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Increase in facet joint loading after nucleotomy in the human lumbar spine

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ABSTRACT

Low-back pain has been related to degenerative changes after nucleotomy. Although several etiologies for pain after nucleotomy have been proposed, there is evidence of pain arising in the facet joints in general, which may be related to changes in load transfer. This study addresses the effect of nucleotomy on facet joint loading.

Nine human lumbar motion segments (age: 40–59 years) were loaded in axial compression and extension-flexion. Reaction forces were compared with soft tissue structures sequentially removed. After nucleotomy the facets supported significantly greater load, almost doubling from a median of 8.6% of the applied external force to 15.8%. Force transmission related to the capsular ligament increased significantly from an intact median of 1.2–5.1% after nucleotomy. No correlation was observed between force increase on the facets and the proportion of disc nucleus removed.

Even a small quantity of nucleus removal (range: 0.7–1.7 g) increased the forces transmitted over the facet joints, both with and without capsular ligaments. This suggests that the proportion of material removed might not be important clinically with regard to facet joint degeneration and pain.

1. Introduction

It was reported in 1998 that 66% of the population in Sweden between 35 and 45 years of age experienced spinal pain during their past year; 56% of these cases were reported to be low-back pain (LBP; Linton et al., 1998). According to a clinical study, the facet (apophyseal) joints are the suspected origin of LBP in 45% of cases (Manchikanti et al., 1999). Pain in the facet joints may arise by irritation of the capsular ligament (Ashton et al., 1992), subchondral bone and synovium (Jaumard et al., 2011), which are all richly innervated. Osteoarthritis of the facet joints might be assumed as a source of LBP, but no direct correlations between LBP and osteoarthritic facets could yet be demonstrated (Kalichman et al., 2008). On the other hand, overloading of healthy facet joints might cause pain in itself, due to increased mechanical loading of the innervated facet structures. In many cases painful facet joints can be related to degenerative changes of the intervertebral disc, which have reduced disc height due to poorer hydration and a more fibrotic structure of the nucleus pulposus (Gunzburg et al., 1992).

The load-bearing roles of the facet joints in compression (Adams and Hutton, 1980) and shear (Skrzypiec et al., 2013) have already been investigated. It was shown that the load-bearing role of the facet joints changes due to spinal degeneration (Adams and Hutton, 1980). It was demonstrated by finite element modelling that disc degeneration can increase the load transferred over the facet joints by up to 66% (Rohlmann et al., 2005). It has also been concluded that nucleotomy, which is a standard operation for nerve decompression due to disc herniation, changes the strains in the annulus fibrosus, which may lead to its degeneration (Meakin et al., 2001; O'Connell et al., 2011). A porcine in vivo investigation showed that partial nucleotomy leads to 32% of disc height loss at 24 weeks, which might increase the load on facet joints, similarly to the effect of disc degeneration (Omlor et al., 2009).

It appears that patients who have undergone nucleotomy have a particularly high susceptibility to both pain and osteoarthritis of the facet joints. In a radiographic study of patients at least 21 years post nucleotomy, about 89% were reported to have arthritis of the facet joints (Mariconda et al., 2010). The same proportion showed a loss of disc height. Degenerative changes were observed radiographically in 97% of patients who had reported pain within the previous 12 months, which was significantly higher than for patients presenting without pain.

In a clinical study it was found that, besides disc height loss, narrowing between articular facets occurred, after nucleotomy (Mochida et al., 1996). Increased stressing of the facet joints or of the capsular ligaments might be the origin of pain after

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nucleotomy. Using pressure sensors in vitro, average peak contact pressures over the facet joints were found to increase form 6.9 MPa to 8.2 MPa after removal of the nucleus (Dunlop et al., 1984). Older specimens with lower disc thicknesses transferred greater load over the tips of the facets directly to the lamina, or to the pars interarticularis (Dunlop et al., 1984). The method used is limited by the invasive nature of the measurements, including damage to the capsular ligaments, and disruption of the natural contact conditions of the facet joint by placing a pressure sensitive film between the articulating surfaces (Zhu et al., 2008).

