HIGH RATE BEHAVIOUR OF THE CERVICAL SPINE SEGMENTS

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ABSTRACT

Soft tissues in the cervical spine are known to exhibit strain rate dependent behaviour. The objective of this study is to test the hypothesis that the response of the cervical spine segment to loading in flexion and extension is also rate dependent. Eight cervical spines were sectioned into segments (four segments in total at each level from C2-C3 up to C7-T1) and tested in flexion and extension at one and five hundred degrees per second. The moment-rotation curves were recorded and a paired comparison test was done to identify evidence of increased spine stiffness at higher strain rates. This study found moderate evidence ($p<0.05$) of increased stiffness for five segments (three in flexion and two in extension).

INTRODUCTION

Neck injury is an important issue in crash safety, where fourteen percent of all car crash injuries occur in this region [Robertson, 2002]. To prevent these serious and costly neck injuries, the auto industry is working towards improving vehicle safety through advanced testing and analysis. In the design of vehicle safety systems, finite element models of the cervical spine can be used to simulate the loading response and predict injury in car crash scenarios. Understanding of the response of the cervical spine to loading at a loading rate that represents a car crash scenario can help in the design and validation of these computation models. However, a finite element model is only as accurate as the experimental data used for validation. Neck injuries occur during high speed car crashes, so for models to accurately predict occupant response, the model must be compared against high strain rate experimental data [Fice 2011].

Previous studies have measured the quasi-static response of the cervical spine in flexion and extension [Nightingale 2002, 2007, Panjabi 2001, Wheeldon 2006]. These studies have been used to develop finite element models [Panzer 2009, 2011]; however, models validated against quasi-static experimental data cannot be used to predict response under high rate loading conditions. Very little research has been done on the dynamic response of cervical spine segments [Voo 1998].

Recent ligament studies have demonstrated increased cervical spine ligament stiffness at higher strain rates [Shim 2006, Yoganandan 1989, Mattucci., 2011]. Studies of the intervertebral discs in the lumbar spine have also concluded that the stiffness of the discs increases under high rate loading [Kemper 2007, Duma 2006, Izambert 2003]. The viscoelastic nature of the ligaments and disc suggests that dynamic effects might play an important role in the response of the cervical spine to high rate loading. In flexion, the posterior longitudinal ligament, the interspinous ligament and the ligamentum flavum resist motion through tension. The disc also

opposes motion through compression of the anterior side of the disc and tension on the posterior side. In extension, the anterior longitudinal ligament is the only ligament in tension, thus it is the only ligament to play a role in extension along with the disc. The stiffness of a segment in flexion or extension is dependent on the load sharing between the disc and ligaments, therefore these studies imply that the segment response should also be rate dependent. The objective of this study was to test the hypothesis that the cervical spine demonstrates increased stiffness in flexion and extension at higher rates of rotation. The end goal of this research was to provide validation data in high speed flexion/extension, currently not available but required for validation of detailed cervical spine models.

METHODS

Five male and three female fresh frozen cervical spines, ranging in age from 29 to 50 (44.5 +/- 7.5) years, were procured for testing. The spines were dissected into segments (four at each level from C2-C3 to C7-T1). A segment consists of two adjacent vertebral bodies with the attaching ligaments and disc intact. The vertebrae were placed into separate, 25mm deep plastic cups (Fig. 1) and set with resin (R1 Fast Cast #891, GoldenWest MFG., Inc. California, USA).
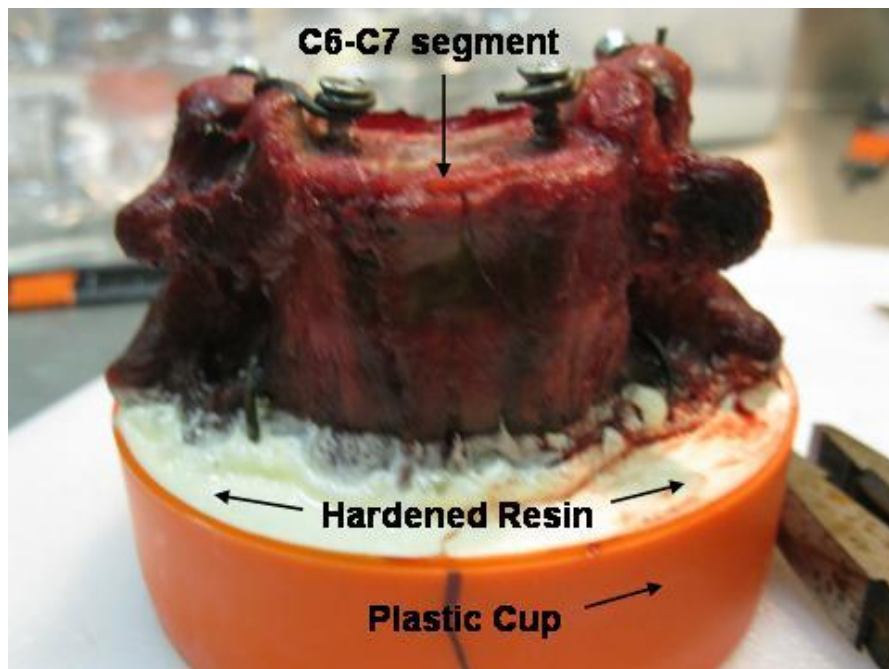

