



The age-specific normative values of standing whole-body sagittal alignment parameters in healthy adults: based on international multicenter data

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Received: 10 August 2022 / Revised: 18 October 2022 / Accepted: 31 October 2022 / Published online: 15 November 2022
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Abstract

Purpose To investigate the age-specific normative values of whole-body sagittal alignment (WBSA) including global balance parameters in healthy adults and to clarify the correlations among parameters based on the data from three international multicenter.

Methods Three hundred and seventeen healthy subjects (range: 20–84 y.o., mean: 43.8 ± 14.7 y.o.) were included and underwent whole-body biplanar X-ray imaging system. Spinopelvic parameters and knee flexion (KF), the center of acoustic meatus (CAM)-hip axis (HA), and C2 dentiform apophyse (OD)-HA, the cranial center (Cr)-HA were evaluated radiologically. Sub-analysis for correlation analysis between age and parameters and among parameters was performed to investigate age-specific change and compensatory mechanisms.

Results For age-related change, C2-7 angle ($r = .326$ for male/.355 for female), KF ($r = .427/.429$), and SVA ($r = .234/.507$) increased with age in both male and female group. For global parameters related to the center of the gravity, correlations with age were not significant ($r = .120/.161$ for OD-HA, $r = .163/.275$ for Cr-HA, $r = .149/.262$ for CAM-HA). Knee flexion (KF) has correlation with global parameters (i.e., SVA, OD-HA, Cr-HA, CAM-HA) and does not have correlations with local spinopelvic alignment.

Conclusion While several local alignment changes with age were found, changes in global parameters related to the center of gravity were kept relatively mild by the chain of compensation mechanisms including the lower limbs. We showed the normative values for a comprehensive WBSA in standing posture from large international healthy subjects' database.

Keywords Global balance · Sagittal balance · Normative values · Healthy subjects · Whole-body alignment

Introduction

Sagittal alignment of the spine is widely recognized as a primary subject for preoperative planning for spine surgery, and many studies have reported strong correlations between

these spinopelvic parameters and clinical symptoms [1–5]. Many studies have shown that spinopelvic parameters, such as the sagittal vertical axis (SVA), T1 pelvic angle (TPA), and spinosacral angle (SSA), are associated with the clinical manifestations and clinical outcomes in patients with spinal disorders [1–3, 5–8].

In addition, the center of acoustic meatus (CAM) and C2 dentiform apophyse (OD), which are indices of the center of gravity of the head, have been used in several studies for the purpose of evaluating whole-body balance in standing posture [9, 10]. The index of the center of gravity in the standing posture is reported to be constant in healthy cohorts and is kept constant by several compensation mechanisms. For compensation in standing posture for imbalance due to spinal malalignment, parameters out of the range of the cervical spine to the pelvis (e.g., hip, knee, and ankle)

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are sometimes mobilized [11, 12]. This whole-body sagittal alignment (WBSA) consists of many chains of balance from the foot to the cranium and changes with degeneration and other spinal morbidities [1, 4, 13]. Several studies have reported relationships between parameters—including parameters out of the spinopelvic range—and clinical outcomes and quality of life [5]. Kim et al. [3] described the CrSVA index, which is the distance between a vertical plumb line from the cranial center and the hip, knee, and ankle, and these are predictors that reflect the postoperative clinical outcome more strongly than the SVA in patients with cervical myelopathy. The lower limb parameters are also important compensation mechanisms in patients to maintain the standing posture in patients with spinal degeneration [5, 14, 15]. Several previous studies have reported that the alignment of the whole body, including the lower extremities, varies with age [1, 13, 16]. Hence, we believe that the clarification of the age-specific normal alignment values of global whole-body sagittal alignment and their mutual relationship are important for evaluating and understanding pathological alignment and balance abnormalities.

Several studies have reported age-specific normative values and correlations of whole-body sagittal parameters, including lower extremity alignment [1, 11, 17]. Le et al. [16] reported normative values for WBSA, including knee flexion, in an international study of 268 asymptomatic subjects. In addition, Lyer et al. [17] reported age-specific normative values for WBSA in a study analyzing 115 asymptomatic volunteers. However, these studies had a limitation in that the cohorts were biased toward younger age groups or were enrolled at a single institution. Therefore, an international multicenter study has been anticipated to determine the age-specific normative WBSA values in healthy subjects, including older subjects, and it was necessary to investigate the correlation between changes in each parameter in a cohort that included elderly individuals, especially the relationship between age-related changes in compensation mechanisms of the lower extremities and spinal parameters.

