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Clinical Biomechanics 19 (2004) 323–329

CLINICAL BIOMECHANICS

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The influence of slouching and lumbar support on iliolumbar ligaments, intervertebral discs and sacroiliac joints

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Received 12 December 2002; accepted 8 January 2004

Abstract

Objective. To investigate lumbopelvic kinematics when moving into a slouch.

Design. A biomechanical model was developed. Load tests in vitro verified the model.

Background. The precise mechanism causing disc herniation and back sprain is still debated. Most biomechanical studies have focused on lifting in a stooped posture. Previous studies address instability situations due to Euler buckling of the spine under axial load. However, no studies address lumbosacral, iliolumbar and sacroiliac kinematics in slouching, i.e. flexing the spine in situations with negligible compressive spinal load.

Methods. Modeling started with the click-clack movement, i.e. the transition from lumbar lordosis to lumbar kyphosis by the combination of backward rotation of the pelvis and ventral flexion of the spine. The flexed spine was compared with a crowbar which uses the iliolumbar ligaments as fulcrum and pivot. To analyse the click-clack movement in sitting, unembalmed erect human trunks were moved from a forward position to a backward position, recording angular changes between L5, sacrum and ilium.

Results. When moving the trunk stepwise backward with support at shoulder level, L5 showed forward rotation with respect to the sacrum, but rotation of the sacrum with respect to the iliac bones was reversed (i.e. counternutation). L5 showed displacement in ventral direction with respect to the ilium. Measurements were in agreement with prediction from the crowbar model of the spine.

Conclusions. Backward rotation of the pelvis combined with flexion of the spine, i.e. slouching, results in backward rotation of the sacrum with respect to the ilium, dorsal widening of the intervertebral disc L5–S1 and strain on the iliolumbar ligaments when protection from back muscles against lumbar flexion is absent. Lumbar backrest support almost eliminates lumbosacral and sacroiliac movement.

Relevance

Understanding why the iliolumbar ligaments are loaded in slouching contributes to the understanding of the biomechanics of low back pain in everyday situations with small or negligible compressive spinal load. The results recommend lumbar support: backrests with free shoulder space.

Keywords: Low back pain; Posture; Iliolumbar ligament; Sacroiliac joint; Sitting

1. Introduction

Biomechanical studies have addressed the loading of separate structures and are used to explain risk factors for low back pain (LBP) such as spinal form (hyperlordotic and hyperkyphotic), trunk posture (stooped and asymmetric), or conditions such as vibration and high, repetitive or unexpected level of load (Dolan and Adams, 2001; Kumar, 1994; Sims and Moorman, 1996). In addition to loading factors, many biological influences on LBP have been investigated, including muscle fatigue, disc degeneration due to age and malnutrition, as well as psychosocial factors such as work satisfaction and insurance benefits (Andersson, 1999).

Although much is known about risk-enhancing conditions, the precise mechanism causing disc herniation

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doi:10.1016/j.clinbiomech.2004.01.006

and back sprain is still debated. In the present study a theory is developed which suggests that back sprain and disc herniation can be caused by a prolonged or sudden lumbar flexion, even without an elevated axial load on the spine.

In contrast to established biomechanical research, our model does not relate to forward trunk inclination and spinal buckling instability. We incorporate the mechanics of the iliolumbar ligaments (IL) and the sacroiliac joints (SIJ) (Pool-Goudzwaard et al., 2001; Snijders, 2001; Snijders et al., 1998) which led us to a new, divergent approach.

Aim of this study is to present a plausible hypothesis about the high incidence of LBP at home (Valkenburg and Haanen, 1982), at school (Gunzburg et al., 1999) and at work (Andersson, 1999). Sitting slouched was selected for verification of the biomechanical model. We measured relative movements of L5 and pelvic bones when moving into a slouch in sitting with support at shoulder level, using human bodies prior to embalming in which rigor mortis had passed in order to exclude the possibility of muscular influence.

The biomechanical model is described in the following, with special attention for relaxed slouching in sitting and its effects on the IL.

