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Full Length Article

Multi-segmental thoracic spine kinematics measured dynamically in the young and elderly during flexion

Dominika Ignasiak[a,*], Andrea Rüeger[b], Stephen J. Ferguson[a]

[a] *Institute for Biomechanics, ETH Zurich, Zurich, Switzerland*
[b] *Schulthess Clinic, Zurich, Switzerland*

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ABSTRACT

In contrast to the cervical and lumbar region, the normal kinematics of the thoracic spine have not been thoroughly investigated. The aim of this study was to characterize normal multi-segmental continuous motion of the whole thoracolumbar spine, during a flexion maneuver, in young and elderly subjects. Forty-two healthy volunteers were analyzed: 21 young (age = 27.00 ± 3.96) and 21 elderly (age = 70.1 ± 3.85). Spinal motion was recorded with a motion-capture system and analyzed using a 3rd order polynomial function to approximate spinal curvature throughout the motion sequence. The average motion profiles of the two age groups were characterized. Flexion timing of the thoracic region of the spine, as compared to the lumbar spine and hips, was found to be different in the two age groups ($p = 0.011$): a delayed/sequential motion type was observed in most of the young, whereas mostly a simultaneous motion pattern was observed in the elderly subjects. A similar trend was observed in flexion of the lower thoracic segments ($p = 0.017$). Differences between age groups were also found for regional and segmental displacements and velocities. The reported characterization of the thoracic spine kinematics may in the future support identification of abnormal movement or be used to improve biomechanical models of the spine.

1. Introduction

Analysis of spine kinematics provides invaluable information on spine function, which can greatly support diagnosis and management of spinal degenerative and pathological processes. Differences in lumbar spine motion characteristics have been observed in persons of advanced age (Intolo et al., 2009; Wong, Leong, Chan, Luk, & Lu, 2004), suffering from low back pain (Teyhen et al., 2007; Wong & Lee, 2004) or lumbar segmental instability (Ahmadi, Maroufi, Behtash, Zekavat, & Parnianpour, 2009; Okawa et al., 1998) when compared to healthy young subjects. Also, abnormal cervical spine kinematics was observed in patients with such dysfunctions as chronic neck pain (Sarig Bahat, Chen, Reznik, Kodesh, & Treleaven, 2015; Tsang, Szeto, & Lee, 2013a) and rheumatoid arthritis (Sugiura et al., 2014). In order to identify such pathological motion patterns, normative databases have to be established. In contrast to the extensive knowledge on the normal kinematics of the lumbar (Wong et al., 2004) and cervical (Anderst, Donaldson, Lee, & Kang, 2014; Tsang, Szeto, & Lee, 2013b) spine regions, only limited information has been reported on normal thoracic spine kinematics. A better understanding of thoracic spine motion could assist diagnosis and therapy of spinal disorders typical for this region, such as thoracic back pain, hyperkyphotic or scoliotic deformities or vertebral fractures.

Thoracic spine flexibility has been studied in vitro on cadaveric specimens (Oda, Abumi, Cunningham, Kaneda, & McAfee, 2002;

* Corresponding author at: Institute for Biomechanics, ETH Zurich, Hönggerbergring 64, HPP-O24, 8093 Zurich, Switzerland.
E-mail address: dignasiak@ethz.ch (D. Ignasiak).

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Panjabi, Brand, & White, 1976) using standardized and simplified loading conditions, typically pure moment multi-axial bending. However, the results potentially might not reflect thoracic spine biomechanics *in vivo*, where motion is influenced by the effects of the ribcage, ligaments, muscles and intrathoracic pressure. Radiographic *in vivo* studies of thoracic kinematics have often been limited to assumed body positions investigated in a static manner (Edmondston, Christensen, Keller, Steigen, & Barclay, 2012; Fujimori et al., 2014). This approach allows for estimation of range of motion or the amount of coupled motion, but lacks the continuous aspect that could allow assessment of higher order kinematics, which could be particularly important for discrimination of pathologies (Lehman, 2004). Continuously measured kinematics of the thoracic spine have been reported for several tasks, but based on the motion analysis of relatively large spine regions (List, Gulay, Stoop, & Lorenzetti, 2013), which lacked a multi-segmental approach important to allow differentiation of individual motion patterns (Preuss & Popovic, 2010). A continuous and multi-segmental description of normal thoracic kinematics during full-range flexion, which imposes relatively large moments and loads on the spine, appears necessary for future biomechanical investigations of thoracic back pain, deformities, or vertebral fractures – problems related to thoracic segmental overloading.

Motion capture technology based on reflective skin markers allows for non-invasive and continuous quantification of spinal motion *in vivo*, without imposing much restriction to subjects' movement. By application of multiple markers, the motion of multiple spine segments can be tracked, e.g. using a detailed trunk marker set developed in the Institute for Biomechanics at ETH Zurich (List et al., 2013). This marker set was previously validated for the assessment of spinal sagittal curvature changes in the healthy individuals (Zemp et al., 2014).