The current study aimed to comprehensively investigate age-specific WBSA parameters in a healthy population, to determine the normative values of these parameters, and to clarify the correlations among parameters based on international multicenter data.

Materials and methods

We enrolled healthy subjects who were confirmed not to have any past and/or current medical history of spinal disease with a questionnaire, and the Oswestry Disability Index was obtained for evaluation of clinical complaints [18]. The ODI score values were compared to previous reports and validated for treatment as a cohort of healthy subjects. Subjects with

neurological disease or with joint disease affecting assessment in the standing posture were not included in this survey.

Participants underwent whole-body X-ray using a scanning X-ray imaging system (EOS Imaging, Paris, France). The examination posture was a “hands-on-cheek” posture in standing horizontal viewing, and participants lightly touched their fingers and were instructed to relax as much as possible during shooting.

This study was approved by the Institutional Review Board of each institution.

Parameters of whole-body sagittal alignment

Whole-body sagittal alignment from cranio-cervical junction to knee joint was analyzed in this study. The occipito-C2 angle (O-C2 angle: McGregor line–C2 endplate) and C2-7 lordotic angle (C2 endplate–C7 caudal endplate) for the cranio-cervical region; the T1 slope for the cervico-thoracic region; upper thoracic kyphosis (Upper TK: T1-4), Lower TK (T4-12), and Global TK (T1-12) for thoracic kyphosis; upper lumbar lordosis (Upper LL: L1–L3), Lower LL (L4–S1), and Global LL (L1–S1) for lumbar lordosis; sacral slope (SS), pelvic tilt (PT), pelvic incidence (PI), and pelvic thickness for the pelvic region; average knee flexion (KF: average of left and right knee flexion angles) for the lower extremities; the sagittal vertical axis (SVA), OD-HA angle (angle between a vertical line and the line to the most superior point of dentiform apophyse of C2 to the center of the femoral head), Cr-HA offset (the distance from the plumb line from the cranial center of mass to the center of the femoral head), CAM-HA offset (the distance from the plumb line from the acoustic meatus to the center of the femoral head), T1 pelvic angle (TPA), spinosacral angle (SSA: the angle between the sacral plate and the center of C7 to the midpoint of the sacral plate), sagittal vertical axis (SVA), cranial sagittal vertical axis (CrSVA: the distance from the plumb line from the cranial center of mass to the posterior edge of the sacral plate) for global alignment. The cranial center of mass was defined as the midpoint of the nasion–inion line (root of the nose to the external occipital protuberance) as past reported [3]. The pelvic thickness means the sacroacetabular distance (the distance from the posterior edge of the sacral plate to the center of the femoral head) [19, 20]. Kyphosis and lordosis are defined as the angle between the upper endplate of a selected vertebra and the lower endplate of another selected vertebra. The parameters measured in this study are shown in Fig. 1.

Data analysis

The SterEOS software program (SterEOS 1.6, Postural assessment workflow, EOS Imaging) was used to measure the WBSA parameters.

