Aus dem Julius Wolff Institut
der Medizinischen Fakultät Charité – Universitätsmedizin Berlin

DISSERTATION

Shape and function of the lumbar spine and the pelvis in the laboratory, in daily life and in the workplace

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Abstrakt (German)

Einleitung

Die Ursachen für die Entstehung von Rückenschmerzen sind multifaktoriell und reichen von genetischer Disposition bis zu psychosozialen Problemen. Aber auch anatomische und mechanische Einflussfaktoren wie die individuelle Form und Beweglichkeit der Lendenwirbelsäule und das Zusammenspiel mit dem Becken, sowie Bewegungsarmut im Alltag oder physische Belastungen am Arbeitsplatz werden immer wieder mit der Entstehung von Rückenschmerzen in Verbindung gebracht. Ziel meiner Dissertation war es, anhand von vier Studien in verschiedenen Settings, Information über diese Faktoren an rückenschmerzfreien Probanden zu gewinnen und den Effekt von moderierenden Variablen wie Alter und Geschlecht zu untersuchen. Diese Untersuchungen und Ergebnisse sind notwendig für ein besseres Verständnis der Entstehung von degenerativen Wirbelsäulenerkrankungen, die klinische Planung von Wirbelsäulen-OP-Verfahren, die Gestaltung alters- und geschlechtsspezifischer Rückenschmerz-Therapieverfahren, die biomechanische Testung und das Design von Implantaten sowie für die Optimierung von Präventionsverfahren am Arbeitsplatz.

Methodik

Mithilfe eines nicht-invasiven Messgeräts wurden Form und Funktion der Lendenwirbelsäule und des Beckens sowie deren Zusammenspiel in einer standardisierten Bewegungschoreographie unter Laborbedingungen untersucht. Die Form der Wirbelsäule sowie die Anzahl an Bewegungen wurden ebenfalls im Alltag über 24 Stunden bestimmt. Ferner wurde der Einfluss von Alter und Geschlecht analysiert. Am Beispiel eines Computerarbeitsplatzes wurde zusätzlich ein bewegungsarmer Teil des Alltags untersucht und die Wirbelsäulenform und Beckenorientierung sowie die Wirbelsäulenbewegung auf verschiedenen Sitzmöbeln evaluiert.

Ergebnisse

Sowohl die Lendenlordose (Unterschied von 7,4° zwischen ältester und jüngster Kohorte) als auch deren Beweglichkeit in Flexion (6,2° Unterschied) nimmt mit dem Alter ab. Ebenfalls verändert sich mit dem Alter signifikant die Beckenorientierung im Stand (Abnahme des Beckenwinkels: 6,6°) sowie das Verhältnis zwischen Wirbelsäule und Becken während der Bewegung (Lumbopelvic (L/P) Ratio Abnahme: 0,15), welches auch geschlechtsspezifische Unterschiede (L/P Ratio Frauen: 0,68, Männer: 0,81) zeigt. Alters- und geschlechtsdifferenziert wurden erstmalig

Wirbelsäulenbewegungen im Alltag erfasst (Median von 4400 Bewegungen insgesamt) wobei sich Frauen deutlich mehr (29%) bewegten als Männer. Am Arbeitsplatz konnte gezeigt werden, dass verschiedene aktive Sitzmöbel, entgegen der Erwartung, die Lendenlordose nicht beeinflussen, langfristig keine Bewegungssteigerung erzielen, jedoch zu einer Veränderung in der Beckenkippung führen.

Schlussfolgerung

Rückenschmerz-Einflussfaktoren müssen zunächst alters- und geschlechtsdifferenziert betrachtet werden um Unterschiede zwischen asymptomatischen und pathologischen Bewegungsmustern ausfindig zu machen. Eine Abnahme der Lordose sowie des Bewegungsumfangs und eine Veränderung im Bewegungsmuster bei der Vorwärtsbeuge treten bei asymptomatischen Probanden auf und sind Teil des natürlichen Alterungsprozesses. Diese Alterungseffekte sowie die deutliche Abweichung der durchschnittlichen Wirbelsäule im Alltag von der klinischen Referenzmessung blieben bisher in OP-Planungen und Rückenschmerz-Therapien meist unberücksichtigt, können jedoch deutlichen Einfluss auf die Erfolgsquoten haben. Implantat-Hersteller können mit der erstmals gewonnenen Angabe über die Anzahl der Wirbelsäulenbewegungen im Alltag das Design und die Dauerfestigkeit ihrer Implantate optimieren. Bezüglich der Prävention von Rückenschmerzen durch gesteigerte Bewegung im betrieblichen Setting konnten die untersuchten Sitzmöbel nur unzureichende Erfolge zeigen. Hier gilt es neue Maßnahmen zu entwickeln oder dem Bewegungsmangel am Arbeitsplatz durch Bewegung im Alltag vorzubeugen [1-4].

Abstract (English)

Introduction

Causes of low back pain (LBP) are multidimensional, ranging from genetic disposition to psychosocial problems. Moreover, anatomical and mechanical factors, such as the individual shape and function of the lumbar spine and its relationship with the pelvis, a lack of motion in daily life or working in constrained positions have been discussed as being related to LBP. The aim of my dissertation was to investigate these factors in asymptomatic volunteers in four studies in different settings and to explore the impact of age and gender. These data are necessary for better understanding the development of degenerative spinal diseases, for clinical planning of spinal surgeries, for the design of age- and gender specific LBP-therapies, for biomechanical testing of spinal implants as well as for optimizing prevention methods in the workplace.

Method

Using a non-invasive measurement tool, the form and function of the lumbar spine and sacrum (as a representation of pelvic orientation) when standing and their interrelation in motion were assessed in a standardized choreography under laboratory conditions. The spinal shape and the number of spinal motions were also assessed over a 24-hour period in daily life. Moreover, effects of age and gender were investigated. Using the example of a sedentary workplace, a less active part of daily life was additionally analyzed, and the shape of spine and pelvis, as well as spinal motion was investigated during sitting on different furniture types.

Results

Lumbar lordosis (difference of 7.4° between the oldest and the youngest cohort) and its mobility in flexion (difference of 6.2°) decreases with age. During aging the pelvic orientation changes while standing (reduction in the sacrum angle of 6.6°) as well as the interrelation between lumbar spine and the pelvis during mobility (decrease in L/P ratio of 0.15), which is additionally affected by gender (L/P ratio females: 0.68, males: 0.81). For the first time, the number of spinal movements was evaluated in relation to age and gender in daily life, resulting in 4400 movements, with females moving more (29%) than males. In the workplace it was demonstrated that, although expected, the tested furniture did neither affect lumbar lordosis nor increase motion in the long run, however influenced the pelvic orientation.

Conclusions

LBP-influencing factors first need to be assessed in relation to age and gender to differentiate between asymptomatic and pathologic spinal movement patterns. A loss in lordosis and RoM and a change in movement pattern during upper body bending occurs in asymptomatic subjects and is part of the natural aging process. These age-effects as well as the significant difference in lordosis in daily life compared to the clinical reference assessment have mostly not been considered in surgical planning and LBP-therapies till today, although they might have implications for long-term success rates. The number of spinal movements within 24 hours, which was for the first time investigated, is of importance for manufacturers of spinal implants as these need realistic and valid values for testing their implants regarding fatigue strength. Regarding LBP prevention in the workplace by increasing spinal motion, it was shown that investigated furniture do not lead to any success and that new methods need to be developed to optimize activity in the occupational setting [1-4].

Introduction

Low back pain (LBP) is one of the leading causes of disability worldwide, is considered one of the main causes for absenteeism at work and is one of the most expensive musculoskeletal diseases in industrialized countries [5-7]. Although the reasons for LBP are regarded as complex, interrelated and multidimensional, ranging from genetic predisposition to psychosocial factors, several influencing anatomical and mechanical factors for the development and the aggravation of existing LBP have been identified [8, 9].

Anatomical parameters, such as the individual lumbar lordosis (shape of the lumbar spine) and its mobility, have been discussed as indicators for abnormal spinal mechanics and are regarded as elementary characteristics in the pathogenesis of LBP [10, 11]. Knowledge about the lumbar spinal shape plays a major role in clinical diagnostics and is of great importance for the design of therapy and surgical planning. Moreover, the so-called “lumbopelvic (L/P) rhythm” (quantified by the L/P ratio, which is the ratio of change in lumbar lordosis to change in pelvic orientation during upper body bending), and describes the complex interrelation between lumbar spinal motion and pelvic rotation during upper body flexion is considered clinically essential for differentiating asymptomatic patients from those with LBP. As changes in the movement pattern and the L/P ratio can result in altered and increased lumbar spine loadings [12], abnormal L/P rhythms are regarded as a risk factor for LBP [8, 13]. Knowledge about the L/P rhythm is furthermore of importance for designing prevention and therapy measures for spinal diseases.

Although the lumbar spinal shape and the pelvic orientation, as well as their interaction, are important parameters for an individual, patient-specific diagnosis and therapy planning, the influence of moderating factors, such as age and gender, still merits discussion. Previous studies have investigated the influence of gender and age on lumbar lordosis and pelvic orientation; however, the effect of these factors remains unknown or the results contradict one other, often due to the studies’ insufficient sample sizes. Most of the studies detected either no differences or a decrease in lordosis with increasing age [14-17]. Studies examining gender-related differences either demonstrated a slightly smaller lordosis in males or detected no significant difference between genders [14, 15, 18, 19]. Research on pelvic orientation in relation to the effects of gender and age showed no gender-related differences in pelvic parameters such as pelvic tilt and pelvic incidence and only weak correlations between pelvic tilt and age [15, 18, 20]. Studies on upper body flexion found a reduction in spinal range of motion (RoM) with aging [21-23]. However, differences between genders on spinal mobility are still controversial, with some studies demonstrating more and other studies finding less mobility in males compared to females [24-27].

Apart from overlooking the impact of age and gender, most investigations of the lumbar spine were only performed in the laboratory setting, and it remains unknown how the lumbar spine performs in daily life. This knowledge, however, is important for the planning of surgical interventions for the reconstruction of a well-balanced sagittal alignment [10]. In addition, the amount of spinal motion of asymptomatic individuals remains unknown, despite a lack of motion in the lumbar spine in daily life (e.g., too little engagement in physical activity or a sedentary lifestyle) has been discussed as another risk factor for LBP development and exacerbation [28, 29]. To date, physical activity has only been measured with the help of pedometers, questionnaires or with calorie expenditure assessments [30-33] and, surprisingly, no normative database on the number of spinal movements in daily life is available for asymptomatic subjects. These data could serve as a benchmark for how much motion occurs in the lumbar spine in individuals without LBP and would help to investigate how much motion is needed in daily life to prevent LBP. Moreover, these data could be used to objectively distinguish asymptomatic subjects from those with spinal disorders and to characterize the level of activity of patients. Such motion data from daily life are needed to improve existing LBP therapies or to develop new approaches to better treat individuals with LBP that is caused by a lack of physical activity. The effects of age might also play an important role in the number of spinal movements in daily life, as fatigue failure and degeneration processes of spinal structures in the elderly and, subsequently, the risk of developing LBP are influenced by the amount of spinal activity.

Too little motion in daily life is often a reflection of the sedentary behavior of our society, as approximately one-third of the day is spent in the workplace, and 70% of employees spend their working time sitting [34-36]. Sitting in the workplace as a risk factor for LBP is controversial, with some studies reporting sitting as a contributing factor [37-40] and others finding no such evidence [41-44]. However, it seems that sitting aggravates and preserves existing low back pain [45-48] and that low back discomfort increases during long periods of sitting [49-52]. Following the recommendations of ergonomists, who advocate the beneficial effects of active or dynamic sitting, furniture that proposes to increase spinal motion and beneficially alter spinal posture (e.g., dynamic chairs or exercise balls) has been studied extensively [50, 53-59]. The success of these tools in increasing spinal motion remains unknown, although this knowledge would be important to improve LBP prevention measures in the workplace and to optimize different seating furniture.

As a complete diagnostic examination using X-rays is ethically not justifiable in a large asymptomatic cohort, a novel motion-capture approach was used in all four studies that allowed the analysis of lumbar lordosis and sacrum orientation (as a representation of pelvic orientation) as well as their mobility. The measurement tool, which combined strain gauge and acceleration sensors, was employed to measure the spinal shape and motion of more than 200 volunteers in a standardized short-term choreography as well as in daily life over a 24-hour period, including the example of a sedentary workplace.

To investigate the above-described research project, four studies were conducted, and the results were documented and summarized in four scientific publications [1-4]. The division of the research project into four parts is schematically presented in Figure 1, where the different research levels (translating knowledge from basic research to applied sciences) and the diverse investigated settings of the project are depicted. The first two studies were conducted in the laboratory, while the third and the fourth studies took place during daily life and in the workplace setting, respectively.

