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ORIGINAL ARTICLE

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Kinematic response of lumbar functional spinal units to axial torsion with and without superimposed compression and flexion/extension

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Dedication: The authors would like to dedicate this article to our co-author Dr. Tracy E. Orr. Tracy died unexpectedly in November 2002 from complications associated with childbirth. We are profoundly saddened by Tracy's death. She was an incomparable scientific collaborator and friend. She will be greatly missed.

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Abstract Experimental data suggest that lumbar torsion contributes to lumbar disc degenerative changes, such as instability, spondylolisthesis and spinal canal stenosis. However, some basic mechanical characteristics of the lumbar spine under torsional loading have not yet been reported in detail. For example, the function of the facet joints under combined mechanical loads such as torsion with superimposed flexion or extension postures is an area of interest about which little biomechanical data have been reported. In this study, the kinematic response to axial torsion with superimposed axial compression (200 N), compression-flexion (3 and 6 Nm) and compression-extension (3 and 6 Nm) was investigated in 10 cadaveric lumbar functional spinal units. Range of motion (ROM), and helical axes of motion (HAM), were analyzed. There was no difference in ROM between no preload, pure compressive and flexion-compression preload conditions. The ROM was significantly reduced by both extension-compression preload conditions (11% reduction for 3 Nm and 19% reduction for 6 Nm of extension) compared to the pure compressive preload. For no preload, the average HAM position in the transverse plane of the intervertebral disc was near the posteriormost part of the disc and located laterally on the side contralateral to the applied torsional moment. In the transverse plane, the HAM position showed a discrete trend towards the posterior part of the specimens during extension. Kinematic data were visualized using computer animation techniques and CT-based reconstructions of the respective specimens. This information may be used for identifying and characterizing physiologic and pathologic motion and for specifying conservative and surgical treatment concepts and, thus, may find application to identifying indications for spinal fusion or in evaluating the effect of future semi-flexible instrumentation.

Keywords Lumbar torsion · Kinematics · Facet joints · Biomechanics · Instability · Helical axis

Introduction

Disabling back pain is one of the most frequent reasons for patients to visit primary care physicians and the second most common cause of working disability [9, 11, 13, 16].

Three-dimensional kinematic information is necessary for the evaluation of the clinical significance of degenerative findings [3]. Common radiologic tools are unable to record multiplanar lumbar motion [39]. This has resulted in the lack of reliable radiologic instability criteria other than in the sagittal plane. Furthermore, clinically important information such as the non-sagittal segmental range of motion, the amount of coupled motion, and the kinematics of facet joints are usually not available in the clinical setting.

Lumbar torsion is often coupled to some degree of sagittal and/or frontal plane rotation [4, 24]. Torsion is of particular interest, since its role in lumbar pathology has

not been conclusively established. Krismer et. al. [19] have shown that fibers of the lumbar annulus fibrosus play an important role in resisting axial rotation. This suggests that torsion may bring forward the development of degenerative conditions involving the intervertebral disc such as instability, spondylolisthesis and stenosis. However, even under experimental conditions, lumbar torsional behavior is not yet conclusively elucidated [8, 10, 17, 18, 27, 30, 33, 36, 41]. In particular, there is little or no data available in which the mechanical role of the facet joints has been examined under combined axial torsion and flexion or extension moments.[31] The effect of some relevant anatomical structures and their variations on torsional spine kinematics remains somewhat controversial [1, 2, 15, 20, 23, 24, 26, 28, 35, 40]. This limited understanding has led to uncertainty in diagnosis and indication and hampers further development of therapeutic options.

Also, there is very limited information on the helical axis of motion (HAM) during torsion of the lumbar spine [29]. The HAM is also referred to as the "screw axis" and is widely used to describe biomechanical behavior. The HAM provides a three-dimensional description of the motion between two rigid bodies in terms of a translation along together with a rotation around a single axis (termed the helical axis of motion or the screw axis).