The aim of this study was to determine whether forces acting over the lumbar facets and through the capsular ligaments are increased by nucleotomy, using a new approach that allows the non-destructive determination of facet joint load transfer.

2. Material and methods

2.1. Principle of testing

The force components acting on the facet joints parallel to the sagittal plane were derived for human spinal specimens before and after nucleotomy. This was achieved by recording the kinematics of each specimen under a particular loading regime (constrained to the sagittal plane), before and after nucleotomy. The recorded kinematics was then applied to the same specimens after particular force-transmitting structures of the specimen had been sequentially removed, until the facet joints alone remained. The loading in each consecutive measurement step was recorded and the differences in facet joint loads for the two distinct kinematics (without and with nucleotomy) were determined. A sequence of eight steps was performed for every single specimen.

2.2. Specimens

The in vitro experiment involved L3–L4 and L4–L5 segments, which are frequently treated by nucleotomy (Mariconda et al., 2010). After obtaining ethical consent, nine lumbar functional spinal units (seven L4–L5 and two L3–L4) were harvested from fresh frozen male human donors with a median age of 50 years (range: 40–59 years). The study was approved by the ethics committee of the Medical Association of Hamburg (number: PV3938). Computed Tomography (CT) scans of the specimens were examined for disc height (Huber et al., 2010), bony defects and pathological degenerations. Specimens were stored at −20 °C in double sealed polyethylene bags and thawed at 8 °C for 16 h before testing. Muscles were removed, taking care not to damage ligaments, facet capsules or the intervertebral disc. Screws were placed in the cranial endplate and facets of the upper vertebra and in the caudal endplate and facets of the lower vertebra, to increase embedding strength. After horizontal alignment of the intervertebral disc, the specimens were embedded in stiff resin (Ureol®, Rencast FC 53, Huntsman Advanced Materials GmbH, Basel, Switzerland). Specimens were kept moist throughout preparation and testing with 0.9% saline ringer solution.

2.3. Test rig

Specimens were tested in a servo-hydraulic test rig (MTS® Bionix 358.2, Eden Prairie, MN, USA) equipped with an additional superstructure (Fig. 1), enabling independent actuation of axial compression, extension–flexion and anterior–posterior shear. Displacement was applied and measured at the upper vertebra. The lower vertebra was mounted on a 6-component load cell (model GT-MKA6.3, Huppert GmbH, Herrenberg, Germany). The test rig was examined for accuracy and repeatability in combination with a similar test procedure (Ivicsics et al., 2013). Mean force repeatability errors were <5% and kinematic repeatability errors were <1%, in each direction (x, y, and z, Fig. 1) and between the steps used for evaluation (kinematic steps, Fig. 2). The mean displacement accuracy error was <3% in each direction. The mean load–cell force accuracy error was <5 N in each degree of freedom employed.

2.4. Test protocol

Specimens were loaded with 700 N constant axial compression, zero antero-posterior shear, and sinusoidal ±5° of extension–flexion, at a frequency of 0.2 Hz, for all loading steps. Zero degrees of extension–flexion were defined by the position of the unconstrained specimen. Pre-conditioning loading was applied for 2100 cycles, based on a preliminary study on similar porcine lumbar specimens, showing that at least 95% of specimen creep occurs during this period.

In step 1 (i_1, Fig. 2.) the kinematic was recorded as a combination of sagittal plane axial translation, extension–flexion angle and anterior–posterior translation during 25 flexion–extension cycles. This was repeated three times. The kinematic

