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Full Length Article

Spinal kinematics during gait in healthy individuals across different age groups

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ABSTRACT

Most studies investigating trunk kinematics have not provided adequate quantification of spinal motion, resulting in a limited understanding of the healthy spine's biomechanical behavior during gait. This study aimed at assessing spinal motion during gait in adolescents, adults and older individuals.

Fourteen adolescents (10–18 years), 13 adults (19–35 years) and 15 older individuals (≥65 years) were included. Using a previously validated enhanced optical motion capture approach, sagittal and frontal plane spinal curvature angles and general trunk kinematics were measured during shod walking at a self-selected normal speed.

Postural differences indicated that lumbar lordosis and thoracic kyphosis increase throughout adolescence and reach their peak in adulthood. The absence of excessive thoracic kyphosis in older individuals could be explained by a previously reported subdivision in those who develop excessive kyphosis and those who maintain their curve. Furthermore, adults displayed increased lumbar spine range of motion as compared to the adolescents, whereas the increased values in older individuals were found to be related to higher gait speeds. This dataset on the age-related kinematics of the healthy spine can serve as a basis for understanding pathological deviations and monitoring rehabilitation progression.

1. Introduction

In human locomotion, the importance of the upper body has been emphasized for over forty years (Saunders, Inman, & Eberhart, 1953). Saunders et al. (1953) identified six major determinants of gait, of which three have been related to the motion of the pelvis. Furthermore, they highlighted the motion of the pelvis and trunk to be essential determinants of bipedal gait. The involvement of the upper body in gait stability as well as a variety of changes in motion patterns due to aging and disease were further pointed out by McGibbon and Krebs (2001). Unfortunately, only few studies are available providing normative data on within-trunk or spinal kinematics (Crosbie, Vachalathiti, & Smith, 1997a, 1997b; Frigo, Carabalona, Dalla Mura, & Negrini, 2003; Kavanagh, Barrett, & Morrison, 2005; Konz et al., 2006; Leardini, Biagi, Merlo, Belvedere, & Benedetti, 2011; Menz, Lord, & Fitzpatrick, 2003; Van Emmerik, McDermott, Haddad, & Van Wegen, 2005), leaving us with a limited understanding of the biomechanical behavior of the healthy spine during gait.

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In contemporary biomechanical research as well as in clinics, gait kinematics are usually measured using skin marker-based motion capture systems. However, most of the studies using this method solely included young adults and evaluated either rigid trunk segments or very simple 2D projection angles. A major disadvantage of such approaches is that they allow only a limited assessment of the actual curvature of the spine. To address this deficit, an enhanced trunk marker set (IfB marker set) was previously introduced and validated for the assessment of sagittal spinal curvature in healthy subjects as well as sagittal and frontal spinal curvature in patients with adolescent idiopathic scoliosis (AIS) (List, Gulay, Stoop, & Lorenzetti, 2013; Schmid et al., 2015; Zemp et al., 2014). The importance of measuring spinal curvature angles in addition to general trunk kinematics was further emphasized by Schmid et al. (Schmid, Studer, et al., 2016), showing clear differences in spinal curvature angles between healthy adolescents and patients with AIS using these techniques, but not in angles based on commonly-used rigid trunk segments.

Walking speed is known to have an influence on pelvis and head movements in healthy adults, whereby increased walking speed corresponds to an increase in the magnitude and variability of the acceleration of these segments (Menz et al., 2003). It has therefore been proposed that an individual's comfortable walking speed is selected in order to minimize the level of acceleration variability as well as to ensure smooth and rhythmic pelvis and head movements (Menz et al., 2003). When looking at differently aged populations, this comfortable walking speed was reported to decline with increasing age (Himann, Cunningham, Rechnitzer, & Paterson, 1988; Imms & Edholm, 1981; Murray, Kory, & Clarkson, 1969) suggesting that older individuals might present kinematic changes due to a decreased walking speed. However, walking speed seems not to be the only factor responsible for altered trunk kinematics with advanced age, since older subjects have been shown to exhibit different head and trunk motion patterns compared to younger subjects even when walking at equal speeds (Kavanagh et al., 2005). In addition, Van Emmerik et al. (2005) reported altered movement amplitudes of the pelvis and trunk segments between young, adult and older individuals that were not related to walking speed. These non-walking speed-related changes might be explained by age-related morphological changes that lead to the previously observed decreases in maximal sagittal range of motion of the lumbar, thoracic and cervical spine in older individuals (Kuo, Tully, & Galea, 2009). Although normal trunk motion during gait was described to be small (i.e. less than 5 degrees range of motion) (Frigo et al., 2003), a reduced maximal range of motion might still have an influence on the neuromuscular control of the respective joints.

In order to be able to comprehensively investigate pathologies that directly or indirectly affect the spine, accurate knowledge of the biomechanics of a healthy spine during gait with respect to age is critical. Using a previously validated enhanced non-invasive optical approach, the main aim of the current study was therefore to assess sagittal and frontal plane spinal curvature angles during gait in healthy adolescents, adults and older individuals and to provide a basis for future investigations involving pathologies. In addition, spatio-temporal gait parameters and absolute and relative angles of a rigid pelvis, lumbar, thoracic and cervical segment were calculated in order to support the interpretation of the primary outcomes.