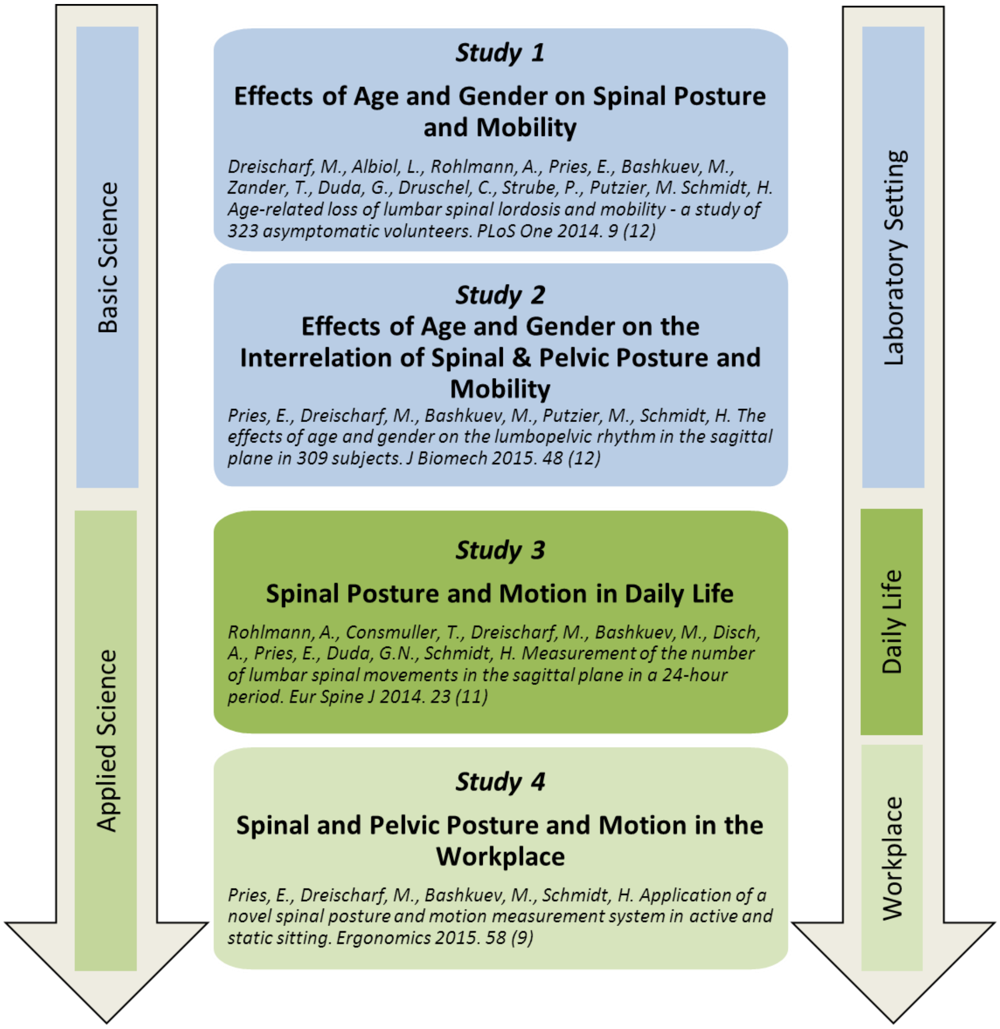

Figure 1: Schematic presentation of the progress of this thesis describing the different research levels and the different settings in which the studies took place.

The following hypotheses were derived and investigated in a large asymptomatic cohort:

Hypothesis 1: Age and gender significantly affect lumbar lordosis during upright standing and the range of motion in flexion. (Study 1)

Hypothesis 2: Age and gender influence the pelvic orientation during standing and the interrelation between the lumbar spine and the pelvis during upper body flexion (L/P rhythm). (Study 2)

Hypothesis 3: Age and gender affect the number of spinal motions that are conducted during a 24-hour period in daily life, which was objectively counted for the first time. (Study 3)

Hypothesis 4: Different types of seating furniture influence spinal and pelvic posture and lead to an increase in spinal activity in the workplace. (Study 4)

Method

Study participants

In the studies performed under laboratory conditions (studies 1 & 2), 309 subjects (175 females / 134 males) were evaluated. From these subjects, 208 (115 females / 93 males) were also measured over a 24-hour period in their daily life (study 3). The study conducted in the workplace examined separate data of ten males (study 4). Studies 1, 2, and 3 examined data obtained from the same subjects. To ensure a high correlation between back shape and spinal shape, only subjects with a body mass index (BMI) below 26 kg/m² were included. Further inclusion criteria for all studies were no LBP for six months prior to the measurements and no history of spinal surgery. The volunteers were classified by gender and assigned to age groups, including 20-35 years (youngest cohort), 36-50 years, and >50 years (oldest cohort) (studies 1-3).

Ethical statement

The Ethics Committee of the Charité – Universitätsmedizin Berlin approved the studies (registry number EA4/011/10). The volunteers were informed about the study’s procedure and provided written consent, which granted their permission to conduct the measurements.

Measurement system

The Epionics SPINE tool (Epionics Medical GmbH, Potsdam, Germany) is a mobile system that is designed to assess back shape and motion and can be applied to estimate sacrum orientation (as a representation of the orientation of the pelvis) and pelvic rotation in the sagittal plane. The tool comprises two flexible sensor strips utilizing strain gauge technology. Each of the sensor strips is divided into twelve 2.5 cm segments (Epionics segments: S1-S12) measuring local curvature angles to quantify the bending of the strip. The sensor strips are each inserted into a hollow plaster that is attached to the back paravertebrally 7.5 cm from the spine on each side. The segments of the sensor strips detect the local back curvature. The lower end of each strip is aligned with the posterior superior iliac spine, which is approximately in line with the first sacral vertebra. A tri-axial accelerometer located at each lower end assesses the sacrum orientation relative to the earth's gravitational field. The sensor strips are connected to a storage unit (12.5 cm x 5.5 cm; weight: 80 g) that collects data with a frequency of 50 Hz. Information about the system's accuracy and reliability can be found elsewhere, along with a more detailed description of the measurement system [4, 60-62].

The measurement system is non-invasive, wireless, portable and radiation-free. The tool enables short-term measurements in the laboratory setting in a predefined standardized choreography, including flexion and extension of the upper body. Moreover, the system is able to conduct long-term measurements of up to 24 hours in daily life without any restrictions for the subject by saving the data in the storage unit.

Measurement protocols

All volunteers were first measured in an upright standing position (studies 1-4) and for the workplace study (study 4) additionally in an upright sitting position during a standardized short-term choreography (duration: approximately 10 minutes). From these reference positions, volunteers were asked to conduct maximal flexion and extension of the upper body up to five times at their own preferred speed.

Moreover, a functional long-term measurement was conducted either over a period of 24 hours of daily life, including work, free time and resting periods without any instructions for the subjects (study 3), or over several 2-hour periods in the workplace (study 4). For the workplace study, the participants were measured at their work desks in front of their computers. Volunteers were asked to sit for 2 hours on different types of furniture that are supposed to alter sitting posture and activity. For assessing baseline data, volunteers were first asked to sit on an ordinary office chair with a static seat pan and a fixed backrest (STATIC). Afterward, they were directed to sit on an office chair with an adjustable back- and armrest that allows the seat pan to displace forward when the backrest tilts backwards (DYNAMIC). To test an apparently highly dynamic sitting condition, the participants sat on an exercise ball (BALL 1st) and continued to use this ball for a 2-week period, to obtain information on habituation effects. After 14 days, the 2-hour measurements on the exercise ball were repeated (BALL 2nd).

Data analysis

Short-term measurements

The lumbar lordosis was individually calculated by summing the Epionics measurement segments that were lordotically curved while upright standing in the reference short-term measurement. The corresponding data from the left and right sensor strips were averaged. These lordotic segments then served as the individual reference for the determination of the lumbar angle during flexion and extension. The sacrum orientation was determined from the orientation of the accelerometers, which are located at the sensor strip's lower end. Ranges of flexion (RoF) for the lumbar spine and the sacrum were calculated by subtracting the lumbar and sacrum angles in standing from the corresponding values in full flexion. For the lumbopelvic rhythm, which was quantified by the L/P ratio, the change in lumbar lordosis was divided by the change in sacrum orientation during upper body flexion.

Long-term measurements

For each participant, the measurement data from the sensor segments were collected over 24 or 2 hours and stored in the storage unit. Prior to analysis, the data were filtered using a higher order low-pass Butterworth filter with a cut-off frequency of 5 Hz for the sensor segments. The lumbar angle was then individually calculated for each time point of the long-term measurement, summing the reference segments from the corresponding short-term measurements. The mean lumbar lordosis in the long-term measurement as well as the percentage of time spent in different positions was assessed. In the workplace study, moreover the mean pelvic orientation for the 2-hour periods was investigated and the data for lumbar lordosis and pelvic orientation were compared between the different seating furniture types.

In addition to posture, spinal movements of different extents were also investigated. For each time point, the difference between the instantaneous lumbar angle during long-term measurements and the reference lordosis value from the short-term measurement was assessed. This resulted in a curve where changes in lumbar lordosis were plotted against time, providing information about spinal movements. To quantify movements, all local minima and maxima were subsequently determined, whereby small fluctuations (when the difference between two consecutive extrema was less than 5°) were discarded. While for the 24-hour measurements all movements ranging from 5° to >65°

(divided into classes in steps of 5°) were analyzed, for the workplace evaluation only three classes of movements (small (5-10°), middle (10-15°) and large (15-20°)) were investigated due to the lack of large movements in this setup.

All data were processed using custom in-house developed MATLAB routines (MATLAB R2009b, MathWorks, Inc., Natick, MA, US.).

Statistical analysis

All data values were tested for normal distribution using Kolmogorov-Smirnov test, and variance homogeneity was analyzed using Levene's test. In cases of normally distributed data, mean and standard deviations were provided and effects of influencing factors were tested by one- or two-way analysis of variance (ANOVA), repeated measures ANOVA or paired t-tests using post hoc Bonferroni's or Scheffé's test. In cases of not normally distributed data, median values and ranges were calculated and effects of influencing factors (e.g., age, gender) were tested by the Mann-Whitney U Test or the Kruskal-Wallis Test, using post hoc test with Bonferroni correction. Data were analyzed using SPSS 21.0 (SPSS Inc., Chicago IL, USA).

Results

Effects of age and gender on lumbar lordosis and sacrum in short-term measurements under laboratory conditions (Studies 1 & 2)

A negative lumbar angle indicated the lumbar lordosis during standing which was -33.8° for the entire cohort, demonstrating no significant differences between males (-32.4°) and females (-34.9°).

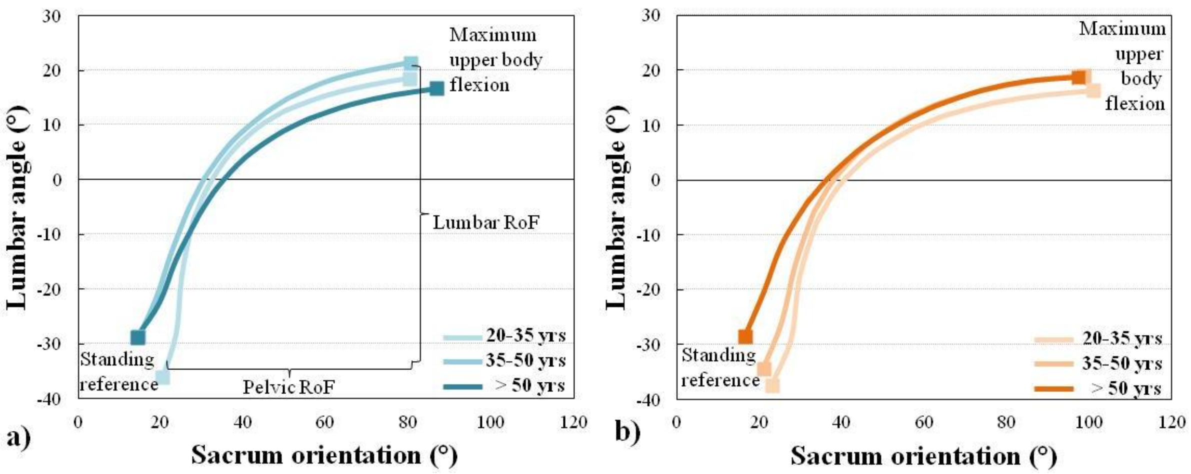

Figure 2: Plot of lumbar angle (y-axis) versus sacrum orientation (x-axis) depicting the L/P rhythm during flexion for males a) and females b) separately.

The mean sacrum orientation in standing was 19.5°, which was significantly different between genders (males: 17.4°; females: 21.1°). As seen in Figure 2a and b (left part of the figures) and in Table 1, with increasing age, the anatomical lumbar lordosis was significantly reduced in standing (showing a change in the absolute lumbar angle of 7.3° in males (change from -36.1° to -28.8°; p=0.007) and 8.9° in females (change from -37.4° to -28.5°; p<0.001) when comparing the oldest and youngest cohorts. For the entire cohort, the decrease in the lumbar lordosis (absolute values) happened with each consecutive age group. While in females the change in the lumbar lordosis was continuous, the reduction in males occurred mostly between the ages 20-35 yrs and 36-50 yrs, showing the smallest lordosis in the middle aged group.

When analyzing the different segments of the sensor it was revealed, that most of the reduction of the anatomical lumbar lordosis was observed in the middle part of the lordosis for both genders. Only small changes of lordosis during aging occurred towards the lumbo-sacral and thoraco-lumbar transitions. The decrease in the anatomical lumbar lordosis during aging was accompanied by a significant decrease in the sacrum orientation angle (sacrum verticalisation), from 20.4° to 14.2° in males (p=0.004; Fig. 2a, Table 1) and from 23.0° to 16.2° in females (p<0.001, Fig. 2b, Table 1).

Moreover, with increasing age, the lumbar RoF significantly decreased and showed a reduction of 9.1° in males (change from 54.6° to 45.5°; p<0.001; Fig. 2a) and of 6.5° in females (change from 53.7° to 47.2°; p=0.007; Fig. 2b, Table 1). On the contrary, the pelvic RoF increased with increasing age and seemed to compensate for the loss in the lumbar RoF. However, the increase in pelvic RoF

		20-35 yrs Mean (SD)	**36-50 yrs Mean (SD)**	**>50 yrs Mean (SD)**	**ANOVA p-values**	**Post hoc analysis 20-35 yrs. vs >50 yrs**
Lumbar angle in standing (°)	**Males**	-36.1 (8.7)	-28.7 (9.9)	-28.8 (12.0)	**<0.001***	**0.007***
	Females	-37.4 (7.1)	-34.3 (6.8)	-28.5 (8.7)	**<0.001***	**<0.001***
Pelvic orientation in standing (°)	**Males**	20.4 (6.9)	14.6 (7.7)	14.2 (9.8)	**<0.001***	**0.004***
	Females	23.0 (5.6)	20.8 (6.6)	16.2 (6.2)	**<0.001***	**<0.001***
Lumbar angle in full flexion (°)	**Males**	18.5 (5.7)	21.4 (7.7)	16.8 (8.1)	0.020	0.536
	Females	16.3 (7.3)	19.1 (9.1)	18.7 (9.1)	0.113	0.403
Pelvic orientation in full flexion (°)	**Males**	80.2 (13.0)	80.4 (11.7)	86.8 (12.7)	0.070	0.087
	Females	100.9 (12.9)	98.4 (13.1)	97.2 (14.5)	0.325	0.426
Lordotic RoF (°)	**Males**	54.6 (8.7)	50.0 (11.4)	45.5 (12.0)	**0.001***	**0.001***
	Females	53.7 (9.2)	53.4 (9.5)	47.2 (10.3)	**0.005***	**0.007***
Pelvic RoF (°)	**Males**	59.8 (14.8)	65.8 (13.1)	72.6 (16.4)	**0.001***	**0.001***
	Females	77.9 (14.7)	77.6 (13.2)	80.9 (16.3)	0.557	0.618

Table 1: Effects of aging on lumbar spine and pelvis and their mobility (mean and standard deviation (SD)). The p-values are based on one- and two- way ANOVAs and posthoc comparisons using Scheffé's test. Asterisks and bold values indicate statistical significance (p<0.01).

during aging was only significant in males (increase of 12.8° from 59.8° to 72.6°; p=0.001, Fig. 2a) and not in females (increase of 3.0° from 77.9° to 80.9°; p=0.618, Fig. 2b, Table 1). Regarding the spinal-pelvic interrelation during the full flexion motion, significant differences between females (L/P ratio = 0.68) and males (L/P ratio = 0.81) have been determined, indicating an overall smaller contribution of the pelvis to the motion in males compared with females. With aging, the L/P ratio significantly reduced in males (from 0.91 to 0.65 comparing the oldest to the youngest cohort) whereas in females no significant differences were detected. This indicates a greater contribution of the pelvis and a smaller lumbar spinal contribution to the upper body flexion during aging.

