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A Robotic Testing Facility for the Measurement of the Mechanics of Spinal Joints

Hans de Visser*, Catherine Rowe, Mark J. Pearcy

School of Engineering Systems, Queensland University of Technology, Brisbane, Australia

* Corresponding author:

Hans de Visser, MSc, PhD

School of Engineering Systems

Queensland University of Technology

GPO Box 2434

Brisbane, Queensland 4001

Australia

Tel: +61 7 3864 1377

Fax: +61 7 3864 1469

e-mail: h.devisser@qut.edu.au

Running Title:

Robotic testing of spinal joint mechanics

Abstract

A robotic testing facility for the measurement of joint mechanics was used to determine the significance of tears in the intervertebral disc on the mechanics of the spinal joint. Ten lumbar joints of sheep were dynamically loaded and manipulated. Comparisons were made between the behaviour of the intervertebral disc in flexion/extension at two test speeds. The influence of the posterior elements and of rim lesions was assessed by testing the joint immediately before and after removal of the posterior elements and after the creation of a 4x10 mm rim lesion in the disc. Stiffness of the spinal joint dropped significantly upon removal of the posterior elements, from 0.81 to 0.23 Nm/° for flexion and from 0.65 to 0.40 Nm/° for extension. Maximum moments dropped 37% for flexion and 63% for extension. The rim lesion caused a further significant stiffness reduction to 0.21 and 0.31 Nm/° respectively. Maximum moments reduced a further 12% and 16% respectively. A higher test speed (2 instead of 0.5 °/sec) usually did not change these results significantly. The novel six degrees-of-freedom robotic testing facility used in this study was demonstrated to be an effective system for studying the mechanics of complex biological joints.

Keywords: Lesions, Intervertebral Disc, Robotic Testing Facility, Dynamic Testing

1 Introduction

Low back pain is a condition with a huge impact on both a personal and a macro-economic level, as it is estimated that up to 80% of the population suffers from it at some stage in life. Annually this costs billions of dollars in treatment costs and lost productivity. Much of this back pain is attributed to degeneration of the intervertebral disc (IVD) [**1**], which has been shown to affect the mechanics of the spinal joint (e.g. [**2-4**]). Altered mechanics may lead to nerve irritation or entrapment and further degeneration. Hence it is important to understand the mechanics of the lumbar spine and how it is affected by defects in the IVDs that may lead to back pain.

In vivo studies on sheep have been conducted by Latham et al. [**6**] and Fazzalari et al. [**7**]. Latham et al. [**6**] found a reduction in stiffness in axial rotation, six months after surgical introduction of a rim lesion in the left antero-lateral portion of the IVD. However, this change in mechanics was attributed to the increasing degenerative state of the IVD rather than rim lesion. Fazzalari et al. [**7**] found that surgically introduced concentric tears did not have measurable effects on the joint mechanics. In a previous study by our group [**5**] in vitro investigations were conducted on sheep lumbar spines into the effects of introduced lesions in the intervertebral discs. While these studies identified measurable changes in the mechanics of the disc the robot used had a limited load capacity and was not able to reproduce physiological loading conditions.

Sheep models are becoming increasingly important in spine research as they provide a good balance between model accuracy and specimen availability, and are invaluable for the validation of other types of spine models, such as finite element models.

The current study introduces a novel six degrees-of-freedom (DOF) robotic testing facility that is used to investigate how the stiffness in flexion and extension of ovine spinal joints is affected by the creation of a right antero-lateral rim lesion and by the speed of deformation. Compared to the robotic facility used by Thompson [**5, 8**], the new facility is capable of creating considerably larger loads and displacements while maintaining a similar accuracy. Robots with several DOF have been used in biomechanics since the early 1990s when the group of Mabuchi, Fujie, et al. [**9, 10**] developed the concept and used it to examine the mechanics of knee joints [**11**]. This and other groups continue to develop robot facilities for the examination of joint biomechanics (e.g. [**12, 13**]).

This study aims to increase our understanding of the lumbar spine mechanics by investigating the stiffness of isolated lumbar spinal joints from sheep in flexion and extension, and how this stiffness is affected by rim lesions in the IVD and by rotation speed. The influence of the latter was not investigated in Thompson's study [**5**]. This is a pilot study to assess the capabilities of our robot facility for basic biomechanical testing before exploring the full potential of the robot in complex multi-axial biomechanical testing.