2. Biomechanical model

Starting point is the (iliolumbar) click-clack movement (Snijders, 1972) (Fig. 1). This change of spinal form can be experienced when sitting upright on the edge of a straight chair. In the forward position of the upright trunk the centre of gravity of the upper body is in front of the ischial tuberosities, which goes together with lumbar lordosis. From this stable position, backward translation moves the centre of gravity over the ischial tuberosities into an unstable position. Further backward translation into a stable position results in backward tilt of the pelvis and (depending on the individual) more or less lumbar kyphosis. After bending into flexion the spine is stiffer beyond the end of the neutral zone, which justifies comparison with a bar. We propose that this bar can act as a crowbar when using the IL at both sides of L5 as fulcrum and pivot (see Fig. 2 and open circles in Fig. 3). These ligaments connect L5 with the cranial parts of the hip bones (Hanson and Sonesson, 1994).

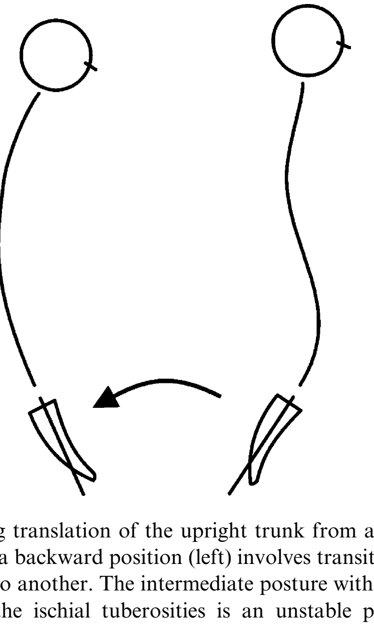

Fig. 1. In sitting translation of the upright trunk from a forward position (right) to a backward position (left) involves transition from one stable position to another. The intermediate posture with the centre of gravity above the ischial tuberosities is an unstable position. This transition from lumbar lordosis to lumbar kyphosis is called the lumbopelvic click-clack movement (Snijders, 1972).

2.1. Relaxed slouching

Of special interest is slouching with relaxed dorsal muscles in a chair with a high straight back (Fig. 3A). In this condition the spine assumes a convex curve, forming the long crowbar handle. The high back of the chair acts as the hand on the crowbar, forcing the L5 vertebra to rotate forwards around the IL, straining the IL and levering open the dorsal side of the intervertebral disc connecting L5 and sacrum.

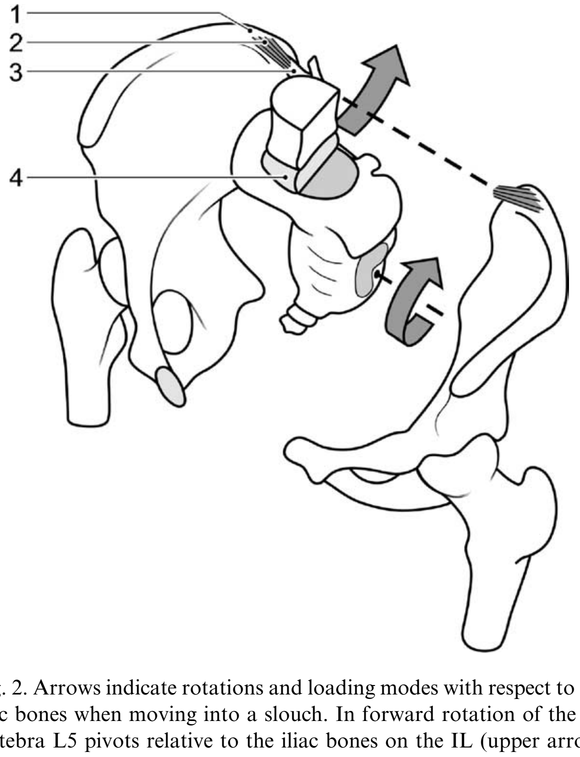

Fig. 2. Arrows indicate rotations and loading modes with respect to the iliac bones when moving into a slouch. In forward rotation of the L5 vertebra L5 pivots relative to the iliac bones on the IL (upper arrow) with backward rotation of the sacrum with respect to the iliac bones (counternutation, lower arrow) and dorsal widening of the L5–S1 disc. Upper body mass and scapular push load this mechanism when a chair does not provide free shoulder space. Upper part of iliac tuberosity (1), iliolumbar ligament (2), L5 transverse process (3), L5–S1 intervertebral disc (4).

