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Technical note

The application of physiological loading using a dynamic, multi-axis spine simulator

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ABSTRACT

In-vitro testing protocols used for spine studies should replicate the in-vivo load environment as closely as possible. Unconstrained moments are regularly employed to test spinal specimens in-vitro, but applying such loads dynamically using an active six-axis testing system remains a challenge. The aim of this study was to assess the capability of a custom-developed spine simulator to apply dynamic unconstrained moments with an axial preload.

Flexion–extension, lateral bending, and axial rotation were applied to an L5/L6 porcine specimen at 0.1 and 0.3 Hz. Non-principal moments and shear forces were minimized using load control. A 500 N axial load was applied prior to tests, and held stationary during testing to assess the effect of rotational motion on axial load.

Non-principal loads were minimized to within the load cell noise-floor at 0.1 Hz, and within two-times the load-cell noise-floor in all but two cases at 0.3 Hz. The adoption of position control in axial compression–extension resulted in axial loads with qualitative similarities to in-vivo data.

This study successfully applied dynamic, unconstrained moments with a physiological preload using a six-axis control system. Future studies will investigate the application of dynamic load vectors, multi-segment specimens, and assess the effect of injury and degeneration.

1. Introduction

In-vivo loading of the spine must be accurately replicated in the laboratory setting in order to accurately define the mechanical properties of spinal tissue, and investigate the efficacy of treatments for spinal injury and degeneration [1]. The complexity of the spine, arising from the triple joint structure at each level, and the large number of stabilizing and actuating muscles, means that simulating the in-vivo environment remains a difficult task to achieve [1,2].

Significant research has been carried out in the development of spine testing systems and, in particular, six-axis testing machines. The stiffening effect of applying a physiological preload on spinal specimens has been well-documented [3–6], with an axial preload leading to an increase in disc stiffness in axial compression–tension, flexion–extension and lateral bending ranging from 100% to as much as 500% [6]. The effect of frequency also leads to significant changes in the stiffness of spinal specimens [7,8]. Costi et al. have reported a linear increase in stiffness against log-frequency increase in testing speed [7]. Previous research has made use of clutches in the non-principal axes in order to impose dynamic pure moments with a physiological preload applied via muscle force simulation [9]. A six-axis test system using position control was also developed to investigate the mechanism of disc herniation [10], demonstrating the importance in complex loading to replicate the in-vivo scenario. Likewise, in recent years there has been an increased focus on the development of testing machines with six-axis load control systems to actively control the load in each axis (Table 1). Such developments offer exciting prospects for the real-time application of complex, biofidelic loading vectors, and provide a means to accomplish the future research objectives outlined by Oxland [11] in more fully understanding disc non-linearity, dynamic effects on the spine, and create more robust links between in-vivo and in-vitro data. However, the testing rate of such machines has thus far been limited, with no system capable of completing tests in flexion–extension, lateral bending, and axial rotation within the 0.5–5.0 °/s testing speed recommended by Wilke et al. [2]. Furthermore, the application of an ideal follower load has been limited to tests in the sagittal plane at 0.35 °/s [12,13].

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Table 1.
Summary of recent in-vitro spine testing systems with active six-axis control.

Study	Preload	Test rate	Primary axis	Primary axis control	Zero load RMS error	Zero moments RMS error
[30]	0 N	~0.86 Hz (0.086–0.131 °/s)	Flexion–extension Lateral bending Axial rotation	Load	1.18 N 0.85 N 0.72 N	0.14 Nm 0.14 Nm 0.14 Nm
[32]	0 N	0.1–0.35 Nm/s (0.15–0.5 °/s)	Flexion–extension Lateral bending Axial rotation	Load	0.61 N 0.56 N 0.56 N	0.02 Nm 0.02 Nm 0.02 Nm
[31]	10 N AL	0.067 °/s	Flexion–extension Lateral bending Axial rotation	Hybrid	1.71 N 1.71 N 1.71 N	0.11 Nm 0.11 Nm 0.11 Nm
[12]	400 N IFL	0.35 °/s	Flexion–extension	Position	0.70 N	0.03 Nm
[20]	0.2 MPa IFL	0.01 Hz 0.01 Hz 0.30 Hz	Flexion–extension Lateral bending Axial rotation	Load	9.78 N 6.82 N 11.7 N	0.11 Nm 0.23 Nm 0.43 Nm
[13]	400 N AL 400 N IFL	0.35 °/s 0.35 °/s	Flexion–extension Flexion–extension	Position	~3 N	~0.05 Nm

