METHODS FOR STUOYING EFFECTS ON THE SPINE UNDER DIFFERENT LOADS

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ABSTRACT

The injury mechanism for cervical vertebrae and spinal ligaments in road accidents are not fully understood today. Thus, we do not seem to know how to develop an optimal seat and head-rest, for minimizing the risk of injuries to the occupants in rear-end car collisions.

For this purpose a mechanical model of relevant cervical sections will be developed, based on experiments carried out on cadaver spine segments.

The experimental model consists of lumbar spine segments. A specially designed fixture is used to hold the specimen in a known orientation. Bending moments are applied to the upper vertebra in different directions. Loads and moments generated in the lumbar segments are then recorded with a biomechanical platform. At the same time the three-dimensional motion behaviour of relevant structures are studied.

First the specimens are exposed to a physiological range of motion, then disruption of ligaments is generated. After the injury generation the motion behavior is investigated again. The results will eventually be compared with clinical observations from real world accidents.

INTRODUCTION

During the last decades the number of severe spinal injuries has increased. Traffic accidents represent more than 50 per cent of all injuries. Spinal injuries can lead to severe impairment of the nervous system (e.g. para- and tetraplegias). Often young people are affected (in our region in Sweden the mean age of the patients with vertebra fractures is around 29 years).

Severe spinal injuries with instability occur in about 50 cases by year and one million population. In spite of this, very little is known about the mechanisms of injury. There is also a need for better diagnostic and rehabilitation methods.

Clinical instability has been defined by White and Panjabi (1978) as the loss of the ability of the spine under physiological loads to maintain relationships between vertebrae in such a way that there is either initial damage or subsequent irritation to the spinal cord or nerve roots.

The mechanics of the injured spine have been studied by among others White et al. (1975) and Panjabi et al. (1975). They have investigated clinical stability of the cervical spine as a function of transection of components (e.g. ligaments) under normal static physiologic loads. A similar study was made by Posner et al. (1982) for the lumbar and lumbosacral spine.

Goel et al. (1984) investigated the three-dimensional motion behaviour of the normal, injured and stabilized cervical spine in the physiological range of motion.

Usually, motion segments are used in the experimental studies. A motion segment (or a functional spinal unit, FSU) consists of two adjacent vertebrae, all intervening ligaments and the intervertebral disc. The functional spinal unit is a three-dimensional structure, which allows one vertebra to move with respect to the other in any direction in space under the application of a given load.

To date, there have been few experimental studies to determine human cervical spine tolerances to impact (Huelke and Nusholtz, 1986). Most laboratory tests on individual cervical vertebrae or cervical segments have been conducted staticly and not under dynamic conditions.

Mertz and Patrick (1971) estimated human tolerances for the cervical spine based on human volunteer testing and on cadaver sled tests. They suggested tolerance levels for the resultant bending moment in flexion (190 Nm) and extension (57 Nm). These are considered lower boundaries, as similar bending moments cause no discernible ligamentous damage in cervical spine segments (Huelke and Nusholtz, 1986).

Nygren (1984) showed that whip-lash injuries in rear-end car collisions often lead to permanent disability. Five years after the accident 10% of those initially complaining about neck pain after a rear-end car collision had remaining problems. We have, however, not found any study, where clinically relevant fractures similar to those in real world accidents, e.g. injuries in rear-end car collisions have been investigated.

Nygren et al. (1985) showed that head-rests have a certain influence on the incidence of neck injuries in rear-end car collisions. There is a great difference in effectiveness between different types of head-rests but there is no reduction of neck injuries in rear-end car collisions for newer car constructions. Thus, we do not seem to know today, how to develop an optimal seat and head-rest, for minimizing the risk of injuries of occupants in rear-end car collisions.

Different methods are described in the literature for studying two- and three-dimensional motion patterns of a rigid body. The various measuring techniques may be classified into two general groups, stereometry and electro-mechanical methods.