Figure 1 - C6-C7 Segment, C7 vertebra potted in the casting resin.

The cup containing the inferior vertebra was securely mounted on a six axis load cell (Model 45E15A4 1000N, JR3, California, USA). The superior vertebra was attached to a specially designed fixed-axis rotating frame (Fig. 2) driven by a Danaher Motion servo motor (Electromate, Ontario, Canada). The potting procedure to fix the vertebral bodies in the resin

ensured that the instantaneous axis of rotation of the segment [Amevo 1991, Bogduk 2000] was in line with the axis of rotation of the testing apparatus.
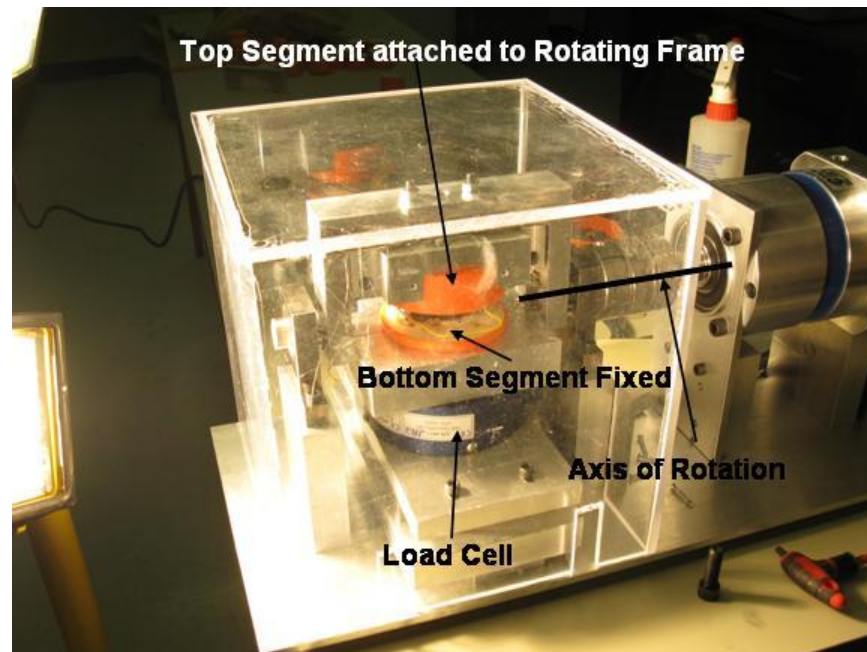

Figure 2 – Rotation Testing Apparatus

Each segment was preconditioned to a rotation of four degrees in both flexion and extension, for 10 load cycles. After preconditioning, the segments were tested three times at rates of 1 degree per second and at 500 degrees per second in flexion and extension. The segments were tested three times in order to establish repeatability. All the segments were rotated up to 10 degrees in flexion and extension, except for C5-C6 (extension only), C6-C7 and C7-T1, which were only rotated up to eight degrees. The rotation was limited so that the specimens did not sustain any soft tissue damage. Five hundred deg/s was chosen for the high rate test since this was typical of the rotation rate observed during 15g and 22g frontal crash scenarios [Fice, 2010].

The moment-rotation relationship was recorded with LabView using a data acquisition card (National Instruments, Model 6216). The one degree per second tests were recorded at 0.1 kHz and the high speed tests were recorded at 10 kHz. A paired difference test was used to evaluate the statistical significance between low and high rate testing. The test compared the average resultant moment of the low and high rate tests at the same rotational displacement in one degree intervals.