2. Methods

2.1. Participants

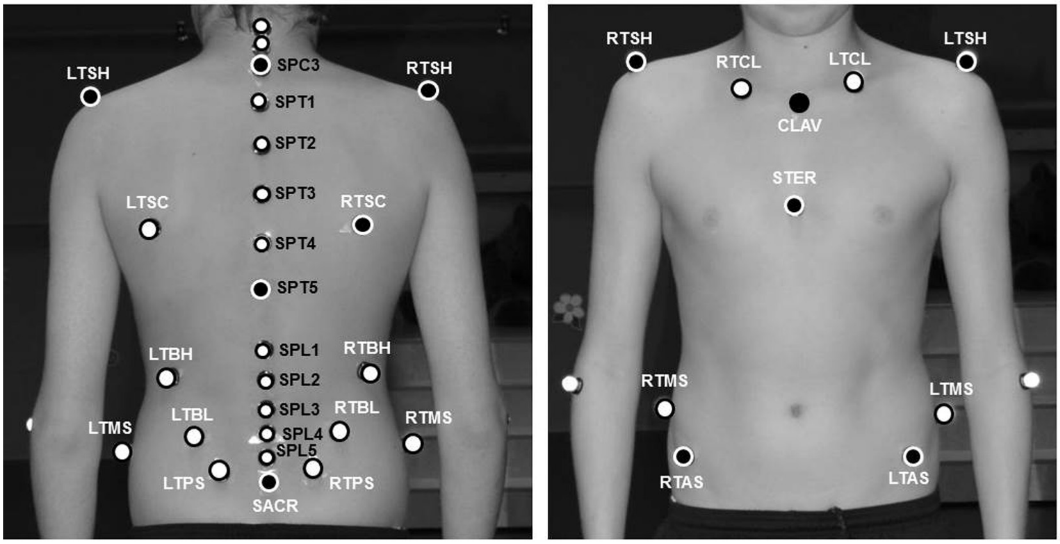
Forty-two healthy individuals, divided into the categories adolescents (10–18 years, n = 14), adults (19–35 years, n = 13) and older individuals (≥ 65 years, n = 15), participated in the current study (Table 1). Subjects were included if they were in good overall health, considered of normal weight (no overweight or obesity), presented no history of spine surgery and did not suffer from back problems that required medical consultation or treatment in the previous 6 months. All participants (as well as the legal guardians of the adolescents) provided written informed consent and the study protocol was approved by the responsible ethics committees.

2.2. Data collection

Measurements of the adolescents were conducted in one movement analysis analysis laboratory using a 12-camera motion analysis system (type MXT20, Vicon, Oxford, UK; sampling frequency: 200 Hz), whereas the adults and older individuals were assessed in another laboratory using a 12-camera motion analysis system (type MXV612, Vicon, Oxford, UK; sampling frequency: 100 Hz). After the assessment of relevant anthropometric data, subjects were equipped with retro-reflective markers in the configuration of the IfB trunk marker set (List et al., 2013) (Fig. 1) in combination with the Plug-in Gait full body marker set (Romkes et al., 2007) (adolescents) and the IfB full body marker set (List et al., 2013) (adults and older individuals). Subsequently, all subjects were measured wearing their own comfortable shoes in a standing upright position for 2 s and during walking at self-selected normal

Table 1
Demographics of the healthy adolescents, adults and older individuals expressed as means with standard deviations (SD) and ranges (in brackets).

	Adolescents (n = 14)	**Adults** (n = 13)	**Older** (n = 15)
Age [years]	13.9 SD 1.5 (12–16)	27.0 SD 2.5 (21–35)	69.7 SD 1.8 (65–76)
Height [m]	1.61 SD 1.0 (1.46–1.84)	1.74 SD 0.6 (1.62–1.93)	1.70 SD 0.5 (1.56–1.83)
Mass [kg]	53.8 SD 10.2 (40.3–70.4)	68.6 SD 8.4 (47.0–86.0)	66.8 SD 6.8 (54.0–97.0)
Gender [male/female]	7/7	6/7	6/9



Cervical segment	
SPC3	Spinous process of C7
RT/LTSH	Right/left shoulder
RT/LTCL	Right/left clavicle

Thoracic segment	
SPT1-5	Spinous process of T3, T5, T7, T9, T11
RT/LTSC	Right/left scapula
RT/LTBH	Right/left lower back, height of costal arch
STER	Apex of sternum

Lumbar segment	
SPL1-5	Spinous process of L1-L5
RT/LTBL	Right/left lower back, height of L4

Pelvis segment	
RT/LTAS	Right/left anterior superior iliac spine
RT/LTMS	Right/left mid superior iliac spine
RT/LTPS	Right/left posterior superior iliac spine
SACR	Sacrum

Fig. 1. Marker placement according to the IfB trunk model in combination with the Plug-in Gait full body model for the assessment of spinal curvature angles and segmental trunk kinematics. White circles with black filling represent markers that were used for both models, while black circles with white filling represent markers that were only used for the IfB model, and markers with black circles were only used for the Plug-in Gait full body model.

speed on a 10 m level ground walkway until at least 4 were recorded. The raw data of these measurements are publicly available as indicated in Appendix A (electronic supplementary material).