In stereometry, two positions of a rigid body in space, at the beginning and at the end of a motion step, are recorded. The position of the body is defined of three non-collinear points of the body. Using geometric procedures the three-dimensional coordinates of the three points in two positions are determined. Principles of kinematics are then utilized to compute the rigid body motion. The body in space can be recorded in two or more views with e.g. visible light (video and high-speed film), X-rays, infrared light (Selspot) or acoustic waves (Graf/Pen).

Selspot and Graf/Pen are new computer based measurement systems for recording and analyzing data of three-dimensional motion on a real-time basis. The Selspot-system uses light emitting diodes as markers working in the infrared region of the light spectrum. The diodes are imaged by two video cameras suitably positioned. This method has been utilized by e.g. Antonsson and Mann (1979) for gait studies and Goel et al. (1985) for studying kinematics of the lumbar spine. In the Graf/Pen system the markers consist of spark generators. Each spark produce an acoustic wave which is picked up by suitably placed microphones. Graf/Pen has been used by Goel et al. (1984) for investigation of the relative motion between the vertebra in the cervical spine under physiological loads.

High-speed films and X-ray recordings can also be computer analyzed, e.g. with a real time image processing system. TV-cameras are used to record relevant parts from the high-speed film, then the analog video signals from the cameras are converted to digital data. Each image is stored as a matrix of picture elements, where each element provides a level of grey tone. To analyze the frames an arithmetic logic processor is used.

Various electro-mechanical transducers have been utilized to measure two- or three-dimensional motion, e.g. mechanical dial gauges or electrical linear variable differential transformers (LVDT). These transducers measure horizontal and vertical displacements in a moving body. Displacement gauges have been used by e.g. Panjabi et al. (1981) for the description of three-dimensional motion in the lumbar spine.

The purpose of this study is to develop methods for studying effects on the spine under different dynamic loads, similar to those in rear-end car collisions.

Knowledge about these effects can lead to a better understanding of the injury mechanism. This in turn, can lead to improved diagnostic methods of spinal injuries and better rehabilitation programs.

When the three-dimensional motion behaviour of the cervical spine has been investigated, a mechanical model of relevant cervical sections based on the experimental data will be developed. This model can be used as a tool in further development studies.

METHODS

Functional spinal units from the lumbar region were used in the experimental studies. When the methods for studying effects on the lumbar spine under different dynamic loads have been further developed and tested, they will be applied to cervical spine segments and to the whole cervical spine.

Handling and preparation of test material

Fresh lumbar spines were obtained during autopsies. The specimens were double-wrapped into plastic bags and frozen at -20° C. For preparation the specimens were thawed at room temperature (+20° C) and kept in the plastic bag to preserve moisture. The spines were divided in appropriate functional spinal units and X-rays were taken to investigate if there were any defects or degenerative changes in the segments. Only intact specimens were used in the study. Data for each specimen were collected regarding e.g. sex, age, spinal levels, size (height and width of the segment), disc degeneration, cause of death and radiologic observations.

The functional spinal units were cleaned and dissected free from muscles and fat with care to preserve the bone-ligament units intact. All work was performed in a high humidity environment in order to preserve the natural hydration of the bone and ligaments. If the specimen was not to be tested immediately it was refrozen.

It has been shown that freezing, thawing and refreezing cycles do not appreciably affect the physical and mechanical properties of the bone, the annulus fibres of the disc, or the longitudinal ligaments (Sedlin and Hirsch, 1966; Galante, 1967; Tkaczuk, 1968; Panjabi et al., 1975).

To obtain a rigid fixation two Kirschner wires (1.16 mm diameter) were inserted perpendicular to each other in the upper and lower bone structures. One third of the upper and lower vertebra of each specimen were then embedded into a two-component cement (Plastic Padding) in specially designed steel cups. Extreme care was taken to ensure that the mid-disc plane of the functional spinal unit was parallel with the lower steel cup. For this purpose a special jig was designed.

At the casting procedure the specimen was mounted in the cups with help of the wires passing through the walls on the cups. The inner surface of the steel cup was covered with a thin coat of lubricating grease to prevent permanent adhesion between the hardened fixative and the cup.

