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Short communication

Robotic application of a dynamic resultant force vector using real-time load-control: Simulation of an ideal follower load on Cadaveric L4–L5 segments

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ABSTRACT

Standard in-vitro spine testing methods have focused on application of isolated and/or constant load components while the in-vivo spine is subject to multiple components that can be resolved into resultant dynamic load vectors. To advance towards more in-vivo like simulations the objective of the current study was to develop a methodology to apply robotically-controlled, non-zero, real-time dynamic resultant forces during flexion–extension on human lumbar motion segment units (MSU) with initial application towards simulation of an ideal follower load (FL) force vector.

A proportional-integral-derivative (PID) controller with custom algorithms coordinated the motion of a Cartesian serial manipulator comprised of six axes each capable of position- or load-control. Six lumbar MSUs (L4–L5) were tested with continuously increasing sagittal plane bending to 8 Nm while force components were dynamically programmed to deliver a resultant 400 N FL that remained normal to the moving midline of the intervertebral disc. Mean absolute load-control tracking errors between commanded and experimental loads were computed. Global spinal ranges of motion and sagittal plane inter-body translations were compared to previously published values for non-robotic applications.

Mean TEs for zero-commanded force and moment axes were 0.7 ± 0.4 N and 0.03 ± 0.02 Nm, respectively. For non-zero force axes mean TEs were 0.8 ± 0.8 N, 1.3 ± 1.6 Nm, and 1.3 ± 1.6 N for F_x, F_z, and the resolved ideal follower load vector FL_R, respectively. Mean extension and flexion ranges of motion were 2.6° ± 1.2° and 5.0° ± 1.7°, respectively. Relative vertebral body translations and rotations were very comparable to data collected with non-robotic systems in the literature.

The robotically coordinated Cartesian load controlled testing system demonstrated robust real-time load-control that permitted application of a real-time dynamic non-zero load vector during flexion–extension. For single MSU investigations the methodology has potential to overcome conventional follower load limitations, most notably via application outside the sagittal plane. This methodology holds promise for future work aimed at reducing the gap between current in-vitro testing and in-vivo circumstances.

1. Introduction

In-vitro biomechanical investigations of the human spine have employed repeatable methods of applying isolated load components such as pure bending moments and/or constant compression. In the in-vivo environment however, the spine is subjected to multiple dynamic load components which resolve into resultant vectors that change in direction and magnitude. Previous studies have reported differences in spinal flexibility with different load applications (Patwardhan et al., 2003) as well as with quasi-static versus continuous load application (Goertzen et al., 2004) indicating that motion segment unit (MSU) kinematics are not load invariant.

Robotic methods hold promise for 6 degree of freedom (DOF) multi-directional coordinated load-control capabilities however, previous applications in spine biomechanics have primarily been limited to quasi-static or iterative approaches that have all attempted to emulate gold standard pure bending tests (Dickey and Gillespie, 2003; Gardner-Morse and Stokes, 2004; Gilbertson et al., 2000; Goertzen and Kawchuk, 2009; Kelly and DiAngelo, in press-b; Thompson et al., 2003; Walker and Dickey, 2007). We are aware of only one published report of a robotic methodology using real-time multi-directional 5-DOF load-control to apply sagittal plane pure moments to a rabbit MSU model (Goertzen and Kawchuk, 2009). While this method did not require complex a-priori modeling of joint force–displacement relationships it has not been subsequently applied.

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We have previously described a Cartesian-based real-time load-controlled testing system (CLTS) (Kelly and Bennett, in press-a). In an effort to develop core capabilities that can be applied towards better simulation of in-vivo resultant spinal loads, the objective of the current study was to use the CLTS to develop and validate a methodology to control application of a real-time dynamic resultant force vector, a capability not previously reported in robotic biomechanics literature. The chosen application was simulation of an ideal follower load (FL) force (Patwardhan et al., 1999) on human L4–L5 spinal segments for which a resultant force vector with constant magnitude and dynamic direction is requisite.

2. Materials and methods

2.1. Testing apparatus

A custom-built system with full 6-DOF control and six-axis force–moment–sensor (FMS) (Model 45E15A4, JR3 Inc.,Woodland, CA) was used. Three harmonic drive motors (FHA-25C, Harmonic Drive LLC, Hauppauge, NY) were assembled in a roll–pitch–yaw (lateral bending, flexion–extension, axial rotation) gimbal configuration. The rotation sequence was the same as that used by Wilke et al. (1994), and best avoided gimbal lock for spinal application. The gimbal was suspended in series from three servo-actuated, orthogonally oriented *x*-(anteroposterior (AP)), *y*-(lateral), and *z*-(craniocaudal (CC)) translational axes collectively comprising a single Cartesian manipulator (Fig. 1) and stationary Cartesian global coordinate system (GCS). Positional accuracies were 6.4 μm and 0.008° for linear and rotary axes respectively. The FMS was rigidly mounted between the gimbal and cranial specimen end. All FMS data were referenced to a moving local force reference system (FMS-CS) with orientation defined by the rotational positions of the gimbal axes.

Axes were controlled via a PID gain controller (UMAC Delta Tau Data Systems Inc., Chatsworth, CA) utilizing customized control loops and motion programs, and were operable in a coordinated manner utilizing position-control or load-control. A custom calibration algorithm was employed in real-time to correct for changes in FMS readings due to gravitational forces on attached fixturing such that the system directly controlled applied specimen loads.