2.3. Data reduction

Raw data (unfiltered marker trajectories) from both laboratories were further processed by one single investigator using identical data analysis procedures. The software Nexus (version 1.8.5, Vicon, Oxford, UK) was used for defining the gait events (i.e. initial contact and toe-off). Kinematic data were evaluated using a custom-built MATLAB-Routine (version R2012a, MathWorks Inc., Natick, MA, USA). Spinal curvature angles in the sagittal and frontal planes were calculated based on the circles that were fitted into the markers on the spinous processes of the vertebrae T11, L1, L2, L3, L4 and L5 (i.e. markers SPT5, SPL1-5) for the lumbar curvature and T3, T5, T7, T9 and T11 (i.e. markers SPT1-5) for the thoracic curvature. In order to minimize possible projection error due to the transverse plane rotation of the thorax during gait, thoracic curves were calculated using a dynamic coordinate system, established on the basis of a moving sagittal plane that was defined by the apical marker of the thoracic frontal curve and the marker on the sternum. For the lumbar curvatures, however, the global coordinate system was used due to a missing meaningful anterior reference point. These procedures have been previously described and successfully implemented for the evaluation of spinal curvature angles during gait in patients with adolescent idiopathic scoliosis (Schmid, Studer, et al., 2016) and hemiplegic cerebral palsy (Schmid, Romkes, Taylor, Lorenzetti, & Brunner, 2016).

In order to analyze overall trunk motion, rigid pelvis, lumbar, thoracic and cervical segments were defined (Fig. 1). The three-dimensional position and orientation of these segments during gait was then calculated in relation to the standing measurement trial (absolute segmental angles) as well as between the adjacent segments (relative segmental angles: cervical vs. thoracic, thoracic vs. lumbar, lumbar vs. pelvis) as described elsewhere (Schmid, Studer, et al., 2016).

The individual curvature and segmental angle curves were time normalized to a left gait cycle consisting of 101 points per trial and averaged over the four trials per subject (i.e. average of four left gait cycles per subject). No filtering routines were applied throughout the data reduction process. The primary outcome parameters of this study were defined as the average and range of motion (RoM) values of the spinal curvature angles over one full gait cycle (expressed in degrees [°]). The RoM values of the absolute and relative segmental angles over one full gait cycle (expressed in degrees [°]) as well as a number of spatio-temporal gait parameters served as secondary outcome parameters. The spatio-temporal parameters were all expressed as dimensionless numbers (Hof, 1996): walking speed was divided by the square root of the product of gravitational acceleration and body height, cadence by the square root of the quotient of gravitational acceleration over body height, stride length by body height and stride time by the square root of the quotient of body height over gravitational acceleration.

2.4. Statistical analyses

Statistical calculations were performed using the software packages SPSS 22 (SPSS Inc., Chicago, IL, USA) and G*Power 3.1.9.2 (Faul, Erdfelder, Lang, & Buchner, 2007). To verify normal distribution of the outcome parameters, the Shapiro-Wilk test was used (normally distributed: $p > 0.05$). Comparisons for several outcome parameters between the adolescents, adults and older individuals groups were carried out using one-way analyses of variance (ANOVA) with Tukey HSD post hoc tests. Due to the explorative character of the study, however, the interpretation of the results was mainly based on the magnitude of the effects (Cohen's f and d, respectively) rather than the p-values. Thereby, pairwise comparisons were carried out when the ANOVA yielded considerable effects ($f \geq 0.1$) (Cohen, 1977). In order to determine the clinical relevance of the findings, mean differences in the curvature and segmental angles were considered in regard to a minimal clinically important difference (MCID) of 5°(Schmid, Studer, et al., 2016). A difference was thereby classified as *clinically relevant* with a large effect ($d \geq 0.8$) and the mean difference above the MCID and as *clinically not relevant* with a small to moderate effect ($0.2 \leq d < 0.8$) or a large effect but the mean difference below the MCID. Curvature angles values that showed clinically relevant differences were additionally evaluated for a possible gait speed dependency using linear regression analyses.

3. Results

3.1. Primary outcome parameters

Adults revealed clinically relevant higher average thoracic kyphosis (+10.6° (0.8°,20.3°), $d = 1.16$, $p = 0.031$) and lumbar lordosis values (+12.6° (-0.2°,25.4°), $d = 0.88$, $p = 0.055$) than the adolescents (Table 2) (Fig. 2). Furthermore, average sagittal curvature angles indicated clinically relevant differences between older individuals and adolescents (thoracic) as well as between older individuals and adults (thoracic and lumbar). However, due to moderate effect sizes, these differences were only considered tendencies. In the frontal plane, the RoM of the lumbar curvature angles was smaller in the adolescents as compared to both the adults (-8.4° (3.4°,13.4°), $d = 1.84$, $p = 0.001$) and older individuals (-6.3° (1.5°,11.2°), $d = 1.26$, $p = 0.007$). Thereby, gait speed dependency was found for the difference in frontal lumbar curvature angle ROM between adolescents and older individuals ($R^2 = 0.169$, $p = 0.027$) (Fig. 3D). No further clinically relevant group differences could be found.