Therefore, the main aim of this study was to investigate normal multi-segmental motion profiles of the whole thoracic spine, coupled with the lumbar spine, recorded continuously *in vivo* with motion capture technology during a flexion maneuver performed by a sample of healthy young and elderly subjects. A reduction in lumbar mobility (Intolo et al., 2009) and velocity (McGill, Yingling, & Peach, 1999), as well as change in lumbar movement patterns (Wong et al., 2004) have been previously reported for the older population. We hypothesized that the thoracic spine kinematics of the elderly will also present different characteristics than that of the young.

2. Methods

2.1. Participants

A sample of convenience of forty-four healthy volunteers was recruited in this pilot study, but the data quality allowed motion analysis of forty-two of them (16 male and 26 female). They were divided into two age groups: young, aged 18–35, and elderly, aged 65 and older (Table 1). Volunteers that had ever undergone a spinal surgery, had a chronic spine disorder, had suffered from back pain or had been treated for spinal problems within 6 months prior to measurement, or reported pregnancy, were excluded from the study. The volunteers had no severe frontal plane deformities (as noted by the physiotherapist performing the measurements), and their sagittal posture was confirmed with SpinalMouse device (Mannion, Knecht, Balaban, Dvorak, & Grob, 2004) to be within normal range, with the elderly showing slightly higher thoracic kyphosis angles (for details see Supplementary Material 1). All participants provided a written consent after receiving detailed information about the study. The study protocol was approved by Eidgenössische Technische Hochschule (ETH) Zurich Ethics Committee.

2.2. Motion capture system

A three-dimensional motion capture system with 12 infrared cameras was used (VICON MX, Oxford Metrics Group, Oxford, UK). The camera resolution was 2352 × 1728 pixels, and the recording frequency was 100 Hz. The marker set used for optical tracking of the body kinematics consisted of 75 reflective skin markers, including a full-body marker set, enhanced by a detailed trunk marker set with 11 markers applied over the spinous processes of the following vertebrae: C7, T3, T5, T7, T9, T11, L1, L2, L3, L4, and L5, as described in (List et al., 2013). In order to minimize intra-observer errors, the palpation of anatomical landmarks and application of skin markers was performed by a single experienced physiotherapist.

Table 1
Demographic data of the recruited sample (mean values and standard deviations).

	Young (N = 21)	Elderly (N = 21)
Gender	13f + 8 m	13f + 8 m
Age range [y.]	20–35	65–80
Mean age [y.]	27.00 ± 3.96	70.10 ± 3.85
Weight [kg][#]	68.33 ± 13.73	67.48 ± 11.31
Height [cm][#]	173.29 ± 9.5	168.52 ± 8.85
BMI [kg/m^2][#]	22.56 ± 2.90	23.72 ± 3.15

[#] Results for two-sample t-tests between two groups show no significant difference (at 5% significance level).

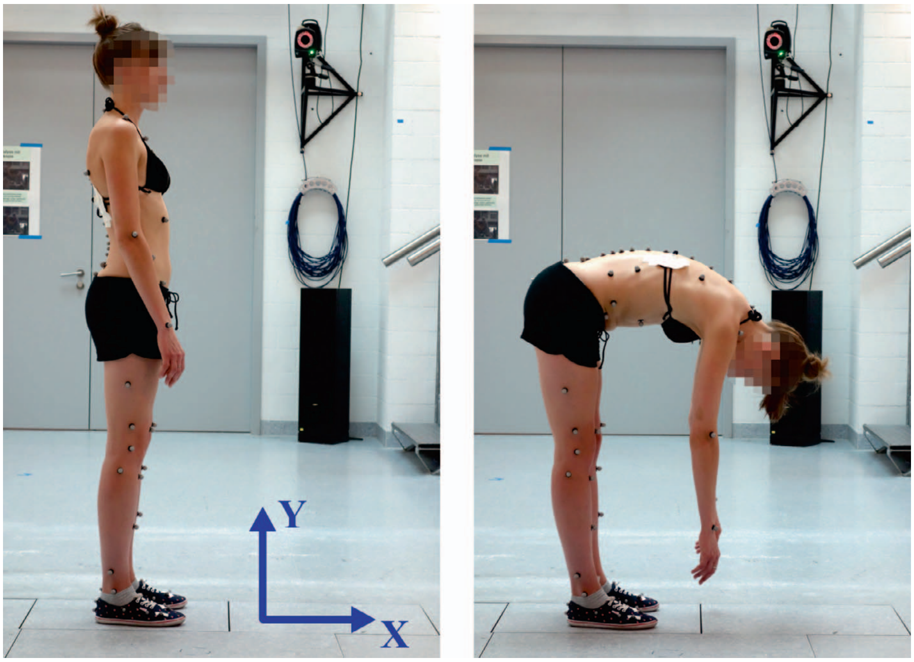

Fig. 1. The recorded task of flexion forward was performed at a self-selected speed. Knees are kept extended, while the arms and head are relaxed.