Spinal posture and motion in long-term measurements in daily life (Study 3)

The volunteers adopted several different postures that resulted in various lordotic angles during the day. Approximately five of the 24 hours were spent in a flexed position relative to the reference lumbar lordosis (between 20° and 30°) while nearly no time (less than 2%) of the overall 24 hours was spent in an extended position. The median regarding the total number of movements greater than 5° in the 208 volunteers in this study was approximately 4400 (range 1248–13029) over 24 hours. Of these movements, 66% (2915 (range 741–9897)) were small (5°-10°) and larger movement changes occurred less often (Fig. 3a). Of the total number of movements, 17% were between 10° and 15°, 6% were between 15° and 20°, and only 11% of movements were larger than 20° (Fig. 3a). In general, males performed 29% fewer movements than females, with 3846

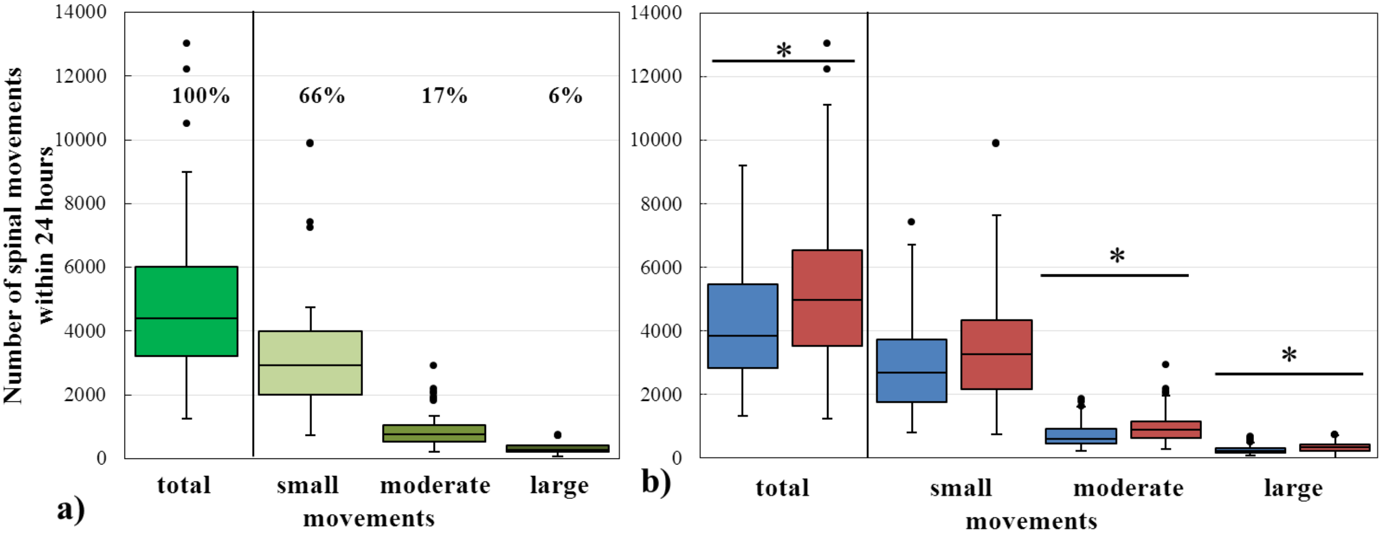

Figure 3: a) Number of spinal movements (total 5-65°, small 5-10°, moderate 10-15°, large 15-20°) conducted over 24 hours (median for the entire cohort) b) Number of spinal movements for males (blue) and females (red) separately. Movements larger than 20° are not displayed. Asterisks indicate statistical significance.

movements for males and 4978 for females (Fig. 3b). Apart from the total number of movements, gender also significantly influenced the number of movements between 10° and 40°. Regarding the total number of movements, the youngest cohort performed in general more movements than the oldest cohort; however this effect was only minor. Divided by gender, it was demonstrated that age significantly affected the number of movements in males only for movements between 10° and 20° and 35° and 50°. For females, age had no effect on the number of movements.

Spinal and pelvic motion in long-term measurements in the workplace (Study 4)

The mean lumbar angle in the short-term measurement during sitting was -15.5° and was significantly smaller than during standing (-35.2°). During sitting in the long-term measurements in the workplace, volunteers sat on average in a flexed posture, with a mean lumbar angle of -1.3° on the static chair (STATIC), -6.3° on the dynamic chair (DYNAMIC), -0.9° for the first 2 hours on the exercise ball (BALL 1st), and -3.8° while seated on the ball the second time (BALL 2nd). There were no significant differences for the total lordosis among the different types of furniture and the exercise ball measurements. However, during sitting in the long-term measurement, the sacrum

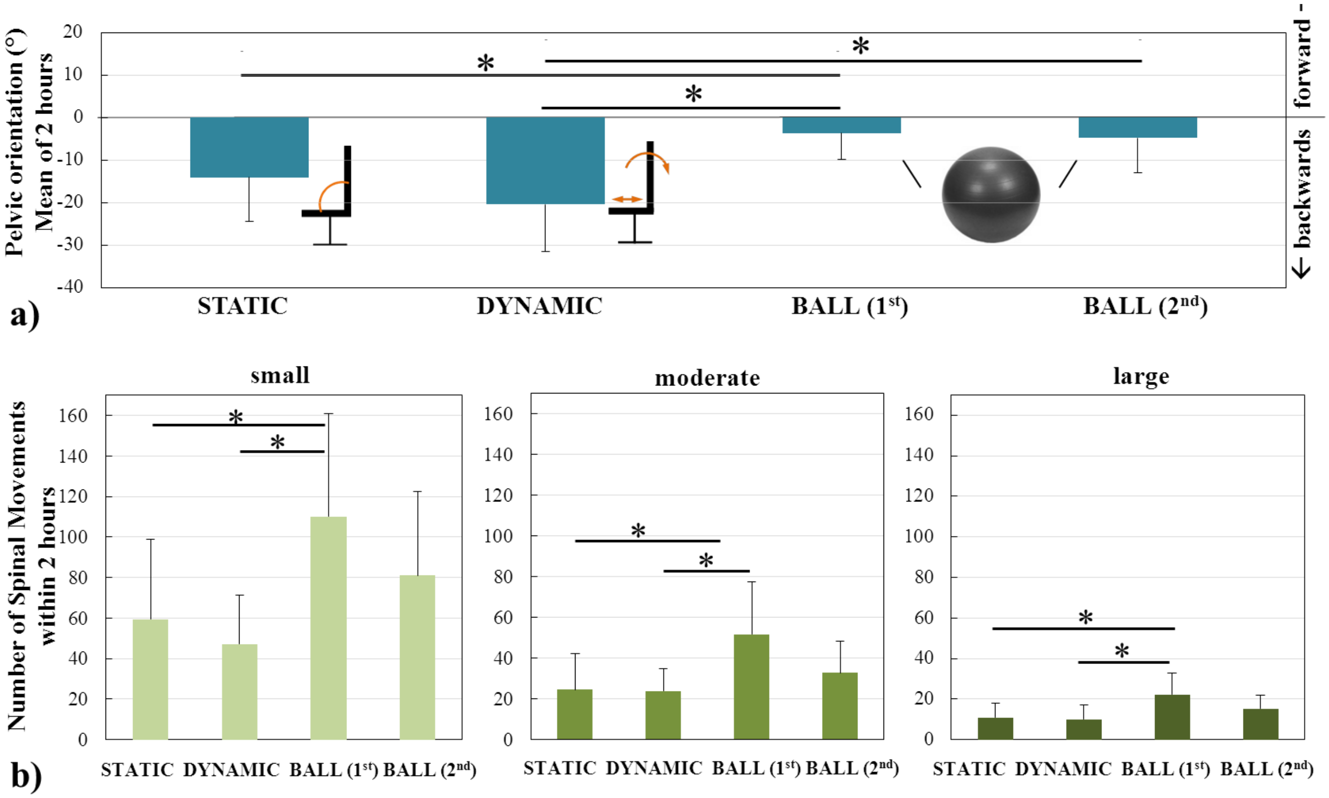

Figure 4: a) Mean pelvic orientation during 2 hours of sitting on the static chair (STATIC), the dynamic chair (DYNAMIC) and the exercise ball during the first (BALL (1st)) and second measurement (BALL (2nd)) b) Number of movements during 2 hours of sitting on the various types of seating furniture for small (5-10°), moderate (10-15°) and large (15-20°) movements. Asterisks indicate statistical significance.

orientation differed significantly between measurements on the exercise ball and the static and dynamic office chairs (Fig. 4a). This indicates a more forward-oriented sacrum on the exercise ball compared to the sacrum orientation on the chairs (Fig. 4a).

ANOVA analysis demonstrated significant differences in the number of movements between the different types of furniture in all movement classes. Post-hoc comparison revealed that only the first measurement on the exercise ball showed a significant increase in the number of movements compared to the dynamic chair and static chair (Fig. 4b). No significant increase in movement was detected on the dynamic chair compared to the static chair (Fig. 4b). After 14 days of habituation on the ball, no significant increase in the number of movements could be detected any longer (Fig. 4b).

Additional and more detailed results of all studies can be found in the attached publications [1-4].

Discussion

In the past, several risk factors for low back pain have been identified. Detailed knowledge of these factors and the effects of influencing variables are important for sophisticated diagnoses, therapies und prevention measures for LBP, as this is still a highly relevant clinical concern in our aging society. A well-balanced spinal shape, good mobility and an adequate amount of motion during the day and while working are important characteristics to maintain lumbar spinal structure and function and to avoid LBP. The present thesis demonstrated the significant effects of age and gender on spinal shape and pelvic orientation, mobility and motion in a large asymptomatic cohort, both in the laboratory setting in standardized short-term choreographies and in long-term measurements in daily life and in the workplace.

In agreement with our first hypothesis, aging led to a significant decrease in lumbar lordosis, which is also in agreement with previous studies [14, 16]. Knowledge of this physiological loss of lumbar lordosis has an essential implication with regard to the spinal loading, the resultant degeneration process and therefore the mechanical challenge, which the lumbar spine has to face. It could be moreover emphasized, that a significant loss of lordosis, which often occurs in patients suffering from LBP, does also occur as an age-related change in asymptomatic subjects [1]. Therefore it is not possible to compare between low back pain patients and young, healthy subjects, but age-specific, symptomatic values are required. The information about the proven level-specific changes in lumbar spinal shape and motion [1] has important implications for patient specific treatment, individual therapy approaches and the differentiation between asymptomatic aging and painful degenerative spinal diseases. Knowledge of this natural loss of lumbar lordosis and the change in pelvic orientation with aging can be used to improve the planning of surgical interventions aimed at reconstructing a well-balanced sagittal alignment that, to date, often use standardized non-specific reference values [10]. However, an individual optimized patient-specific approach to reconstruct the sagittal balance requires an age-specific estimation of the lumbar lordosis as provided in our study 1. While gender did not affect lumbar lordosis, it had an effect on the pelvic orientation while standing and influenced the spino-pelvic movement pattern during upper body flexion, corroborating hypothesis 2. This result is supported by previous studies that investigated the lumbopelvic rhythm, which only included males [12, 63] and found higher L/P ratios than those studies that included both males and females [64, 65].

Furthermore, a previous study [12] on the loads in the lumbar spine during upper body flexion demonstrated that the overall compression and shear loading was substantially affected by the individual L/P ratio. This computational model study found a load increase at spinal level L5-S1 for smaller L/P values. In our study 2 on the interrelation of the lumbar spine and the pelvis, it was emphasized that aging significantly reduced the L/P ratio. This implies a significantly higher loading of lumbar spinal structures in older volunteers compared to young volunteers for the same inclination angle in the early phase of flexion. These higher loads might partly explain, of course beside other factors, the higher risk of injury and subsequent LBP in the elderly, as many tasks in the daily routine, such as washing the dishes or vacuum cleaning are performed in this position [2].

Moreover, the results emphasize the importance of the differentiation between spinal and pelvic motion in clinical examinations and functional tests before and after therapy to guarantee a sophisticated evaluation of a patient’s ability to move.

The actual clinical assessment not only neglects the complex interrelation between the lumbar spine and the pelvis, but is also only a “snap-shot” of the actual spinal performance in daily life [66]. The valid assessment of the lumbar spinal shape and motion is an elementary characteristic for the diagnosis and therapy of LBP; however, a meaningful functional long-term evaluation of these factors in daily life has not been described to date. For the first time, the spinal shape was analyzed over 24 hours and it was revealed that the volunteers conducted a flexed position nearly one-third of the time. This decrease in lumbar lordosis during the day is probably caused by the dominance of sitting postures [35] that are adopted by our “sedentary population”. This finding might have implications for the preclinical testing and designing of spinal implants. The results of study 3 moreover emphasize the importance of assessing lumbar lordosis in everyday life, as this might help to understand the outcome of surgical procedures as well as postoperative problems. Not only does the spinal shape during daily life remain elusive but also little is known about “normal” lumbar spinal motion behavior in daily life, which has not been monitored till now. It could be emphasized that genders behave differently regarding the amount of spinal motion, corroborating our third hypothesis, and that age had only minor effects. Linton and van Tulder [67] showed in their systematic review that activity and exercise is effective for chronic LBP. However, there is a lack of information regarding the dose-response relationship as regards physical activity and the effects on LBP [68]. The results of our study 3 set a baseline for a better understanding of people’s everyday spinal performance and for ongoing research that aims to establish a database of spinal movements for the differentiation between subjects with and without motion pathologies. Furthermore, these motion data can help to improve existing LBP therapies and to develop new approaches to better treat individuals with LBP that is caused, for example, by a lack of physical activity. The result, that the lumbar spine is on average in a much more flexed position during the day than in the standard clinical assessment is highly important to improve the closeness to reality of current in vitro tests for new spinal implants. Those tests usually assume a standard standing alignment configuration that does not frequently occur during the day. With the here presented data those tests can be adapted to patients’ individual and real conditions and can hence improve the quality of in vitro and in silico investigations of the lumbar spine [66]. The number of spinal movements that was investigated in study 3 is of importance for manufacturers of spinal implants as these need realistic and valid values for testing their implants regarding fatigue strength.