After casting, ten specimens were X-rayed and the angle between the mid-disc plane and the lower steel cup was measured.

Measuring System

Loads were applied to the functional spinal units through a vertical metal bar at the center of the upper steel cup. With the help of a metal wire passing over pulleys different weights could produce specified forces and moments oriented correctly with respect to the x, y and z axes. With this arrangement physiological loads as well as transient dynamic loads providing failure could be applied in flexion, extension and lateral bending. The experimental set up is shown in Figure 1.

Loads and moments generated in the functional spinal units are measured with a biomechanical platform (AMTI MC12-6-1000). With the use of a strain gauge system the transducer resolve applied loads into three orthogonal force components (F_x, F_y, F_z) and three orthogonal moment components (M_x, M_y, M_z).

The platform has a capacity of 4,500 N for the force channels and 700 Nm for the moment channels. The resonant frequency is 880 Hz for vertical loads (F_z) and 450 Hz for loads applied in the horizontal plane (F_x and F_y).

The electrical output signals from the platform were calibrated and amplified (Johne+Reilhofer, 8MV1) before being recorded at an Y-t plotter (Figure 2).

The three-dimensional motion behaviour of the specimen was monitored with a 16 mm high-speed film at 500 frames per second. With the help of a mirror the motion behaviour in the sagittal plane as well as in the transversal plane could be detected. Small metal markers were attached to the functional spine unit with an acrylic glue. The motion picture made it possible to measure the displacements of different structures in the functional spine unit by tracing the location of the markers. With the help of geometric calculations, displacements in different directions could be determined with an accuracy of 2 mm.

By comparing the motion picture analysis with the force and moment values from the platform at different times, it is possible to see when and under which loads different structures have moved.

Experimental procedure

First, the functional spinal units were exposed to a physiological range of motions by applying different static loads in flexion, extension and lateral bending. The motion pattern at different loads and the horizontal and vertical displacements for each specimen were determined from the platform recordings and from the film analysis.

The specimens were then exposed to dynamic loads providing failure in the segments. With the help of weights different kinds of damage, e.g. fractures and disruption of ligaments, were generated (Figure 1).

The posttraumatic motion pattern of the segment was then investigated and compared with the previous results. The results were also compared with clinical observations from real world accidents. The posttraumatic instability was evaluated in terms of translation and angular displacement and assessed in relation to the stability necessary for intact nerve and functional spine unit function.

Finally pathoanatomical studies were performed on the damaged segments.