2.3. Measurement procedure

The volunteers stood with their feet hip-wide apart, arms hanging relaxed at the sides, and a natural upright posture with forward gaze. They were positioned with their feet parallel to the horizontal axis of the laboratory (see Fig. 1) to minimize the out-of-plane movement, as planar angles (projected onto the sagittal plane) were to be analyzed. They were instructed to slowly bend forward at a self-selected speed until the end of range of motion is achieved and then return to the upright position, while keeping their knees extended during the entire task (Fig. 1). The subjects wore their normal comfortable flat shoes.

2.4. Data analysis

The markers positions were processed using Vicon software; the markers were identified and labeled, and small gaps in markers trajectories were filled using interpolation tools. The markers positions were further analyzed using Matlab.

2.4.1. Task cycle definition

The task cycle was defined based on the time-course analysis of spine inclination (defined as the angle formed by a vector connecting markers at the Sacrum and C7 vertebra with a global laboratory vertical axis). The beginning of the task was the time point when flexion velocity (the spine inclination time-derivative) changed from zero to positive, and the end of the task when it equaled again zero. The task cycle was then normalized between the subjects, so 0% and 100% of the task indicate initial and final upright posture, and 50% of the task corresponds to the maximum spine inclination. In this way, both flexion and extension phases are scaled to the spine inclination progress, reflecting overall trunk flexion.

2.4.2. Spine motion estimation

In order to estimate the flexion of particular segments of the spine, as delineated by the applied markers, the marker trajectories in the sagittal plane were first smoothed over 5 consecutive time frames (0.05 s) in Matlab R2014a (no noise filtering of the marker data was performed) and then analyzed. At each time point, a cubic polynomial function was fit to the markers positions, approximating an S-shaped spine curvature with thoracic kyphosis and lumbar lordosis curves. The results of a prior study indicated that fitting a cubic polynomial function ensures the most robust estimate of postural angles (see Supplementary Material 2). Based on the angles between calculated lines normal to the curve passing through the marker positions at each time frame, the time course of angular displacements (i.e. flexion angles) of thoracic (C7-L1) and lumbar regions (L1-S), as well as of individual segments were found (Fig. 2). Noise reduction of the calculated angular displacement and velocity profiles was performed by applying a Gaussian filter (Smith, 1997) with a window width of 0.5 s and standard deviation of half the window width (0.25 s).

2.4.3. Analysis of thoracic motion characteristics

Individual thoracic motion patterns of every measured volunteer were found for thoracic segments C7T3, T3T5, T5T7, T7T9, T9T11, and T11L1 as well as for entire regions: thoracic (C7-L1), lumbar (L1-Sacrum) and hip (pelvis – upper leg). Several motion

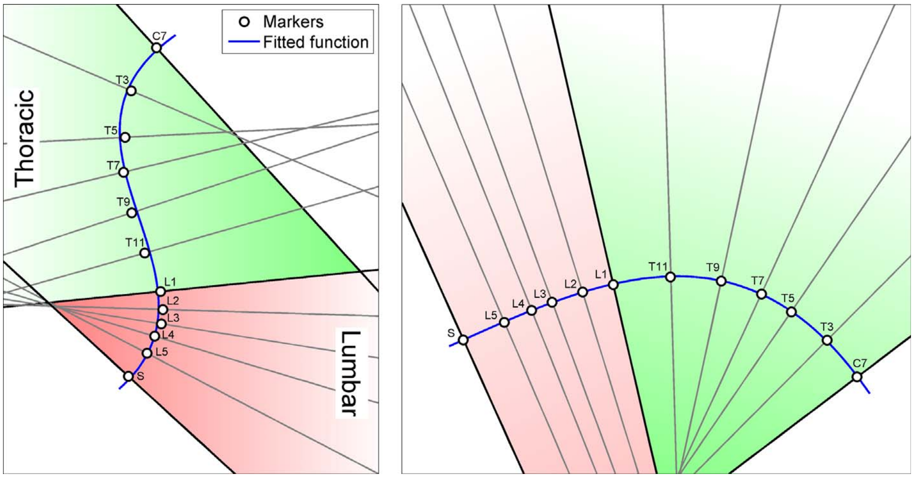

Fig. 2. The method of intersegmental angle estimation based on approximating the spine curvature by fitting a 3rd-order polynomial function to the recorded spine marker positions in the sagittal plane.

features were observed allowing classification of the individual motion patterns into common types.