Notes on the preload application methods: axial load (AL), and ideal follower-load (IFL).

It is well-known that spinal posture affects the axial load through the spine, resulting in increased intradiscal pressure [14,15]. However, when a preload is applied to pure moment testing in-vitro, it is generally maintained at a constant magnitude by means of an axial preload or passive follower-load [4,16–19], and only recently has an ideal follower-load of physiological magnitude been adopted using an advanced testing system [12,13]. However, the stiffness matrix testing of spinal specimens has demonstrated that flexion–extension about a fixed position does lead to substantial changes in axial load [6]. It is possible that maintaining the axial position during the application of otherwise unconstrained moments may lead to physiologically representative axial loads being applied to spinal specimens.

The aim of this research was to determine whether a custom-developed spine simulator was able to operate dynamically with an axial preload to complete physiological loading regimes with off-axis moments and shear forces minimized through load control using a porcine lumbar spinal specimen. Success was determined by the ability of the system to complete tests with positional demand errors close to the system resolution, and as previously used as pass criteria in such tests, zero load demand errors within two-times the load cell noise floor [20]. Additionally, the change in axial load due to rotational motion will be discussed in relation to previously published in-vivo data of the intradiscal pressure of the intervertebral disc in different postures [15,21–23]. Achieving these objectives would demonstrate the test system capabilities to complete complex in-vitro loading regimes, which will improve the ability to replicate in-vivo loads to study the effects of injury, degeneration, and treatment of the spine.

2. Materials and methods

2.1. Test apparatus

A previously developed dynamic six-axis spine simulator [24] was upgraded to operate as a six-axis electromechanical spine simulator with fully integrated control system (dSPACE Ltd., Melbourne, UK) allowing real-time test capabilities in both load and position control (Fig. 1) (Table 2). A vertical axis provided translations in axial compression–tension (*TZ*), an *XY* platform provided translations in anterior–posterior shear (*TX*) and lateral shear (*TY*), and a gimbal head provided rotations in lateral bending, flexion–extension, and axial rotation (*RX*, *RY*, and *RZ*, respectively) (Fig. 2). A cranial specimen holder was fixed to the gimbal head, and a caudal specimen holder was fixed to the base plate via a six-axis load cell (AMTI MC3-A-1000, Advanced Mechanical Technology Inc., MA, USA). A previous study had established that the load cell had a noise floor of 5 N and 0.25 Nm [6]. The six-axis assembly was mounted on a crosshead (*XH*) to allow the vertical adjustment necessary to accommodate specimens of varying lengths.

2.2. Test protocol

Biomechanical tests were completed in flexion–extension, lateral bending, and axial rotation over physiological ROMs at two dynamic frequencies (0.1 and 0.3 Hz). The ROMs used to test each axis (Fig. 2) were within the physiological limits measured in-vivo [25,26], and the same as used previously in the literature [6,24,27]: ±3 mm in *TX*; ±1.5 mm in *TY*; ±0.4 mm in *TZ*; and ±4° in *RX*, *RY*, and *RZ*. The frequencies were chosen to approximately cover the range recommended [2] of 0.5–5 °/s, whilst also allowing comparisons to previous tests in the literature [6,24,28,29] (Table 1). The frequencies of 0.1 and 0.3 Hz equated to rotational speeds of 1.6 and 4.8 °/s, respectively.

The principal axis was operated in position control to ensure a consistent test rate, and negate viscoelastic effects. The