3.2. Secondary outcome parameters

Older individuals walked considerably faster than the adolescents (+0.09 (0.04,0.15), $d = 2.01$, $p = 0.001$) but not than the adults (Table 2). In addition, cadence and stride time was found to be considerably different between all three groups, whereas cadence seemed to increase (adolescents vs. older individuals: +4.9 (2.8,7.0), $d = 2.89$, $p < 0.001$; adults vs. older individuals: +2.2 (0.0,4.3), $d = 0.80$, $p = 0.051$; adolescents vs. adults: +2.7 (0.5,4.9), $d = 1.09$, $p = 0.011$) and stride time to decrease (adolescents vs. older individuals: −0.50 (−0.28,−0.71), $d = -3.09$, $p < 0.001$; adults vs. older individuals: −0.23 (−0.10,−0.45), $d = -0.84$, $p = 0.039$; adolescents vs. adults: −0.27 (−0.05,−0.49), $d = -1.03$, $p = 0.014$) with advancing age.

Looking at the RoM values of the absolute and relative segmental angles (Table 2), several group differences seemed to be indicated. However, none of these differences appeared to be of clinical relevance (Fig. 4).

4. Discussion

The main aim of this study was to investigate spinal kinematics during normal walking in healthy adolescents, adults and older individuals to shed some light into the age-dependent biomechanical behavior of the healthy spine and to provide a basis for future investigations on spinal pathologies.

The analyses revealed that adults exhibit more distinct thoracic kyphosis and lumbar lordosis angles than the adolescents. In addition, adults showed greater frontal plane curvature motion in the lumbar region compared to adolescents, whereas the greater frontal plane curvature motion in older individuals was found to be related to higher gait speeds in this group.

These observed average lumbar lordosis angles in adults and older individuals were similar to the values established by Dreischarf et al. (2014), who used two flexible sensor strips that were attached over the paravertebral muscles (Consmuller et al., 2012) in order to assess the lumbar shape and its mobility as a function of age in 323 standing asymptomatic subjects. Their total lumbar lordosis angle decreased from 36.4° in 20–29 years old subjects to 29° in subjects aged 50 years and more. By taking a closer look at the lumbar shape, they further revealed that the lower part of the lumbar spine retained its shape and mobility, while the middle section flattened and became less mobile with increasing age (Dreischarf et al., 2014). The observed decrease in average lordosis angle in the current study, however, showed only moderate effects and can therefore only be regarded as a tendency. Looking at the comparisons

Table 2
Primary and secondary outcome parameters: Reported are mean, standard deviation (SD) and 95% confidence intervals (within the brackets) for the average (AVG) and range of motion (ROM) values of the spinal curvature angles and trunk segmental angles in the sagittal (Sag.), frontal (Fron.) and transverse (Tran.) planes over one gait cycle (all angles expressed in degrees [°]) as well as the spatio-temporal gait parameters (expressed as dimensionless numbers) in healthy adolescents, adults and older individuals. In addition, results for the group comparisons (one-way analyses of variance (ANOVA) and Tukey's post hoc tests as well as effect sizes (Cohen's f and d, respectively) are presented.