Distinct thoracic motion types

The temporal sequence of thoracic flexion with respect to lumbar and hip flexion was evaluated by comparing when the maximum angular displacement was achieved in each region. If the thoracic maximum angular displacement occurred within ± 5% of the task cycle of the maximum in the lumbar spine or hips, it was considered simultaneous; otherwise, it was interpreted as sequential (Fig. 3A).

The types of temporal sequence of the lower thoracic segments during flexion and extension phases (Fig. 3B and C) were defined by dominant patterns observed through more than half of a flexion or extension phase. Flexion or extension of two segments was considered to be simultaneous if their relative rotation (rotation magnitude/maximum rotation) matched temporally within 5% of task cycle. The following motion types were differentiated: a sequential "bottom top" motion type, with T11L1 flexion/extension preceding T9T11 and T7T9, a simultaneous type and a mixed sequential-simultaneous type, with T7T9 flexion (extension) preceding simultaneous flexion or following simultaneous extension of the distal T9T11 and T11L1 segments.

Also, comparison of relative angular displacement of the lower thoracic segments (T7T9, T9T11, T11L1) at the end-of-flexion (i.e., at 50% of the task cycle) allowed to classify thoracic motion patterns based on thoracolumbar junction T11L1 extent of flexion.

2.4.4. Statistical analysis

The Chi-square test for categorical data was used to explore dependency between distinct motion types and age groups. The average motion profiles were also compared between the groups based on analysis of variance (ANOVA) of segmental and regional ranges of flexion. The effect sizes were estimated by calculating Cramer's V and eta-squared (η^2), for categorical and numeric variables, respectively. All statistical analyses were performed in Matlab, and a toolbox "Measures of Effect Size" (Hentschke & Stuttgen, 2011) was used for effect size calculations.

3. Results

3.1. Thoracic motion types

The classification based on thoracic flexion timing was found to be dependent on the age group ($p = 0.011$, $V = 0.51$): most of the young subjects showed a delayed thoracic flexion type. Simultaneous and "thorax first" types were more prevalent in the elderly (Fig. 4A).

Also, the types of temporal sequence of the lower thoracic segments (T7T9, T9T11, T11L1) during flexion and extension phases were found to be correlated to age groups ($p = 0.017$, $V = 0.49$ and $p = 0.020$, $V = 0.48$, respectively). In the flexion phase, a sequential "bottom top" motion type was the most commonly seen pattern in the young, whereas a simultaneous type was clearly dominant in the elderly (Fig. 4B). More than one third of volunteers in both groups showed a mixed sequential-simultaneous type. During extension, the lower segments would begin returning to upright before the upper ones in almost half of the young but only in 1 elderly volunteer (Fig. 4C). Simultaneous extension of the lower thoracic segments was observed in a considerable proportion of the elderly, and only in a few of the young.

The relative angular displacement of the lower thoracic segments (T7T9, T9T11, T11L1) at the end-of-flexion was found to be significantly different between the age groups ($p = 0.008$, $V = 0.53$). The thoracolumbar junction T11L1 was found to be flexed the most in the majority of the young and less than a third of the elderly (Fig. 4D). On the contrary, T11L1 was found to be least flexed in