RESULTS

For ten degrees of rotation in flexion at one degree per second, the average moments for the C2-C3, C3-C4, C4-C5, and C5-C6 segments were 7.2 Nm, 5.1 Nm, 5.2 Nm, and 5.5 Nm, respectively. At five hundred degrees per second, the maximum moments for these segments were 9.2 Nm, 6.2 Nm, 6.2 Nm, and 7.6 Nm respectively.

The C6-C7 and C7-T1 segments were only rotated to eight degrees in flexion. For C6-C7, the average moment was 8.8 and 10.0 Nm at one degree and five hundred degrees per second, respectively. The moment at one degree per second was 12.2 Nm for the C7-T1 segment, and the moment for the same segment was 19.0 at the higher loading rate. Fig. 3 shows the average response of all segment tested in flexion at low and high rotation rates.
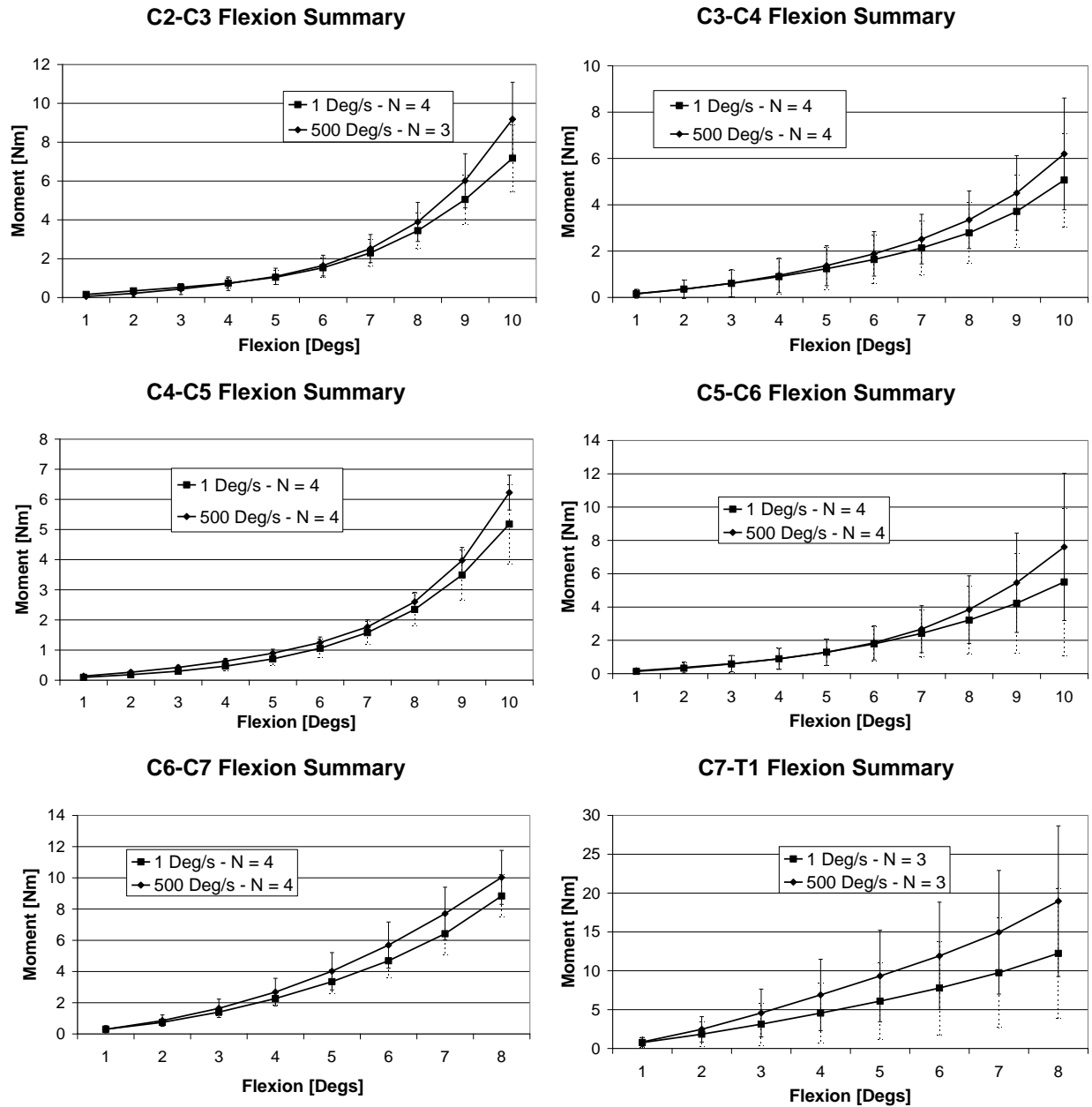

Figure 3 - Cervical spine segments in flexion at low and high loading rates.