2 Methods

2.1 The Robotic Testing Facility:

The testing facility (Figure 1) created for this project consisted primarily of an ABB IRB 4400/60 industrial robot (ABB, Västerås, Sweden) and a 6-degree-of-freedom JR3 160M50A force sensor (JR3, Woodland, CA, USA). The robot was used to physically load and manipulate the spinal joint, and the sensor used to measure the forces and moments experienced by the joint during testing. An external PC was used to control, and record data from, both the robot and the JR3 sensor. For this purpose software was developed that allowed use of the PC to specify the type and magnitude of motion and load used in the test. Robot positional data were stored in the robot computer at a rate of approximately 14 times a second and downloaded to the PC at the end of each test. The robot was operated in displacement control. Force and moment data were collected on the PC at a rate of approximately 18 times a second. Software was developed to interpolate and combine these data allowing analysis of the force and moments experienced by the joint with respect to position. [INSERT FIGURE 1 HERE]

The robot had a positional repeatability of 0.07 mm and a rotation resolution of 0.01°, and was able to exert a payload at full extension of 60kg. The JR3 sensor had a resolution of 0.01N and 0.01Nm and was capable of reading a 1000N maximum force and 160Nm maximum moment.

2.2 The Specimens:

Ten lumbar spinal joints (two L1-L2, one L3-L4 and seven L5-L6 joints) from seven different sheep were used in this study. The sheep lumbar intervertebral joints were used because of the similarity of their mechanics to human joints [**14-16**]. Whilst the cross-sectional area of the vertebrae endplates is smaller in sheep, the height of the disc itself is proportional to that of a human IVD [**17**]. The anatomy of the surrounding musculature is also very similar to that of the human lumbar spine [**5**]. It was therefore deemed that mechanical testing on a sheep spine would give a reasonable insight into the behaviour of human spinal joints.

The sheep were euthanased by a qualified veterinarian, and the lumbar spine harvested. The procedure was approved by the University's Animal Ethics Committee. Prior to removal of the lumbar spine from the sheep, rivets were inserted into the transverse processes of each lumbar vertebra. The distance between each consecutive rivet was measured before and after removal of the spine. X-rays were also taken of the spine and attached rivets after removal. The measured rivet distances were used later to determine an accurate scale for the X-rays.

Upon removal, the spines were kept frozen at a temperature of -28°C until testing. A study by Thompson [**18**] concluded that freezing of the intervertebral disc had no significant effects upon its behaviour.

2.3 Determining the IAR location:

The X-rays taken at the time of spine retrieval were used to determine the joints' natural point of rotation or the instantaneous axis of rotation (IAR). Pearcy and Bogduk [**19**] conducted a study determining the average location of the IAR in human intervertebral joints as a proportion of the disc height and width. This data was used to determine the approximate location of the IAR for the sheep joints. However because of the typically trapezoidal shape of the sheep intervertebral disc, calculations were instead based on the perpendicular width of the disc rather than the length of the inferior disc endplate. The distance in three axes of the IAR from each rivet in the inferior lateral processes was recorded for use during testing.

2.4 Specimen Preparation:

Prior to testing the spines were removed from the freezer and allowed to thaw at room temperature. They were then separated into two-vertebrae sections, ensuring that no harm was caused to the intervertebral disc. The superior vertebra was mounted in a stainless steel cup using dental cement.

Once the cement had cured the distance between the rivets in the inferior exposed vertebrae and a fixed origin in the specimen cup was measured. This distance was later used to locate the rivets with respect to the robot and, by incorporating the calculated position of the IAR with respect to the rivets, to determine the location of the IAR about which the robot would move during testing.

After these measurements were taken the half mounted specimen was attached to the robot tool, and the robot slowly moved so as to lower the unmounted vertebra into the lower specimen cup. Dental cement was then poured around the vertebra and cured, effectively restraining the specimen at both ends.

The specimen was kept moist throughout this process by wrapping it in saline soaked paper towel. Once the cement had cured, the paper was removed and the environmental chamber that surrounded the specimen was closed, heated to 37°C and exposed to 100% humidity using a vaporising atomiser within a container of water. Temperature was controlled by pumping warm water into the container. Because of the 100% humidity environment, there should be no movement of water in and out of the disc. This method was preferred over disc immersion techniques, as the difficulty with these techniques is that, once exposed with a lesion, the nucleus is likely to imbibe water when unloaded, which would alter its mechanical response [**20**]. A flexible plastic membrane was used to seal the top of the chamber, allowing for the significant movement of the robot tool. The environmental chamber and specimen cups are shown in greater detail in Figure 2. [INSERT FIGURE 2 HERE]

