FLEXIBILITY TESTING OF THE HUMAN UPPER CERVICAL SPINE UNDER CONTINUOUS LOADING AND UNLOADING

KH Chin (1), KW Tan (2), JCH Goh (3,4), SL Toh (1,4), VSP Lee (2,4)

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

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

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

(4) Division of Bioengineering
National University of Singapore
Singapore

INTRODUCTION

While studies delineating the biomechanics of the human cervical spine are abound, a good majority focus on the lower cervical spine. Metaphorically classified into four functional units, the cervical spine consists of the cradle (C0–C1), axis (C1–C2), root (C2–C3) and column (C3–C7), each with a distinct morphology that determines its kinematics and contribution to the functions of the complete cervical spine [1]. With the upper cervical spine accounting for three-quarters of the above functional units, it certainly merits more attention.

Flexibility testing of spine specimens yield important mechanical properties such as the range of motion (ROM) and neutral zone (NZ). Most existing studies [2–4] impose stepwise loading and unloading, and often do not report unloading response. Studying a full cycle of continuous loading and unloading, on the other hand, may help improve our understanding of load–response characteristics.

The present flexibility study of the human upper cervical spine is an alternative to stepwise loading and unloading. It aims to supplement the dearth of data in literature on the upper cervical spine, and to yield hysteresis curves that depict a full loading and unloading cycle.

MATERIALS AND METHODS

Spine Testing System. The spine testing system incorporates a custom-built motorized loading system and a 3D motion analysis system. A servo operated torque motor on the loading system is capable of applying a bending moment to the superior end of the spine specimen. An electric cylinder can apply and maintain a longitudinal force using feedback control. The specimen is unconstrained in the non-actuated directions by way of multiple frictionless bearings on the loading jig for rotations and low friction linear guides for translations. The Vicon 370 motion analysis system (Vicon Motion Systems, Oxford, UK), commonly used in large volume space gait analysis labs, has been adapted and validated for small volume space use.

Experimental Testing. Four human cadaveric C0–C3 specimens (mean age 79, range 71–97) were harvested. The muscular and connecting tissues were removed for the specimens to be tested in their osseoligamentous state. The superior and inferior ends of each specimen were mounted on potting plates using cement. Three 6 mm diameter spherical markers make up a marker set rigidly attached to each vertebra. The marker sets for C1 and C2 were inserted into the anterior portion of the vertebral body. Those for C0 and C3 were affixed on the potting plates instead, as these two vertebrae were rigidly cemented (**Figure 1**). A 3D digitizer was used to define the relationship between the markers and selected anatomical landmarks.

The specimens were loaded under continuous flexion and extension and continuous right and left lateral bending, with an angular displacement-control of 0.5°/s up to a limiting torque of ±1.5 Nm, which is within physiological loading. The feedback control maintained the longitudinal force at zero, to simulate pure bending. Two cycles of preconditioning were first carried out. Torque and marker motion data were captured at 50 Hz in the third cycle. Postprocessing to obtain the 3D intervertebral motions was done using an in-house software. The load–displacement hysteresis curves were plotted for each intervertebral level.

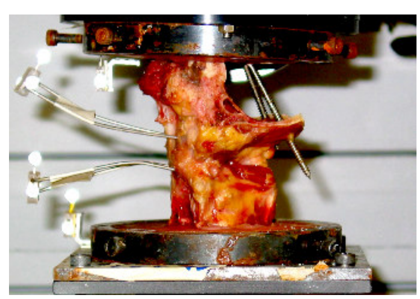

Figure 1. C0–C3 specimen cemented between potting plates with marker sets rigidly attached

RESULTS AND DISCUSSION

Continuous flexion and extension. The average ROM for combined flexion and extension, decreasing inferiorly from the occiput, are 19.3° for C0–C1, 13.1° for C1–C2 and 6.7° for C2–C3 (**Figure 2**). While this decreasing order is similar to existing studies (**Table 1**), the magnitudes for C0–C1 and C1–C2 average ROM are notably smaller. Only C2–C3 ROM is comparable.