For ten degrees of rotation in extension at one degree per second, the average moments for the C2-C3, C3-C4, and C4-C5 spines were 12.3 Nm, 11.2 Nm, and 8.7 Nm, respectively. At five hundred degrees per second, the moments for these segments were 13.7 Nm, 13.5 Nm, and 10.4 Nm respectively.

The C5-C6, C6-C7 and C7-T1 segments were only rotated to eight degrees in extension. The measured moments for the C5-C6 segment were 5.0 and 6.7 Nm for the low and high loading rates, respectively. For C6-C7, the moments were 8.2 and 9.1 Nm at one degree and five hundred degrees per second, respectively. The maximum moment at one degree per second was 13.2 Nm for the C7-T1 segment, and the maximum moment of the same segment 14.5 Nm at the higher loading rate. The average response curves for low and high rate testing are shown for each segment level (Fig. 4).
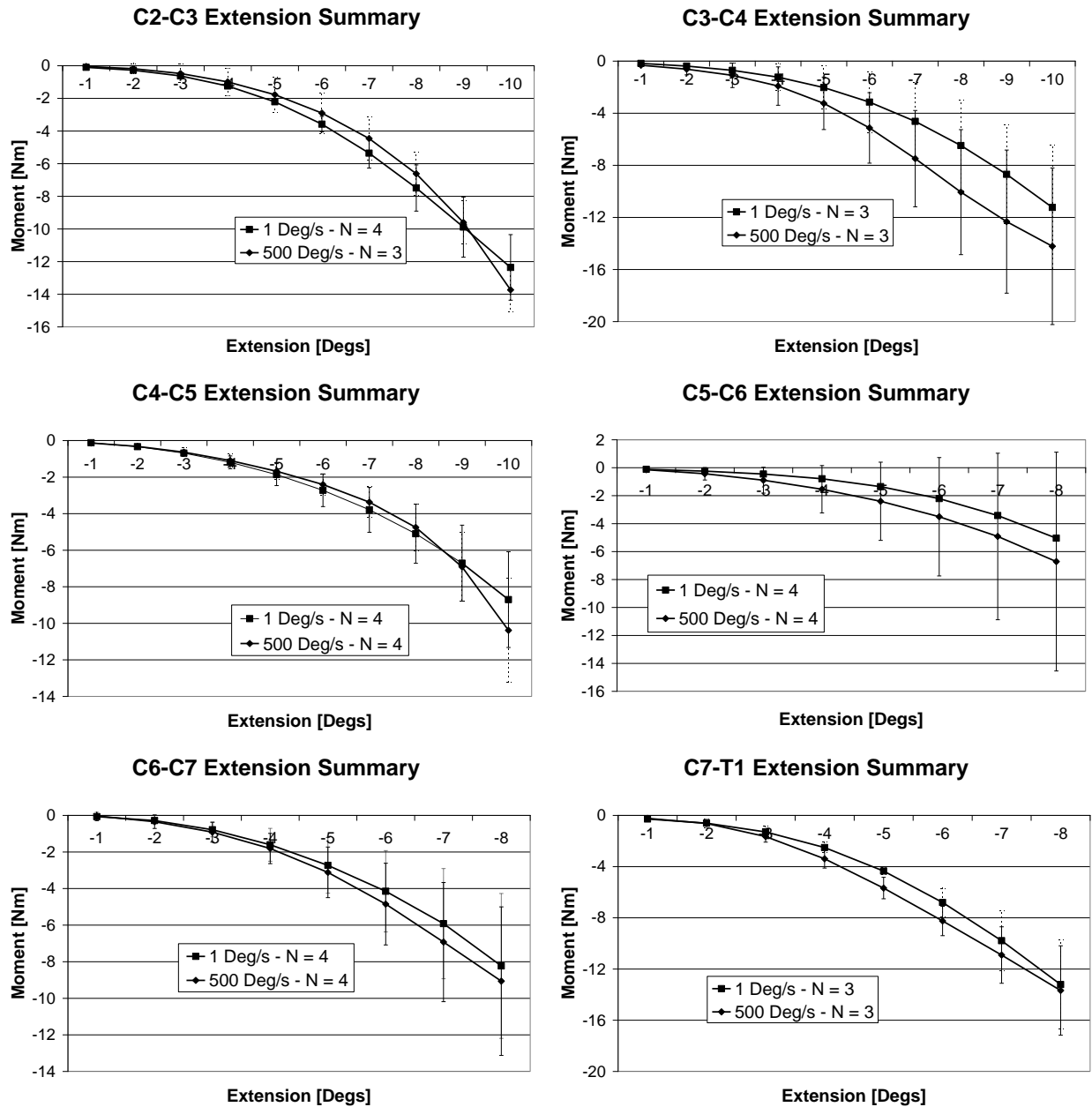