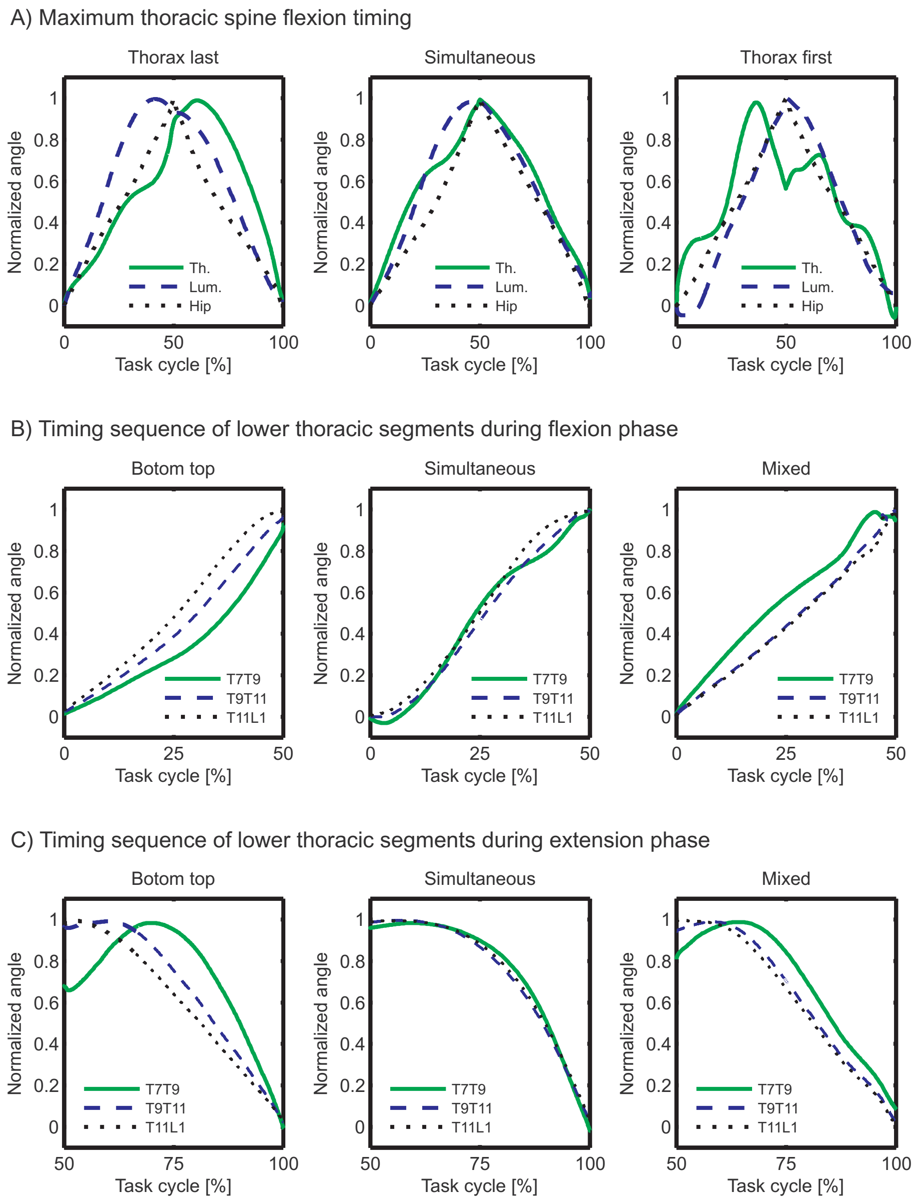

Fig. 3. Example motion patterns representative for distinct types, based on temporal characteristics of the thoracic spine flexion.

half of the elderly.

3.2. Thoracic motion patterns

Mean angular displacement and velocity profiles of thoracic segmental kinematics were established for the two age groups (Fig. 5). Differences in both ranges and the task time-course were observed. On average, the young completed the task in a slightly shorter time than the elderly (7.2 ± 2.2 s and 8.8 ± 2.3 s, respectively, $p \leq 0.05$, $\eta^2 = 0.11$).

3.3. Range of flexion

The range of flexion (ROF) was defined as an angular displacement at end-of-flexion (50% task cycle) with respect to the upright posture (0% task cycle). No statistically significant difference was found between the age groups for the overall spine, thoracic or hip ROF. The lumbar spine ROF was lower in the elderly, 37.8° ± 9.0°, compared to the young group, 48.9° ± 8.8° (ANOVA, $p \leq 0.001$, $\eta^2 \geq 0.25$) (Fig. 6). Segmental ROF was reduced in the segments from T9T11 to L5S, but increased in T5T7.