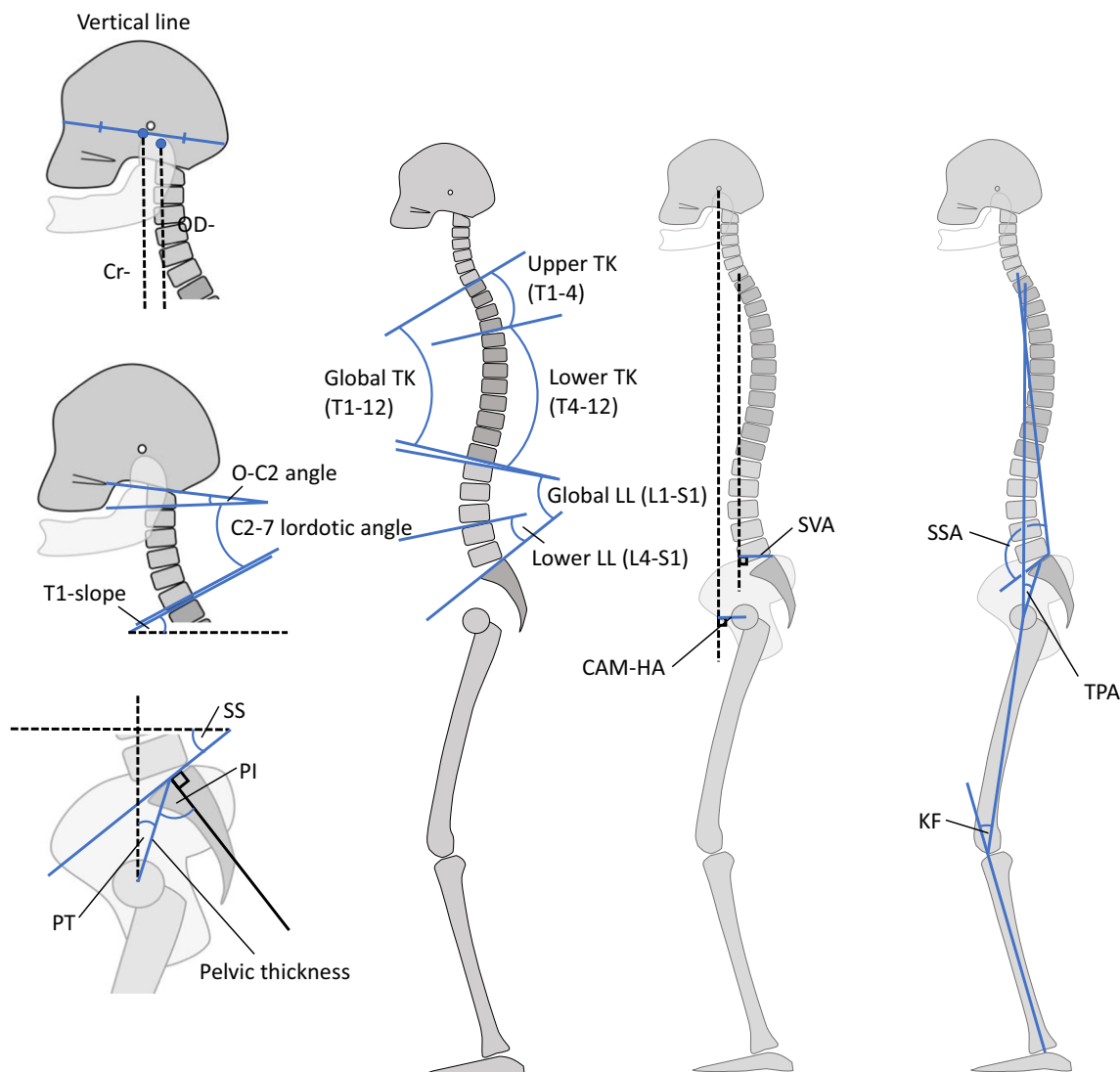


Fig. 1 Spinopelvic parameters and whole-body sagittal alignment parameters

We divided the subjects into three groups according to age (20–30 s, 40–60 s, ≥ 60 s) and analyzed these results among age groups. As a sub-analysis of the study, to clarify differences in parameters with age, we analyzed correlations between age and WBSA parameters by sex. Among these parameters, SVA, OD-HA, Cr-HA, CAM-HA, TPA, and SSA were distinguished as global parameters, and the mutual influence among each of the spinopelvic parameters and between spinopelvic parameters and global parameters was investigated in a correlation analysis.

Statistical analysis

IBM SPSS Statistics version 23.0 (IBM Corp., Armonk, NY, USA) was used for the statistical analyses. All values are expressed as the mean \pm standard deviation. Pearson's

correlation coefficient (r) was used to measure the strength of correlations between each parameter, and between age and each parameter. The strength of the correlation between each parameter was described using the absolute value of r ($r=0.00$ – 0.19 : very weak, $r=0.20$ – 0.39 : weak, $r=0.40$ – 0.59 : moderate, $r=0.60$ – 0.79 : strong, and $r=0.80$ – 1.0 : very strong). P values of <0.05 were considered statistically significant.