The goal of the present study was to determine the three-dimensional kinematic response of the lumbar functional spinal unit (FSU) to axial torsion under pure axial preload and combinations of compression-extension and compression-flexion. The obtained kinematic data were visualized using CT-based animations including depiction of the helical axis of motion (HAM) of the specimens in order to study certain features, such as the hidden clearance of opposed facet joint surfaces or the association of facet joint position and coupled motion over time.

Materials and methods

For the experiments 10 fresh human cadaveric lumbar specimens (levels L3–L5) with a mean age of 55 years (range of 28–69 years) were dissected so as to form functional spinal units (FSU), consisting of two vertebrae, their intact intervertebral disc and ligaments. Pre-test CT-scans were used to exclude pathological changes. All surrounding non-ligamentous soft tissue was removed. Four aluminum spheres (diameter 3.0 mm) were glued to each vertebra and used as fiducial markers [7]. The specimens were CT-scanned with a reconstructed slice thickness of 1 mm. They were then molded in polymethylmethacrylate (PMMA) blocks and mounted in a custom-designed testing machine, capable of applying pure, non-constraining axial torsion moments and various configurations of axial preload and sagittal plane moments [22] (Fig. 1).

The following loading protocols were performed:

1. Pure axial torsion with no preload
2. Axial torsion with a pure compressive preload of 200 N
3. Axial torsion with a combined flexion-compression preload (200 N and 3 or 6 Nm)
4. Axial torsion with an extension-compression preload (200 N and 3 or 6 Nm).

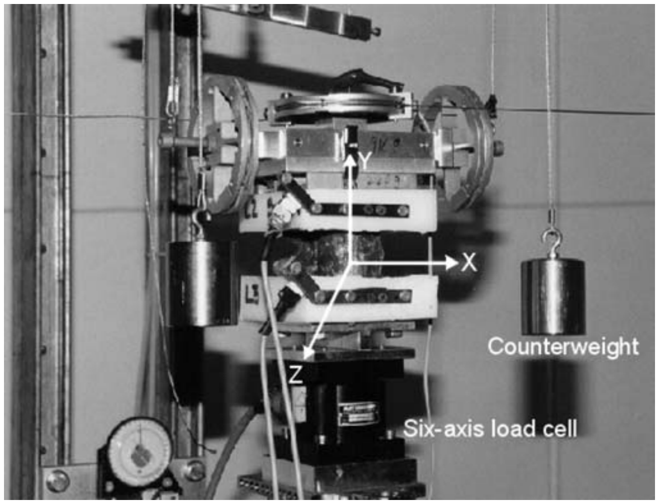


Fig. 1 Experimental setup. The co-ordinate system used during the analysis is indicated. The pulley mounted above the specimen was used to apply the axial torsion moments. The counterweights supported the weight of the testing apparatus that was mounted above the specimen. The 6-axis load cell mounted below the specimen was used to measure the applied flexion or extension moment and ensure that it was at the desired magnitude (3 or 6 Nm)

For each test, pure axial torsion of 12.5 Nm in 5 equal steps was applied to the FSU. Both right and left torsional moments were applied to the specimens. Each loading step was held constant for 30s to allow for dissipation of the viscoelastic behavior of the specimens. Each test was repeated for three identical load cycles with the first two cycles applied to precondition the specimen and the last cycle was taken as the measurement cycle. A 2 min interval was allowed between tests. The preload of 200 N was applied to the upper vertebra for load type 2 [6] (Fig. 2). For load types 3 and 4 the combined flexion-compression and extension-compression preloads were applied by the anterior (for flexion) or posterior (for extension) eccentric application of preload weights. A 6-axis load cell was used to limit the flexion or extension moment to 3 and 6 Nm. The three-dimensional motions of the superior vertebra with respect to the inferior vertebra were measured and recorded using a three-dimensional optoelectronic motion analysis system (Optotrak, Northern Digital, Waterloo, ON, Canada). For this purpose, infrared light emitting diodes (IRLED) were attached to each vertebra. The three-dimensional kinematics of the specimen were calculated as a range of motion (ROM) using the Euler Angles convention and the helical axis of motion (HAM) parameters were also calculated [18]. The ROM, HAM orientation and the HAM intersection on the superior endplate of the inferior vertebrae were calculated for each load type and at each of the 5 equal load steps between 0 and 12.5 Nm during the test. Differences among the specimens ROM and HAM intersections were analyzed using one-way repeated measure analysis of variance (ANOVA). Student-Neumann Keuls post-hoc tests were performed to determine differences between the groups with different load types. Custom software was used to transfer the obtained test data to a three-dimensional reconstruction of each specimen, based on pre-test CT scans to produce a post-test animation of each load regime [7].

