INTRODUCTION

Each possible distribution of forces - for example that generated by an ensemble of muscles such as the autochthon musculature of the trunk - can be traced back to a corresponding force wrench. This comprises a pure force $F$ (with a specified spatial position for its line) and a torque $T$ which acts parallel to the force $F$. The regulation and impact of forces and reactions of single muscles on the control of movements has been the subject of numerous studies (1-4). Dumont et al. (5) have shown that the physiological functions of the human finger are determined by an interplay of diverse muscles with guidance provided by the joints. In the trunk, the axial force wrench of the autochthon musculature can be shifted in parallel whilst holding the amount of force $F$ constant by means of differing distributions of this parameter among the muscles, so that only the geometrical configuration of the wrench is altered. The goal of the study presented here was to measure the influence of geometrically varying configurations of axial wrench on the kinematics of lumbar motion segments under constant resulting axial force.

MATERIAL AND METHODS

Material

Preserved segments (three L1/L2, two L3/L4, three L4/L5: 59.8±16.6 yrs) were stabilized using a solution that hardly altered the hardness and shape of the osseous structures, so that each joint, whilst remaining harder than the intervertebral disc and the ligaments, could take over guidance of segment motion in the event of force closure (6). Abnormalities were excluded on the basis of CT scans.

Measuring methods

The segments were first subjected to a stationary axially directed preload $F_z$ (200N) in an unconstraining and non-reactive manner. The position of this $F_z$-line served as a geometrical parameter. The line and consequently the geometrical configuration of the wrench were set with an accuracy of ±0.5mm. The axially directed pure torque ($T_z(t)$) was applied parallel to and independent of the preload $F_z$. Torque $T_z(t)$ varied within a cyclic triangular time function (period: ≈1min) to stimulate the segments to undergo axial rotation. The segment kinematics were characterised by the moving instantaneous helical axis (IHA) and stiffness by the segment’s range of motion (ROM). In order to determine IHA migration in a valid way at least 400 subsequent positions of IHA were measured within a movement cycle with an unique, precision measuring, custom-made apparatus (7).
2. The path of IHA depended greatly on the position of the force line $F_z$.

3. The line of the migrating IHA was not accurately aligned parallel to the axial torque vector $T_z(t)$: IHA tilted laterally, to some extent, from the left/right to the right/left side with increasing axial rotation to the left/right. In addition, it was more or less constantly moderately inclined to the dorsal. But, these deviations were small.

$L1/L2$-segments

The intersections of the IHA with the x-y plane revealed wide IHA migrations whose paths represent the corresponding centrodes. At the largest rotated position of the upper vertebra to the right/left, IHA was found near the left/right joint (Fig. 1). From this right/left rotated segment position, IHA migrated along a wide ventral bow (length more than 40 mm) in axial rotation to the left/right, therefore these centrodes match up for both directions of rotation. Note: The major part of IHA migration was seen between -1° and +1°. An increase in the preload $F_z$ from 200 N to 400 N did not alter the shape of these centrodes, but ventral or dorsal shifting of the line of the preload $F_z$ (200 N) did (Fig. 1).

The ROM increased with a ventral or dorsal shifting of the $F_z$-line (Table 1).

$L3/L4$ segments

In both $L3/L4$ segments, the shape of the centrodes for axial rotation depended greatly on the position of the $F_z$-line. In the ventral position, the IHA of axial rotation migrated along wide ventral bows from one joint to the other and vice versa (Fig. 2). In dorsal positions, however, the axial IHA ran along a dorsal bow. In maximum rotation to the left/right, the IHA was located at the right/left joint. The lengths of the centrodes reached up to about 60 mm (ventral $F_z$-line) and 30 mm (dorsal $F_z$-line) in both segments. Note: the major part of the IHA migration was seen between -1° and +1°. Increasing the preload $F_z$ from 200 N to 400 N did not alter the shape of these centrodes.

$L4/L5$ segments

In the central position of the preload $F_z$, the application of the additional axial torque ($T_z(t)$) was followed by IHA migration within the spinal canal. The corresponding centrode was shaped like a loop. This special IHA migration was seen in all three segments. Again, the shapes of the centrodes depended greatly on the position of the preload $F_z$ (Fig. 3). Under the dorsally positioned $F_z$-line, the centrodes curled within the spinal canal. But, under a ventrally positioned $F_z$-line, the centrodes bulged to wide bow shapes. The length of the centrodes reached ≈40 mm altogether, but with the major part within the angular interval ±1°. In this case, the IHA was near the left/right joint in the most rotated position of the segment to the right/left.