Figure 4 - Cervical spine segments in extension at low and high loading rates.

At displacements of six degrees or less, the statistical analysis demonstrated no evidence of increased stiffness at the higher rotation rate for any segment. Above six degrees of rotation, the test identified moderate ($p<0.05$) evidence of increased stiffness in flexion at the higher rotation rate for the C3-C4, C5-C6 and C6-C7 segments and weak evidence ($p<0.10$) for the C2-C3 and C7-T1 segments. In extension, the C4-C5, C5-C6 and C6-C7 segments showed moderate evidence and the C2-C3, C3-C4, and C7-T1 segments showed weak evidence of increased stiffness at more than six degrees of rotation. The C4-C5 segment displayed no evidence of increased stiffness ($p > 0.10$) in flexion.

DISCUSSION

In general, there was very little difference between the two rotation rates at low levels of rotation. It is possible that this was due to the viscoelastic nature of the soft tissues in the neck that resist flexion and extension. In flexion, the posterior longitudinal ligament, the ligamentum flavum and the interspinous ligament are in tension while the anterior portion of the intervertebral disc is under compression. In extension, the anterior longitudinal ligament is in tension and the posterior end of the disc is compressed. The force-displacement curve of the ligaments displays a toe-region. In the toe region, the ligaments exhibit such a small force compared to the peak force that any difference between low and high speed response has little effect in flexion and extension. As the ligaments are elongated and the tensile force approaches the peak, the difference between the two strains rates increases and the change becomes evident in the flexion and extension response curves.

In compression, the intervertebral disc response does not have a toe region and the stiffness curve is approximately linear. However, as with the ligament response, the difference between the low and high strain rate responses is more pronounced as the strain increases. The effect of the disc in flexion and extension cannot be determined with certainty because the response of the disc in flexion and extension has not been studied due to difficulties in isolating its response from the rest of the segment and because it is loaded in shear, compression and tension at the same time.

Previous studies have either used a pure-moment apparatus (Fig. 5) or a displacement controlled lever bar mechanism (Fig 6). A displacement controlled rotation device was chosen over a pure-moment apparatus because a pure-moment apparatus cannot accurately apply moments at a constant strain rate. In contrast to displacement control, the load in a load-controlled machine is applied by a system of weights or pulleys. With weights, the moment applied to the system is constant and the resultant moment between the two vertebrae is measured by a fixed load cell. The strain rate is dependent on the segment resistance to rotation and cannot be predetermined. With a system of pulleys, the moment can be varied by changing the force acting on the pull cables. In theory, the strain-rate can be controlled by using the displacement feedback to adjust the force of the cables accordingly. The force feedback to the actuators controlling the force on the pull cords is not instantaneous, so there will always be a lag between actual force and desired force. At high strain-rates, this lag becomes very significant and limits how high one can accurately set the strain rate.
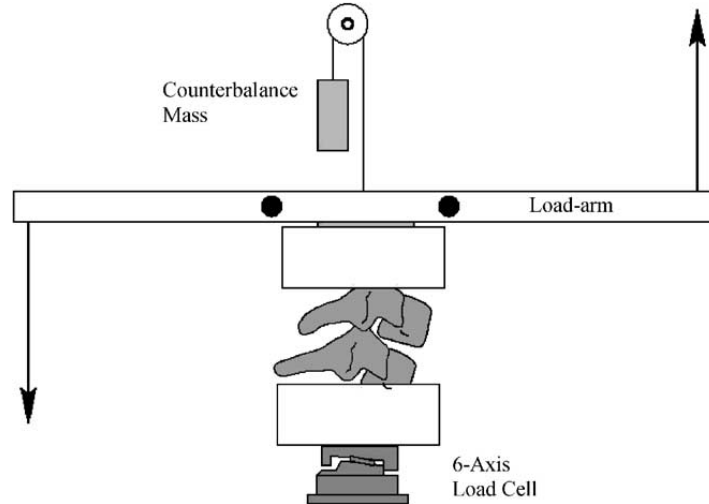
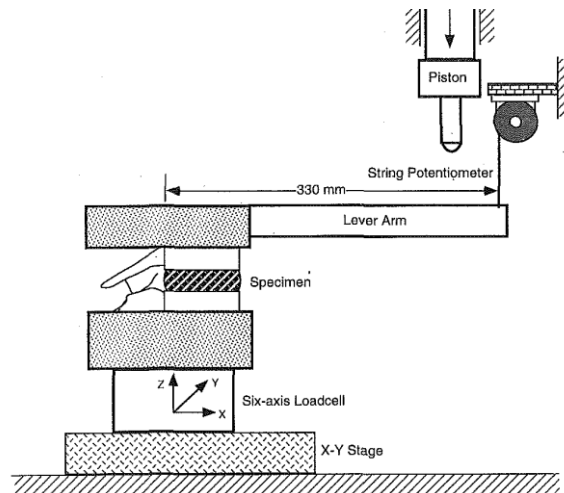**Figure 5 - Pure moment Machine (adapted from Nightingale 2002)**