Results

In general, the average total (left plus right) range of motion tended to decrease with the application of preload and

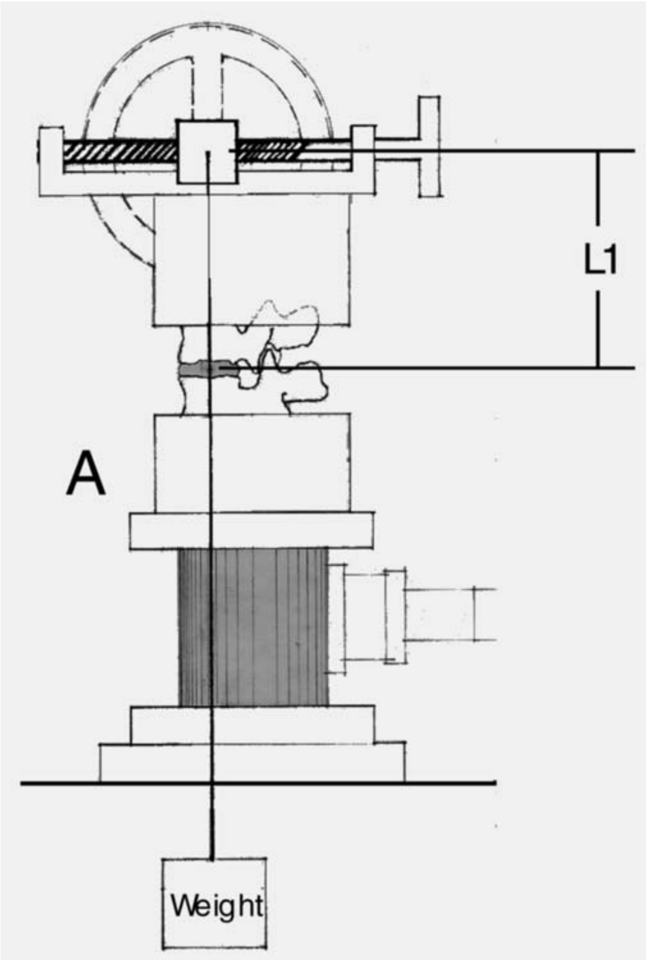


Fig. 2 Preload used. The 200 N preload was suspended from a point (a distance L1) above the intervertebral disc. The preload application point was adjustable in the anterior-posterior direction using the threaded connector shown. The preload application point was moved anteriorly to apply the (3 or 6 Nm) flexion moments and posterior to apply the (3 or 6 Nm) extension moments

with the application of flexion-compression compared to the no-preload load case (Fig. 3). Extension-compression loading resulted in a statistically significant decrease of 11% for 3 Nm ($P<0.002$) and an 18% decrease for 6 Nm ($P<0.0002$) compared with no preload (Fig. 3).