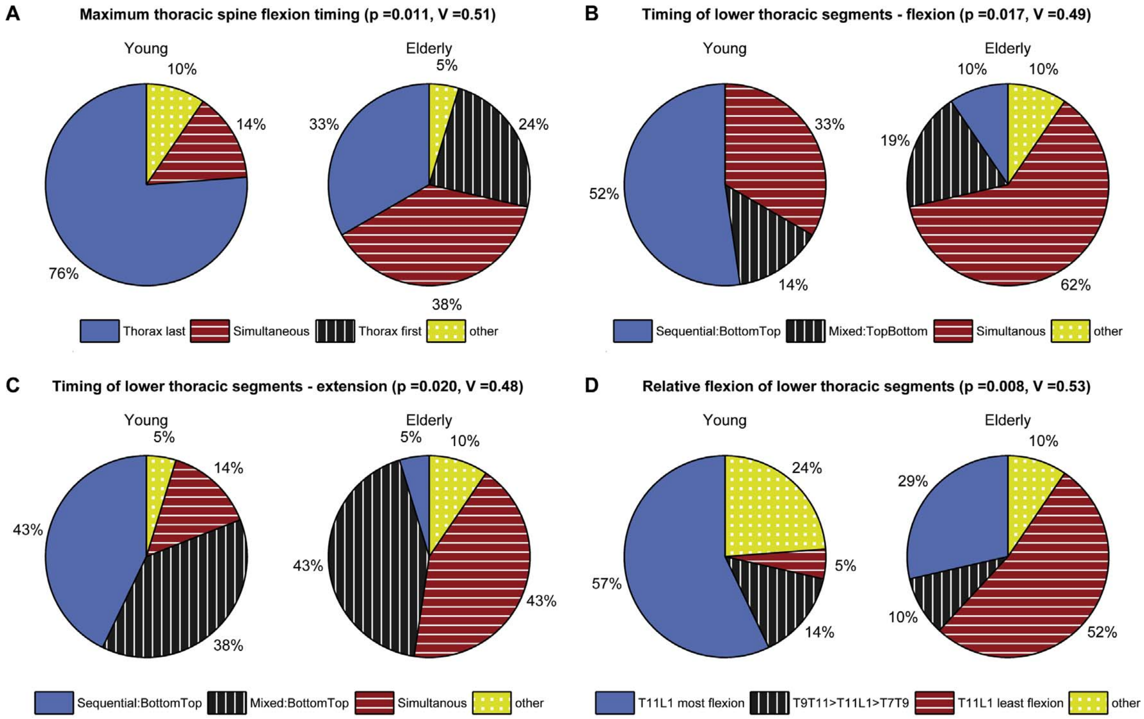

Fig. 4. The prevalence of thoracic motion types observed in the young and the elderly.

4. Discussion

Functional evaluation of the spine has the potential to support the identification of spinal pathologies; however this requires an in-depth knowledge of the normal vertebral kinematics. In contrast to the cervical and lumbar spine, information on the motion of the thoracic region is scarce, even though this is a typical site for a number of spinal disorders. We report thoracic spine kinematics of healthy young and elderly subjects, measured and analyzed in a continuous and multi-segmental fashion during a full-range, forward flexion maneuver.

The differences between the young and elderly group were reflected in the prevalence of specific, distinct temporal motion types: the young tended to flex the lower spine and hips before the thorax, and distal thoracic segments before proximal, whereas the kinematics of the elderly subjects more often showed simultaneous motion of regions and segments. Although there is lack of similar data on thoracic spine motion time sequencing, the simultaneous (Lee et al., 2002; Wong et al., 2004), sequential (Kanayama, Abumi, Kaneda, Tadano, & Ukai, 1996), or both types (Okawa et al., 1998) have been previously reported as normal timing sequences of the lumbar vertebrae.

The upper thoracic segmental motion patterns could not be classified efficiently into common types, due to substantial inter-subject variability. In order to minimize the influence of cervical spine flexion-extension on the movement of the upper thoracic vertebrae (Fiebert, Spyropoulos, Peterman, & Dotson, 1993), the volunteers were instructed and trained to move their head smoothly with the trunk. In practice, though, different strategies can be employed and the relative neck-trunk movement may vary between persons and throughout the task duration. Together with the small angles of flexion in this region, additionally influenced by superoinferior stretching of the skin under the applied markers (Moga, 2010), this might explain large inter-subject variability.

Even though the overall spine ROF was not significantly different in the elderly, it was reduced in lumbar region and several thoracic segments. The lumbar spine flexibility (Intolo et al., 2009) and lumbar contribution to trunk flexion (Vazirian, Shojaei, Agarwal, & Bazrgari, 2016) were shown to generally decrease with age, while the contribution of the pelvic flexion was found to increase (Pries, Dreischarf, Bashkuev, Putzier, & Schmidt, 2015). Similar observation was found in our study, suggesting that healthy elderly (without pain symptoms) might adopt motion strategies that avoid lumbar motion. The thoracic segmental mobility has not been extensively studied in the past; and the few reports (White, 1971) differ from our study in the segment definition. However, our results are in agreement with the general trend of increased segmental mobility at the uppermost and lowermost thoracic segments. The early thoracic flexion observed more commonly in the elderly ("thorax first" motion type) might lead to more frequent flexion of the thoracic spine (i.e. during movements of small range of flexion), perhaps contributing to the development of the thoracic hyperkyphosis. Finally, analysis of normalized mean segmental flexion and extension velocities (see Supplementary Material 3) revealed differences between the two age groups in the thoracic and lumbar spine. All these results show that spine kinematics during a flexion task are different at an older age; however the biomechanical consequences of these changes remain to be addressed in the future studies.