			1)Adolescents (n = 14)	2)Adults (n = 13)	3)Older (n = 15)	ANOVA	Post hoc (Tukey HSD)		
						f	3–1 d	3–2 d	2–1 d
Thoracic Curves	Sag.	AVG	34.7 SD 8.3 (29.9, 39.5)	45.2 SD 9.8 (39.3, 51.2)	39.9 SD 12.3 (33.1, 46.8)	**0.41****	0.49	−0.47	**1.16**$^{++}$
		ROM	3.3 SD 2.2 (2.1, 4.6)	3.3 SD 1.0 (2.7, 3.9)	3.4 SD 1.3 (2.7, 4.2)	0.03	–	–	–
	Fron.	AVG	4.4 SD 3.5 (2.3, 6.4)	0.5 SD 3.7 (−1.7, 2.8)	0.6 SD 3.8 (−1.5, 2.7)	**0.49****	−**1.04**$^{++}$	0.03	−**1.08**$^{++}$
		ROM	8.6 SD 3.2 (6.7, 10.4)	7.9 SD 2.2 (6.6, 9.2)	8.8 SD 3.6 (6.8, 10.8)	**0.12***	0.06	0.30	−0.25
Lumbar Curves	Sag.	AVG	−24.9 SD 11.7 (−31.7, −18.2)	−37.5 SD 16.7 (−47.6, −27.4)	−28.8 SD 12.3 (−35.7, −22.0)	**0.38***	−0.32	0.60	−**0.88**$^{+}$
		ROM	6.1 SD 1.3 (5.4, 6.9)	5.8 SD 2.3 (4.5, 7.2)	7.4 SD 2.5 (6.0, 8.8)	**0.33***	0.65	0.66	−0.16
	Fron.	AVG	0.1 SD 2.6 (−1.4, 1.6)	−2.8 SD 3.7 (−5.1, −0.6)	−3.0 SD 5.9 (−6.3, 0.3)	**0.33***	−0.67	−0.04	−**0.91**$^{+}$
		ROM	11.6 SD 2.6 (10.1, 13.1)	20.0 SD 6.0 (16.3, 23.6)	17.9 SD 6.5 (14.4, 21.5)	**0.66****	**1.26**$^{++}$	−0.33	**1.84**$^{++}$
Cervical Segment	Sag.	ROM	3.6 SD 1.1 (2.9, 4.2)	3.6 SD 1.1 (2.9, 4.2)	3.3 SD 0.9 (2.7, 3.8)	**0.14***	−0.30	−0.30	0.00
	Fron.	ROM	3.8 SD 1.5 (2.1, 3.8)	4.0 SD 2.1 (2.8, 5.3)	3.5 SD 1.4 (2.7, 4.3)	**0.12***	−0.21	−0.28	0.11
	Tran.	ROM	6.0 SD 2.0 (4.8, 7.1)	7.7 SD 2.4 (6.2, 9.1)	5.6 SD 2.5 (4.2, 7.0)	**0.39***	−0.18	−**0.86**$^{+}$	0.77
Thoracic Segment	Sag.	ROM	3.8 SD 0.9 (3.3, 4.3)	3.4 SD 0.8 (2.9, 3.8)	3.3 SD 0.9 (2.8, 3.8)	**0.25***	−0.56	−0.12	−0.47
	Fron.	ROM	3.1 SD 1.0 (2.6, 3.7)	3.7 SD 1.5 (2.8, 4.7)	4.0 SD 1.8 (3.0, 5.0)	**0.26***	0.61	0.18	0.47
	Tran.	ROM	5.0 SD 1.2 (4.3, 5.7)	6.7 SD 1.7 (5.7, 7.7)	5.8 SD 2.3 (4.6, 7.1)	**0.38***	0.43	−0.44	**1.16**$^{++}$
Lumbar Segment	Sag.	ROM	3.6 SD 1.1 (2.9, 4.2)	4.4 SD 1.2 (3.7, 5.1)	5.0 SD 2.6 (3.6, 6.5)	**0.32***	0.69	0.29	0.70
	Fron.	ROM	4.8 SD 2.3 (3.5, 6.1)	6.5 SD 2.1 (5.3, 7.8)	6.8 SD 2.7 (5.3, 8.3)	**0.37***	**0.80**$^{+}$	0.12	0.77
	Tran.	ROM	9.0 SD 3.3 (7.1, 10.9)	9.9 SD 3.8 (7.6, 12.2)	10.9 SD 4.7 (8.3, 13.4)	**0.20***	0.46	0.23	0.25
Pelvis Segment	Sag.	ROM	3.8 SD 0.9 (3.3, 4.3)	3.8 SD 1.6 (2.9, 4.8)	4.2 SD 2.3 (2.9, 5.4)	**0.11***	0.23	0.20	0.00
	Fron.	ROM	7.1 SD 2.8 (5.4, 8.7)	7.1 SD 2.8 (5.5, 8.8)	6.2 SD 2.6 (4.8, 7.7)	**0.16***	−0.33	−0.33	0.00
	Tran.	ROM	11.0 SD 3.3 (9.1, 13.0)	12.0 SD 4.3 (9.4, 14.6)	11.8 SD 4.5 (3.9, 14.3)	**0.11***	0.20	−0.05	0.26
Cervical vs. Thoracic	Sag.	ROM	1.8 SD 0.9 (1.3, 2.3)	2.0 SD 0.6 (1.6, 2.4)	2.2 SD 0.7 (1.8, 2.6)	**0.22***	0.50	0.30	0.26
	Fron.	ROM	4.1 SD 1.0 (3.5, 4.6)	4.2 SD 1.4 (3.3, 5.0)	3.9 SD 1.4 (3.1, 4.6)	**0.10***	−0.16	−0.21	0.08
	Tran.	ROM	3.8 SD 1.0 (3.2, 4.3)	3.0 SD 1.4 (2.1, 3.8)	2.6 SD 1.5 (1.8, 3.4)	**0.38***	−**0.93**$^{++}$	−0.27	−0.66
Thoracic vs. Lumbar	Sag.	ROM	2.5 SD 0.9 (2.0, 3.0)	3.7 SD 1.2 (3.0, 4.5)	4.3 SD 2.9 (2.7, 5.9)	**0.39****	**0.83**$^{++}$	0.26	**1.14**$^{+}$
	Fron.	ROM	5.6 SD 1.3 (4.9, 6.4)	9.2 SD 2.5 (7.7, 10.8)	8.4 SD 2.5 (7.0, 9.8)	**0.70****	**1.39**$^{++}$	−0.32	**1.83**$^{++}$
	Tran.	ROM	9.6 SD 3.4 (7.7, 11.6)	12.0 SD 4.7 (9.1, 14.9)	12.3 SD 4.3 (9.9, 14.6)	**0.29***	0.69	0.07	0.59
Lumbar vs. Pelvis	Sag.	ROM	4.1 SD 1.4 (3.3, 4.9)	4.3 SD 1.5 (3.4, 5.2)	4.1 SD 1.4 (3.3, 4.9)	0.06	–	–	–
	Fron.	ROM	4.0 SD 1.7 (3.0, 5.0)	3.2 SD 1.0 (2.6, 3.8)	3.3 SD 1.1 (2.7, 4.0)	**0.27***	−0.49	0.09	−0.57
	Tran.	ROM	4.5 SD 1.5 (3.7, 5.7)	3.8 SD 1.1 (3.1, 4.4)	3.8 SD 1.1 (3.2, 4.4)	**0.26***	−0.54	0.00	−0.53
Speed (m/s)			1.28 SD 0.10 (1.22, 1.34)	1.50 SD 0.25 (1.35, 1.65)	1.62 SD 0.13 (1.55, 1.69)	–	–	–	–
Speed (normalized)			0.46 SD 0.04 (0.44,0.49)	0.51 SD 0.09 (0.46,0.56)	0.55 SD 0.05 (0.53,0.58)	**0.61****	**2.01**$^{++}$	0.58	0.74
Cadence (normalized)			31.8 SD 1.2 (31.1,32.5)	34.5 SD 3.4 (32.5,36.6)	36.7 SD 2.1 (35.5,37.8)	**0.87****	**2.89**$^{++}$	**0.80**$^{+}$	**1.09**$^{++}$
Stride length (normalized)			1.74 SD 0.14 (1.66,1.83)	1.76 SD 0.17 (1.65,1.86)	1.81 SD 0.11 (1.75,1.87)	**0.21***	0.55^{+}	0.35	0.13
Stride time (normalized)			3.78 SD 0.14 (3.70,3.86)	3.51 SD 0.35 (3.30,3.72)	3.28 SD 0.18 (3.18,3.38)	**0.88****	−**3.09**$^{++}$	−**0.84**$^{++}$	−**1.03**$^{++}$