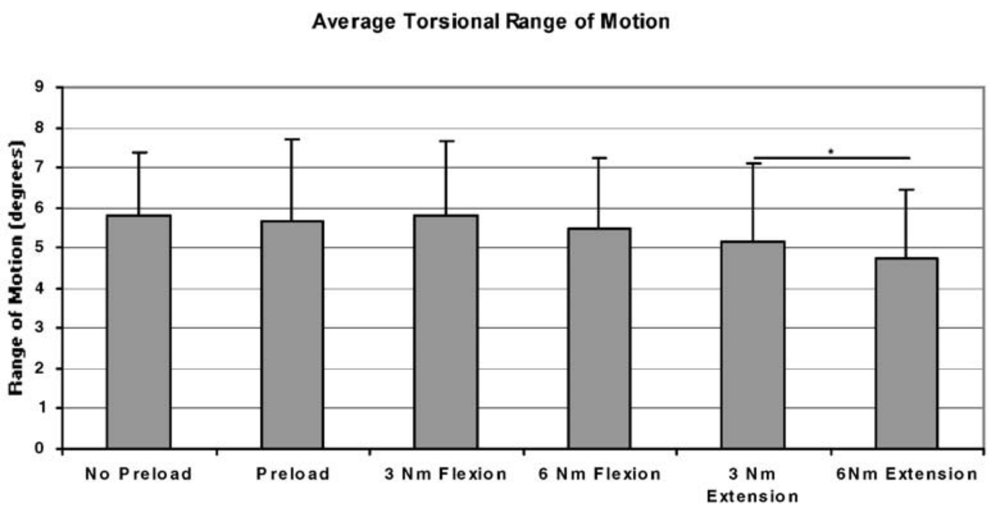
The average transverse plane HAM intersections at the superior endplate of the inferior vertebra are presented in Fig. 4. In general, the intersections are grouped within the posterior third of the vertebral body. A consistent but non-significant trend of posterior placement of the HAM intersection was observed for flexion-compression and extension-compression loading cases (ANOVA $P<0.06$). Loading direction significantly influenced the position of the HAM intersection (ANOVA $P<0.004$) in the lateral (x) direction. Left axial torsion resulted in HAM intersections on the right and right axial torsion resulted in HAM intersections on the left.

Animation results

A complete set of animations for six representative specimens is published on the World Wide Web at http://cranium.unibe.ch/lumbar_ham/. The animations of six randomly selected specimens were analyzed with respect to individual motion characteristics. Although the rotations were generally small the following observations were made.

In all loading and posture cases, the segment rotation prior to contact between the facet joint surfaces occurred around a HAM that passed through the intervertebral disc, was oriented approximately parallel to the cranial-caudal axis of the spine and was usually parallel to and close to the mid-sagittal plane (Fig. 5). During right axial torsion the left facet joints were pressed into contact while the right joints were distracted and vice versa. At contact between the facet joints, the superior facet generally moved slightly cranially on the inferior facet producing a small

Fig. 3 Average total (left plus right) torsion of all specimens after application of an axial moment of 12.5 Nm. * Indicates statistically significant difference ($P<0.05$)