Once all tests on the intact specimen were done, the posterior elements were removed with an electrical bone saw and nibblers. Care was taken to remove the entire zygapophysial joints (z-joints) and as much as possible of the other posterior elements. Tissue structures directly connected to the vertebral body, such as the posterior and anterior longitudinal ligaments, were left intact to avoid causing any damage to the IVD. The isolated IVD specimen was then tested. Once these tests had been completed, a rim lesion was made by horizontally inserting a flat 4mm wide scalpel blade 10mm into the right antero-lateral region of the IVD, just below the endplate of the superior vertebra, and the specimen was tested again. The chosen position was in accordance with a previous study [5]. As described in that paper, according to the literature rim lesions exist more commonly in the anterior anulus.

2.5 The tests:

The testing of one specimen incorporated 6 separate tests. These tests were separated into three sections: “Intact”, the intact joint; “Disc only”, once the zygapophysial joints had been removed; and “Lesion”, the disc only with an inserted rim lesion in the right antero-lateral region. At each of these stages the joint was tested in flexion/extension (+6° to -4°). This range was similar to that used in the study of Thompson et al. [**5**]. It was based on a study by Pearcy [**21**] who determined the range of motion of the human lumbar spine of healthy volunteers. The range of motion of the ovine specimens was chosen conservatively compared to the results of Pearcy’s study to avoid overstretching and damaging of specimens. Tests were performed at speeds of 2°/sec and 0.5°/sec. The first is similar to previous studies by Thompson et al. [**5**] and Wilke et al. [**14**], who used 3°/sec and 1.7°/sec respectively. The second test speed was chosen to assess the influence of the strain rate on the resulting moments. The two speeds will be referred to as “v2” and “v05” respectively. At v05 5 cycles were performed and at v2 10 cycles. It was observed that the first cycle would often differ somewhat from the following cycles due to some “settling” behaviour. The remaining cycles were generally very similar. The first cycle of each test was considered to be a preconditioning cycle and therefore excluded from the results. One of the L5-L6 joints was only tested at v2 and not at v05, due to technical and time constraints on the day of the test.

2.6 Stiffness calculations:

Stiffness was calculated by taking the linear gradient of the Moment/Angle curve between 60% and 80% of the maximum angle for each test. The 60% to 80% region was chosen because the mechanical behaviour in this region appeared consistent, as it was well away from any irregularities occurring at the points of direction change (i.e. the maximum angles) and the neutral zone around 0°.

3 Results

For both flexion and extension the stiffnesses and maximum moments decreased significantly (two-tailed paired Student's T-test with correction for multiple comparison) upon removal of the zygapophysial joints, as shown in Figure 3 and Table 1. The stiffness reduction is significantly higher for flexion (72% at v05 and 71% at v2) than for extension (38% and 43% for the two speeds respectively). In the intact joint the flexion stiffnesses are somewhat higher than extension stiffnesses but not significantly ($p>0.2$), however, once the z-joints are removed flexion stiffnesses are significantly lower than extension stiffnesses ($p<0.01$). The maximum moments reduced more for extension (63% and 67% at v05 and v2 respectively) than for flexion (37% and 39% at v05 and v2). Rim lesions caused further reductions in stiffness and maximum moments, which were all significant. These reductions were relatively small for flexion stiffness: 9% to 12%. For stiffness in extension they were slightly larger: 15% to 23%. For the maximum moments the reductions were similar for flexion and extension: about 11% to 16%.

The stiffness per specimen is an average taken over 4 (for v05) or 9 (for v2) cycles. Typically, the variation within each specimen was low: The standard deviations (SDs) for all flexion tests were below 0.05 at v05 and below 0.13 at v2 (with one exception of 0.24). For the extension tests at v05 the SDs per specimen were below 0.08, and at v2 below 0.15 (with one exception of 0.22).

Rotation speed had limited influence on the stiffness with most averages of measurements at v2 being higher than those at v05, but this was only significant for flexion of the intact joint ($p<0.01$) and extension of the disc with lesion ($p<0.02$). Apart from extension of “Disc only” ($p<0.02$), rotation speed had no significant influence on the maximum moments. [INSERT FIGURE 3 AND TABLE 1 HERE]

4 Discussion

Considering the geometrical restrictions the z-joints cause to the spinal joint’s mobility, it is not surprising that both flexion and extension stiffness and the maximum moments of the ovine lumbar joint decrease significantly after removal of the z-joints.