Because most working-age people in industrialized countries spend about one-third of their daily life in their workplaces, the examination of ergonomic risk factors in the workplace is of great importance [37, 69, 70]. Study 4 highlighted that although there was no significant difference in the total lordosis between the different chairs and the exercise ball, the assessed pelvic orientation was significantly altered on the sitting ball. This emphasizes the necessity for future research to determine not only the spinal shape but also the pelvic orientation in the assessment in ergonomic studies, as this orientation can vary and thus influence the load bearing of the lumbar spine [71]. Although the amount of motion necessary to prevent low back pain remains unknown, ergonomists advocate dynamic sitting. However, the results of the study in the workplace indicate that spinal motion during sitting is not substantially affected by motion-promoting furniture, including expensive dynamic office chairs or simple sitting balls. This finding contradicts our fourth hypothesis and is in agreement with previous studies [55, 59]. These results can be applied in the manufacturing of chairs that are meant to increase the spinal activity at work. Office chair manufacturers can moreover use the tool, which we further developed in our study, to test the efficacy of their devices. Moreover, health care managers and ergonomists in companies should keep in mind, that sitting is individual: To differentiate between responder and non-responder to different seating furniture, an individualized subject analysis is required, as the variability between our volunteers emphasized. This may help to determine individual and specific solutions in the workplace, allowing the objective evaluation of workplace interventions and to be able to control for habituation effects. These conclusions can help to develop and improve successful measures for adapting people's activity in the workplace to a reasonable degree.

Several limitations regarding the four conducted studies need to be discussed. All of our studies investigated only asymptomatic subjects, who did not suffer from LBP. However, the results of the present dissertation are required to establish baseline data of asymptomatic subjects, matched by gender and age, collected outside the laboratory setting which is missing till today. As the differentiation into age and gender groups has now been set and real-life values have been collected, further research needs to take subjects suffering from LBP into account, to guarantee a sophisticated comparison between these two groups. Knowledge about population-based differences and subjects with specific spinal diseases will in the future improve the ability to better diagnose and treat LBP.

The workplace study investigated only ten male subjects who were not divided by age and, therefore, must be regarded as preliminary. Although the study's conclusion is in good agreement with previous studies, further research that includes a larger sample size needs to be conducted in the workplace. Regarding the measurement method used, the system has the potential to objectively analyze the lumbar spine and the pelvis in both short-term choreographies and measurements of daily life; nevertheless, a number of limitations remain for its current applicability. The system measures the volunteers' back shape and not the spinal shape directly. However, our own validation studies as well as previous studies compared surface and radiographic lumbar spinal shape and motion, resulting in good correlation for normal-weight subjects with a BMI of less than 26 kg/m² [72-74]. This is why we included only volunteers with a BMI not exceeding this limit in our studies. The system's acceleration sensors do not directly reveal pelvic parameters that can only be obtained from radiographs, but they do provide an approximation of sacrum orientation and pelvic motion

[2]. Regarding the measurements in the workplace, the system is currently not able to determine movements such as lateral bending or upper body rotation, although these are relevant ergonomic risk factors.

To summarize, this thesis highlighted the impact of age and gender on the lumbar spine, pelvic orientation and their interrelation, both when standing and during motion in short- and long-term assessments in daily life. The presented results emphasize that for a sophisticated functional analysis of subjects, it is essential to first consider age- and gender-dependent changes and, moreover, to investigate mobility and motion in daily life additionally to the laboratory setting. Knowledge of influencing factors on lumbar lordosis and pelvis, their motion, and performance in daily life and in the workplace is of great importance for developing new diagnostic procedures, improving patient-specific therapeutic programs and designing individual prevention measures for reducing the incidence and prevalence of LBP.

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Affidavit

I, Esther Pries certify under penalty of perjury by my own signature that I have submitted the thesis on the topic “Shape and function of the lumbar spine and the pelvis in the laboratory, in daily life and in the workplace”. I wrote this thesis independently and without assistance from third parties, I used no other aids than the listed sources and resources.

All points based literally or in spirit on publications or presentations of other authors are, as such, in proper citations (see "uniform requirements for manuscripts (URM)" the ICMJE www.icmje.org) indicated. The sections on methodology (in particular practical work, laboratory requirements, statistical processing) and results (in particular images, graphics and tables) correspond to the URM (s.o) and are answered by me. My contributions in the selected publications for this dissertation correspond to those that are specified in the following joint declaration with the responsible person and supervisor. All publications resulting from this thesis and which I am author of correspond to the URM (see above) and I am solely responsible.

The importance of this affidavit and the criminal consequences of a false affidavit (section 156,161 of the Criminal Code) are known to me and I understand the rights and responsibilities stated therein.

Date: 04 October 2016 Signature:

Declaration of any eventual publications

In general, Esther Pries made substantial contribution to conception and design, analyses and interpretation of data of all four studies. She participated in drafting the articles or revising them critically for important intellectual content and gave final approval to the versions to be submitted and to any revised versions of all four publications. In particular, she had the following share in the following publications:

Pries, E., Dreischarf, M., Bashkuev, M., Schmidt, H. Application of a novel spinal posture and motion measurement system in active and static sitting. Ergonomics 2015. 58(9): p. 1605-10.

- **Contribution in detail:** Esther Pries conducted the literature review prior to the study, had the idea for the study, and was responsible for the development of the study design and creating the measurement setup. She also took care of the recruiting and scheduling process of the volunteers for measurements and, together with the co-authors, established the process of further developing the measurement method for the study purposes. She conducted and coordinated the experiments and measurements and supported the development of the data programming routines together with the co-authors. She conducted the entire data analysis using Excel, the statistical analysis using SPSS and the interpretation of the data, in collaboration with the co-authors. She designed the study's figures and tables, drafted and wrote the manuscript. Esther Pries conducted the proofreading and discussed and edited the publication during the review process, supported by the co-authors.

Pries, E.*, Dreischarf, M.*, Bashkuev, M., Putzier, M., Schmidt, H. The effects of age and gender on the lumbopelvic rhythm in the sagittal plane in 309 subjects. J Biomech 2015.48(12) p. 3080-7.

* The authors contributed equally to this work.

- **Contribution in detail:** Esther Pries carried out the research of the existing literature, had the idea for the study and was primarily responsible for the planning and preparation of the study methodology. She collaborated with the co-authors in the rewriting process of the programming routines for the data evaluation using MATLAB. She performed the entire preparation, formatting, analysis and evaluation process of the data. She conducted the statistical analysis using SPSS and Excel. Together with the co-authors, she discussed and interpreted the results. She drafted the figures and tables as well as the manuscript. Esther Pries wrote the main parts of the manuscript and was supported by the co-authors in the revising and editing of the manuscript. She conducted the publication and review process of the publication supported by the co-authors.

Dreischarf, M., Albiol, L., Rohlmann, A., Pries, E., Bashkuev, M., Zander, T., Duda, G., Druschel, C., Strube, P., Putzier, M., Schmidt, H. Age-related loss of lumbar spinal lordosis and mobility--a study of 323 asymptomatic volunteers. PLoS One 2014. 9(12): p. e116186.

- **Contribution in detail:** Esther Pries supported the first author regarding the design and planning of the study. She collaborated and discussed the analysis and interpretation of data and their results with the co-authors. She cooperated in drafting the manuscript and improving the paper together with the first author. Esther Pries proof-red and edited the manuscript together with the co-authors. She assisted the first author in the publication and review process of the manuscript.

Rohlmann, A., Consmuller, T., Dreischarf, M., Bashkuev, M., Disch, A., Pries, E., Duda, G.N., Schmidt, H. Measurement of the number of lumbar spinal movements in the sagittal plane in a 24-hour period. Eur Spine J 2014. 23(11): p. 2375-84.

- **Contribution in detail:** Esther Pries supported the first author regarding the literature review. She supported and discussed the development of the data programming routines and the process to adapt the measurement method for our purposes. She conducted parts of the data analysis and the statistical analysis using SPSS, together with the co-authors. She cooperated with the other authors in the interpretation and scientific evaluation of the data. Esther Pries discussed and interpreted the study’s outcomes and conclusions with the first author. She collaborated in the preparation process of the manuscript, and supported the proofreading, editing and review process of the publication.

Signature, date and stamp of the supervising University teacher:

Signature of the doctoral candidate:

Curriculum Vitae

My curriculum vitae does not appear in the electronic version of my paper for reasons of data protection.

Complete list of publications

Scientific Journals

- Pries, E., Dreischarf, M., Bashkuev, M., Schmidt, H. Application of a novel spinal posture and motion measurement system in active and static sitting. Ergonomics 2015. 58(9): p. 1605-10.
- Pries, E.*, Dreischarf, M.*, Bashkuev, M., Putzier, M., Schmidt, H. The effects of age and gender on the lumbopelvic rhythm in the sagittal plane in 309 subjects. J Biomech 2015. 48(12): p. 3080-7.

  * The authors contributed equally to this work.
- Dreischarf, M., Albiol, L., Rohlmann, A., Pries, E., Bashkuev, M., Zander, T., Duda, G., Druschel, C., Strube, P., Putzier, M., Schmidt, H. Age-related loss of lumbar spinal lordosis and mobility--a study of 323 asymptomatic volunteers. PLoS One 2014. 9(12): p. e116186.
- Rohlmann, A., Consmuller, T., Dreischarf, M., Bashkuev, M., Disch, A., Pries, E., Duda, G.N., Schmidt, H. Measurement of the number of lumbar spinal movements in the sagittal plane in a 24-hour period. Eur Spine J 2014. 23(11): p. 2375-84.
- Dreischarf M.*, Pries E.*, Bashkuev M., Putzier M., Schmidt H. Differences between clinical "snap-shot" and "real-life" assessments of lumbar spine alignment and motion - What is the "real" lumbar lordosis of a human being? J Biomech. 2016. 49(5): p. 638-44

  * The authors contributed equally to this work.

Book article

- Pries E., Dreischarf M., Bashkuev M., Schmidt H., Haltungs- und Bewegungsanalyse am Arbeitsplatz – Identifikation von Fehlhaltungen zur Vermeidung von Rückenschmerz. In Prävention von arbeitsbedingten Gesundheitsgefahren und Erkrankungen - 21. Erfurter Tage, Erfurt, Deutschland: herausgegeben von I. Dienstbühl, M. Stadeler, H.-C. Scholle, Verlag Bussert & Stadeler, 2015, p. 275-78

Congress Presentations

- Form und Beweglichkeit der Wirbelsäule während des Sitzens auf unterschiedlichen Sitzmöbeln, DKOU, Berlin 2014
- Haltungs- und Bewegungsanalyse am Arbeitsplatz – Identifikation von Fehlhaltungen zur Vermeidung von Rückenschmerz, Erfurter Tage, Erfurt 2014
- Das Zusammenspiel von Wirbelsäule und Becken bei der Oberkörperneigung – Untersuchungen an 309 asymptomatischen Probanden, dvs Sektion Biomechanik, Berlin 2015
- Einfluss von Alter und Geschlecht auf den Lumbopelvic Rhythm - Untersuchungen an 309 rückenschmerzfreien Probanden, Jahrestagung Deutsche Gesellschaft für Biomechanik, Bonn 2015
- Klinische Kurzzeitanalysen spiegeln die komplexe Form und Beweglichkeit der Lendenwirbelsäule im Alltag nur unzureichend wider: Langzeitmessungen an 208 Probanden, Jahrestagung Deutsche Gesellschaft für Biomechanik, Bonn 2015

- The Effect of Age and Gender on Lumbar Lordosis, Pelvic Orientation and the Lumbopelvic Rhythm in the Sagittal Plane in 309 Asymptomatic Subjects without Low Back Pain, International Workshop on Spine Loading and Deformation, Berlin 2015

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Selected publications

- Pries, E., Dreischarf, M., Bashkuev, M., Schmidt, H. Application of a novel spinal posture and motion measurement system in active and static sitting. Ergonomics 2015. 58(9): p. 1605-10.
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- Pries, E.*, Dreischarf*, M., Bashkuev, M., Putzier, M., Schmidt, H. The effects of age and gender on the lumbopelvic rhythm in the sagittal plane in 309 subjects. J Biomech 2015. 48(12): p. 3080-7.
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- Dreischarf, M., Albiol, L., Rohlmann, A., Pries, E., Bashkuev, M., Zander, T., Duda, G., Druschel, C., Strube, P., Putzier, M., Schmidt, H. Age-related loss of lumbar spinal lordosis and mobility--a study of 323 asymptomatic volunteers. PLoS One 2014. 9(12): p. e116186.
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  Original publication attached

- Rohlmann, A., Consmuller, T., Dreischarf, M., Bashkuev, M., Disch, A., Pries, E., Duda, G.N., Schmidt, H. Measurement of the number of lumbar spinal movements in the sagittal plane in a 24-hour period. Eur Spine J 2014. 23(11): p. 2375-84.
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RESEARCH ARTICLE

Age-Related Loss of Lumbar Spinal Lordosis and Mobility – A Study of 323 Asymptomatic Volunteers

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Abstract

Background: The understanding of the individual shape and mobility of the lumbar spine are key factors for the prevention and treatment of low back pain. The influence of age and sex on the total lumbar lordosis and the range of motion as well as on different lumbar sub-regions (lower, middle and upper lordosis) in asymptomatic subjects still merits discussion, since it is essential for patient-specific treatment and evidence-based distinction between painful degenerative pathologies and asymptomatic aging.