Positive/negative AVG curvature angles: Kyphosis/lordosis (sagittal plane), right/left lateral bending (frontal plane).
$^{++}$and highlighted in bold: Large effect size for Tukey's post hoc test (d ≥ 0.8) with statistical significance (p ≤ 0.05).
* Considerable effect size for ANOVA (f ≥ 0.1) without statistical significance (p > 0.05), post hoc tests indicated.
** and highlighted in bold: Considerable effect size for ANOVA (f ≥ 0.1) with statistical significance (p ≤ 0.05), post hoc tests indicated.
$^{+}$ Large effect size for Tukey's post hoc test (d ≥ 0.8) without statistical significance (p > 0.05).

between adolescents and adults, on the other hand, the results indicate a clinically relevant age-related increase in average lumbar lordosis. Considering these and previous findings, it can be postulated that lumbar lordosis increases during adolescence, reaches its peak during adulthood and then again decreases with further advancing age, although the latter is likely to be dependent on the highly variable effects of ageing. The thoracic kyphosis seemed to follow a similar pattern from adolescence to adulthood by showing clinically relevant increases in curvature angles. However, contrary to an expected further increase of thoracic kyphosis with advancing age, older individuals showed even tendencies for smaller curvature angles compared to the adults. This could be ascribed to a previously reported bimodal distribution of thoracic kyphosis in older men and women without vertebral compression, suggesting the presence of two populations, those who tend to develop excessive curvature and those who remain near the younger thoracic curve (Bartynski, Heller, Grahovac, Rothfus, & Kurs-Lasky, 2005). The older individuals in the current study showed no

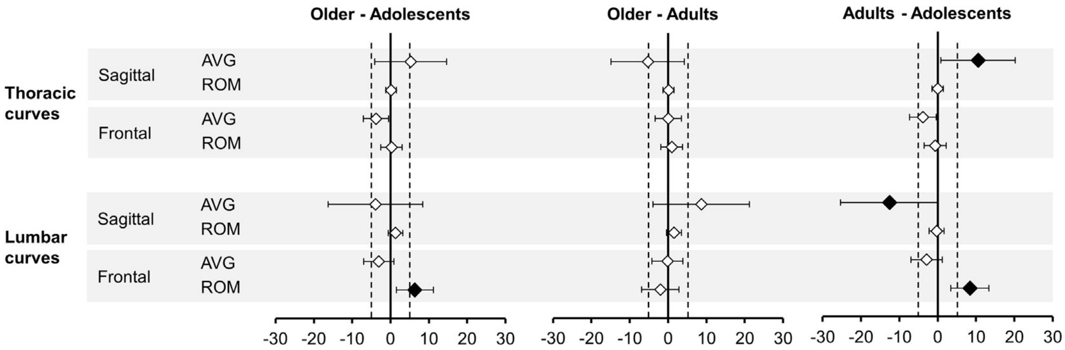


Fig. 2. Results of the pairwise group comparisons (mean differences with 95% confidence intervals) for the primary outcomes. Thoracic curvature angles were derived from markers on the spinous processes of T3, T5, T7, T9 and T11 (i.e. markers SPT1-5) and lumbar curves from T11, L1, L2, L3, L4 and L5 (i.e. markers SPT5, SPL1-5). All angles are expressed in degrees [°]. The dashed vertical lines represent the minimal clinically important difference of 5°. Differences were categorized as clinically relevant (large black diamonds) and clinically not relevant (small white diamonds). AVG: average; RoM: range of motion.