Figure 6 - Level Bar Mechanism (Adapted from Voo 1998)

If the strain-rate is the independent variable, then the machine must be displacement controlled. The feedback from an encoder mounted on the motor is instantaneous unlike the feedback from a load cell. There are two options for a displacement controlled machine for this type of rotational testing: fixed axis rotation and free rotation. The fixed axis mechanism was chosen over the lever bar mechanism because the angle measured by the fixed axis mechanism is more accurate. In the lever bar mechanism, the angle, often calculated by the string potentionmeter, can be inaccurate due to bending and translation (instead of pure rotation) of the lever arm.
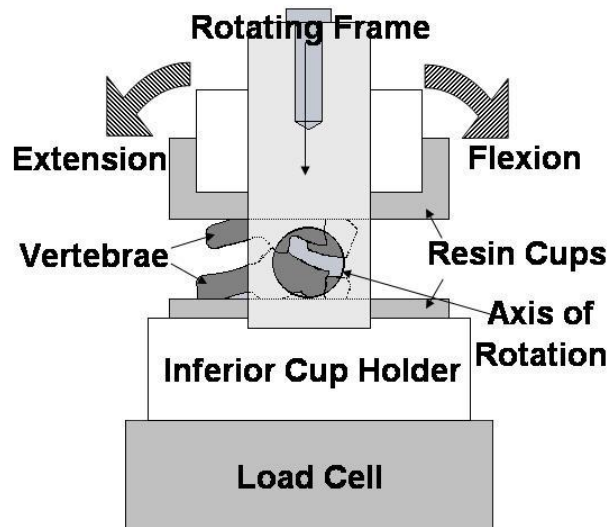
Figure 7 - Fixed-Axis Machine

When compared to the response reported in previous studies, the segment data from this study was much stiffer (Fig 8 and 9). There are a few possible explanations for the differences. There is an spine age discrepancy between studies. The average age of donors in this study is 44, while it is 51 [Nightingale, 2002] and 66 [Nightingale 2007] for the earlier studies. Research has shown that the mechanical properties of spinal ligaments degrade with age [Iida, 2002].

Previous studies have suggested that preload conditions can affect the moment recorded by the load cell and that comparing studies with difference initial boundary conditions, the differences must be acknowledged [Cripton 2000]. This study employed a fixed axis setup with zero preload (the compression recorded by the load cell was the same before and after the segment was loaded into the testing apparatus). The previous studies used a moment controlled machine with a 0.5N tensile preload.