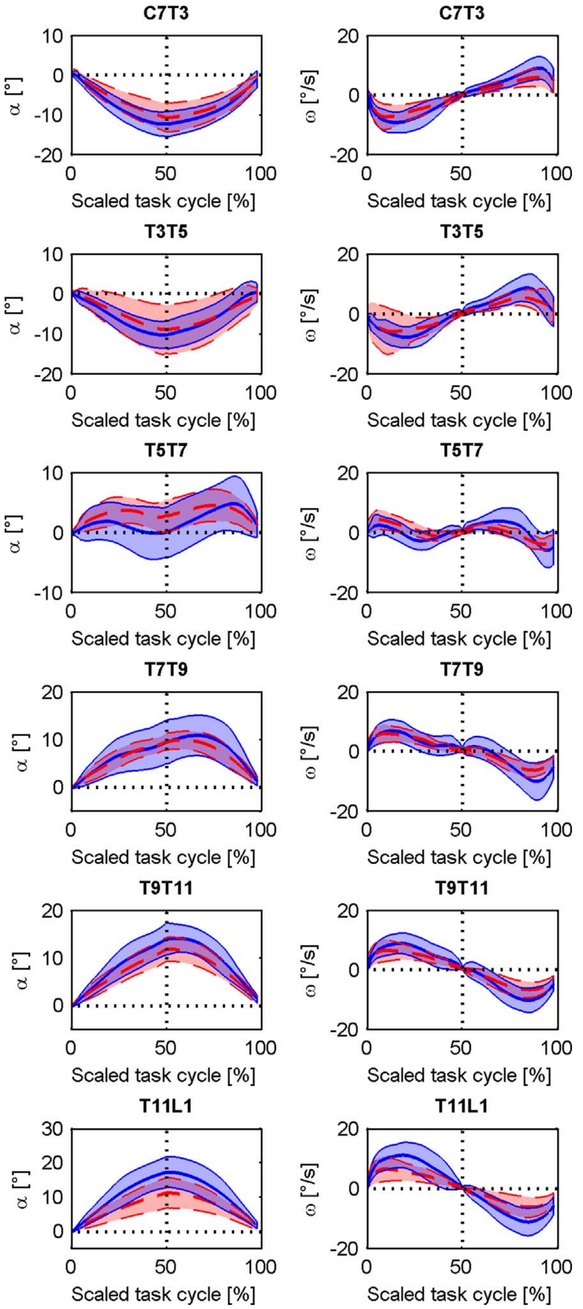

Fig. 5. Average angular displacement α (left) and velocity ω (right) profiles (± SD) of the young (blue continuous line) and elderly (red dashed line) during flexion-extension task. The shaded area represents +/− one standard deviation.

As this work focused on the age-related differences in spinal kinematics of general population, mixed gender samples of young and elderly were investigated. However, previous studies reported gender-related differences in spinal kinematics (Kienbacher et al., 2015; Muriuki et al., 2016; Vazirian et al., 2016) or lumbopelvic ratio (Pries et al., 2015), suggesting that gender might have strong influence on spinal motion in addition to or regardless of age. In our study, the age-related differences in thoracic spine kinematics were indeed greater in females, but similar trends were observed in males (see Supplementary Material 4).

Since all the measured participants were in good health and had not experienced serious spine problems, the differences in spine kinematics between the age groups are likely due to age-related changes in motor control or normal degenerative processes affecting the spinal structures. As the trunk motion has a great effect on muscle forces and spinal loading (Davis & Marras, 2000), these age-related changes in spine kinematics might alter the optimal load distribution, thus contribute to the increased risk of disc degeneration or vertebral fractures at an advanced age. Interestingly, the greatest differences in vertebral motion were observed for the T5T7 and T11L1 segments, which are around the most common sites of vertebral fractures in the elderly (Cooper, Atkinson,

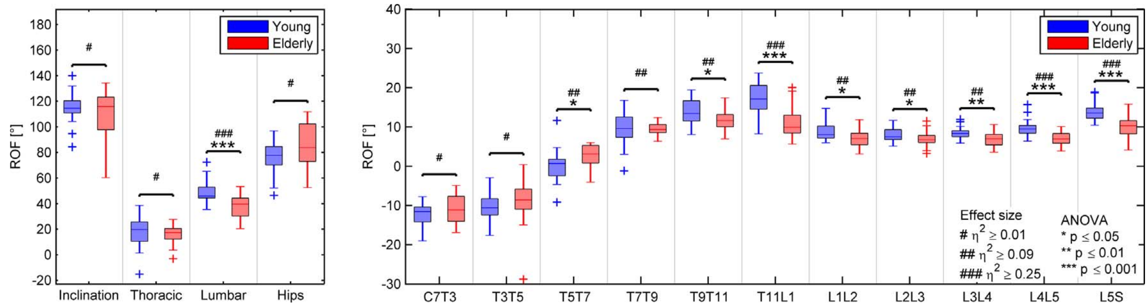

Fig. 6. Global (left) and segmental (right) range of flexion values measured dynamically in the young and the elderly. Negative ROF values indicate extension at the end-of-flexion (with respect to upright posture).

O'Fallon, & Melton, 1992). Future simulation work will be pursued in order to investigate in detail the biomechanical implications of the age-related changes in spine kinematics for the spinal segmental loading.