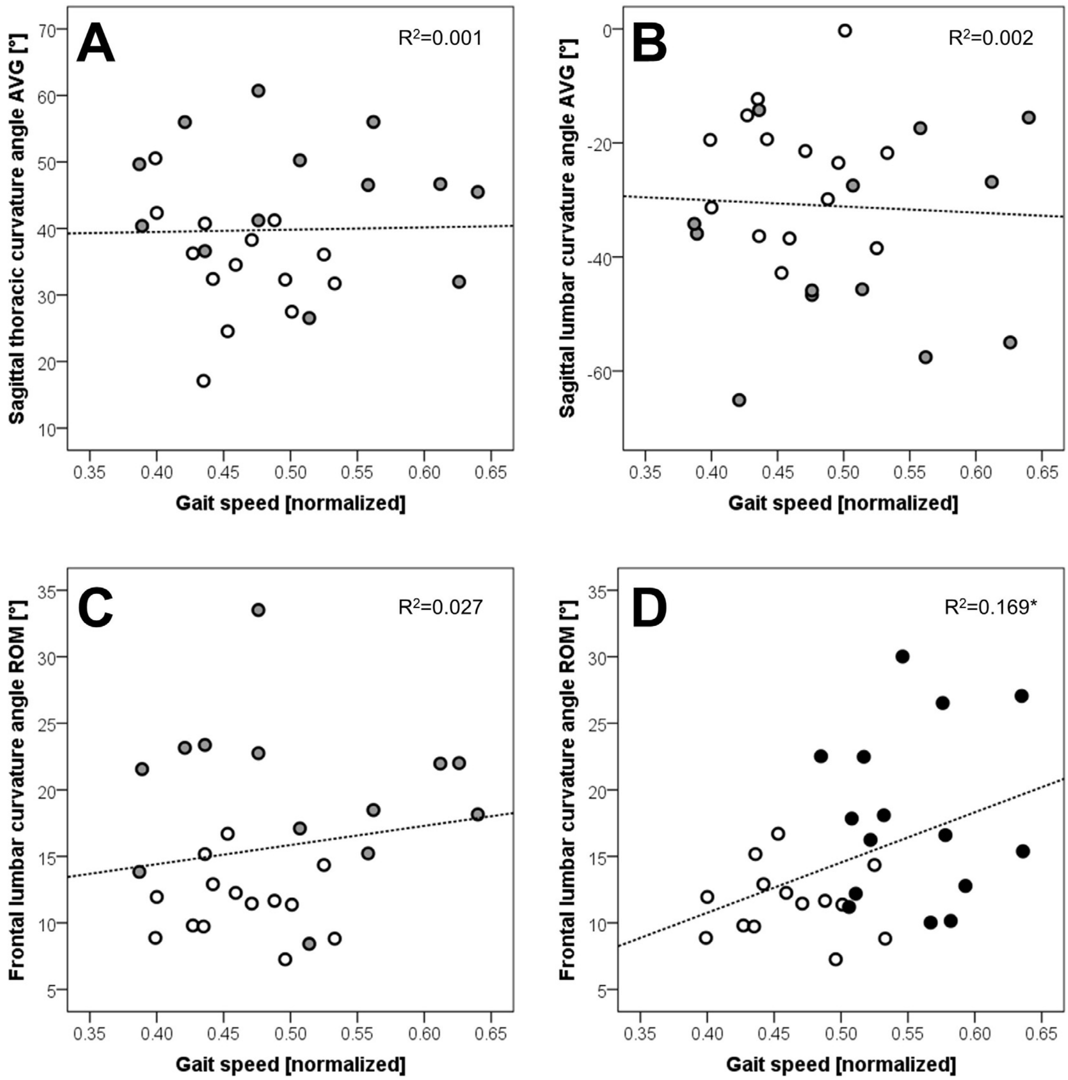


Fig. 3. Scatterplots and coefficients of determination (R^2) illustrating the correlations for gait speed and the curvature angles which showed clinically relevant differences between adolescents and adults (A-C) as well as adolescents and elderly individuals (D). Black circles with white filling represent the adolescents, black circles with gray filling the adults and black dots the older individuals. Gait speed was normalized according to Hof (1996). The asterisks (*) indicate a statistically significant coefficient of determination ($p \leq 0.05$).