Methods and Findings: A novel non-invasive measuring system was used to assess the total and local lumbar shape and its mobility of 323 asymptomatic volunteers (age: 20–75 yrs; BMI $<$26.0 kg/m^2; males/females: 139/184). The lumbar lordosis for standing and the range of motion for maximal upper body flexion (RoF) and extension (RoE) were determined. The total lordosis was significantly reduced by approximately 20%, the RoF by 12% and the RoE by 31% in the oldest ($>$50 yrs) compared to the youngest age cohort (20–29 yrs). Locally, these decreases mostly occurred in the middle part of the lordosis and less towards the lumbo-sacral and thoraco-lumbar transitions. The sex only affected the RoE.

Conclusions: During aging, the lower lumbar spine retains its lordosis and mobility, whereas the middle part flattens and becomes less mobile. These findings lay the ground for a better understanding of the incidence of level- and age-dependent spinal disorders, and may have important implications for the clinical long-term success of different surgical interventions.

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Introduction

The individual shape of the lumbar spine is an essential predictor for different lumbar degenerative pathologies and for the success of various surgical interventions [1–5]. Moreover, the mobility of the lumbar spine is discussed as an indicator for abnormal spinal mechanics [6, 7]. The influence of the factors age and sex on the total lumbar lordosis and the range of motion (RoM) still merits discussion, because it is essential for a patient-specific treatment, for example, with regard to patient age and disease localisation, and evidence-based distinction between painful degenerative pathologies and asymptomatic aging. Despite their influence, the impact of these factors on certain regions of the lumbar spine and its mobility, including upper, middle and lower lumbar spine, remains unknown.

Most studies on the effect of age showed that lumbar lordosis decreases or remains constant during the lifetime [8–21]. Only a few studies demonstrated an increase in lumbar lordosis with aging [22, 23]. Studies investigating sex-related differences in lordosis showed either a slightly greater lordosis in females or no significant dependency on sex [24–27]. However, several of these studies investigating age and sex were limited in their sample sizes, did not differentiate between males and females and subjects with or without low back pain. Moreover, in almost all of these studies the whole lumbar lordosis was usually described by a single angle (e.g. Cobb's method), which strongly simplifies the complex lumbar curvature [28–30]. A more detailed analysis, including of different lumbar sub-regions, may reveal that the upper, middle or lower lumbar lordosis are affected specifically, for example, by aging.

In addition to the individual shape of the lumbar lordosis, it is generally accepted that the total RoM in flexion-extension is reduced with increasing age [6, 31–39]. However, similar to lumbar lordosis, it remains unknown, which lumbar sub-region is affected dominantly by aging in males and females. Knowledge about local changes in spinal function with aging may therefore help to optimise and adapt the treatment to the diseased spinal level.

Because detailed segmental diagnostic X-ray examinations are ethically questionable in healthy individuals and very laborious in large cohorts, a new technological approach was first identified and further developed by our group [40], which would allow analysis of the total and local lordosis as well as the spinal function (e.g. by means of RoM). Using this sophisticated, strain-gauge based tool that had been validated previously, the present study investigated the effect of age and sex on the lordosis and on the RoM for the whole lordosis as well as for the different lumbar sub-regions in asymptomatic volunteers across the adult lifespan. It was hypothesised that:

1. aging reduces the total lumbar lordosis and the total range of motion in flexion (RoF) and extension (RoE) of the lumbar spine,
2. locally, the change in lordosis and mobility with aging varies between different lumbar sub-regions,
3. the total lumbar lordosis is larger in females than in males.

Materials and Methods

Measuring system

The lumbar and thoraco-lumbar shape and the mobility of the spine in the sagittal plane were dynamically determined with the Epionics SPINE system (Epionics Medical GmbH, Potsdam, Germany). The system has the advantage over X-ray techniques that the volunteers are not exposed to radiation and thus several repeated measurements are possible. Furthermore, different sub-regions of the lumbar lordosis, including the lower, middle and upper lordosis, can be analysed. The high accuracy and reliability of the system was reported previously [40, 41].

The system consists of two flexible sensor strips, which are placed in hollow plasters onto the volunteers' back (Fig. 1). Each of the strips are positioned paravertebrally approximately 7.5 cm from the mid-sagittal plane while the lowest part of the strips is positioned at the level of the posterior superior iliac spine (approximately first sacral vertebra). Each sensor strip consists of twelve 25-mm-long single sensor units (Epionics segments: S1–S12) containing strain-gauge technology. Each sensor unit detects the local back curvature as illustrated in Fig. 1. The data from all 12 sensors is collected at 50 Hz and saved locally on a small storage unit (12.5 cm × 5.5 cm; mass: 120 g) carried on a belt, allowing free unhampered movements of the volunteer. An accelerometer is located at the lower end of each sensor strip to assess the orientation of the sensors in relation to earth's gravitational field. A detailed description of the system has been published elsewhere [40, 41].

Volunteers

Measurements were performed on 429 asymptomatic volunteers (198 males, 231 females). Subjects were free from acute low back pain and had no low back pain within the previous 6 months. Furthermore, volunteers had no previous spinal surgery.

Own validation and previously published studies showed that there is a significant correlation (Spearman's correlation: 0.86, $p<0.01$ [42]) between the total lumbar lordosis measured on the back and the radiologically determined lordosis in subjects with a BMI <26.0 kg/m^2. Moreover, this value of 26.0 kg/m^2 is considered as the normal-weight limit for subjects with an age similar to the mean age of the here investigated cohort (National Research Council, [43]) and was set to the BMI-limit in the present study.

The volunteers were classified for sex and assigned to four age groups: 20–29 years, 30–39 yrs, 40–49 yrs and>50 yrs, as was done in previous studies (e.g.: [15, 44]).

Measurement protocol

The volunteers performed standardised motion choreographies in the sagittal plane. For guidance and standardisation, the volunteers watched a video prior to the exercise, which explained and demonstrated the exercise. Starting from a

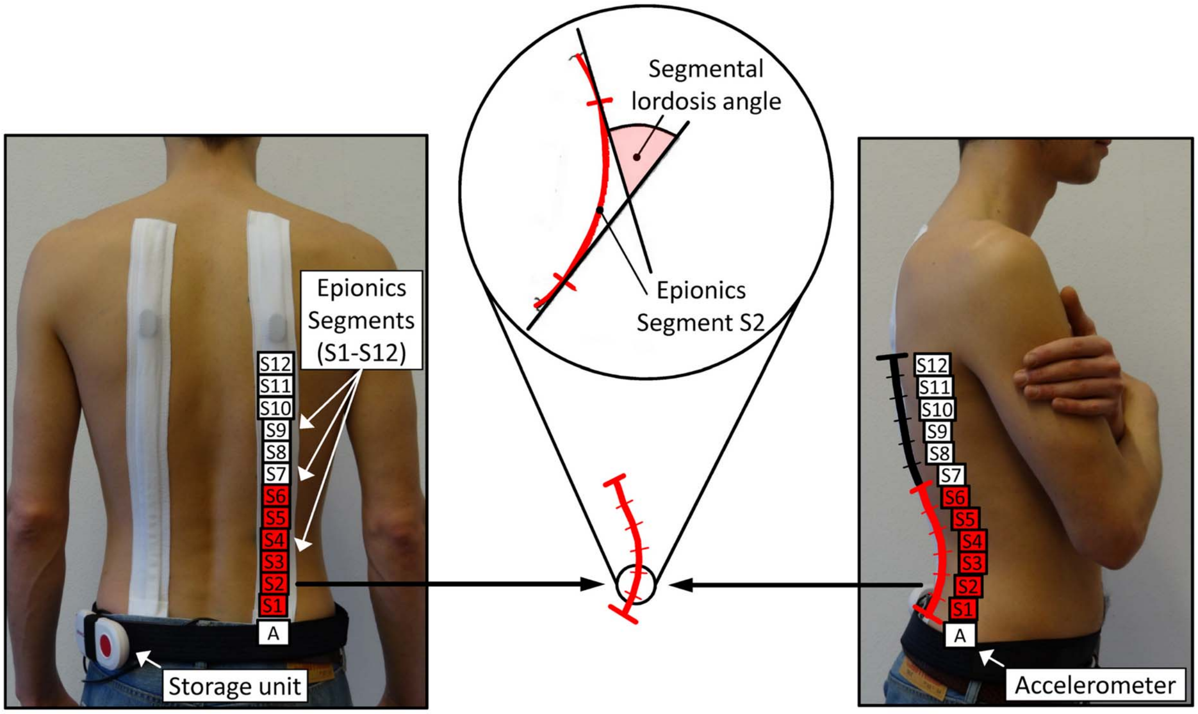

Fig. 1. Epionics SPINE system with the positions of the Epionics segments S1–S12. On average, the lumbar lordosis is covered by the first six segments (shown in red). Middle: Schematic sketch of the definition of the determined segmental angle is shown for a single exemplary sensor unit S2.

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relaxed standing position, the volunteers were asked to perform a maximal upper body flexion and extension with extended knees up to six times. Before each exercise, the subjects were measured in a relaxed standing position. Each volunteer performed the movements at his or her own preferred speed.

Data analysis

All Epionics sensor segments (S1–S12, Fig. 1) and the total lumbar lordosis were evaluated for the three investigated body positions: standing, maximal flexion and maximal extension of the upper body. The results of the left and right sensor strips were averaged. The total lumbar lordosis in standing of each volunteer was determined individually as the sum of all lordotically curved segments. The total angles for flexion and extension were calculated individually as the sum of the segments, which were identified as being lordotic during upright standing. The total RoF and RoE in the lumbar spine for each subject were calculated as the maximal or minimal angle difference with respect to standing.

Statistical Analysis

Descriptive statistics (mean, standard error, standard deviation) were analysed using SPSS 21.0 (SPSS Inc., Chicago IL, USA). The Kolmogorov-Smirnov test was performed to evaluate the normal distribution for each investigated group. In addition, the Levene's test was performed to test equality of variance. A two-way analysis of variance (ANOVA) with the factors age and sex was performed to evaluate the effects on the total lumbar lordosis, total RoF and total RoE. Subsequently, the mean values of the lordosis, RoF and RoE of the Epionics segments of different age groups were compared sex-specifically using a one-way ANOVA followed by post-hoc analysis using Scheffé's test. A *p*-value <0.01 was considered as statistically significant.

Ethics Statement

This study was approved by the Ethics Committee of the Charité – Universitätsmedizin Berlin (registry number EA4/011/10). The procedure of this study was explained to each volunteer in detail and they signed a written informed consent, which allows spinal shape determinations with the Epionics SPINE device.

Results

Volunteers

Due to the defined BMI-threshold of 26.0 kg/m^2, 106 volunteers were excluded from the initial sample of 429, which resulted in a final number of 323 subjects (males: 139, females: 184). The mean values for body height, body weight and BMI for all the age cohorts are given in Table 1.

Total and local lumbar lordosis during standing

The Kolmogorov-Smirnov test showed that the lumbar lordosis followed a normal distribution for both sexes. Two-way ANOVA demonstrated that the total lumbar lordosis was only significantly associated with age, but not with sex (Table 2). For the whole sample, this reduction of the total lordosis with age occurred with each consecutive age group (Fig. 2 top; Table 3). There was a significant reduction of approximately 7.4° (≈20%) between the youngest and the oldest cohort. This decrease was more evident in females, who showed a significant reduction of 7.9°, than in males with 6.7°, which was only close to significant ($p=0.034$). For both sexes, there was only a small lordosis reduction between 20–29 yrs and 30–39 yrs. In the following aging process, females showed a continuous decrease, while the reduction in males mostly occurred between the ages 30–39 yrs and 40–49 yrs. The smallest total lordosis in males was measured within the 40–49 yrs group. Post-hoc comparison demonstrated no statistical differences between the 40–49 yrs and>50 yrs age groups ($p=0.977$) in males, whereas there was a significant reduction of the lordosis between the 20–29 yrs and the 40–49 yrs age groups ($p=0.009$).

On average, the first six Epionics segments (S1–S6) were lordotic in the present cohort (Figs. 1, 3 A) and are therefore presented here. Epionics segments above

Table 1. Number of volunteers and mean values (standard deviation) for age, body height, body weight and body mass index.

		All	20–29 yrs	30–39 yrs	40–49 yrs	>50 yrs
Volunteers	**entire cohort**	323	115	70	71	67
	female	184	66	40	41	37
	male	139	49	30	30	30
Age (in years)	**entire cohort**	38.6 (14.0)	25.1 (2.7)	34.0 (3.3)	44.5 (3.2)	60.3 (7.9)
	female	38.4 (14.1)	24.8 (2.7)	34.0 (3.3)	44.2 (3.3)	60.8 (8.0)
	male	38.9 (13.7)	25.6 (2.8)	34.0 (3.3)	44.9 (3.1)	59.6 (7.8)
Body height (in cm)	**entire cohort**	173.0 (9.5)	173.8 (9.3)	173.2 (9.3)	172.9 (9.2)	171.5 (10.2)
	female	167.6 (6.9)	168.3 (7.0)	167.7 (6.4)	168.0 (7.2)	165.8 (7.0)
	male	180.1 (7.4)	181.2 (6.5)	180.6 (7.1)	179.6 (7.2)	178.4 (9.2)
Body weight (in kg)	**entire cohort**	67.6 (10.1)	66.9 (10.0)	66.7 (10.2)	68.6 (10.0)	68.6 (10.4)
	female	61.7 (7.5)	60.7 (6.8)	61.0 (8.2)	62.8 (7.6)	62.8 (7.7)
	male	75.4 (7.5)	75.1 (7.2)	74.3 (7.2)	76.6 (6.7)	75.8 (8.8)
BMI (in kg/m^2)	**entire cohort**	22.5 (2.0)	22.0 (1.9)	22.2 (2.2)	22.9 (2.0)	23.2 (1.8)
	female	21.9 (2.1)	21.4 (1.9)	21.7 (2.3)	22.2 (2.1)	22.8 (1.9)
	male	23.2 (1.7)	22.9 (1.7)	22.8 (1.9)	23.7 (1.4)	23.7 (1.4)

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those were part of the thoraco-lumbar transition and lower thoracic kyphosis. Locally for both sexes, the greatest loss of lordosis occurred in the middle part of the lordosis with a tendency towards the upper part. Generally, less reduction was

Table 2. Results of two-way analysis of variance (ANOVA) for age and sex for each of the three dependent variables: lumbar lordosis, range of flexion and range of extension.