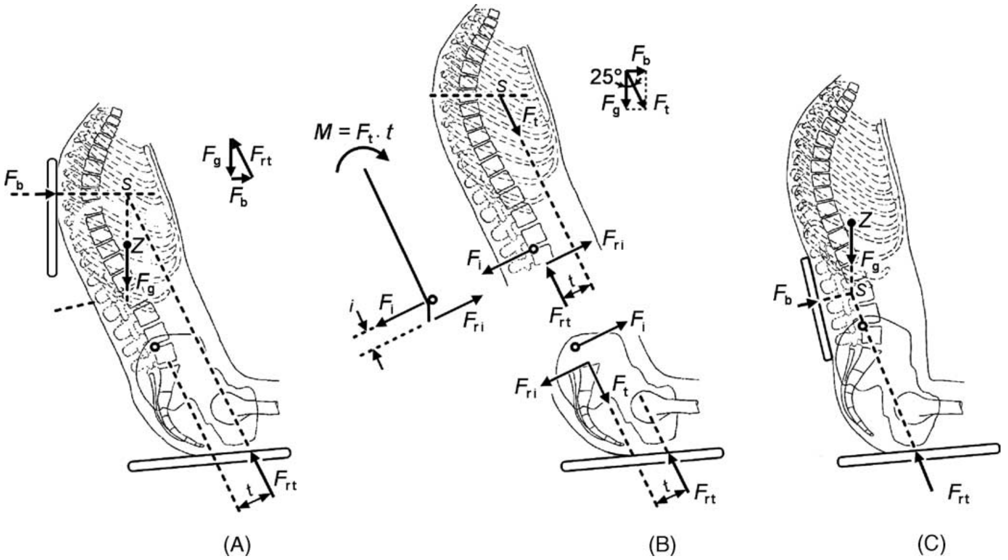

Fig. 3. (A) Sitting slouched against a high back rest forces the spine with a crowbar effect into a more or less convex curve, depending on the individual. Free body diagram of the part of the body without the legs and with all muscles relaxed. For static equilibrium: back rest force (F_b), weight force (F_g) and seat force (F_{rt}) intersect in one point (S) and form a closed triangle. Z is mass centre of gravity of upper body. (B) F_{rt} is the resultant support force acting on the ischial tuberosities, with lever arm t with respect to the centre of the L5–S1 disc. Equilibrium of pelvis: $F_{rt} \cdot t = F_{ri} \cdot i \cdot F_t = -F_{rt}$ is largely spinal compression. The distribution of mass across the body and other contributions to the bending moment are neglected. Equilibrium of body part above the L5–S1 level: $F_t \cdot t = F_i \cdot i$, which means force magnification because t is larger than i in this situation. (C) Figure taken from an X-ray picture (male, age 25 years) sitting with lumbar support. Lever arm t with respect to the L5–S1 disc is eliminated because intersection point S is positioned more caudally.

Because the upper body weight is dorsal to the ischial tuberosities, the force on the IL (F_i) does not cause the hip bones to tilt forward (Fig. 3B). A lower backrest (level of (F_b) in Fig. 3C) eliminates the crowbar effect by lowering the intersection point S of backrest force and weight force. The resultant force (F_t) (Fig. 3A and B) of back rest force (F_b) and upper body weight (F_g) runs in longitudinal direction of the trunk. F_t produces relatively small spinal compression, but loads the crowbar in bending because of the lever arm t. According to the geometry in Fig. 3A and B and neglecting the distribution of mass across the body, resulting in sub-mass centres of gravity, this bending moment $M = F_t \cdot t$ could be in the order of magnitude of 30 N m at the L5 level (see data in following paragraph). When L5 was loaded in ventral flexion with 10 N m Paul (1989) and Müller-Gerbl et al. (1988) measured strain in the posterior band of the IL of about 5% (SD 4.6%) as an average (6 fresh specimens of L4, L5 and pelvis with intact ligaments, average age 45 (SD 13) years). However, the change of angles between L5 and sacrum and between sacrum and ilium was not measured.

