstanding the observation that the hybrid control algorithm of the present study successfully minimized coupled loads without “overshoot”, future direct comparison would be needed to determine whether the hybrid control flexibility test is superior in performance to a traditional “closed-loop” load control flexibility test.

The present study offers a direct comparison between “hybrid control” and “displacement control”. The high magnitude of the off-axis loads in BDC confirm Panjabi’s caveat regarding the non-physiologic and injurious loads that may result from an improper, rigid AOR estimation. This is confirmed in the HAM plots which show that the orientation and the location of the HAM changes significantly when the systems actively adjusts to determine the specimen’s preferred motion path. Minimization of off-axis loads and differences in the HAM present in hybrid control suggest that the hybrid control’s larger ROM and larger/more defined NZ results from actively seeking the specimen’s preferred motion path and updating its AOR. A limitation of this study is that the loading rates were not consistent between the BDC and the hybrid control algorithm. The fact that the hybrid control algorithm operated at a slower testing rate could have contributed to the increased ROM resulting from this algorithm due to the effects of viscoelastic creep. However, it should also be noted that the ROM data of the hybrid control falls into the range of reported ROM from flexibility tests of subaxial cervical motion (DiAngelo and Foley, 2004; Miura et al., 2002).

One of the primary advantages and future directions of the robot-based system presented herein is the control systems ability to store the exact kinematics determined during the hybrid control mode. The stored kinematics can be used to drive the displacement control module (with the load control module silenced). Replaying the exact kinematics for the specimen in the intact state would result in a unique situation wherein hybrid control and displacement control are functionally equivalent. A broad implication of this implementation (together with the above observation that the hybrid control algorithm was able to perform a flexibility test which is usually only associated with load control), is that equivalent spinal function may be attainable by the neural control system using different control strategies—in other words, normal spinal functioning may not depend upon a single control scheme. Additionally, replaying the exact kinematics for the specimen in an altered state would enable determination of the removed structures in-situ forces based on the principle of superposition (Kawchuk et al., 2010; Livesay et al., 1995; Rudy et al., 1996). Replaying exact kinematics in an altered stated (Hartman et al., 2009) is similar in concept to the hybrid method presented by Panjabi (Panjabi, 2007) and should be explored further in future

work. Some of the potential criticisms/barriers of this future work with the methodology as presented here are the quasi-static nature (0.067 ± 0.0014 degrees/second) of the hybrid algorithm which could affect the determined kinetics due to the viscoelastic properties of the biologic material as well as the limited stiffness of the robot end-effector which may result in end-effector deformation /altered kinetics in response to the cut (Gillespie and Dickey, 2004).

The single FSU model with 10N of axial compressive load was chosen for this study in order to minimize the variability and focus on the control algorithm rather than the specimen characteristics. However, these characteristics are also a limitation of this study in regards to the current trends in literature (Goel et al., 2006; Wilke et al., 1998), wherein most studies have included the entire subaxial cervical spine and many include follower loading in order to simulate physiologic compression (Patwardhan et al., 2000; Patwardhan et al., 1999). In-house studies (unpublished) are ongoing which utilize the methodology presented here for full cervical spine testing in the presence of follower loading.

Although the data and analysis presented in this study lends support to the hybrid control algorithm over BDC, it cannot be concluded that either control method is more or less physiologic as data was not directly compared to in vivo kinematics. Additionally, the current work did not include neural and muscular contributions. Therefore, future work should compare the in-vitro testing methodologies to in-vivo kinematics as well as attempt to include neural and/or muscular contributions so as to more thoroughly assess the efficacy of the hybrid control algorithm.

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Figure 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.

Figure 2.

Flow chart of hybrid control algorithm. An iterative “load control” loop is embedded within the “displacement control” loop to minimize undesired coupled forces/moments induced by motions applied under displacement control.

Figure 3.

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

Figure 4. Performance comparison of the three load control modules, based on experiments using the rigid-body-spring model. The fuzzy logic controller minimized undesired coupled loads without characteristic “overshoot” of the other controllers.

Figure 5. Performance comparison of the BDC and ADC modules, showing results from a representative experiment with the rigid-body-spring model. The ADC module automatically adapted to the test object's natural axis of motion—resulting in smaller coupled forces to be minimized by the load control module.

Figure 6.

Representative Raw Data (n=1) – side-by-side comparison of the primary moment-rotation response of cervical FSU in flexion/extension, achieved by the robotics-based spine testing system with displacement control vs. hybrid control. Corresponding off-axis forces as well as HAM are also displayed. This representative figure highlights the observed reduction in off-axis forces and moments and shift in HAM.

Figure 7. Comparison of displacement control and hybrid control off-axis forces and moments represented as median RMSE through the motion path. The hybrid control algorithm significantly reduced the off-axis forces and moments in all degrees of freedom.

Figure 8.

Comparison of displacement control and hybrid control change in center of rotation represented as change of location and orientation of the overall helical axis of motion through the motion path. This graph highlights the adaptation of the hybrid control algorithm to the specimen preferred HAM with the displacement and orientation of the axis significantly shifting for all degrees of freedom tested.

Figure 9.

Comparison of displacement control and hybrid control range of motion (ROM) and width of the neutral zone (NZ). The adaptation of the hybrid control algorithm to the specimen's preferred path of motion also in an overall in the specimen's ROM and NZ width.