	p-value	*Partial Eta-squared*
Total lumbar lordosis		
Age	<**0.001***	0.123
Sex	0.017	0.018
Age × Sex	0.287	0.012
Total range of flexion		
Age	<**0.001***	0.080
Sex	0.134	0.007
Age × Sex	0.212	0.014
Total range of extension		
Age	<**0.001***	0.132
Sex	<**0.001***	0.088
Age × Sex	0.188	0.015

*Statistically significant ($p<0.01$).

doi:10.1371/journal.pone.0116186.t002

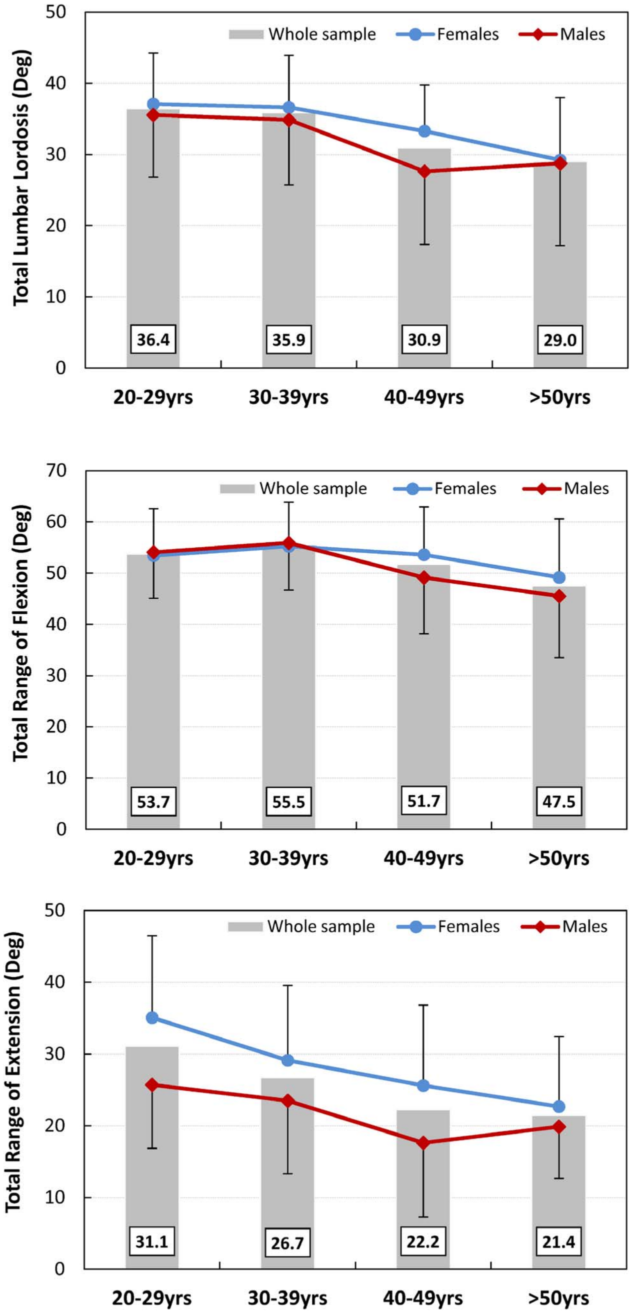

Fig. 2. Mean values of the total lumbar lordosis (top), total range of flexion (middle) and total range of extension (bottom) in all four investigated age groups for the whole cohort (grey columns). The red lines represent males and the blue lines females. Error bars represent the standard deviation.

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observed towards the thoraco-lumbar and lumbo-sacral transitions (Fig. 3B; Table 3). The largest absolute loss of lordosis between the youngest and oldest cohorts occurred in the Epionics segment S4 with values of 2–3°. The lower segments S1 and S2 and the upper segment S6 showed no significant differences

Table 3. Mean total lumbar lordosis (standard error; standard deviation) for investigated age groups.

	Parameter	20–29 yrs	30–39 yrs	40–49 yrs	>50 yrs	ANOVA p-value*	Post-hoc: 20–29 yrs vs.>50 yrs**
Entire cohort (n=323)	**Total Lumbar Lordosis**	36.4 (0.7; 7.9)	35.9 (1.0; 8.1)	30.9 (1.0; 8.7)	29.0 (1.2; 10.0)	<**0.001**	<**0.001**
	S1 Lordosis	5.6 (0.2; 2.4)	5.8 (0.3; 2.6)	5.4 (0.4; 3.2)	5.2 (0.4; 3.1)	0.599	0.752
	S2 Lordosis	6.3 (0.2; 2.3)	6.3 (0.3; 2.3)	5.5 (0.3; 2.5)	5.4 (0.4; 2.9)	0.020	0.085
	S3 Lordosis	7.3 (0.2; 2.1)	7.0 (0.3; 2.3)	6.0 (0.3; 2.3)	5.6 (0.3; 2.5)	<**0.001**	<**0.001**
	S4 Lordosis	6.7 (0.2; 1.8)	6.1 (0.2; 2.0)	5.0 (0.3; 2.3)	4.5 (0.3; 2.1)	<**0.001**	<**0.001**
	S5 Lordosis	5.1 (0.2; 1.8)	4.7 (0.2; 1.8)	3.7 (0.2; 2.1)	3.2 (0.2; 1.9)	<**0.001**	<**0.001**
	S6 Lordosis	3.2 (0.2; 1.8)	3.2 (0.2; 1.6)	2.5 (0.2; 2.0)	2.3 (0.2; 2.0)	**0.001**	0.015
Males (n=139)	**Total Lumbar Lordosis**	35.5 (1.2; 8.7)	34.9 (1.7; 9.1)	27.6 (1.9; 10.2)	28.8 (2.1; 11.6)	**0.001**	0.034
	S1 Lordosis	6.6 (0.3; 2.2)	7.0 (0.6; 3.3)	7.2 (0.7; 3.8)	6.7 (0.7; 3.7)	0.881	0.999
	S2 Lordosis	7.2 (0.3; 2.3)	6.9 (0.5; 2.9)	6.3 (0.6; 3.1)	6.5 (0.6; 3.3)	0.576	0.801
	S3 Lordosis	7.6 (0.3; 2.3)	7.1 (0.5; 2.7)	5.7 (0.4; 2.5)	6.0 (0.5; 2.6)	**0.003**	0.065
	S4 Lordosis	6.3 (0.3; 2.0)	5.7 (0.4; 2.2)	4.0 (0.4; 2.0)	4.1 (0.4; 2.1)	<**0.001**	<**0.001**
	S5 Lordosis	4.4 (0.3; 1.8)	4.1 (0.3; 1.9)	2.3 (0.3; 1.8)	2.4 (0.4; 2.0)	<**0.001**	<**0.001**
	S6 Lordosis	2.4 (0.2; 1.6)	2.6 (0.3; 1.8)	1.1 (0.3; 1.7)	1.3 (0.4; 2.0)	**0.001**	0.075
Females (n=184)	**Total Lumbar Lordosis**	37.1 (0.9; 7.2)	36.6 (1.2; 7.3)	33.3 (1.0; 6.4)	29.2 (1.4; 8.8)	<**0.001**	<**0.001**
	S1 Lordosis	4.9 (0.3; 2.3)	4.9 (0.2; 1.3)	4.2 (0.3; 2.0)	3.9 (0.3; 1.9)	0.041	0.119
	S2 Lordosis	5.7 (0.3; 2.1)	5.8 (0.3; 1.7)	4.9 (0.3; 1.8)	4.4 (0.4; 2.2)	**0.003**	0.016
	S3 Lordosis	7.1 (0.2; 1.9)	6.9 (0.3; 1.9)	6.2 (0.3; 2.2)	5.2 (0.4; 2.4)	<**0.001**	**0.001**
	S4 Lordosis	6.9 (0.2; 1.6)	6.4 (0.3; 1.9)	5.8 (0.3; 2.2)	4.8 (0.3; 2.1)	<**0.001**	<**0.001**
	S5 Lordosis	5.7 (0.2; 1.6)	5.1 (0.2; 1.5)	4.8 (0.2; 1.5)	3.9 (0.3; 1.6)	<**0.001**	<**0.001**
	S6 Lordosis	3.9 (0.2; 1.6)	3.8 (0.2; 1.3)	3.6 (0.2; 1.4)	3.1 (0.3; 1.6)	0.118	0.133

All measurements are in degrees.
Bold values indicate statistical significance ($p<0.01$).
*p-values base on one-way ANOVA. **Post-hoc comparison using Scheffé's test.

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for the whole sample, nor for males and females separately. For the relative change, the lordosis of the youngest cohort was set to 100% in Fig. 3 C. In males, the largest relative reduction of the lordosis occured in S6 (to 54% of the reference) with continuously less reduction towards the most caudal segment S1 (to 101%). In females, the largest relative reduction occurred in S5 (to 69%), with continuously less reduction to the most caudal segment S1 (to 80%) and furthermore less in S6 (to 81%). These local changes in males and females led to a characteristic change between the 'young' and the 'old' lordosis as illustrated in Fig. 4.

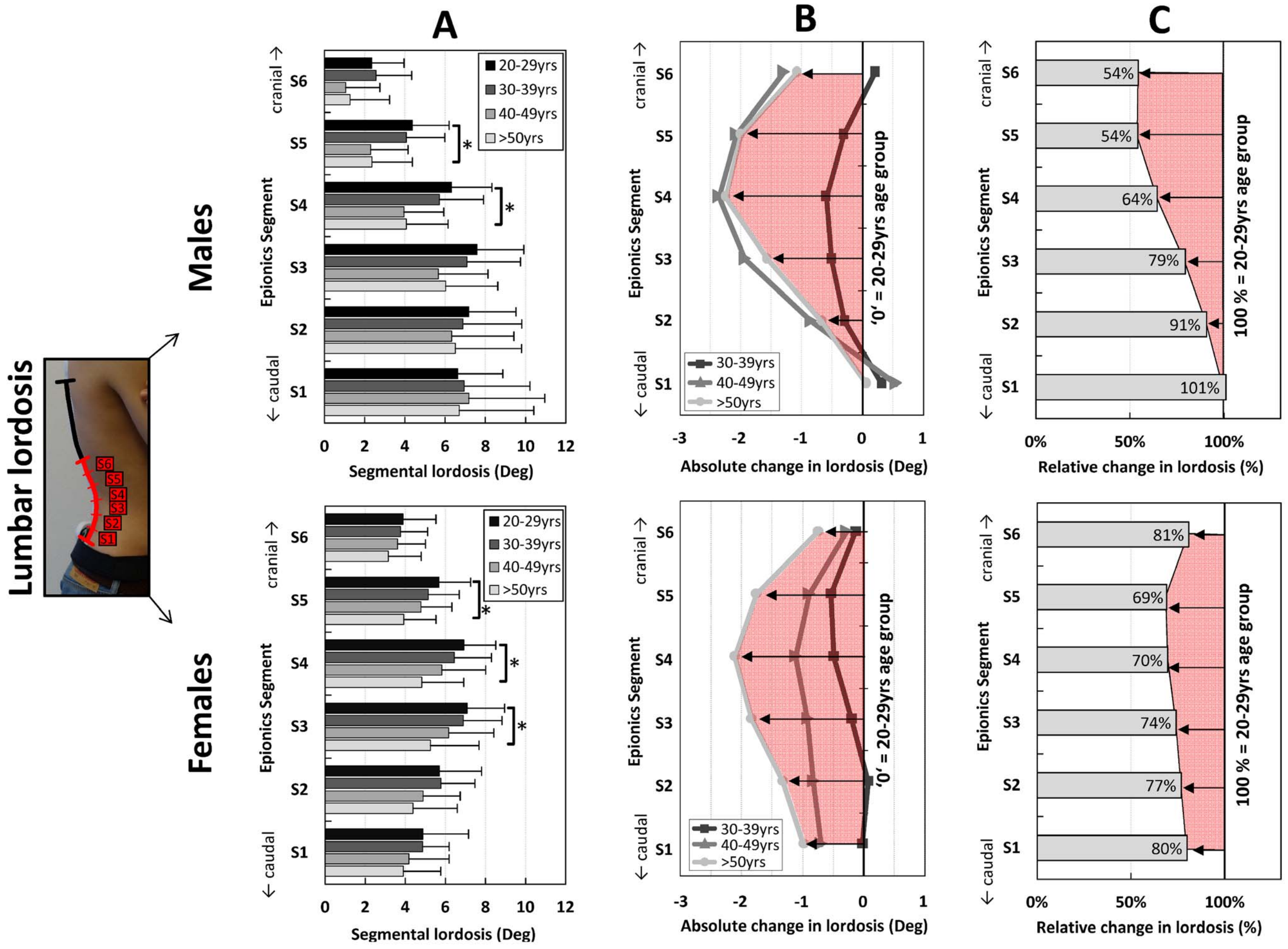

Fig. 3. Mean values of the segmental lordosis for the Epionics segments S1 to S6 in all investigated age groups (**A**). Males (above) and females (below) are shown separately. Error bars represent the standard deviation. (**B**): Absolute change in segmental lordosis for the Epionics segments S1 to S6 in all investigated age groups in relation to the youngest cohort (20–29 yrs) for males (above) and females (below) separately. The youngest cohort is normalised to 'zero' as a reference. The red area highlights the pattern of the absolute change between the oldest and youngest cohorts. (**C**): Relative change in segmental lordosis for the Epionics segments S1 to S6 between the oldest and youngest age groups for males (above) and females (below) separately. The youngest cohort is normalised to 100% as a reference. Values indicate the percentage of lordosis that the oldest cohort possesses in relation to the youngest cohort. The red area highlights the pattern of the relative changes between the oldest and youngest cohorts.

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Total and local range of flexion and extension during standing

The Kolmogorov-Smirnov test showed that the RoF and RoE were normally distributed in male and female cohorts. The total RoF and RoE were significantly associated with age (Table 2). Moreover, the total RoE, but not the total RoF, was significantly associated with sex.

For the whole sample as well as for males and females separately, the total RoF showed no significant difference between the 20–29 yrs and 30–39 yrs age cohorts, but a consecutive decrease for the subsequent age groups (Fig. 2 middle; Table 4). Although significant, the total RoF was reduced by only approximately 12% (6.2°) when comparing the youngest and oldest cohorts of the whole sample.