The ROM differences for C0–C2, where intervertebral discs are absent, is attributed to the sensitivity to preload. In a separate sensitivity analysis study, a compressive preload of 20 N instead of 0 N was maintained. This resulted in an ROM disparity of more than 5°. Variations in experimental protocol in existing studies produce different preloads, inevitably resulting in dissimilar ROM. In fact, another study even reported an average ROM of 35° for C0–C1 [5].

Secondary motions were insignificant in flexion and extension and hence not reported.

Continuous right and left lateral bending. The average ROM for combined right and left lateral bending, also decreasing inferiorly from the occiput, are 9.1° for C0–C1, 8.1° for C1–C2 and 4.7° for C2–C3 (**Figure 3**). The ROM for C0–C1 and C1–C2 are of reasonable closeness to existing studies (**Table 2**).

Axial rotation is the main secondary intervertebral motion resulting from lateral bending (**Figure 4**). The average combined left and right axial rotation ROM for C0–C1 (4.9°) and C2–C3 (4.0°) are notably smaller than C1–C2 (15.5°). The presence of condylar joints that primarily allow flexion and extension between C0 and C1 and an intervertebral disc between C2 and C3 restrict axial rotation movements.

CONCLUSION

The above ROM results serve to fill the gap in literature on the biomechanics of the human upper cervical spine. The hysteresis profiles obtained from this study provide more insight into load–response characteristics than stepwise loading-only curves. The approach of continuous loading and unloading may be useful to clinicians who are interested in studying a protracted loading situation, for instance from a fully flexed to a fully extended posture, rather than loading starting from the neutral position.

REFERENCES

[1] Bogduk N and Mercer S, 2000. Biomechanics of the cervical spine. I: Normal kinematics. *Clin Biomech*, 15, 633–648.
[2] Nightingale RW et al., 2002. Comparative strengths and structural properties of the upper and lower cervical spine in flexion and extension. *J Biomech*, 35, 725–732.
[3] Panjabi MM et al., 1988. Three-dimensional movements of the upper cervical spine. *Spine*, 13, 726–730.
[4] Panjabi MM et al., 2001. Mechanical properties of the human cervical spine as shown by three-dimensional load-displacement curves. *Spine*, 26, 2692–2700.
[5] Fielding JW, 1957. Cineroentgenography of the normal cervical spine. *J Bone Jt Surg*, 39A, 1280–1288.

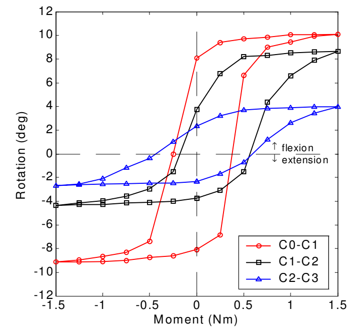

Figure 2. Average principal intervertebral motion under continuous flexion and extension

	C0–C1	C1–C2	C2–C3
Panjabi et al. [3]	24.5	22.4	-
Panjabi et al. [4]	27.4	24.4	6.2
Current study	19.3	13.1	6.7

Table 1. Average flexion + extension ROM (°) comparison

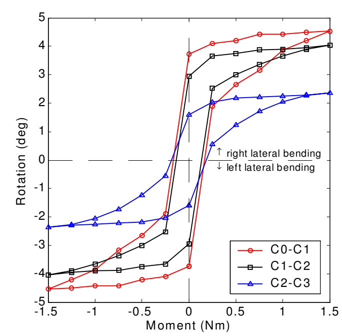

Figure 3. Average principal intervertebral motion under continuous right and left lateral bending

	C0–C1	C1–C2	C2–C3
Panjabi et al. [3]	11.0	13.4	-
Panjabi et al. [4]	9.1	6.5	9.5
Current study	9.1	8.1	4.7

Table 2. Average right + left lateral bending ROM (°) comparison

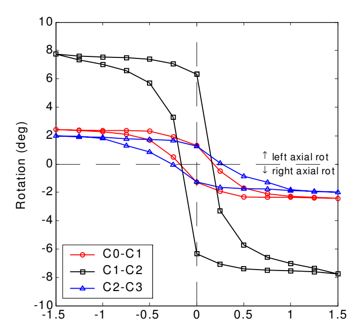

Figure 4. Average main secondary intervertebral motion under continuous right and left lateral bending