NON-CONSTRAINING PURE BENDING LOADING OF C4-C6 USING A COMPREHENSIVE SPINE TESTING SYSTEM

KH Chin (1), JCH Goh (2, 3), SL Toh (1, 3), PVS Lee (3, 4)

(1) Department of Mechanical Engineering
National University of Singapore
Singapore

(2) Department of Orthopaedic Surgery
National University of Singapore
Singapore

(3) Division of Bioengineering
National University of Singapore
Singapore

(4) Defence Medical Research Institute
Defence Science and Technology Agency
Singapore

INTRODUCTION

Past studies have introduced bending moment to spine specimens through eccentric loading [1]. However this subjects the specimens to both compressive load and bending moment. Although there are merits in studying the response in this loading mode, there are also merits in loading a spine specimen in pure bending moment mode. One of which is pure bending moment loading ensures the moment to be constant throughout the entire length of the specimen [2] and is useful for the evaluation of the performance of spinal constructs.

In recent years, pure bending loading systems have been designed and fabricated and many impose stepwise loading and unloading, and often did not report unloading response [3, 4]. For an improved understanding of load-response characteristics, we advocate studying a full cycle of continuous loading and unloading. In the case of flexion and extension for example, one can view the unloading from flexion followed by the loading to extension essentially as a protracted loading to extension from a flexed position. Such results may be of interest to researchers who are concerned with acquiring range of motion (ROM) data starting from an extreme position instead of the neutral position.

As such a spine testing system, comprising of a motorized loading system and a motion analysis system, has been designed and fabricated. The motorized loading system uses a servo motor to introduce continuous pure bending moment to the specimens. The loading modes possible are continuous flexion-extension, and continuous right-left lateral bending. The motion analysis system can be used to determine the 3D inter-segmental motions of the spine.

MATERIALS AND METHODS

Motorized loading system

An overview of the loading system is shown in Figure 1. A fixture known as the gimbal provides motion about all the three rotational DOFs. The gimbal is fitted with multiple frictionless bearings to allow for unconstrained rotations of the spine specimen about the Y- and Z-directions. A servo operated torque motor applies continuous bending moment about the X-direction. This motor is capable of loading the spine specimens up to ±27 Nm with a loading rate of up to ±50 Nm/s. The torque motor has an angular displacement encoder to allow for displacement control of up to ±180^{o} with a displacement rate of up to ±50^{o}/s. A torque transducer is also available to determine the bending moment introduced to the specimen.

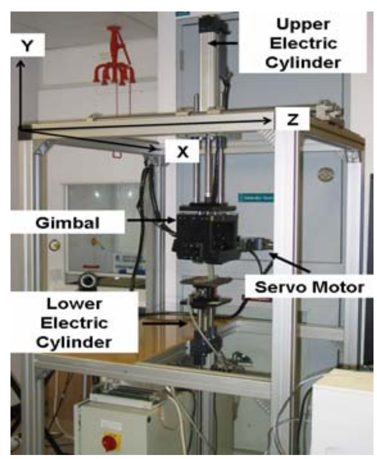

Figure 1: Overview of the loading system

An upper electric cylinder allows translational motion along the Y-direction and the gimbal is affixed inferiorly to the upper cylinder. A load cell fitted at the gimbal provides feedback load control of the resultant longitudinal force acting on the specimen. The upper cylinder sits on a low-friction linear guide system atop the chassis and hence allows for unconstrained translations along the X- and Z-directions. The lower electric cylinder also provides translation along the Y-direction, but is used to move the spine specimen to a suitable height, and is locked during experiment. The maximum clearance between the lower end of the gimbal to the top of this cylinder is 350 mm. A six-axis load cell is mounted atop the lower cylinder and used to determine the reaction loads experienced by the inferior-most vertebra.

Motion analysis system

The Vicon 370 motion analysis system is commonly used for gait analysis studies. The system can be used to track markers of 25 mm in diameter in an estimated volume space of 8 m^3. In contrast, our studies used 6 mm diameter markers and a volume space of less than 0.001 m^3 was captured. In our setup, the Vicon 370 workstation is used alongside three CCD cameras. To the best of our knowledge, we are the only research group which has managed to adapt this system for spine motion analysis. Accuracy tests have been conducted and the measurement errors were found to be less than 1%.

A 3D digitizer was used to identify the coordinates of the spherical markers and selected anatomical landmarks on the vertebrae. Using a technique that has been described elsewhere [5], the kinematics at each vertebral level can be described using local coordinate systems based on selected anatomical landmarks.