Another reason for the variation in stiffness is that the moment in the previous studies [Nightingale 2002, 2007] was applied in steps and held for 30 seconds before the position was recorded. During the 30 seconds, the segment may rotate away from the starting position due to creep. With moment held constant, the stiffness is inversely proportional to the measured displacement. When creep is permitted to occur over 30 seconds, the displacement increases, and the calculated stiffness decreases accordingly. If the rotation was recorded immediately, the segment response may have been stiffer because the measured displacement would have been smaller.
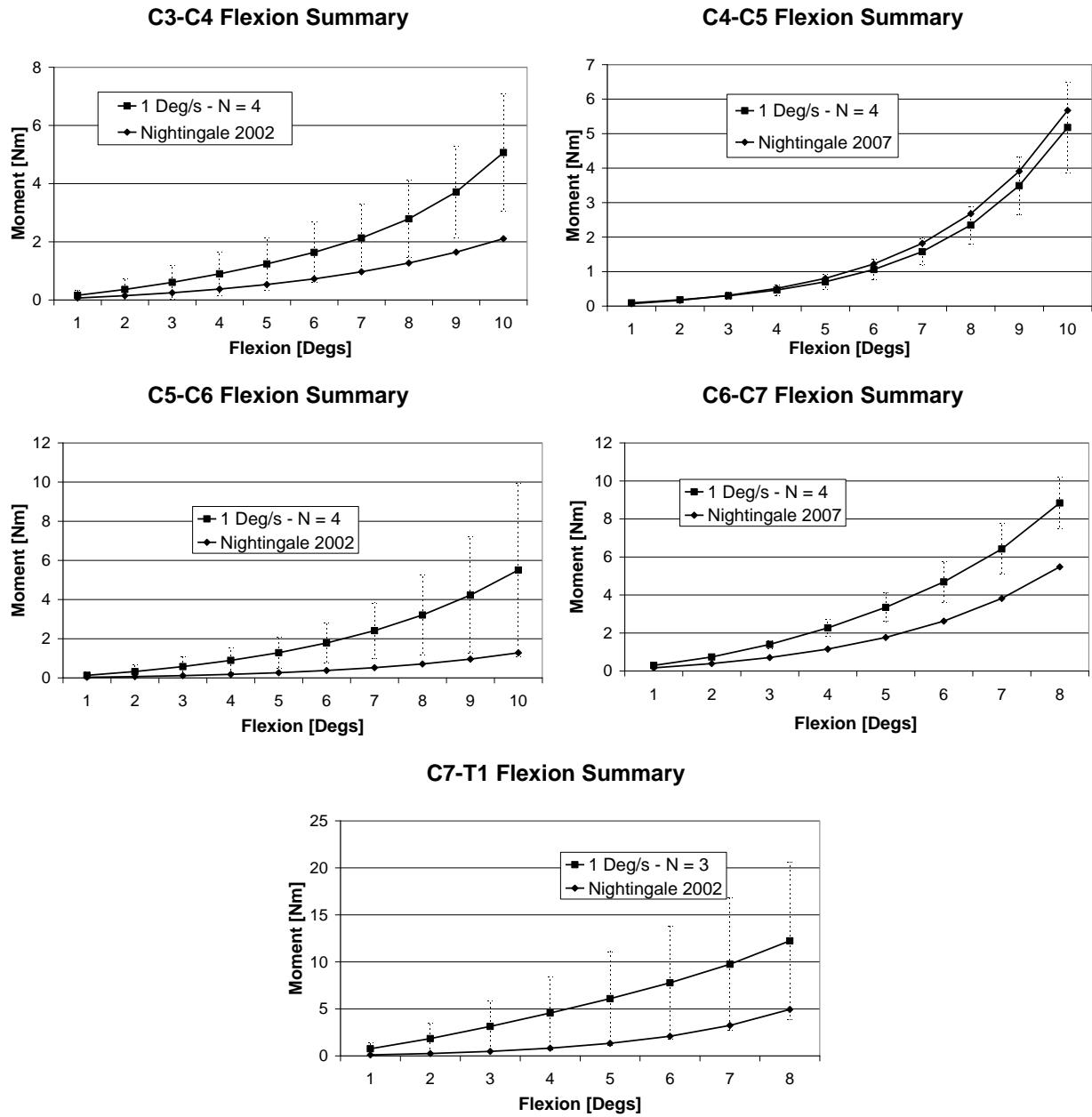
C3-C4 Flexion Summary