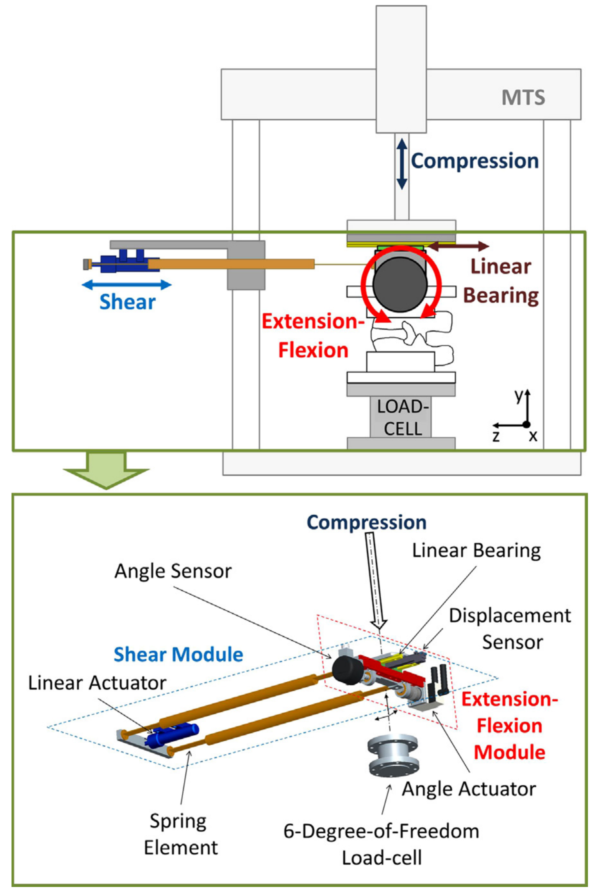

Fig. 1. Custom test rig providing shear (z) and rotation degrees of freedom (x) in the sagittal plane, mounted on a standard servo-hydraulic test machine providing axial compression (y).

recorded for the third repetition ('intact kinematics') was used as the input file for step 2 (MATLAB®, MathWork Inc., Natick MA, USA).

In step 2 ($i2$, Fig. 2.) three series of 'intact kinematics' were applied and loads recorded. For this and for all kinematic steps compression, shear and extension–flexion were actively controlled, simultaneously (Fig. 1). For the following steps, eight specimens were assigned to a main group subjected to nucleotomy, and one specimen (L4–L5) was left intact as a control. The control specimen was used to demonstrate that measured differences were due to nucleotomy and not due to other effects (for example repeated testing or creep). This has already been shown statistically in a similar porcine study (Ivicsics et al., 2013), so that a single specimen was considered sufficient as a demonstration in human specimens in the current study. Mentioned study showed, using the same apparatus with porcine specimens and a control group that measured force-increases in the nucleotomy group was indeed due to nucleotomy and not due to creep or other effects related to the test procedure. The nucleotomy was performed through a 6–8 mm wide, horizontal, right-posterolateral incision in the mid-plane of the intervertebral disc. Approximately 1 g of the nucleus pulposus was extracted by means of a rongeur, in accordance with surgical recommendations (Mochida et al., 1996).

The two groups were treated identically: all specimens were subjected to a second pre-conditioning event for 540 cycles with the same loads applied as those in the initial pre-conditioning stage. This step resulted in further creep of the disc after nucleotomy, since nucleotomy changes the load distribution in the disc (Meakin et al., 2001). The 540 cycles were applied to match the final rate of axial creep with that for the first pre-conditioning cycle, as measured in a previous study with the same apparatus (Ivicsics et al., 2013).

In step 3 ($n1$, Fig. 2.), step 1 was repeated and 'nucleotomy kinematics' recorded.

In step 4 ($n2$, Fig. 2.) recorded 'nucleotomy kinematics' from the third repetition of step 3 were applied three times and the forces measured, similarly to step 2 for the intact spine.

The disc was then completely removed, leaving only the facet joints and the capsular ligaments intact, allowing force transmission by these two structures alone. Cranial parts of the spinous process were removed using a Leur Rongeur on the lower vertebra, to prevent contact during the extension-flexion cycle.

In step 5 and step 6 ($i3$, $n3$, Fig. 2.) the resected specimens were again subjected to recorded 'intact kinematics' and 'nucleotomy kinematics', respectively, applied three times each, and forces were recorded.