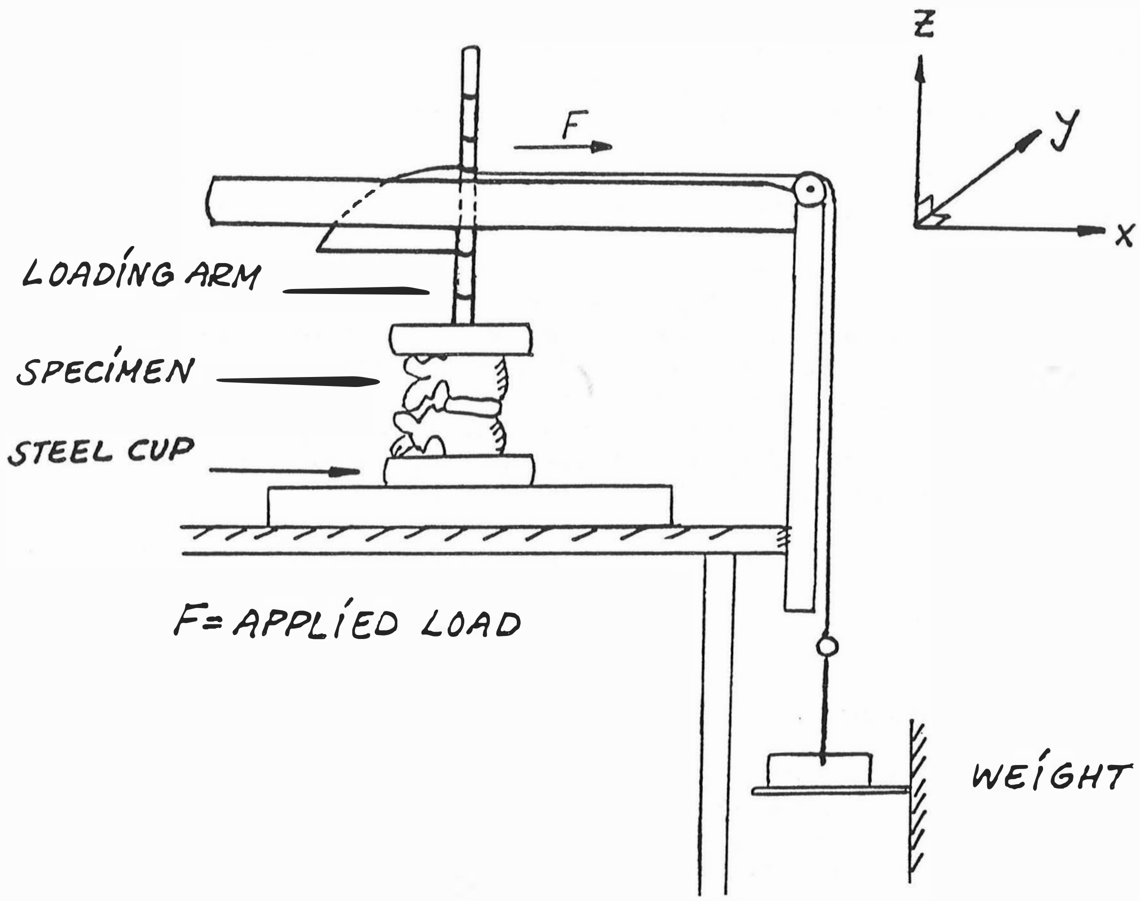

Figure 1 Experimental set up

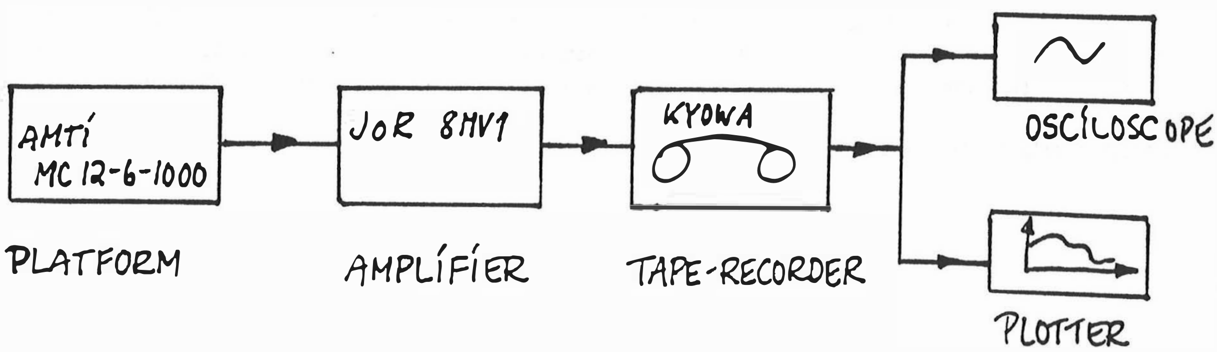

Figure 2 Measuring system

RESULTS

Static loads were applied in increments of 100 N for each specimen. After each loading step there was a four minutes waiting period to eliminate the creep effect in the ligaments. The static loads correspond to a bending moment in flexion, extension or lateral bending of 25, 50, 75, 100, 125, 150 and 175 Nm. Measurements were taken during the whole loading sequence.

Four functional spinal units from the lumbar region (age 20-50 years) have been studied so far. The physiologic range of motion in flexion was investigated for two functional spinal units. These segments were then exposed to dynamic loads in flexion of 125 Nm and 175 Nm respectively. The other two specimens were exposed to motions in extension and lateral bending.