Results

Study subjects

A total of 317 subjects from three cohorts were included in this study (Table 1), including 206 Japanese adults and 111

Caucasian adults. The average age of the subjects included in the statistical analysis was 43.8 ± 14.7 years, 60.6% of the subjects were female ($n = 192$), and the average ODI score was 4.3 ± 6.2 . The ODI score values were compared to previous reports (5.1–10.2) and were determined to be acceptable for treatment as a cohort of healthy subjects [10, 18].

Parameters of WBSA

The results, including the mean and standard deviation of all measured parameters according to age, are reported in Table 2. The mean spinopelvic parameters were as follows: O-C2 angle, $15.9 \pm 8.1^\circ$; C2-7 lordotic angle, $1.3 \pm 12.6^\circ$; T1-slope, $22.7 \pm 8.4^\circ$; Upper TK, $11.1 \pm 6.3^\circ$; Lower TK, $33.6 \pm 10.5^\circ$; Global TK, $40.5 \pm 10.8^\circ$; Upper LL, $11.3 \pm 10.5^\circ$; Lower LL, $35.2 \pm 7.1^\circ$; Global LL, $54.1 \pm 11.5^\circ$; SS, $38.2 \pm 8.4^\circ$; PT, $12.6 \pm 7.6^\circ$; PI, $50.8 \pm 10.9^\circ$; and Pelvic thickness, 10.8 ± 0.9 cm. We also described the average values of the lower extremity and global parameters, which were as follows: KF, $-0.8 \pm 5.5^\circ$; SVA, -0.2 ± 2.6 cm; OD-HA, $-9.9 \pm 20.6^\circ$; Cr-HA, -1.7 ± 2.9 cm; CAM-HA, -2.1 ± 3.0 cm; TPA, $8.0 \pm 7.6^\circ$; SSA, $129.1 \pm 17.2^\circ$; and CrSVA, 2.1 ± 2.6 cm.

Correlation between age and parameters

In both males and females, weak or moderate correlations were found in spinopelvic parameters (i.e. C2-7 lordotic angle [male: $r = 0.326$, $P = 0.000$; female: $r = 0.355$, $P = 0.000$], T1 slope [male: $r = 0.242$, $P = 0.007$; female: $r = 0.279$, $P = 0.000$], and KF [male: $r = 0.427$, $P = 0.000$; female: $r = 0.429$, $P = 0.000$]). SVA (male: $r = 0.234$, $P = 0.009$; female: $r = 0.507$, $P = 0.000$) also showed a weak correlation in males and a moderate correlation in females. Meanwhile, other global parameters (i.e., Cr-HA [$r = 0.275$, $P = 0.000$], CAM-HA [$r = 0.262$, $P = 0.000$], and TPA [$r = 0.442$, $P = 0.000$]) only showed a correlation with age in females. Age-related changes in pelvic parameters (i.e., PT [$r = 0.357$, $P = 0.000$], PI [$r = 0.236$, $P = 0.001$] and Pelvic thickness [$r = -0.316$, $P = 0.000$]) were only observed in females. We found that the ODI score was weakly correlated with age in both males and females. The correlation between age and each parameter is shown in Table 3.

Correlation among parameters

The results of the analysis of correlation between spinopelvic parameters and between spinopelvic parameters and global parameters are summarized in Table 4. A very strong positive correlation ($r = 0.80$ – 1.0) was seen between T1 slope and Global TK ($r = 0.800$, $P = 0.000$), Lower TK and Global TK ($r = 0.833$, $P = 0.000$), Global LL and SS ($r = 0.817$, $P = 0.000$), and PT and TPA ($r = 0.914$, $P = 0.000$). A strong positive correlation ($r = 0.60$ – 0.79) was seen between the C2-7 lordotic angle and T1 slope ($r = 0.658$, $P = 0.000$), T1 slope and Lower TK ($r = 0.627$, $P = 0.000$), Upper LL, and Global LL ($r = 0.649$, $P = 0.000$), SS and PI ($r = 0.714$, $P = 0.000$), PT and PI ($r = 0.638$, $P = 0.000$), and PI and TPA ($r = 0.636$, $P = 0.000$).

Discussion

This is the first multicenter international study to evaluate age-specific WBSA in a cohort that included older subjects. This study presents the normative values for whole-body alignment, including lower limb and balance parameters, by age and sex in a healthy population and the correlations among them.