2.2. Specimen preparation

Six fresh-frozen human cadaveric L4–L5 lumbar MSUs (male, mean age 44 ± 8.9 years standard deviation (SD)) were radiographically pre-inspected for degenerative changes, harvested, and cleaned of excessive soft tissue. Segments were potted in bismuth alloy (Cerrobend™) in specimen-specific, natural lordotic alignment referenced to the assumed horizontal cranial endplate of L1 (Fig. 2) and frozen until testing.

2.3. Disc midline and coordinate systems

Using pixel counting software (Image-J NIH) a sagittal x-ray image of each potted specimen was analyzed to determine the orientation of the midline of the disc. Corners of the cranial and caudal endplates were located (Fig. 2) and cross-disc lines drawn connecting the two anterior points and two posterior points. Cross-disc line midpoints were connected with a line that defined the disc midline, and subsequently its neutral angular orientation β in relation to the GCS horizontal (Fig. 3). Measurement resolution was approximately 0.15 mm^2/pixel.

To evaluate kinematic displacements between moving L4 and fixed L5 vertebral bodies an anatomic tracking point was chosen at the anterior corner of the L4 endplate. Recorded displacements of the anatomic tracking point in the GCS were transformed to a static disc-oriented coordinate system (βGCS) with origin at the anatomic tracking point when the specimen was under no load, and x_{disc}- and z_{disc}-axes parallel to the disc midline and its normal, respectively (Fig. 2).

A second mobile disc coordinate system (DCS) was also defined that remained aligned with the moving midline of the intervertebral disc during flexion–extension tests (Fig. 3).

2.4. Ideal follower load simulation

The ideal FL applies a compressive force vector perpendicularly to the mid-plane of the disc (Fig. 3) (Patwardhan et al., 1999). During sagittal bending the mid-plane of the disc (and hence the DCS) rotates half as much as the cranial body requiring the normal load vector to change orientation (Patwardhan et al., 2003). Sagittal plane rotation was programmed under position-control to regulate rotational velocity at 0.35°/s while lateral and axial rotation axes operated in load-control to zero moments. Linear axes operated under force control with lateral (y-axis) forces controlled to zero. A magnitude of 400 N was chosen for simulation (Gaffey et al., 2010; O'Leary et al., 2005; Renner et al., 2011). Dynamic components of force in the FMS-CS required to apply the FL force in the DCS were commanded at each 0.2° increment of sagittal rotation as:

$$F_x = 400 \sin(B/2 - \beta) \tag{1}$$

$$F_z = 400 \cos(B/2 - \beta) \tag{2}$$

where B is the flexion/extension angle (degrees) (Fig. 3).

To ensure the FL force did not build up moment artifacts, isolated F_x and F_z forces were initially sequentially applied while constraining flexion–extension

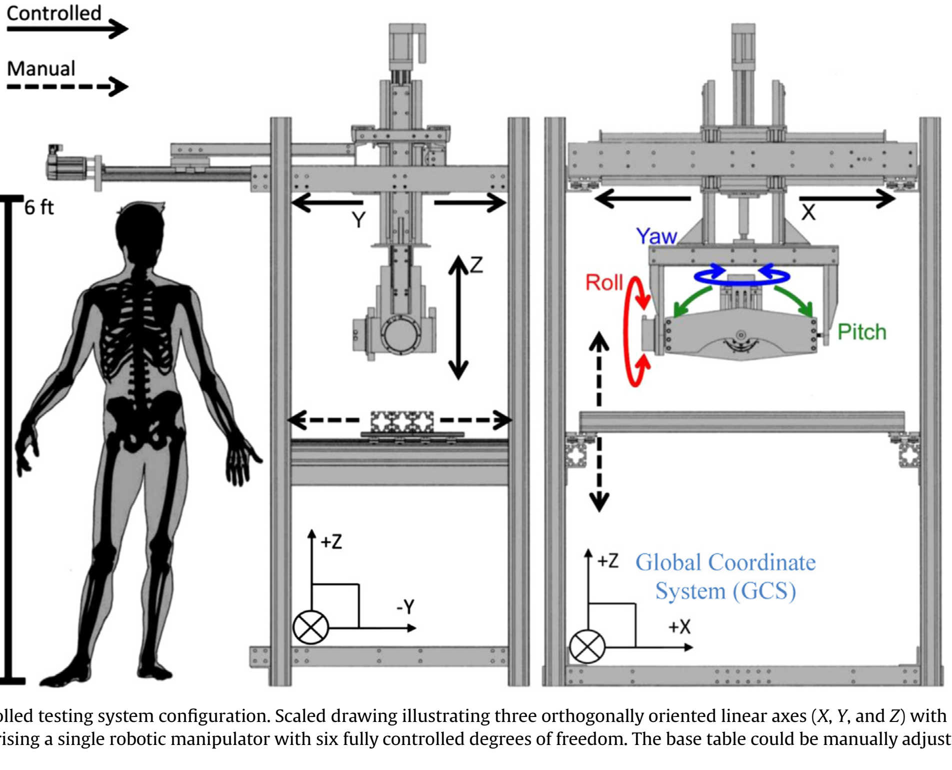

Fig. 1. Cartesian load-controlled testing system configuration. Scaled drawing illustrating three orthogonally oriented linear axes (X, Y, and Z) with suspended Roll, Pitch, and Yaw gimbal assembly comprising a single robotic manipulator with six fully controlled degrees of freedom. The base table could be manually adjusted and locked in the Z and Y directions.