Experimental Testing

Four human C4–C6 specimens were reduced to their osseoligamentous state and loaded in continuous flexion-extension. Potting plates were cemented to the superior and inferior ends of the each specimen. A marker set, comprising of three 6 mm diameter spherical markers, was inserted into the laminas of the C5. The marker set and C5 can be considered as one rigid body. As the C4 and C6 were rigidly cemented to their respective potting plates, the marker sets were attached to the potting plates instead.

Bending moment was applied to the superior end of the specimen at a displacement rate of 0.5^o/s and loaded up to ±1.5 Nm. Zero preload was applied. Two cycles of preconditioning were carried out and data was captured in the third cycle. Reaction loads measured by the 6-axis load transducer were simultaneously collected.

RESULTS

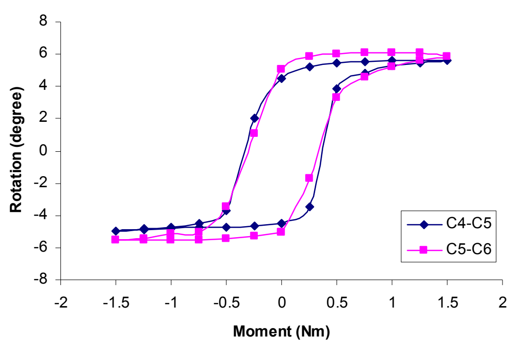

Figure 2: Primary motion of the C4-C6 spine specimens.

The inter-segmental motions of the spine specimens are illustrated in Figure 2. The ROMs for the principal motions of C4–C5 flexion and extension at bending moment of ±1.5 Nm are 5.6^o and 5.0^o, respectively. The ROMs for the principal motions of C5–C6 flexion and extension at bending moment of ±1.5 Nm are 5.9^o and 5.5^o, respectively. The secondary motions were insignificant.

Reaction loads at the inferior-most end were measured. The secondary moments were significantly less than the primary moment and the secondary forces were smaller than ±5 N. This ascertains the “pureness” of the applied bending moment.

DISCUSSIONS

The motorized loading system is capable of introducing pure bending, as verified by the small secondary loads experienced at the inferior end. The Vicon motion analysis system, commonly used in large volume space analysis laboratories, has found its use in small volume space 3D motion analysis of the spine. With measurement errors of less than 1%, the accuracy of the system is ensured.

The average ROM values, compared with past *in vitro* studies [3, 6, 7], showed reasonable closeness (Table 1). In addition, these studies reported that flexion ROM is larger than extension ROM at both the C4–C5 and C5–C6 levels. The same observation was also made in the current investigation.

Table 1: Comparison of ROM values

	Flexion (deg)		Extension (deg)	
	C4-C5	C5-C6	C4-C5	C5-C6
Panjabi, 1986	6.3	6.3	3.6	3.6
Moroney, 1988	5.6	5.6	3.5	3.5
Panjabi, 2001	5.3	5.5	4.8	4.4
Current study	5.6	5.9	5.0	5.5

In conclusion, the load response of the C4-C6 has been determined using a comprehensive spine testing system.

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REFERENCES

[1] Smith T.J., 1991. In vitro spinal biomechanics experimental methods and apparatus. Spine, 16, 1204-1210.
[2] Panjabi, M. M., 1988. Biomechanical evaluation of spinal fixation devices: I. A conceptual framework. Spine, 3, 1129–1134.
[3] Panjabi, M M; Crisco, J J; Vasavada, A; Oda, T; Cholewicki, J; Nibu, K; Shin, E, 2001. Mechanical properties of the human cervical spine as shown by three-dimensional load-displacement curves. Spine, 26, 2692-2700
[4] Nightingale, R. W., Winkelstein, B. A., Knaub, K. E., Richardson, W. J., Luck, J. F., Myers, B. S., 2002. Comparative strengths and structural properties of the upper and lower cervical spine in flexion and extension. J Biomech, 35, 725–732.
[5] Crawford, N. R., Dickman, C. A., 1997. Construction of local vertebral coordinate system using a digitizing probe. Spine, 22, 559–563.
[6] Moroney, S. P., Schultz, A. B., Miller, J. A. A., Andersson, G. B. J., 1988. Load-displacement properties of lower cervical spine motion segments. J Biomech, 9, 769–779.
[7] Panjabi, M. M., Summers, D. J., Pelker, R. R., Videman, T., Friedlaender, G. E., Southwick, W. O., 1986. Three-dimensional load-displacement curves due to forces on the cervical spine. J Orthop Res, 4, 152–161.