Standing posture is made up of a chain of balance starting from the foot to the cranium. Humans change their respective variable alignment and chain, keeping the center of gravity balance within the range of the cone of economy with the minimum effort of the muscles and taking the standing horizontal view posture [10, 21]. Amabile et al. [9] reported the constancy of CAM-HA and OD-HA, while cervical lordosis, PT, PI and SVA showed compensatory change in elderly people in a study that compared asymptomatic young and elderly people. Even in the asymptomatic population, the parameters that make up balance vary with age, but compensation for local alignment is provided to equalize global balance parameters to maintain standing whole-body balance [9, 13, 16, 17]. If spinal degeneration advances and eventually reaches a level that is outside the range of compensation, and a collapse of global balance occurs, then the health-related quality of life (HRQOL) declines [1, 2, 5–7, 22]. Hasegawa et al. [5] conducted a cluster analysis of

Table 1 Baseline characteristics of healthy subjects from the three cohorts

Characteristics	Total sample		Cohort 1		Cohort 2		Cohort 3	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
No. of subjects	317		106		100		111	
Race			Mongoloid		Mongoloid		Caucasian	
Age (years)	43.8	14.7	52.6	12.3	39.4	12.1	39.2	15.2
Female, <i>n</i> (%)	192 (60.6)		76 (71.7)		63 (63.0)		53 (47.7)	
ODI score	4.3	6.2	8.0	7.4	4.3	5.4	0.7	2.2

Table 2 The mean and standard deviation of all measured parameters according to age group

	Total			Male						Female									
	Mean	SD		Total (n = 125)		20–30 s (n = 62)		40–50 s (n = 45)		≥ 60 s (n = 18)		Total (n = 192)		20–30 s (n = 74)		40–50 s (n = 84)		≥ 60 s (n = 34)	
				Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
O-C2 angle (°)	15.9	8.1		15.6	7.6	15.3	6.6	16.3	8.1	14.8	9.8	16.1	8.4	17.1	9.9	15.6	7.3	15.2	7.8
C2-7 lordotic angle (°)	1.3	12.6		3.8	12.0	1.2	10.1	4.0	12.6	12.1	13.5	-0.4	12.8	-3.7	12.7	-1.2	10.8	8.8	13.7
T1-slope (°)	22.7	8.4		24.9	8.4	23.8	7.1	24.7	9.5	29.4	8.8	21.3	8.1	19.5	6.8	20.9	7.9	25.9	9.8
Upper (T1-4) TK (°)	11.1	6.3		13.0	6.6	12.6	6.1	12.5	7.1	15.4	6.9	9.8	5.8	10.7	4.8	9.7	5.9	8.1	7.1
Lower (T4-12) TK (°)	33.6	10.5		35.2	10.4	35.2	9.1	34.5	11.7	37.1	11.4	32.5	10.5	31.3	9.1	30.3	9.6	40.5	12.0
Global (T1-12) TK (°)	40.5	10.8		43.5	11.4	43.1	9.1	42.2	13.4	48.0	12.4	38.6	10.0	38.5	8.7	36.5	10.3	43.9	10.2
Upper (L1-3) LL (°)	11.3	10.5		11.8	10.5	13.3	10.4	11.1	10.1	8.1	11.0	11.0	10.6	11.9	9.6	10.6	10.8	9.9	12.1
Lower (L4-S1) LL (°)	35.2	7.1		36.4	6.1	37.4	5.4	35.1	6.9	36.4	6.4	34.4	7.6	36.0	7.1	32.7	7.3	35.1	8.9
Global (L1-S1) LL (°)	54.1	11.5		55.1	11.8	56.6	10.3	54.5	12.3	51.4	14.7	53.4	11.3	55.5	10.1	52.1	12.2	52.1	11.2
SS (°)	38.2	8.4		38.1	8.9	38.9	8.4	37.9	9.6	36.4	9.1	38.2	8.1	38.2	8.0	38.3	8.4	37.6	7.6
PT (°)	12.6	7.6		11.4	6.8	10.2	6.2	13.0	7.6	11.9	6.6	13.4	8.0	10.4	6.8	14.8	7.8	16.4	9.2
PI (°)	50.8	10.9		49.6	10.4	49.1	10.4	50.8	10.7	48.1	9.5	51.6	11.2	48.7	10.1	53.1	12.0	54.0	10.3
Pelvic thickness (cm)	10.8	0.9		10.6	1.0	10.6	0.8	10.6	0.8	10.9	1.9	10.8	0.7	11.1	0.7	10.8	0.7	10.5	0.7
Knee flexion (°)	-0.8	5.5		0.5	4.8	-1.7	4.5	2.1	4.1	3.8	4.2	-1.6	5.7	-4.5	5.5	-0.5	4.3	1.8	6.3
SVA (cm)	-0.2	2.6		-0.5	2.4	-1.0	2.1	-0.3	2.2	0.7	3.1	-0.1	2.8	-1.5	1.9	0.3	2.3	2.2	3.6
OD-HA (°)	-9.9	20.6		-10.1	20.4	-12.7	23.3	-8.5	17.1	-5.0	16.2	-9.9	20.8	-15.2	23.6	-6.2	16.5	-7.2	22.0
Cr-HA (cm)	-1.7	2.9		-1.7	2.8	-2.2	2.4	-1.5	2.7	-0.7	4.1	-1.7	2.9	-2.5	2.7	-1.5	2.4	-0.1	3.7
CAM-HA (cm)	-2.1	3.0		-2.2	3.0	-2.6	2.7	-2.2	2.6	-0.8	4.6	-2.1	3.0	-2.9	2.8	-1.9	2.6	-0.6	3.6
TPA (°)	8.0	7.6		6.7	6.2	5.7	6.0	7.8	6.7	7.7	5.0	8.8	8.2	5.1	6.3	10.2	7.9	13.2	9.6
SSA (°)	129.1	17.2		130.5	8.0	131.6	7.7	130.4	8.4	127.2	7.7	128.1	21.1	131.5	8.5	129.4	8.1	117.5	45.9
CrSVA (cm)	2.1	2.6		1.8	2.4	1.6	1.8	1.8	2.5	2.5	3.9	2.2	2.7	1.4	1.8	2.3	2.4	4.0	3.8
ODI score	4.3	6.2		2.8	4.5	1.7	3.8	3.6	4.7	4.4	5.3	5.3	6.9	2.2	4.3	6.9	7.2	8.1	8.3