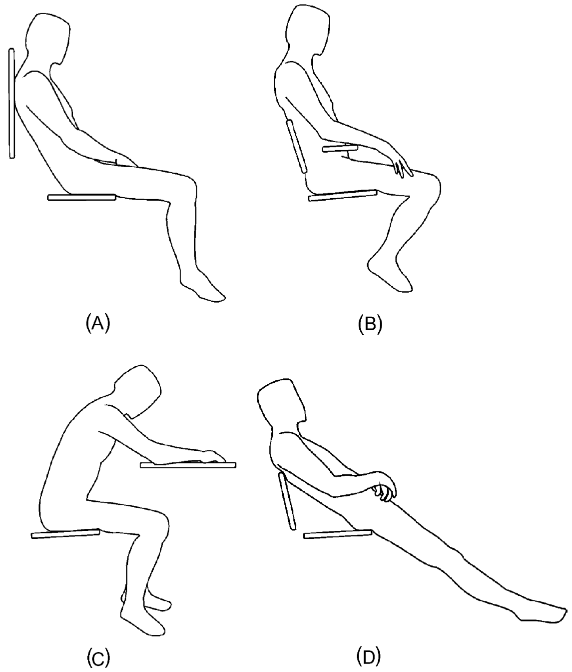

Fig. 4. (A) The model predicts risk of IL strain in sitting when two conditions are fulfilled: Loss of lumbar lordosis and upper body weight positioned behind the ischial tuberosities. (B–D) Only one condition is fulfilled: no excessive IL strain.

From our model Fig. 4 can be derived. Risk of IL strain occurs when two conditions are fulfilled. Firstly: the lumbar spine is an anteriorly convex curve with relaxed dorsal muscles (moment $M = F_t \cdot t$ flexes the lumbar spine). Secondly: upper body weight is positioned behind the ischial tuberosities (pelvis tends to rotate backwards by the moment $M = F_{rt}.t$). Fig. 4A and B refer to Fig. 3A and C. Fig. 4C shows lumbar kyphosis, but the upper body weight is in front of the ischial tuberosities which promotes forward rotation of the pelvis rather than resisting IL pull at the level of the cristae (see equilibrium of the pelvis in Fig. 3B). Lumbar kyphosis is absent in Fig. 4D because, as compared to Fig. 3A, the backrest force is more vertical and the seat force (F_{rt}) acts more dorsally. This results in a smaller lever arm (t) with respect to the centre of L5–S1. Furthermore head and shoulder balance weight of the thorax and the hips are in extension.

2.2. Strain on the iliolumbar ligaments

To assess strain on the IL, we consider as a first approach the situation without a significant bending moment from the L5–S1 disc. This (extreme) situation can be expected after sustained strain on the fascia and ligaments at the dorsal side of the spine, causing elongation of soft tissue by creep (Adams and Dolan, 1996; Fujiwara et al., 2000; McGill and Brown, 1992; Solomonow et al., 1999). Then a force (F_i) might be applied at the L5–S1 level and on the IL of 1200 N. This follows from $F_i \cdot i = F_t \cdot t$ with $F_t = F_g/\cos 25° = 500/0.9 = 555$ N (Fig. 3B, upper). The value of F_g is taken from literature (Snijders, 2001) for an average male. The lever arm (t) of the resultant force acting on the trunk (F_t) to the middle of the L5–S1 disc is taken $t = 5.5$ cm. The value of t is taken as a proportion in Fig. 3A from the distance of 10.5 cm between the middle of the disc L5–S1 and the middle of the rectus abdominis muscles running between sternum and os pubis. This value is taken from McGill et al. (1988). The distance (i) between the transverse process of L5 (attachment of the IL) and the middle of the L5–S1 disc is taken $i = 2.5$ cm.

If the force of 1200 N is divided over two IL, and taking into account an angle of 20° between IL and coronal plane (Fujiwara et al., 2000; Paul, 1989), this would result in $600 : \sin 20° = 1750$ N tensile force. A cross-section of about 50 mm^2 of the ventral and dorsal parts of the ligament (Hanson and Sonesson, 1994) would result in 35 MPa tensile stress. This is near the tensile strength of the anterior longitudinal ligament at the L4–L5 level (36.9 MPa), the anterior cruciate ligament (45.7 (SD 19.5) MPa) and the coracoacromial ligament (46.9 (SD 30.7) MPa) (Abé et al., 1996). For the IL no data on tensile strength could be found.