For the specimens used in flexion the results show that they withstand a static physiological load of 175 Nm. Up to this load the bending moment and the shear force generated in the functional spinal unit showed no changes nor were there any discernible damage at the ligaments.

The results from the specimens exposed to static loads in extension and lateral bending show a maximum physiological load of about 80 Nm for extension and 125 Nm for lateral bending. If the bending moment was increased above these levels the loads produced damage to the posterior elements, e.g. fractures of processus spinalis.

Figure 3 shows the bending moment and the shear force generated in a functional lumbar spine unit exposed to a dynamic load in flexion. The load of 175 Nm was applied at a rather low velocity (1 m/s). After this, the posterior ligaments showed signs of damage. The posttraumatic motion pattern was then investigated and compared with the earlier tests. There was increased mobility in flexion after the loading sequence.

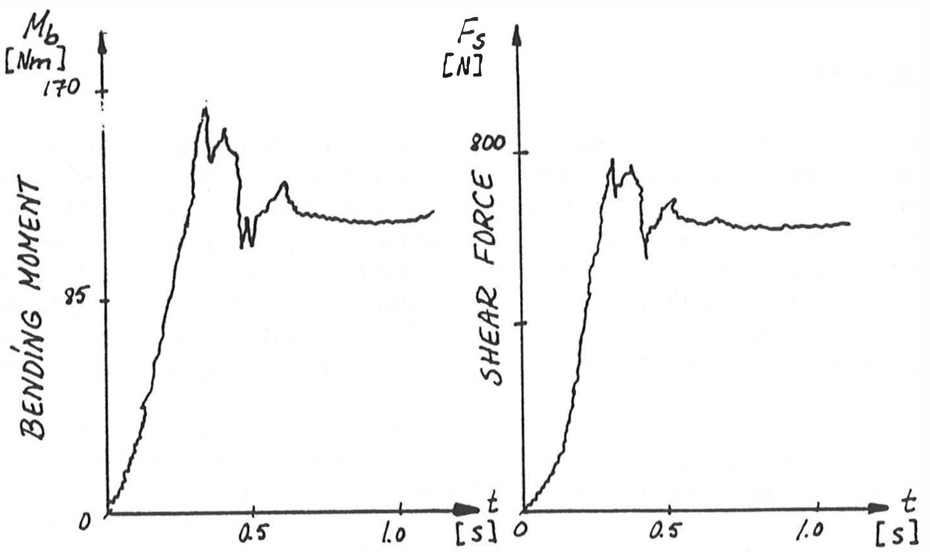

Figure 3 Bending moment and shear force generated in a functional lumbar spine unit exposed to a dynamic load of 175 Nm in flexion

Another functional lumbar spine unit was exposed to a dynamic load of 125 Nm (1 m/s) in flexion. This segment showed no damage and the physiologic range of motion was the same as before.

Figure 4 shows the bending moment for a specimen exposed to a dynamic load of 100 Nm in flexion. In the same figure the rotation around the z-axis is shown. The rotation in the functional spinal unit is very small compared with the bending moment. This demonstrates that there is nearly no rotation in the segment when it is exposed to small dynamic loads.