Table 3 Correlation between age and whole-body sagittal alignment parameters

	O-C2 angle	C2-7 lordotic angle	T1-slope	Upper TK (T1-4)	Lower TK (T4-12)	Global TK (T1-12)	Upper LL (L1-3)	Lower LL (L4-S1)	Global LL (L1-S1)	SS	PT
<i>Male</i>											
<i>r</i>	.020	.326	.242	.152	.055	.147	-.166	-.146	-.181	-.155	.176
<i>P</i>	.822	.000	.007	.091	.543	.103	.065	.105	.043	.084	.050
<i>Female</i>											
<i>r</i>	-.108	.355	.279	-.163	.244	.137	-.062	-.061	-.139	-.031	.357
<i>P</i>	.137	.000	.000	.024	.001	.058	.396	.401	.054	.672	.000
	PI	Pelvic thickness	Knee flexion	SVA	OD-HA	Cr-HA	CAM-HA	TPA	SSA	CrSVA	ODI score
<i>Male</i>											
<i>r</i>	-.020	.062	.427	.234	.120	.163	.149	.169	-.233	.117	.241
<i>P</i>	.824	.491	.000	.009	.182	.072	.098	.060	.009	.198	.007
<i>Female</i>											
<i>r</i>	.236	-.316	.429	.507	.161	.275	.262	.442	-.173	.349	.302
<i>P</i>	.001	.000	.000	.000	.026	.000	.000	.000	.016	.000	.000

three groups with different compensatory status in WBSA (normal, compensated, and decompensated) and reported differences in compensatory parameters among them and the association between the compensatory status and the HRQOL score. The motivation of the current research is to investigate the change of each parameter involved in the compensatory function for standing posture with age and the correlations among the parameters. With the introduction of a new scanning X-ray imaging system, the evaluation of comprehensive parameters, including head to feet, became possible with low radiation exposure and high accuracy and several studies using this technique have reported the parameters asymptomatic subjects [1, 10, 15, 17, 23]; however, such studies seem to have relatively small study populations or include an age bias. The strengths of this study are that it included data with unified standards from a large population with less age group bias and that a comprehensive evaluation from the head to the lower extremities was conducted.