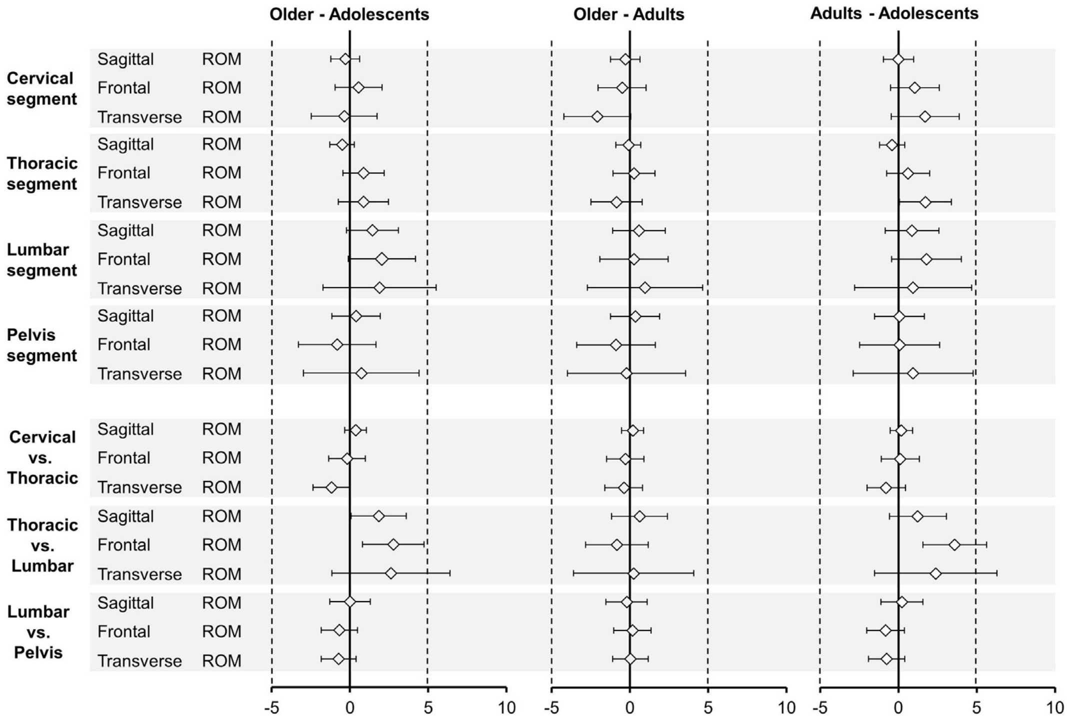


Fig. 4. Results of the pairwise group comparisons (mean differences with 95% confidence intervals) for the secondary outcomes. All angles are expressed in degrees [°]. The dashed vertical lines represent the minimal clinically important difference of 5°. Differences were categorized as clinically relevant (large black diamonds) and clinically not relevant (small white diamonds). RoM: range of motion.

bimodal distribution and might therefore all be part of the latter population. Another factor that could have influenced the thoracic curvature during gait is of motivational origin and will be discussed later on in this article.

In the frontal plane, although not clinically relevant, the lumbar and thoracic curvature angles tended to be slightly different between the adolescents and both the adults and older individuals. These tendencies were not only recognizable during walking but also in the static measurement trial (values not presented). Since it is not very likely that such group-specific frontal plane differences are of physiological nature, a possible explanation could be that the measurements were carried out by two different examiners (i.e. adolescents vs. adults and older individuals). Gorton, Hebert, and Gannotti (2009), for example, investigated the variability of the measurements of one single healthy subject conducted in 12 different motion analysis laboratories. While the motion capture systems themselves contributed a negligible amount to the overall variability, marker placement differences between examiners were shown to have the largest impact on variability (Gorton et al., 2009). But again, the differences observed in the current study were considered clinically not relevant and can therefore be considered negligible.

Another rather surprising finding was the observed increased RoM of the frontal lumbar curvature angle in older individuals compared to adolescents. Considering the fact that the spine becomes less mobile with advancing age (Dreischarf et al., 2014) and that segmental trunk motion is known to decrease in older adults (Crosbie et al., 1997a), one could have expected that the RoM of the spinal curvature angles in the older individuals group would decrease. However, since earlier experiments have shown that decreases observed in segmental trunk motion (especially in the anteroposterior axis) with advancing age were most likely not related to age but rather to a reduced walking speed (Crosbie et al., 1997a), it seems plausible that the currently observed increased walking speed in the older individuals group caused clinically relevant increases in frontal plane RoM. It remains unclear, however, why the older participants in the current study increased their walking speed, while the literature clearly suggests a decrease in walking speed with advancing age (Himann et al., 1988; Imms & Edholm, 1981; Murray et al., 1969).

A possible explanation for this might be found in a phenomenon called the “Hawthorne effect”, or more recently known as “research participation effect” (McCambridge, Witton, & Elbourne, 2014). This effect describes the possible impact on behavior that occurs in an experiment as a result of the awareness of being treated, studied or observed (Lied & Kazandjian, 1998). Looking at the older population in the current study, the attention given to them by asking them to be part of a biomedical research project in a laboratory with sophisticated technical equipment at a prestigious university seemed to have led to an overly motivated behavior to deliver their best possible performance, which was most likely directly associated with the increased walking speed. In addition, this highly motivated behavior might also have had an influence on the thoracic kyphosis angle, i.e. a higher motivational level corresponding to a more upright posture, especially in the thoracic spine. The adolescents were surely not less motivated, since they were all excited to see the systems that are being used to create their heroes in animated movies and video games. However, the strict laboratory atmosphere and the fact that the laboratory was located in the basement of a children's hospital seemed to have an overwhelming and almost slightly intimidating effect on some of the young participants, leading to a rather shy behavior and hence slower walking speeds. The increased RoM values in adults compared to the adolescents might be explained as an indirect consequence of the greater lumbar lordosis angles.

The atypically high gait speed found in older individuals was considered a limitation. It is therefore very important for future studies aiming at the comparison of spinal kinematics between different groups to consider gait speed as a factor that could influence RoM measurements. Another limitation was the lack of a dynamic coordinate system for the lumbar curvature angles due to a missing anterior reference point. Therefore, projection errors for this part of the spine were more likely to occur than in the thoracic spine.

5. Conclusions

The current study indicated postural differences in the sagittal plane between adolescents and adults, whereby the magnitude of lumbar lordosis and thoracic kyphosis seemed to increase during adolescence and reach their peak in adulthood. The absence of excessive thoracic kyphosis in older individuals could be explained by a previously reported subdivision of this population in those who develop excessive thoracic kyphosis and those who remain near the younger thoracic curve. Furthermore, adults displayed increased lumbar spine frontal plane RoM as compared to the adolescents, whereas the increased values in older individuals were found to be related to higher gait speeds. This dataset on the age-related kinematic behavior of the healthy spine during gait can serve as an important basis for investigations on spinal pathologies or treatment effects.

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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.2017.04.001.

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