Although not verified by experiments, these rough calculations on an extreme condition provide a plausible explanation for the occurrence of considerable strain and possibly microtrauma in the IL. The crowbar model is used to facilitate understanding of the role of the IL. We emphasise, however, that the spine forms a continuum with the sacrum; this is where the comparison with a crowbar falls short.

According to Hanson and Sonesson (1994) the length of the posterior band of the IL is 10–12 mm. An IL with a length of 11 mm would elongate 0.55 mm. This value is taken from Paul (1989) and Müller-Gerbl et al. (1988) who found 5% (SD 4.6%, $n = 12$ IL) strain at 10 N m bending moment on L5. Taking into account an angle of 20° between IL and coronal plane (Fujiwara et al., 2000; Paul, 1989) would result in $\Delta d = 1.4$ mm displacement of L5 in ventral direction with respect to the ilium. This value follows from $\Delta d = \sqrt{[(l + \Delta l)^2 - (l \cdot \cos 20°)^2]} - l \cdot \sin 20°$ with $l =$ hypotenuse (representing the IL), $d =$ sagittal side and $a = l \cdot \cos 20° =$ coronal side of the triangle in the transverse plane. The coronal side is taken as a constant. The larger moment of 30 N m about the L5–S1 level in the model (Fig. 3A) would possibly result in $3.\ 1.4 = 4.2$ mm, ignoring non-linearity. We emphasize that this calculation can only serve as an indication of the order of magnitude because it follows from schematization of geometry and assumptions. For example: according to the 3-D MRI study by Hartford et al. (2000) large variations in size and direction of the IL exist.

Mutatis mutandis, the above approach can be followed when the IL is present at the level of L4. However, occasionally weak attachments occur at the L4 transverse process (Hartford et al., 2000; Pool-Goudzwaard et al., 2001), or no ligament may be attached at all (Hanson and Sonesson, 1994; Yamamoto et al., 1990).

Further study is required to determine the distribution of load between the IL, the intervertebral disc and the dorsal fascia and ligaments at the L5–S1 level. Other issues are SIJ laxity and asymmetry.

Relevant for the biomechanical model are e.g. abrupt backward tilt of the hip bones, when moving into a slouch, squatting, abrupt lifting of one leg and pulling an unexpected load. However, the effects of these dynamic loading modes are not measured in the present study.

2.3. Hypothesis

The biomechanical model leads to the following hypothesis: when the L5 vertebra as part of the crowbar rotates forward with respect to the sacrum, the sacrum rotates backward with respect to the ilium. To verify this hypothesis we measured relative rotations between L5, sacrum and ilium in a test related to sitting in which the lumbopelvic click-clack movement (Snijders, 2001) is performed stepwise (see Fig. 1).

According to literature (Müller-Gerbl et al., 1988; Paul, 1989; Yamamoto et al., 1990) forward flexion of L5 causes IL elongation. Therefore we expect displacement of L5 in ventral direction with respect to the ilium.

3. Methods

The click-clack movement was induced in 3 male and 3 female human bodies (age range 51–99 years), admitted for embalming at the department of Neurosciences. The experiments were performed prior to embalming since a pilot study showed that embalmed specimens were too stiff for this experiment.

The bodies were positioned on a specially designed apparatus which allowed for controlled postural change while seated (Fig. 5). One forward-backward translation was performed with shoulder support only, and one with shoulder support combined with lumbar support. The shoulder support supplies only a more or less horizontal force on the body, as vertical translation is left free by the construction. Head, torso and lower legs were stabilised with straps. In the sagittal plane needles (1.5 mm diameter) were inserted into the ilia (the posterior superior iliac spines), sacrum (the median sacral crest of S1, so more cranial than drawn in Fig. 5) and L5 (the spinous process). In the first body the needle at L5 was not included. The backward translation of the upper body was accomplished using a spindle, moving the shoulder rest in steps of 1 cm. After each step, photographs were taken from the side view using two cameras, one registering the entire body and the other the needles in detail. A third camera registered the top view of the trunk to check whether the pelvis showed torsion; this would influence the accuracy of the photographs taken from the side view. Due to the restricted experimental conditions of this test, we did not use markers on the needles for videorecording of movement.