Regarding the spinopelvic parameters, the results of the present study were comparable to values previously reported in the relevant literature [1, 9, 13, 17, 24]. The analysis of parameters correlated with age revealed that OD-HA, Cr-HA, and CAM-HA were constant. Age showed a weak positive correlation with OD-HA and CAM-HA in female subjects but not male subjects. The sex differences in this study may be due to a lack of statistical power due insufficiency of the elderly age group in the male population. Age-related changes were observed in several parameters, even in the asymptomatic healthy cohort. In both male and female group, age-related change was shown in C2-7 lordotic angle, T1 slope, KF, and SVA. Compensatory changes of local alignment in cervical and lower extremities occur to maintain horizontal gaze in standing posture. Age-related changes in cervical lordosis, TPA, SVA and increasing LL, pelvic anteversion and KF have been described in previous reports [1, 9, 13, 17], which are almost compatible with the results of this study. The cervical spine is one of the most variable compensation mechanisms [25, 26].

Interestingly, age-related changes in pelvic parameters, including PT and PI pelvic thickness, were observed in females, and this tendency was not statistically significant in the males in this study population, while these pelvic parameters have been often treated as an inherent value of individuals. Vialle et al. [27] reported differences between male and female in PT, and Yukawa et al. [13] reported that there was a significant difference of PT between male and female in the elderly group. We hypothesized that the mechanism of degeneration of the sacroiliac joint differs between males and females. Although the event considered to have had the most influence is pregnancy or delivery [28], unfortunately the data of the present study did not include information on factors affecting pelvic parameters, such as pregnancy history; thus, further investigation is necessary in the future.

Table 4 Correlation among whole-body sagittal alignment parameters

		O-C2 angle	C2-7 lordotic angle	T1-slope	Upper TK (T1-4)	Lower TK (T4-12)	Global TK (T1-12)	Upper LL (L1-3)	Lower LL (L4-S1)	Global LL (L1-S1)	SS	PT	PI	Pelvic thickness	Average Knee flexion
C2-7 lordotic angle	<i>r</i>	-.470													
	<i>P</i>	.000													
T1-slope	<i>r</i>	-.061	.658												
	<i>P</i>	.280	.000												
Upper TK (T1-4)	<i>r</i>	.008	.241	.513											
	<i>P</i>	.881	.000	.000											
Lower TK (T4-12)	<i>r</i>	-.107	.493	.627	-.042										
	<i>P</i>	.057	.000	.000	.457										
Global TK (T1-12)	<i>r</i>	-.100	.582	.800	.392	.833									
	<i>P</i>	.075	.000	.000	.000	.000									
Upper LL (L1-3)	<i>r</i>	-.137	.136	-.092	-.103	.284	.242								
	<i>P</i>	.015	.016	.103	.068	.000	.000								
Lower LL (L4-S1)	<i>r</i>	-.072	.126	.073	-.051	.305	.277	.038							
	<i>P</i>	.198	.024	.193	.363	.000	.000	.505							
Global LL (L1-S1)	<i>r</i>	-.099	.045	.000	-.016	.431	.407	.649	.538						
	<i>P</i>	.080	.429	.996	.770	.000	.000	.000	.000						
SS	<i>r</i>	-.024	-.064	-.071	.012	.126	.116	.444	.426	.817					
	<i>P</i>	.664	.257	.210	.832	.025	.040	.000	.000	.000					
PT	<i>r</i>	-.052	.162	.059	-.093	-.051	-.070	.049	-.244	-.153	-.082				
	<i>P</i>	.355	.004	.292	.097	.366	.211	.381	.000	.006	.144				
PI	<i>r</i>	-.056	.066	-.012	-.057	.063	.041	.378	.158	.525	.714	.638			
	<i>P</i>	.319	.242	.831	.309	.261	.463	.000	.005	.000	.000	.000			
Pelvic thickness	<i>r</i>	.102	-.162	-.024	.110	-.120	-.068	-.227	-.205	-.306	-.319	-.213	-.399		
	<i>P</i>	.069	.004	.670	.051	.032	.225	.000	.000	.000	.000	.000	.000		
Knee flexion	<i>r</i>	-.048	.177	.228	.057	.064	.075	-.140	-.116	-.155	-.068	.198	.087	-.080	
	<i>P</i>	.398	.002	.000	.313	.254	.180	.012	.039	.006	.225	.000	.124	.156	
SVA	<i>r</i>	-.037	.347	.433	-.091	.189	.078	-.074	-.286	-.230	.018	.342	.255	-.136	.327
	<i>P</i>	.517	.000	.000	.107	.001	.163	.187	.000	.000	.749	.000	.000	.015	.000
OD-HA	<i>r</i>	.131	-.092	.270	.149	.016	.040	-.414	-.209	-.183	-.005	-.077	-.058	.056	.247
	<i>P</i>	.019	.103	.000	.008	.773	.476	.000	.000	.001	.924	.172	.301	.320	.000
Cr-HA	<i>r</i>	.136	.091	.411	.016	.191	.141	-.188	-.101	-.136	.048	-.156	-.073	-.058	.306
	<i>P</i>	.016	.109	.000	.778	.001	.012	.001	.074	.016	.396	.006	.199	.307	.000
CAM-HA	<i>r</i>	.170	.074	.438	.037	.217	.168	-.187	-.108	-.114	.096	-.158	-.037	-.046	.285
	<i>P</i>	.002	.192	.000	.515	.000	.003	.001	.054	.042	.088	.005	.516	.415	.000
TPA	<i>r</i>	-.052	.221	.166	-.128	.014	-.053	.068	-.293	-.162	-.008	.914	.636	-.254	.251
	<i>P</i>	.352	.000	.003	.022	.800	.351	.227	.000	.004	.888	.000	.000	.000	.000
SSA	<i>r</i>	.028	-.119	-.070	.024	.058	.067	.153	.286	.401	.399	-.177	.184	-.136	-.106
	<i>P</i>	.622	.034	.212	.673	.301	.232	.007	.000	.000	.000	.002	.001	.016	.060
CrSVA	<i>r</i>	.019	.107	.368	-.044	.186	.125	-.121	-.147	-.230	-.093	.190	.062	-.047	.328
	<i>P</i>	.742	.057	.000	.433	.001	.026	.032	.009	.000	.098	.001	.274	.402	.000