Rim lesions caused a further stiffness reduction in both extension and flexion which was significant in all cases. This demonstrates the important role of the anular fibres not only when the disc is in tension but also when it is compressed. The maximum moments reduced a further 11% to 16% after the introduction of a rim lesion, which is similar to the 14% to 20% reduction found by Thompson et al. [**5**] for rim lesions in sheep L1/L2 and L3/L4 discs.

It was found that the flexion stiffness of the intervertebral joint with the z-joints intact was slightly higher than the extension stiffness, but without the z-joints the extension stiffness was significantly higher than the flexion stiffness. This suggests that the z-joints and the ligaments encapsulating these joints play an important role in preventing not only hyperextension but hyperflexion as well, although the larger drop in stiffness for flexion suggests that flexion stiffness is also influenced considerably by the removal of the supraspinous and interspinous ligaments. The fact that extension stiffness was significantly higher than flexion stiffness when the z-joints were removed might suggest that, of the remaining structures, the anterior longitudinal ligament plays a more important role in preventing hyperextension than its counterpart, the posterior longitudinal ligament, does in hyperflexion prevention. However, the anterior longitudinal ligament is not always present in sheep, and if present, consists only of a thin fibrous band [**5**]. Therefore, it is more likely that the difference in stiffness between flexion and extension when all posterior elements have been removed is caused by the asymmetric kidney shape of the IVD.

The faster rotation speed tended to result in a slightly higher average stiffness, but only significantly so for flexion of the intact joint and extension of the disc with lesion. These two speeds, while reproducing earlier studies and falling within physiological rates, only differed by a factor of four and a larger difference in speed may reveal a greater deformation rate dependence.

Most specimens were from the lower lumbar region (L5-L6). The specimens from higher lumbar levels of the same sheep were included in the study as it was found that their results did not differ noticeably from the L5-L6 results.

The robot is operated under displacement control to reveal the true relative affect of interventions to components of a joint. If pure moments are applied or load control is used for this type of study then the specimen is likely to rotate around different centres of rotation after each intervention.

This results in the remaining components of the joint producing a different resistance to the motion and hence the true comparative affect of removing or injuring components cannot be deduced. While displacement control could lead to non-physiological loads this potential is limited by maintaining the primary deformations imposed on the specimen to within physiological limits. To be able to compare pre and post lesion moments properly, all other factors including the motion path must be the same before and after, hence the use of displacement control in the current study.

5 Conclusions

These tests indicated the ability of the robot, incorporating an appropriate six degree of freedom load-cell, to measure the complex mechanics of spinal joints. This study has shown the system's ability to reproduce tests conducted in previous work while extending the data to examine the effect of strain rate. Future work will be aimed at studying more complex movements, such as combinations of flexion/extension, lateral bend and axial twist. The posterior elements of the intervertebral joint have been shown to be important in flexion as well as extension and lesions in the disc cause reproducible changes to the mechanics of the disc. These studies provide evidence for the mechanisms of degenerative changes to alter the mechanics of the intervertebral joint and criteria needed for the design of artificial discs.

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	Rotation speed (°/sec)	Intact		Disc only		Lesion
Flexion stiffness (Nm/°)	0.5	0.81±0.42	*p=0.003*	0.23±0.07	*p=0.003*	0.21±0.07
		p=0.01		p=0.2		p=0.2
	2	0.87±0.47	*p=0.003*	0.25±0.07	*p=0.009*	0.22±0.06
Extension stiffness (Nm/°)	0.5	0.65±0.20	*p=0.0004*	0.40±0.13	*p<0.0001*	0.31±0.13
		p=0.05		p=0.6		*p=0.02*
	2	0.68±0.25	*p=0.0001*	0.39±0.14	*p=0.002*	0.33±0.13
Maximum flexion moment (Nm)	0.5	2.63±0.66	*p<0.0001*	1.65±0.52	*p=0.005*	1.46±0.52
		p=0.1		p=0.7		p=0.5
	2	2.63±0.84	*p<0.0001*	1.61±0.55	*p=0.0002*	1.41±0.51
Maximum extension moment (Nm)	0.5	3.90±1.56	*p=0.001*	1.46±0.34	*p=0.003*	1.23±0.33
		p=0.04		*p=0.02*		p=0.8
	2	4.10±1.97	*p=0.001*	1.36±0.30	*p=0.002*	1.21±0.29