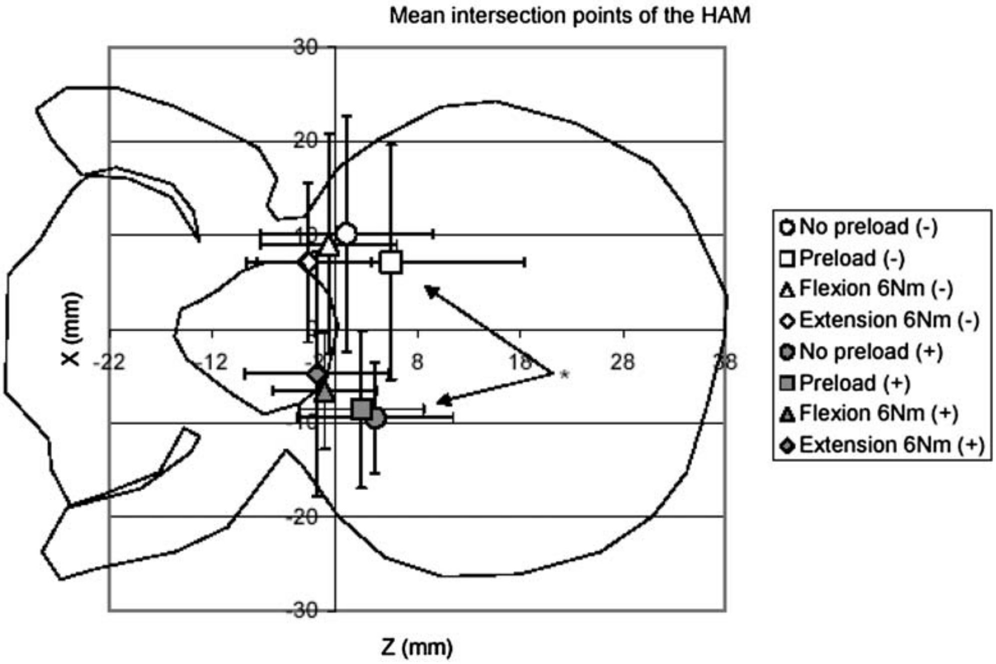


Fig. 4 Mean intersection points of the HAM at the superior endplate of the inferior vertebrae. Note: (+) represents an applied left axial torsion and (–) represents an applied right axial torsion. * Indicates that the lateral location of the intersection points were significantly different for left as compared to right axial torsion for all loading cases (P<0.006)

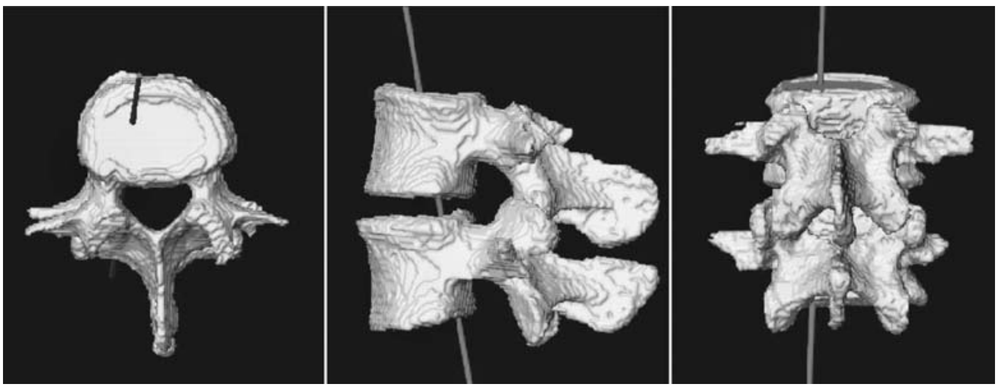


Fig. 5 HAM position and orientation during pre-facet contact left rotational motion from superior (*left*), lateral (*center*) and posterior (*right*)

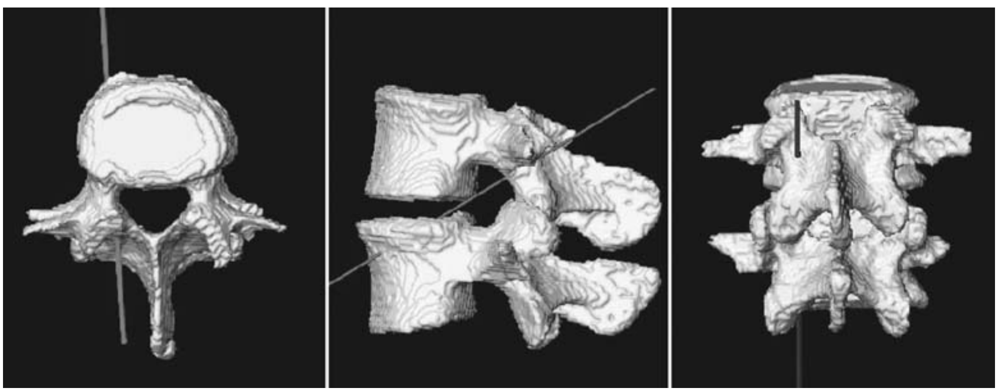


Fig. 6 HAM position and orientation during right axial rotation and after contact of the left facet joints from superior (*left*), lateral (*center*) and posterior (*right*)