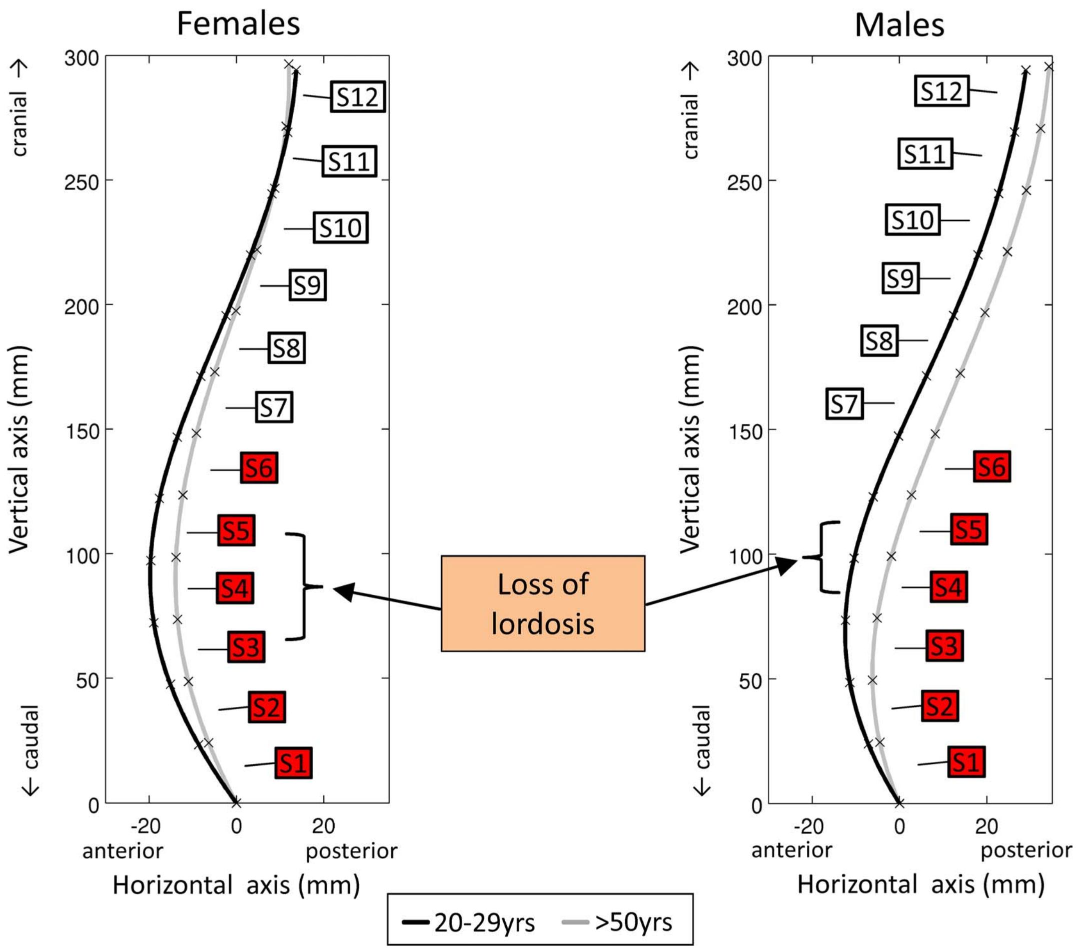

Fig. 4. Age-related postural adaptations of the 12 Epionics segments between the oldest and youngest age cohorts for females (left) and males (right).

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This decrease was only significant for males, with a loss of 8.6°. In females, the reduction was only 4.2°.

Males and females showed similar local patterns for the reduction of the RoF with increasing age. This local reduction was most dominantly in the middle part (S3, S4) of the lumbar region (Fig. 5 A, B; Table 4). In general, the Epionics segments close to the thoraco-lumbar and lumbo-sacral transition (S1, S6) showed non-significant absolute changes with increasing age. Males tended to display a slightly greater reduction relative to the youngest cohort than females, with the greatest loss in segment S5 (to 73% of the reference; Fig. 5 C). In females, the largest relative reduction occurred in S4 (to 80%).

The total RoE of the whole sample was reduced for each consecutive age cohort and was significantly decreased by approximately 31% when comparing the youngest and oldest cohort (Fig. 2 bottom; Table 4). The loss of the RoE was more pronounced and only significant in females (12.4°). Males showed a smaller

Table 4. Mean range of flexion (RoF) and range of extension (RoE) (standard error; standard deviation) for investigated age groups.

	Parameter	20–29 yrs	30–39 yrs	40–49 yrs	>50 yrs	*ANOVA p-value**	*Post-hoc: 20–29 yrs vs.>50 yrs***
Entire cohort (n=323)	**Total range of flexion**	53.7 (0.8; 9.0)	55.5 (1.1; 8.8)	51.7 (1.2; 10.2)	47.5 (1.4; 11.8)	<**0.001***	**0.001***
	RoF S1	6.6 (0.2; 2.5)	7.3 (0.3; 2.7)	7.3 (0.4; 3.3)	7.1 (0.3; 2.5)	0.270	0.720
	RoF S2	8.8 (0.2; 2.2)	9.0 (0.3; 2.3)	8.2 (0.3; 2.3)	7.8 (0.3; 2.3)	**0.006***	0.046
	RoF S3	10.9 (0.2; 2.3)	10.6 (0.3; 2.4)	9.6 (0.3; 2.2)	8.7 (0.3; 2.4)	<**0.001***	<**0.001***
	RoF S4	10.2 (0.2; 2.3)	9.7 (0.3; 2.1)	9.0 (0.2; 2.1)	7.9 (0.3; 2.3)	<**0.001***	<**0.001***
	RoF S5	7.8 (0.2; 2.2)	7.7 (0.2; 1.9)	7.5 (0.2; 2.0)	6.4 (0.3; 2.1)	<**0.001***	<**0.001***
	RoF S6	4.9 (0.2; 1.9)	5.3 (0.2; 1.7)	5.4 (0.3; 2.1)	4.8 (0.3; 2.1)	0.211	0.986
	Total range of extension	31.1 (1.1; 11.3)	26.7 (1.3; 10.6)	22.2 (1.4; 11.5)	21.4 (1.1; 8.8)	<**0.001***	<**0.001***
	RoE S1	5.4 (0.3; 3.3)	4.7 (0.3; 2.4)	4.2 (0.4; 3.1)	3.9 (0.3; 2.8)	**0.007***	0.017
	RoE S2	7.0 (0.3; 2.9)	5.9 (0.3; 2.6)	4.5 (0.3; 2.8)	3.8 (0.3; 2.3)	<**0.001***	<**0.001***
	RoE S3	7.9 (0.3; 3.0)	6.5 (0.3; 2.8)	4.6 (0.4; 3.1)	3.9 (0.3; 2.2)	<**0.001***	<**0.001***
	RoE S4	6.2 (0.3; 3.0)	5.0 (0.3; 2.5)	3.6 (0.3; 2.9)	3.4 (0.2; 2.0)	<**0.001***	<**0.001***
	RoE S5	3.4 (0.2; 2.6)	2.8 (0.2; 2.0)	2.5 (0.3; 2.2)	2.7 (0.2; 1.8)	0.038	0.311
	RoE S6	1.2 (0.2; 2.3)	1.3 (0.2; 2.0)	1.6 (0.2; 2.0)	2.1 (0.2; 1.8)	0.032	0.048
Males (n=139)	**Total range of flexion**	54.1 (1.3; 9.0)	55.9 (1.7; 9.2)	49.1 (2.0; 10.9)	45.5 (2.2; 12.0)	<**0.001***	**0.005**
	RoF S1	7.2 (0.4; 2.6)	8.1 (0.7; 3.6)	8.8 (0.7; 3.9)	7.7 (0.6; 3.1)	0.191	0.931
	RoF S2	9.5 (0.3; 2.3)	9.6 (0.5; 2.8)	9.2 (0.5; 2.8)	8.3 (0.5; 2.5)	0.182	0.274
	RoF S3	11.5 (0.3; 2.4)	11.1 (0.5; 2.6)	9.8 (0.4; 2.4)	9.2 (0.4; 2.4)	<**0.001***	**0.002**
	RoF S4	10.6 (0.3; 2.3)	10.1 (0.4; 2.2)	8.6 (0.4; 2.2)	7.9 (0.4; 2.3)	<**0.001***	<**0.001***
	RoF S5	8.2 (0.3; 2.1)	8.1 (0.4; 2.1)	6.8 (0.4; 2.0)	5.9 (0.4; 2.1)	<**0.001***	<**0.001***
	RoF S6	4.9 (0.3; 1.8)	5.4 (0.4; 2.0)	4.7 (0.4; 2.2)	4.0 (0.4; 2.0)	0.072	0.334
	Total range of extension	25.7 (1.3; 8.8)	23.5 (1.9; 10.2)	17.6 (1.9; 10.3)	19.9 (1.3; 7.2)	**0.001***	0.061
	RoE S1	5.3 (0.4; 2.9)	4.4 (0.4; 2.3)	4.9 (0.6; 3.5)	5.0 (0.5; 2.9)	0.601	0.973
	RoE S2	6.5 (0.4; 2.6)	5.3 (0.5; 2.6)	4.2 (0.5; 2.7)	4.3 (0.4; 2.1)	<**0.001***	**0.005**
	RoE S3	6.8 (0.4; 2.6)	5.7 (0.5; 2.9)	3.5 (0.5; 2.5)	3.9 (0.4; 2.0)	<**0.001***	<**0.001***
	RoE S4	4.7 (0.3; 2.4)	4.2 (0.5; 2.5)	2.1 (0.4; 2.3)	2.9 (0.4; 2.0)	<**0.001***	0.013
	RoE S5	2.2 (0.3; 2.1)	2.4 (0.3; 1.9)	1.3 (0.4; 2.0)	2.0 (0.4; 1.9)	0.184	0.990
	RoE S6	0.5 (0.3; 1.8)	1.1 (0.3; 1.6)	1.0 (0.3; 1.9)	1.4 (0.3; 1.7)	0.160	0.204
Females (n=184)	**Total range of flexion**	53.4 (1.1; 9.1)	55.2 (1.4; 8.6)	53.6 (1.5; 9.3)	49.2 (1.9; 11.5)	0.041	0.199
	RoF S1	6.2 (0.3; 2.3)	6.6 (0.2; 1.5)	6.3 (0.3; 2.2)	6.6 (0.3; 1.9)	0.633	0.788
	RoF S2	8.3 (0.2; 1.9)	8.5 (0.3; 1.7)	7.5 (0.3; 1.7)	7.4 (0.3; 2.1)	0.012	0.151
	RoF S3	10.4 (0.3; 2.1)	10.2 (0.3; 2.1)	9.4 (0.3; 2.1)	8.4 (0.4; 2.4)	<**0.001***	<**0.001***
	RoF S4	9.9 (0.3; 2.2)	9.5 (0.3; 2.2)	9.3 (0.3; 2.0)	7.9 (0.4; 2.4)	<**0.001***	<**0.001***
	RoF S5	7.6 (0.3; 2.3)	7.5 (0.3; 1.8)	8.0 (0.3; 1.9)	6.9 (0.3; 2.0)	0.126	0.392
	RoF S6	4.9 (0.3; 2.0)	5.2 (0.2; 1.5)	5.8 (0.3; 2.0)	5.4 (0.3; 2.0)	0.121	0.677
	Total range of extension	35.1 (1.4; 11.4)	29.1 (1.6; 10.4)	25.6 (1.8; 11.2)	22.7 (1.6; 9.7)	<**0.001***	<**0.001***
	RoE S1	5.3 (0.4; 3.6)	4.9 (0.4; 2.5)	3.8 (0.4; 2.8)	3.0 (0.4; 2.3)	<**0.001***	**0.002**
	RoE S2	7.4 (0.4; 3.1)	6.3 (0.4; 2.6)	4.7 (0.4; 2.8)	3.4 (0.4; 2.3)	<**0.001***	<**0.001***

Table 4. Cont.

	Parameter	20–29 yrs	30–39 yrs	40–49 yrs	>50 yrs	*ANOVA p-value**	*Post-hoc: 20–29 yrs vs.>50 yrs***
	RoE S3	8.7 (0.4; 3.0)	7.1 (0.4; 2.7)	5.5 (0.5; 3.2)	4.0 (0.4; 2.5)	**<0.001***	**<0.001***
	RoE S4	7.3 (0.4; 2.9)	5.5 (0.4; 2.4)	4.8 (0.4; 2.8)	3.7 (0.3; 1.9)	**<0.001***	**<0.001***
	RoE S5	4.3 (0.3; 2.6)	3.2 (0.3; 2.1)	3.3 (0.3; 2.0)	3.3 (0.2; 1.5)	0.026	0.192
	RoE S6	1.7 (0.3; 2.5)	1.4 (0.4; 2.2)	2.1 (0.3; 2.1)	2.7 (0.3; 1.8)	0.067	0.205

All measurements are in degrees.
Bold values indicate statistical significance (p<0.01).
*p-values base on one-way ANOVA. **Post-hoc comparison using Scheffé's test.