Table 1. *Stiffness and maximum moments of the spinal joint for 6° of flexion and 4° of extension at two different rotation speeds for the intact joint ("Intact"), the joint with the z-joints removed ("Disc only") and with a rim lesion ("Lesion"). Values given are the averages ± standard deviations of 10 specimens for the higher speed and 9 specimens for the lower speed; and the p-values of the comparisons between the different conditions (italic font indicates a significant difference, i.e. p<0.025; two-tailed paired Student's T-test with correction for multiple comparison).*

Figure 1. *Overview of the robot facility and the environmental chamber, shown in detail in figure 2.*

Figure 2. *Close up of the environmental chamber. The apparatus used to mount the spinal specimens comprised three main sections: The Robot Tool (1), the JR3 attachment (2) and the specimen cups (3). The robot tool provided an attachment point between the robot and the specimen without inhibiting the robot's range of motion. The JR3 attachment provided a way to translate the specimen attachment point away from the JR3 sensor (4) itself, and therefore prevent damage due to fluid contact. 100% humidity was produced with an ultrasonic atomiser (5). A temperature gauge (6) was used to monitor the temperature inside the environmental chamber (7).*

Figure 3. *Stiffness (Nm/°) of the spinal joint for 6° of flexion (top figure) and 4° of extension (bottom figure) at two different rotation speeds for the intact joint ("Intact"), the joint with the z-joints removed ("Disc only") and with a rim lesion ("Lesion"). The bars indicate the average stiffnesses taken over 9 (for the lower speed) or 10 (for the higher speed) specimens. The error bars represent the standard deviations.*

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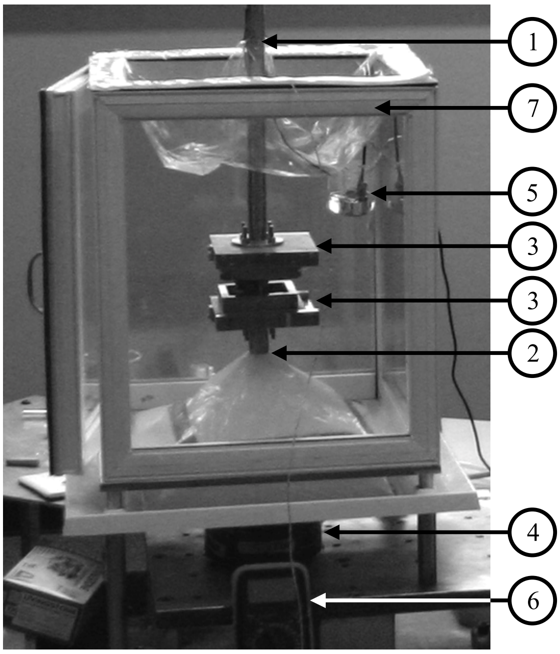

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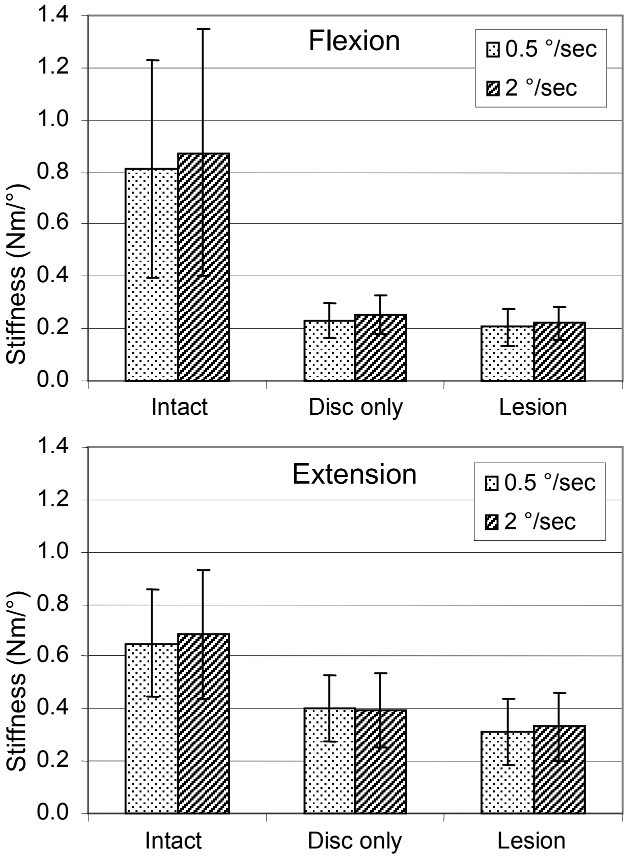

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