coupled flexion motion of the cranial vertebra. In some cases, the sliding facet joint surfaces also caused lateral bending. At contact the HAM moved laterally, toward the facet joints that were in contact and changed direction in the frontal plane (Fig. 6). The post-facet joint contact motion of the HAM was highly variable in both direction and position but the HAM usually remained on the same side of the specimen as the facet in contact. Visually, contact between the facet joints appeared to act as a mechanical stop to the axial rotation.

Discussion

This investigation describes the kinematic behavior of the lumbar FSU subjected to axial torsion as a function of preload and different flexion-extension postures. In addition, the obtained kinematic response was visualized using CT-based animation. These animations allow intuitive and detailed study of the complex coupled motion of the FSU under axial torsion.

Our results indicate that variations in posture together with the application of axial compressive preload, significantly affect the range of motion of the lumbar spine under axial torsion. Significant but subtle differences of the average ROM of 2° or less were observed. These results are consistent with those of other investigators [4, 15, 21, 31, 32, 34]. The effects of variations in posture and application of axial compressive preload under axial torsion most likely occurred as a result of changes in loading and relative positioning at the facet joint surfaces. Compression of the FSU reduced the gap between the facet joints. This effect was further increased by the addition of an extension moment and the resulting extension posture. We believe this is the mechanism whereby the FSU torsional ROM is significantly reduced for compression-extension postures compared to other loading conditions. Schendel et. al. [35], using an in vitro experimental technique measured large loads on the facet joints during extension, torsion and lateral bending and no load under flexion, reflecting increased facet contact during extension and compressive preload and less contact during flexion, which is consistent with our findings.

Ahmed et. al. [2] did not find a significant correlation between the facet geometry and axial rotation. However, they did not address the relationship between facet geometry and coupled motion. Our animation results suggest that the range of motion for axial rotation is a function of the initial gap between the facet pairs. Upon contact between the facet joints the axial rotation effectively stops. The observed coupled flexion and lateral bending motions occurred after facet contact. Our animation results suggest that the facet joint surface geometry at the articulating surfaces dictated the coupled motions. Similar coupled motions have also been observed using three-dimensional finite element models [37, 38].

Previous investigations do not provide a consensus regarding the lumbar spine center of rotation (CR) or HAM location under torsional loading (the CR represents a two-dimensional analogue to the three dimensional HAM). Cossette et al. [5] reported the CR to be within the posteriormost aspect of the disc and to exhibit considerable inter-specimen and intra-specimen variation in its lateral location. Oxland et al. [29] reported the intersection of the HAM with the cranial endplate to be located at the posterior vertebral wall and somewhat left of the mid-sagittal plane for both left and right axial torsional loading. In contrast to these studies, Nägerl et al. [27] in their concept of a dimeric link chain, suggested that the instant CR may be positioned on a centrode far dorsal of the spinal canal. We found that the HAM intersection was located at the posterior wall of the vertebra. HAM intersection location exhibited considerable inter-specimen variability and on average it was located approximately at the posteriormost margin of the vertebral body and on the side contralateral to the direction of the applied torsion. The differences between our results and those reported previously may have arisen as a result of greater measurement resolution achieved in this study as a result of the high accuracy of the optoelectronic measurement system and/or as a result of differences in loading protocol. Furthermore, our analysis incorporated the full three-dimensional kinematics of the spine segments. In contrast, Cossette et al. [5] measured only two-dimensional spine motion and would thus have neglected coupled sagittal and frontal plane rotations.