Figs. 1–3: Axial rotation of individual lumbar motions segments: centrodes of IHA-migration following axially directed wrenches for dorsal (blue), central (red) and ventral (green) positions of the preload. Dots: positions of the preload in reference to the anatomical structures (blue: dorsal, red: central, green: ventral). Arrows: Direction of IHA-migration for rotation to the left from the largest rotated position of the upper vertebra to the right. Further details in the text.
Table 1. ROM following ±3250 Ncm amplitudes of axial torque (T).

<table>
<thead>
<tr>
<th>Segment</th>
<th>Position of the Fz-line (Fz = 200N)</th>
<th>Central</th>
<th>Ventral</th>
<th>Dorsal</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1/L2A</td>
<td>4.15°</td>
<td>4.97°</td>
<td>4.31°</td>
<td></td>
</tr>
<tr>
<td>L1/L2B</td>
<td>4.78°</td>
<td>5.20°</td>
<td>5.16°</td>
<td></td>
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<tr>
<td>L1/L2C</td>
<td>4.92°</td>
<td>5.66°</td>
<td>5.19°</td>
<td></td>
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</tbody>
</table>

Table 2. ROM following ±2500Ncm (L3/L4A) or ±1350Ncm (L3/L4B) respectively amplitudes of axial torque (T).

<table>
<thead>
<tr>
<th>Segment</th>
<th>Position of Fz-line (Fz = 200N)</th>
<th>Central</th>
<th>Ventral</th>
<th>Dorsal</th>
</tr>
</thead>
<tbody>
<tr>
<td>L3/L4A</td>
<td>6.30°</td>
<td>6.70°</td>
<td>5.50°</td>
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<tr>
<td>L3/L4B</td>
<td>7.55°</td>
<td>8.50°</td>
<td>6.70°</td>
<td></td>
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</tbody>
</table>

Table 3. ROM following ±3250Ncm amplitudes of axial torque (T).

<table>
<thead>
<tr>
<th>Segment</th>
<th>Position of Fz-line (Fz = 200N)</th>
<th>Central</th>
<th>Ventral</th>
<th>Dorsal</th>
</tr>
</thead>
<tbody>
<tr>
<td>L4/L5A</td>
<td>6.30°</td>
<td>6.70°</td>
<td>5.50°</td>
<td></td>
</tr>
<tr>
<td>L4/L5B</td>
<td>7.55°</td>
<td>8.50°</td>
<td>6.70°</td>
<td></td>
</tr>
<tr>
<td>L4/L5C</td>
<td>4.95°</td>
<td>5.80°</td>
<td>4.65°</td>
<td></td>
</tr>
</tbody>
</table>

DISCUSSION

A lot of investigations show comparison of geometrically varying configurations and force to anatomical structures (8-10).

Method

Up until now, there have been no high spatial resolution measurements of IHA migration for motion of spinal segments reported in the literature. The resolution of only 0.1 mm of the WinJaw/WinBiomechanics ultrasound motion analysis system was not sufficient in order to measure IHA migrations (11). The enhancement of the necessary resolution (0.5 μm) of the 6D-position measuring system used in this study enabled IHA migration to be observed experimentally for the first time (7).

Main findings

1. The shape of IHA-migration was structurally different between and structurally equal within the three types of segments. 2. In all segments, the maximum velocity of IHA migration was seen for the small angles of rotation (within the interval ±1°). 3. The kinematics of each segment type strongly depended on the geometrical configuration of the applied force system. 4. The same was true for the segment stiffness as indicated by reduced ROM. In the all segments under ventral positions of the Fz-line increased the ROM.

Conclusions

1. The wide IHA migration within an interval of ±1° of the angle of rotation suggests that the joint guidance predominates in segment kinematics. 2. Segment kinematics can be adjusted by the geometrical configuration of the acting parts of the muscular system. 3. The same was true for the ROM. This means that stiffness and the kinematics of axial rotation can be adjusted without changing the force of the muscular system. In particular, in relation to an enhancement of segment stiffness, an overall increase in muscular forces is not necessary. By altering the distributions of acting motor units, the stiffness and axial kinematics can be parametrically controlled. This control mechanism does not require an increased energy input. We suggest that this mechanism is made possible by a co-operation of the muscular system with the guidance of the vertebral joints. Therefore, the design of non-fusion spine implants (e.g. TDA, TFA, dynamic stabilization systems) has to consider joint guidance. FE calculations of segment motions should primarily take joint guidance and muscular forces distributions into account. The unknown curvature morphology of the articulating surfaces and the unknown alignment of the surfaces in the various lumbar segments must be clarified by using high-precision anatomical measurements.

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REFERENCES


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