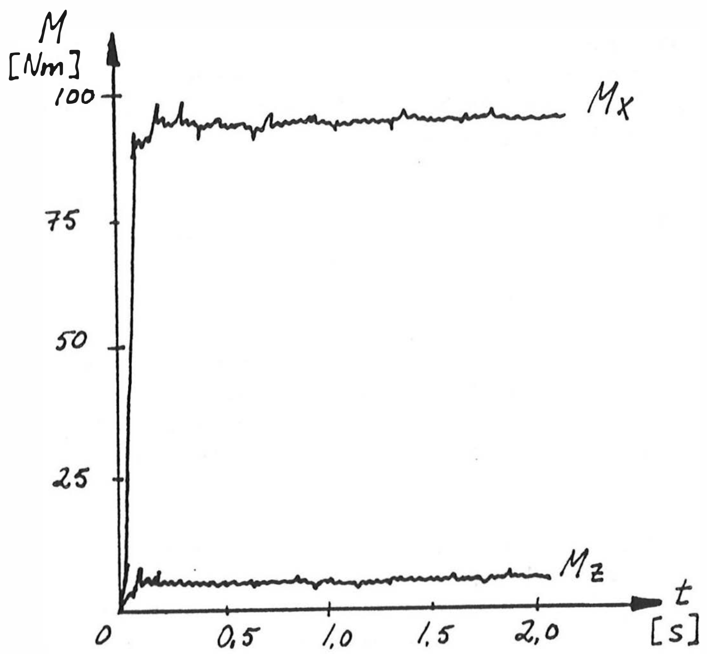

Figure 4 Bending moment and rotation in the same specimen at a dynamic load of 100 Nm

DISCUSSION

At the experimental procedure, it is important that the functional spinal units perform normal motions and not are forced to act in an unrealistic way. The loading arrangement must allow for complex freedom of motion of the upper vertebra with respect to the fixed vertebra below. Normally, spine motions occur in three dimensions, including flexion, extension, right and left lateral bending, rotation and translation. In the physiological range, pure loads in a certain direction never exists (Panjabi et al., 1976). Usually complex loadings, including axial compression, shear force and bending moment occur at the same time.

To provide pure bending moment in flexion, extension and lateral bending, the applied load must be perpendicular to the vertical axis of the segment during the whole loading sequence (Figure 1). When applying loads, it is also important to determine a defined point of application at the upper vertebra. Figure 4 shows that the rotation in the segment was very small when small bending moments were applied in flexion. The translation y-component was neglible. This tells us that the loading arrangements can provide pure loads in all directions tested.

At the casting procedure care was taken to have the lower steel cup and the midplane of the disc in parallel. With defined parallel planes a three-dimensional orthogonal coordinate system can be utilized when studying e.g. the motion pattern of the segments. A X-ray study was undertaken to investigate if the specimens were mounted correctly in the steel cups. The results showed that the mid-disc plane was parallel to the horizontal plane with a difference of a maximum of 3 degrees. This is in accordance with the results from Panjabi et al. (1977).

Different methods for applying static loads to a functional spinal unit have been described in the literature. Usually, forces are applied in incremental steps up to the maximum force with help of pulleys, strings and weights. Measurements (e.g. load as a function of displacement) are then performed after each step.

There are only a few studies reported for dynamic loading of segments e.g. Willén et al. (1984), where axial dynamic loading was used to produce crush fractures in the thoracolumbar region. In order to obtain dynamic loading, they used a metal drop weight with a mass of 10 kg, which was allowd to fall freely from a height of two meters.

Our results show that a dynamic load of 175 Nm (1 m/s) in flexion provides failure (e.g. disruption of ligaments) in the lumbar region, but the load is too small to cause fractures in the vertebrae. In further experiments the velocity will be increased to 5-8 m/s (18-30 km/h). This is more similar to those in the majority of rear-end car collisions.

Different mechanical load transducers and load cells for determination of static loads in one direction are utilized when studying the mechanical behaviour of the spine, e.g. Adams and Hutton (1981) and Lee and Landgrana (1984). The AMTI biomechanical platform used in our study, measure forces and moments generated in the functional spinal unit in three dimensions. The platform can be used to record high dynamic traumatic loads as well as physiological loads in the normal range of motion.

In our study high-speed photography has been used for studying the motion pattern in the sagittal- and transversal planes. This gives good information about the motion patterns but takes considerable time to evaluate the film in detail. In further experiments our intension is to use a computer based measurement system when analyzing the motion behaviour of the spine.

The development of methods for studying effects on the spine under different loads continues and further experimental studies are planned for the lumbar spine as well as for the cervical spine.

The results from these investigations will then be used for the development of a mechanical model of the cervical spine.

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