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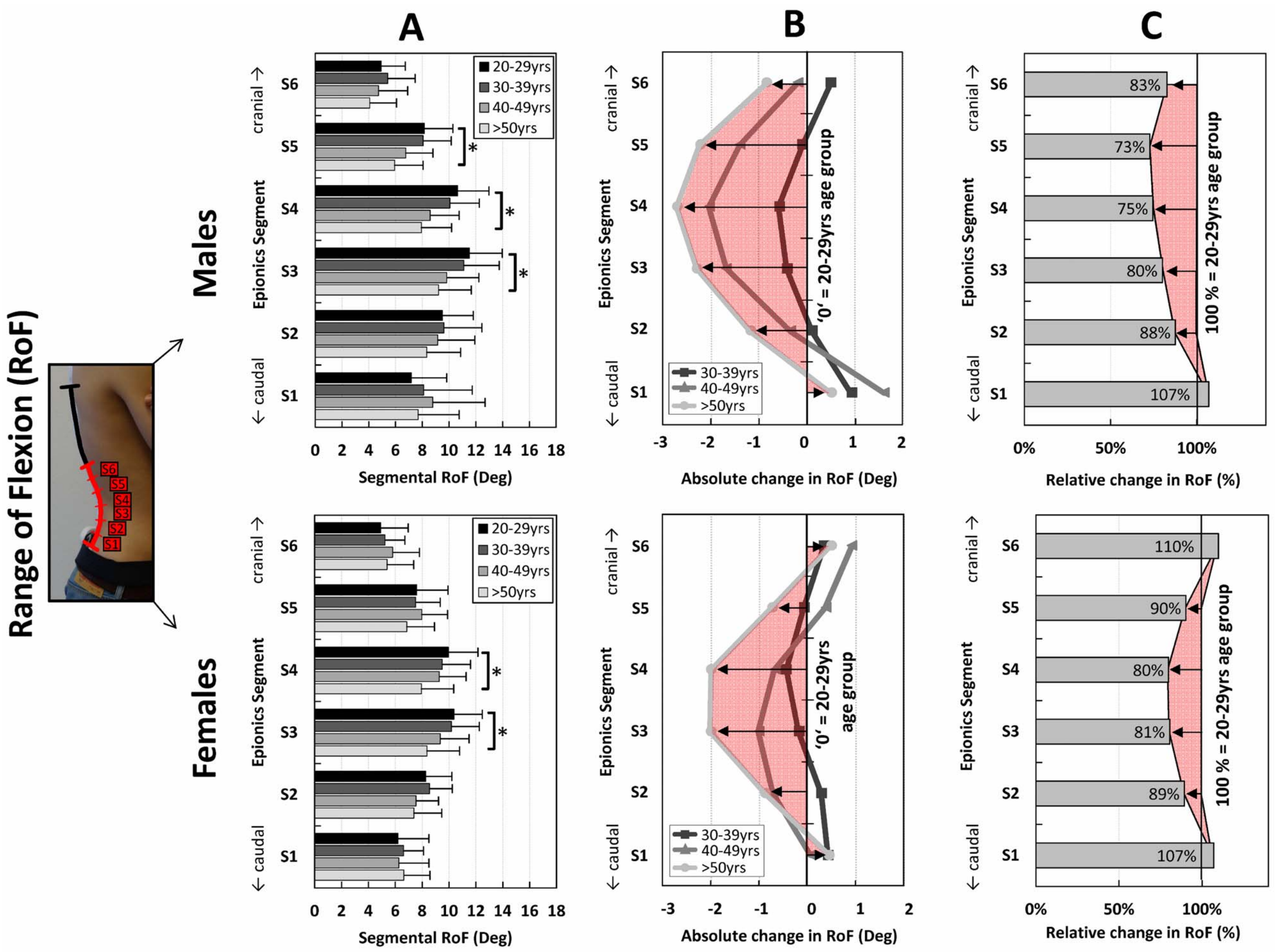

Fig. 5. Mean values of the segmental range of flexion (RoF) for the Epionics segments S1 to S6 in all investigated age groups (**A**). Males (above) and females (below) are shown separately. Error bars represent the standard deviation. (**B**): Absolute change in the segmental RoF for the Epionics segments S1 to S6 in all investigated age groups in relation to the youngest cohort (20–29 yrs) for males (above) and females (below) separately. The youngest cohort is normalised to a value of 'zero' as a reference. The red area highlights the pattern of the absolute change between the oldest and youngest cohort. (**C**): Relative change in the segmental RoF for the Epionics segments S1 to S6 between oldest and youngest age groups for males (above) and females (below) separately. The youngest cohort is normalised to 100% as a reference. Values indicate the percentage of the RoF the oldest cohort possesses in relation to the youngest cohort. The red area highlights the pattern of the relative changes between the oldest and youngest cohorts.

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reduction of only 5.8°. Independent of age, males had a smaller total RoE than females.

For the local RoE, males and females both showed the largest absolute reduction in the middle part of the lordosis (S3; Fig. 6 A, B) and, similar to the local RoF, less reduction towards the transition zones. However, in females, the absolute and relative reductions were more pronounced in the middle and lower Epionics segments (Fig. 6 C). Males showed no significant and only small relative changes in the Epionics segment S1. In both sexes only small non-significant changes in the RoE occurred in segments close to the thoraco-lumbar transition (S5, S6).

Discussion

This study investigated the effect of age and sex on the lordosis and the RoM of the whole lumbar spine as well as for different lumbar sub-regions in asymptomatic volunteers across the adult lifespan. The results of the present study emphasise the importance of the factor age on the lumbar lordosis and the RoM. We demonstrated that the age-related changes in the lordosis and the RoM differ between men and women and are strongly level dependent. The lordosis and RoM in the middle part of the lumbar spine are dominantly reduced with aging, with less reduction towards the lumbo-sacral and thoraco-lumbar transitions. The sex affects only the RoE.

The loss of total lordosis with aging as demonstrated in this study (Fig. 4) is in agreement with measurements in the literature [9, 11, 17] and corroborates our first hypothesis. This study provides evidence that this aging process is not uniform throughout lifespan and differs between males and females. In both sexes, the decrease of lordosis appears only marginal between 20–29 yrs and 30–39 yrs. While in females the process of aging is subsequently more continuous, the loss of lordosis in males mostly occurs between the 30–39 yrs and 40–49 yrs age groups. This discontinuous loss of lordosis explains why in some studies, in which only cohorts older than 40 years with no young control group were investigated, no significant loss of lordosis was found [14, 20]. In the present study, a high inter-subject variability was found, which necessitates a sufficient cohort size with a homogeneous composition to detect these age effects. Furthermore, in the present study, asymptomatic subjects were investigated, whereas in other studies subjects with acute or chronic low back pain participated. However, the change in lordosis during aging differs between asymptomatic and symptomatic subjects, because the latter may already have, for example, a flat sagittal alignment or spinal diseases that affected the spinal curvature during an earlier stage of life [1–3]. Similar to the lordosis in standing, aging is also the crucial factor for a reduction in total RoM, especially in extension, where it is reduced by 31% between the oldest and youngest cohorts. This is consistent with previous studies [38, 39, 45].

In opposite to our third hypothesis, the lumbar lordosis was not significantly different between both sexes, which is in agreement with several studies

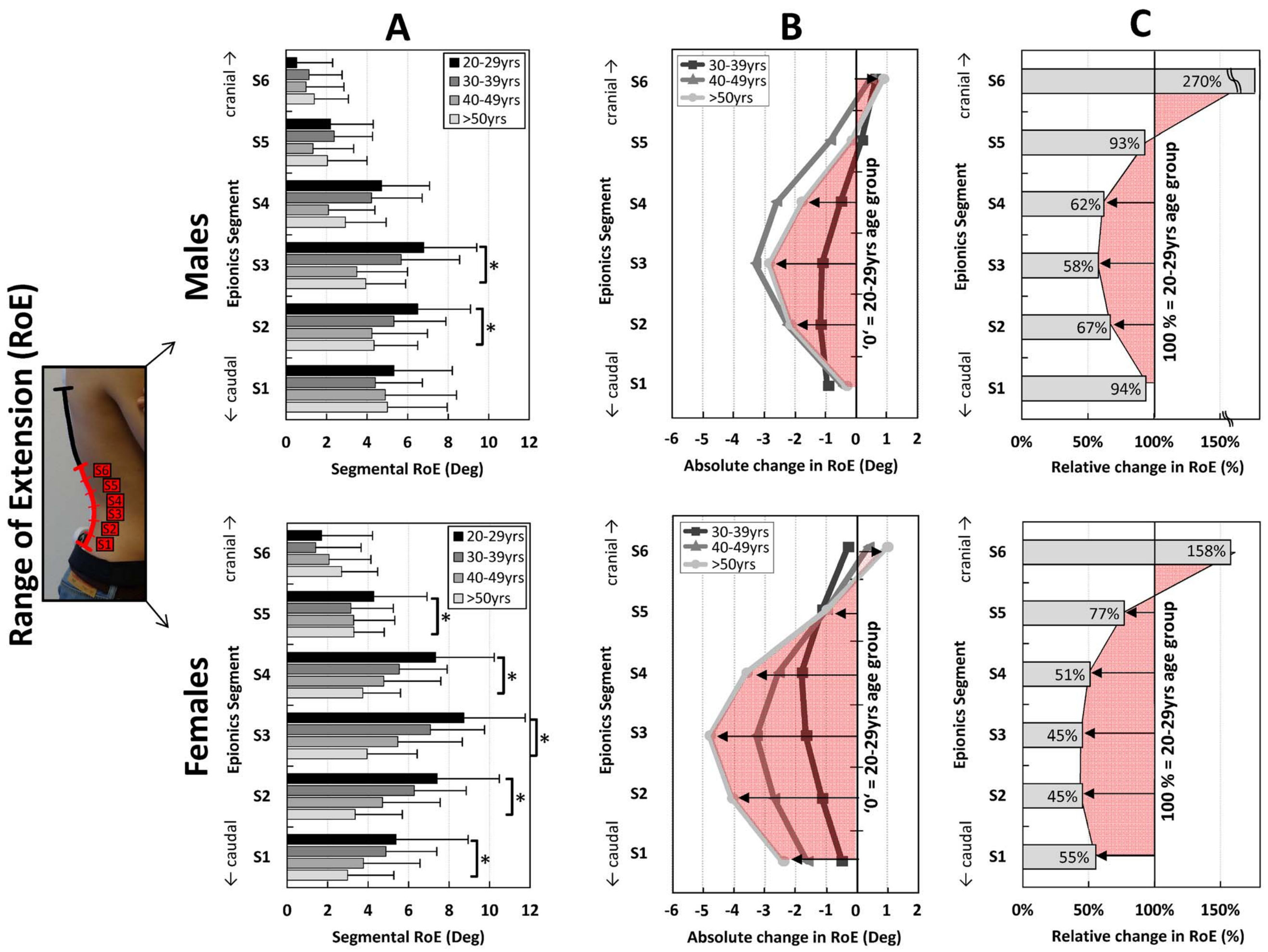

Fig. 6. Mean values of the segmental range of extension (RoE) for the Epionics segments S1 to S6 in all investigated age groups (**A**). Males (above) and females (below) are shown separately. Error bars represent the standard deviation. (**B**): Absolute change in the segmental RoE for the Epionics segments S1 to S6 in all investigated age groups in relation to the youngest cohort (20–29 yrs) for males (above) and females (below) separately. The youngest cohort is normalised to 'zero' as a reference. The red area highlights the pattern of the absolute change between the oldest and youngest cohort. (**C**): Relative change in the segmental RoE for the Epionics segments S1 to S6 between the oldest and youngest age groups for males (above) and females (below) separately. The youngest cohort is normalised to 100% as a reference. Values indicate the percentage of the RoE the oldest cohort possesses in relation to the youngest cohort. The red area highlights the pattern of the relative changes between oldest and youngest cohorts.

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[9, 14, 24, 26], however in opposite to other investigations [12, 46]. The present study suggests that the difference in lordosis between men and women is small and varies between age groups. This might partly explain why studies with varying cohort sizes and different mean ages show contradictory results. Furthermore, in this sample, only subjects with a BMI <26.0 kg/m^2 participated, which resulted in a mean BMI of 22.5 kg/m^2. Therefore, the impact of being overweight or obese was not investigated.

Currently, a detailed investigation of the age effect on certain regions of the lordosis and its motion is lacking in the literature. In accordance with our second hypothesis, the lower Epionics segments were less affected by aging than the middle segments, which characteristically changes the total lordosis and 'concentrates' the lordotic shape of the lumbar spine to the lower segments. Only one radiological study on a small cohort supports our findings of a significant correlation between age and lordosis loss restricted to the middle lordosis (L3–4) [9]. Only a trend was observed in the adjacent segments L2–3 and L4–5, and no significant influence was found in L5–S1. Previous studies reported a close relationship between the morphology of the pelvis, as, for example, characterised by the pelvic incidence [47], and the degree of total lumbar lordosis [25, 26, 48, 49]. The level specific changes in lumbar lordosis during aging suggest that different parts of the lumbar spine may substantially change their relationship to the individual pelvic incidence.

In analogy to the aging process of the lordosis, the RoM characteristically changes with age. The RoM in the middle lumbar lordosis also decreases, whereas the RoM next to the thoracic and sacral transitions only shows a small change. Therefore, not only the lower lumbar lordosis but also its mobility is preserved during aging. These facts may have important implications for the spinal loading and the prevalent degeneration process in the lower lumbar spine during life, and could help to understand the mechanical challenges the lower lumbar spine has to withstand. However, these results also have consequences for the treatment of degenerative spinal diseases. Because the shape and motion differently change for certain regions of the lumbar spine, an age- and lumbar level-specific treatment may be important for long-term patient satisfaction.

This study emphasises that a reduction of the lordosis in symptomatic subjects with a severe, painful degenerated lumbar spine partly consists of a natural adaptive process during aging, which also occurs in asymptomatic subjects. Knowledge of this physiological loss of lordosis in asymptomatic individuals may, however, be essential for surgical reconstruction concepts of the sagittal alignment of the spine. In these concepts, the degree of lordosis is estimated mostly with the help of the individual pelvic incidence of the patient, which is assumed to be independent of posture and age (e.g.: lumbar lordosis = pelvic incidence $\pm 9°$; [50]). Because of the physiological loss of lordosis with aging, the relationship between the lumbar lordosis and pelvic incidence appears to also be dependent on age. Therefore, an optimal patient-specific reconstruction may require an age dependent estimation of the lordosis.

Although the results presented here are consistent with radiological measurements, it should be noted that the Epionics SPINE system determines the curvature of the back and not directly the shape of the spine. Multiple studies previously demonstrated that the curvature and motion measured on the back and the spine significantly correlate with each other [42, 51, 52]. In our own preliminary validation studies, we could additionally show that the correlation between the back and spinal shape is poor in overweight and obese persons, which limits this study to normal-weight subjects (BMI <26.0 kg/m^2). However, this study investigated the spinal shape and motion of a large asymptomatic cohort for which a radiological study design is ethically not supportable. Furthermore, this study is limited by investigating the motion only in the sagittal plane, although the motion of the lumbar spine in other anatomical planes such as during axial rotation and lateral bending might be affected by aging as well.

In conclusion, this study characterises the adaptive response of the lumbar spinal shape and its mobility as a function of age in asymptomatic males and females. While the lower part of the lumbar spine retains its lordosis and mobility, the middle part flattens and becomes less mobile. This may have important implications for the clinical long-term success of different surgical interventions, for instance for the surgical reconstruction of the sagittal alignment. Furthermore, the results can help to better understand the incidence of level- and age-dependent spinal disorders, and are essential for patient specific treatments and an evidence-based distinction between painful degenerative pathologies and asymptomatic aging.

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Author Contributions

Conceived and designed the experiments: MD AR HS. Performed the experiments: MD LA AR HS. Analyzed the data: MD LA AR EP MB TZ GD CD PS MP HS. Wrote the paper: MD LA AR EP MB TZ GD CD PS MP HS.

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