Spinal movement has been studied so far with a number of methods, including sensor-equipped bone pins (Gercek et al., 2008), videofluoroscopy (Ahmadi et al., 2009; Kanayama et al., 1996; Lee et al., 2002; Okawa et al., 1998; Takayanagi et al., 2001; Teyhen et al., 2007; Wong et al., 2004) and inertial (Lee, Laprade, & Fung, 2003) or electro-magnetic skin sensors (Peach, Sutarno, & McGill, 1998; Pearcy & Hindle, 1989; Willems, Jull, & Ng, 1996). In contrast to these methods, an optoelectronic motion-capture system is both non-invasive and suitable for tracking multiple segments over the full range movement, and has been previously applied for the investigation of spinal kinematics (Lee, Lee, & Kim, 2013; List et al., 2013; Preuss & Popovic, 2010). Representation of the spinal shape as a deformable curve rather than a kinematic chain of segments has been proposed to be more realistic (Ranavolo et al., 2013). The approximation by a 3rd-order polynomial fit offers robustness in terms of accuracy and repeatability of the results (see Supplementary Material 2), as well as reduced sensitivity to skin motion artifact.

The skin tissue artifact is one of the most important drawbacks of the motion capture technology (Leardini, Chiari, Della Croce, & Cappozzo, 2005). In contrast to the lower extremity, it has been relatively less investigated in the context of the spine. This artifact was demonstrated to contribute considerable error to the spine motion measurement during axial rotation (14–16 mm during 35° rotation) (Heneghan & Balanos, 2010). Also, the measurement error associated with static mild flexion has been estimated to be around 9–10 mm for the spine markers (Zemp et al., 2014). Yet the relative changes in the spine markers positions were found to be a valid representation of the spinal sagittal motion (Zemp et al., 2014). Furthermore, the relationships between skin surface curvature and markers to the vertebrae positions have been reported (Bryant, Reid, Smith, & Stevenson, 1989; Morl & Blickhan, 2006; Schmid et al., 2015), motion measurement results based on skin markers were found to be consistent with radiographic findings (Gracovetsky et al., 1995; Hashemirad, Hatef, Jaberzadeh, & Ale Agha, 2013) and the application of motion capture technology for tracking the spinal motion has been advocated (Chockalingam, Dangerfield, Giakas, & Cochrane, 2002).

The trunk kinematics described in this study is limited to the sagittal plane only. However, in this plane the relative coupling is the smallest when compared to other planes of motion. The out-of-plane rotations were estimated to be in the range of 12–41% of the flexion extent for the thoracic spine (Willems et al., 1996), and around 10–20% of the flexion extent for the lumbar spine (Hindle, Pearcy, Gill, & Johnson, 1989; Peach et al., 1998), which in terms of rotation between two individual vertebrae is extremely small (Gercek et al., 2008). Also, the linear displacement of the two adjacent vertebrae during flexion was found smaller than 3.5 mm (Ahmadi et al., 2009; Takayanagi et al., 2001). Therefore, neglecting the coupling of movements in other planes and translational displacements should not have a dramatic impact on findings of this study.

The description of the healthy thoracic spine kinematics at young and older age, reported in this study may in the future support identification of abnormal movement, especially by distinguishing changes in movement patterns caused by healthy aging from those due to pathologies. Also, it may attract clinicians' attention to the mobility of the thoracic spine, which is often regarded as rigid, and encourage to use kinematic measures in clinical examination. Although differences in quantitative measures (such as ROF) between the age groups were of relatively small magnitude, which might not be meaningful clinically, the distinct motion patterns could be observed and included in clinical evaluation. Moreover, a detailed description of thoracolumbar spine kinematics will serve to construct more realistic dynamic models of the spine, replacing assumed definitions of the vertebral movement sequence. Inverse dynamics simulations of such models may reveal the segmental loading conditions related to the reported movement patterns, casting more light on the biomechanics of the ageing spine. Further studies, involving sophisticated musculoskeletal models or their combination with finite element analysis approach have a potential to reveal how the load is distributed between different spinal structures or within them.

5. Conclusion

In this study, multi-segmental and continuous motion of the healthy thoracolumbar spine was investigated during a flexion maneuver, in young and elderly subjects, using a motion-capture method. Differences between the two age groups were found in the timing of thoracic spine flexion with respect to lumbar spine and hips, as well as in the timing of lower thoracic segments: a delayed/sequential motion type was dominant among the young, while the majority of the elderly presented simultaneous motion pattern. Differences between age groups were also found in regional and segmental ranges of flexion and velocities. The results reported in this study provide novel detailed data of healthy young and elderly thoracic spine kinematics (and thoracolumbar coupling) during a forward flexion maneuver.

Conflict of interest and source of funding

Dominika Ignasiak and Stephen J. Ferguson received a research grant (Project CPP FFOB_OC_14) from AOSpine International, Switzerland. Andrea Rüeger has no conflicts of interest to declare.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.humov.2017.05.011.

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