C4-C5 Flexion Summary

C5-C6 Flexion Summary

C6-C7 Flexion Summary

C7-T1 Flexion Summary

Figure 8 – Comparison of segmental behavior in flexion with existing data

C3-C4 Extension Summary

C4-C5 Extension Summary

C5-C6 Extension Summary

C6-C7 Extension Summary
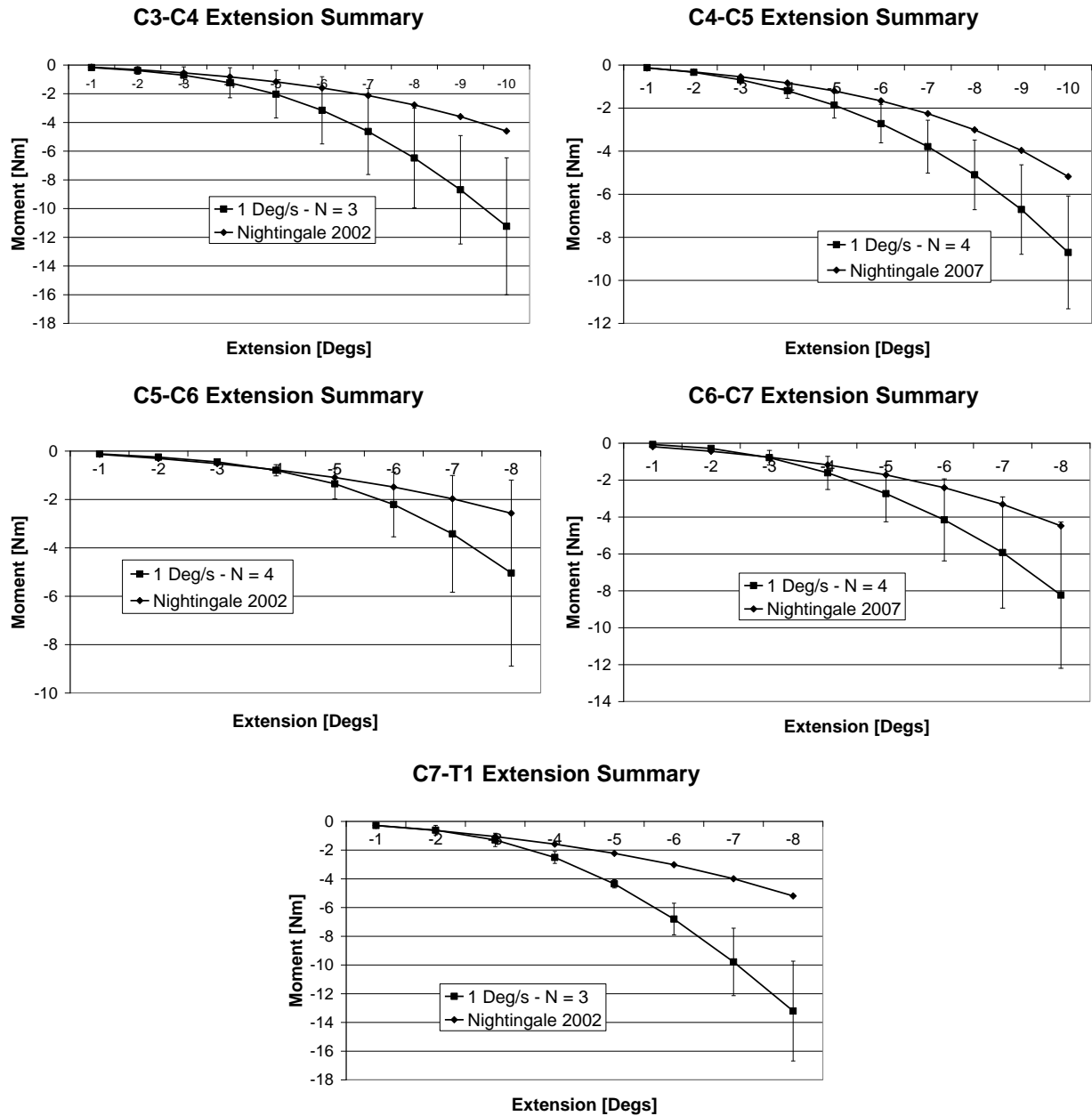
C7-T1 Extension Summary

Figure 9 - Comparison of measured segmental behavior in extension with existing data

CONCLUSIONS

The experimental results have verified the hypotheses that segment stiffness increases at higher rates of rotation, indicating the possible influence of the ligament and disc behaviour. The statistical testing only found moderate evidence of increased stiffness in some of the segments due to low sample size, and small differences between low and high speed tests. The data from this study will be used to validate a finite element model of the cervical spine. Future work will focus on lateral bending at high rotation rates and the strain rate effects of the intervertebral disc.

Understanding the strain rate effects of the disc and the ligaments together may explain the increased effect of rotation rates at higher rotation.

ACKNOWLEDGEMENTS

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