The axis location exhibited a trend of increasing dorsal shift during compression-flexion and compression-extension. Laterally, the axis was located at approximately the facet joint contralateral to the applied moment (ie., at the left facet for right axial torsion). This was the case for all preload and posture conditions. Similar locations and behavior for the CR has been reported previously based on three-dimensional finite element models [38]. This is the first time this behavior has been demonstrated experimentally. It should be noted that the presented HAM intersection data represent the average location of the HAM for the entire axial rotation excursion. As such this incorporates both, the phase of motion that occurred prior to facet joint contact (primarily pure rotation about the disc) and also motion that occurred after facet joint contact (coupled rotations driven by the facet joint geometry). Therefore the dorsal shift of the HAM with increasing facet joint contact (as occurs during extension) probably resulted as a consequence of the greater time and compression of facet joint contact during flexion and extension postures.

In contrast to the HAM in the cervical spine which has been shown to have its cranialmost portion sloping towards the posterior [7] during axial torsion, the HAM in this study was variable but often oriented vertically or sloping anteriorly, especially prior to facet joint contact. This illustrates the difference in facet joint function in the two regions. In the cervical spine, the facet joints are oriented to guide the highly coupled motion at that level and they are oriented obliquely with respect to the cranial-caudal axis of the spine. In contrast, the results of the present study confirm that lumbar facet joints, consistent with their vertical orientation, provide a physical limit or stop to the axial rotation after a very modest amount of rotation illustrated by the small ranges of motion we observed.

As any other in vitro experimental biomechanical investigation this study has some limitations. The applied preload of 200 N represents a relatively minor load for the

lumbar spine compared to the loads believed to be present in vivo [25]. However, we selected this preload in order to maximize the range of motion available for characterization. We felt that larger compression loads would further decrease the already small ROMs and the differences between the varying load regimes. Limitations to this study also arose as a result of errors inherent to the CT data segmentation procedure and this data's subsequent registration with the kinematic data [7]. Another factor to consider is that because the reconstructed CT models were rigid, any elastic deformation of the facet joints, pedicles or other structures of the vertebra would not be represented in the animations. As a result of these effects, facet contact may have happened at a slightly different point in time than that indicated in the animations. The excellent concordance between facet contact and the corresponding abrupt stop of the main axial rotation and replacement with coupled lateral and flexion moments, suggests that the accuracy of the animations was more than sufficient for the qualtitative purposes for which there were used in this study. It should also be noted that the small coupled flexion moments that we observed during the tests would have resulted in corresponding changes in the applied flexion or extension moment.

Our approach concerning animations of the vertebral motion may be suited to extrapolate "typical" axes of motion from a larger number of specimens, which then could be used to animate reconstructed CT-data of patients, thus transforming them into a virtual kinematic investigation. In combination with new imaging tools like the Siemens Siremobil ISO-C 3D (http://energized.esiemenshealthcare.com/SIREMOBIL/) obtaining CT data from standing patients in a rotated position, the customized navigation software might be used to calculate the corresponding HAM.

Conclusions

The lumbar spine's torsion ROM was significantly reduced under extension postures compared to no-preload. Flexion postures and compression alone had no significant effect.

The HAM intersection was located at the side of the vertebral body contralateral to the applied preload and in the posteriormost third of the vertebral body.

Our results indicate that the torsional kinematic behavior of the lumbar FSU is significantly affected by changes in sagittal plane posture together with axial compression.

The visualization of the obtained kinematic response using CT-based animations, supports the assumption that the variation of the relative position of opposed joint surfaces represents the essential mechanism of the described kinematic changes. In particular, the reduction of the gap between the facet joints through compression and extension significantly reduces torsional ROM.

Furthermore, the transfer of individual motion patterns to a three-dimensional reconstruction of the same FSU offers the opportunity to create a database of motion patterns related to typical morphologic constellations. The derived information may be interesting for applications like virtual motion studies in patients suffering from degenerative spinal changes or the development of individual instrumentations for spinal fusion, permitting a defined range of motion.

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