From the photographs the following parameters were measured: (1) the horizontal position of the estimated mass centre of gravity of the trunk in relation to the ischial tuberosities; (2) angular changes between the respective needles in the sagittal plane (i.e. the angle between L5 and sacrum and sacrum and ilium); and (3) the displacement of L5 with respect to the ilium in posterior–anterior direction as an indication of IL elongation. For the position of L5 the top of the needle in L5 (located at the level of the IL) was used.

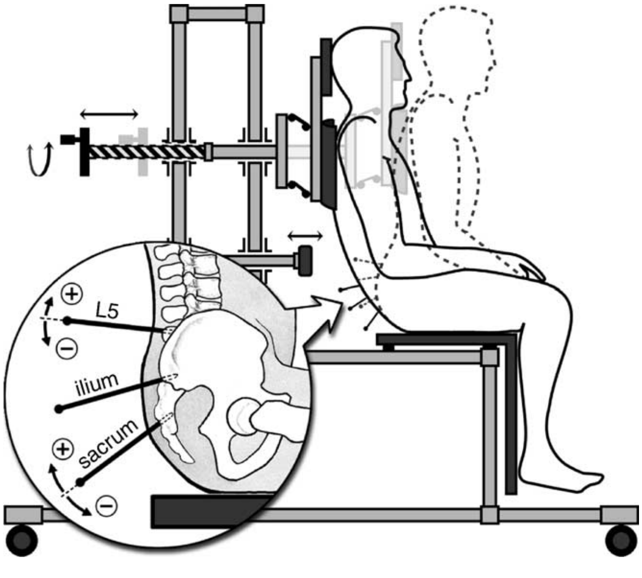

Fig. 5. Simulation of the click-clack movement (see Fig. 1) through backward movement of the upright upper body, with and without lumbar support. Pins in L5, sacrum and ilium are used to measure relative movement.

Angles and translations were measured (all photographs by four persons) on a drawing-table, with an accuracy of 0.25° and 0.33 mm, respectively.

This study was approved by the medical ethical committee of the Erasmus MC, University Medical Center Rotterdam.

4. Results

All unembalmed bodies showed an identical pattern of relative motions between L5, sacrum and ilium, although absolute values were different. For stepwise backward motion of the erect trunk, Fig. 6 shows for the more backward positions a more negative angle between sacrum and iliac bones, implying backward rotation of the sacrum with respect to the iliac bones. Fig. 6 shows furthermore for these backward positions a more positive angle between L5 and sacrum, so dorsal widening of

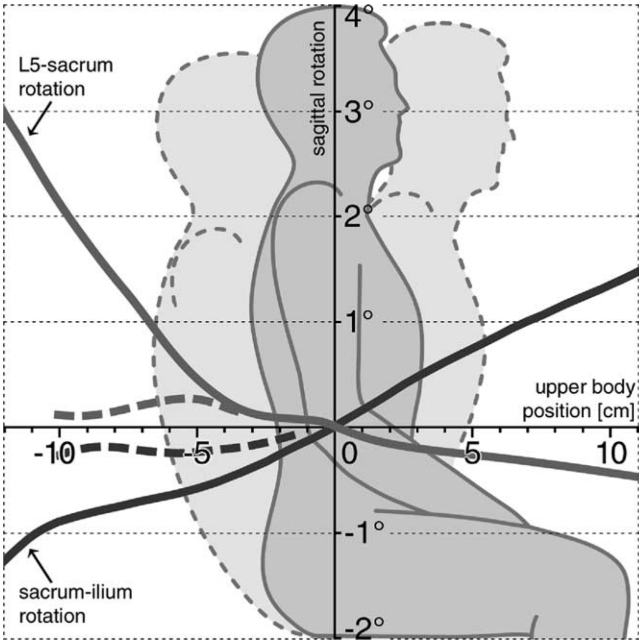

Fig. 6. Stepwise backward movement of the upright upper body progressively widens the L5-sacrum angle dorsally (grey line), while the sacrum rotates backward with respect to the iliac bones (counternutation, black line). Adding lumbar support (dotted lines) practically eliminates these rotations. Horizontal axis: estimated horizontal position of centre of gravity of upper body in cm with respect to the ischial tuberosities. Vertical axis: average values of relative rotations of L5, sacrum and ilium in the sagittal plane of all specimens ($n = 6$) in degrees. SD values at −10, 0 and +10 are without lumbar support, respectively, 0.5°, 0° and 1.44° for sacrum–ilium, 0.95°, 0° and 0.60° for L5-sacrum. At −10 with lumbar support SD values are, respectively, 0.57° and 0.91°.

the L5-sacrum angle. The forward rotation of L5 with respect to the iliac bones in the more backward positions can also be derived from Fig. 6 by subtraction of the sacrum–ilium rotation from the L5-sacrum rotation. A lumbar support applied at the level of L5 practically eliminated relative motion between L5, sacrum and ilium in the backward positions and prevented dorsal widening of the L5-sacrum angle.

One subject, aged 99 years, showed a deviating L5-sacrum angular change, but only in the forward positions of the trunk. In this subject the forward rotation of the ilium with respect to the horizontal was about 50% smaller than in the other subjects, and the knees were difficult to bend, possibly due to rigor mortis. Leaving out this subject would result in steeper curves in the forward positions.

During the tests no rotation of the pelvis in the horizontal plane was observed (no torsion).

Total displacement of the needle in L5 with respect to the ilium, was 1.21 (SD 0.67) mm in the ventral direction. This value is substantially smaller than the estimated value obtained from the model calculation using data from literature and Fig. 3A, but is in the same order of magnitude.

5. Discussion

This study showed typical kinematics of joints in the lumbopelvic junction when moving into a slouch. Stepwise backward movement of the erect trunk resulted in forward rotation of L5 with respect to the sacrum and backward rotation of the sacrum with respect to the ilium. The rotation in the SIJ (see Fig. 6) was in agreement with the physiological range of motion (≈3.5°) (Sturesson et al., 1989). We also found ventral displacement of L5 with respect to the ilium which indicates elongation of the IL. Elongation of IL due to forward rotation of L5 has been reported in literature (Paul, 1989; Müller-Gerbl et al., 1988). We found smaller rotation at the L5–S1 disc and, via model calculation, smaller IL elongation as compared to literature (Paul, 1989; Müller-Gerbl et al., 1988). This may among others be ascribed to our test on intact bodies instead of specimens caudal to the L3–L4 disc as used in the literature.

For explanation of the loading mode in slouching we compared the spine with a crowbar, using the IL as fulcrum and pivot. This comparison illustrates the kinematics as well as the expected force magnification. Characteristic for the crowbar model is forward flexion of the spine combined with backward tilt of the sacrum relative to the pelvis. This loading mode is maximal when back muscle protection against flexion is absent, e.g. in relaxed slouched sitting. In this respect model calculations resulted in IL stress near failure load. Here, resistance against flexion from other structures than the IL was neglected. Further studies are needed to assess IL stress in vivo, particularly after prolonged sitting in flexion which causes elongation and weakening of soft tissue structures at the dorsal side of the spine (Adams and Dolan, 1996; Fujiwara et al., 2000; McGill and Brown, 1992).

Stress of the IL is of interest because of the surmised role of the IL in LBP (Gunzburg et al., 1999; Paul, 1989; Sims and Moorman, 1996). Stress at the ligamento-osseous junction of the IL at the ilium, and stress in the innervated IL, can trigger pain, although the duration and level of stress and strain required for pain initiation are not known. This is the premise behind local injections of anesthetics (Sims and Moorman, 1996).

Measurements in the present study demonstrated a significant reduction of movement between L5 and sacrum as well as between sacrum and ilium using a lumbar support. This is in agreement with the study by Andersson et al. (1979) on lumbar lordosis. In a previous study we showed that use of a chair with a high backrest easily overrules lumbar support due to force exerted on the scapulae; we determined that at least 6 cm free shoulder space (6 cm behind the tangent to the lumbar support) is a minimal requirement (Snijders et al., 1999). Because the ribcage is stiff, back support is not required above the level just below the scapulae. Still a popular misconception is that high backrests provide superior support for seated activities, for example in the office, lecture hall or at the dinner table (Goossens et al., 2000; Snijders, 2001; Snijders et al., 1999).

Acknowledgements

The authors would like to thank M. de Groot, W.H. Groeneveld, M.A. van Veelen, F.C. Velkers and E. Vlaanderen for their valuable contributions. Financial support was given by the Anna Foundation.

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