	<i>r</i>
very weak	0.00-0.19
weak	0.20-0.39
moderate	0.40-0.59
strong	0.60-0.79
very strong	0.80-

The analysis of correlation between parameters showed “strong” or greater correlations between adjacent parameters, such as C2-7 lordotic angle and T1 slope, T1 slope and Global TK, and Global LL and SS. Cervical spine alignment is the most substantial compensation mechanism for maintaining the horizontal view because the viewpoint exists in the head [25, 26]. For this reason, it is conceivable that T1 slope is strongly correlated with C2-7. Roussouly et al. [29] stated that the inflection point located on the L1 level on average and the characteristics of lumbar lordosis are highly dependent on the orientation of the sacral slope and the pelvis as a result of studies of young asymptomatic populations. There are inflection points at each transition between cervical lordosis, thoracic kyphosis, and lumbar lordosis, and a standing posture with minimum muscle effort is maintained by the chain of each variable of spinal alignment. Despite numerous reports that state that increased PT (i.e., retroversion of the pelvis) is an important compensatory parameter in populations with spinal degeneration [7, 8, 12, 21], this study did not show any strong correlation between PT and

the parameters from the cervical spine to the lumbar spine. Similar findings were found for KF. Parameters of the lower extremities, including the hip joint and knee joint, are also involved in compensation mechanisms in patients with sagittal imbalance [11, 12, 30]; it is considered that mobilizing the compensation mechanism of pelvic retroversion or the lower limb, including KF, is a balancing mechanism for the entire spine rather than responding to certain local alignment changes. As evidence to support this, KF was found to be correlated with almost all global parameters (i.e., SVA, OD-HA, Cr-HA, CAM-HA, TPA, CrSVA).

The present study was associated with some limitations. First, this was a cross-sectional study. In order to consider changes due to age, a longitudinal study should be conducted that observes the same group. It is not strictly clear whether changes in parameters or group-specific differences were due to age or occurred in the different age groups. However, it is impractical to observe a large number of people over the long term using the same measurement methods. In addition, the small number of cases in the elderly group could

have resulted in statistical under-power in the analysis of this study. Further studies with different designs are needed to infer the process of spinal balance failure and to suggest factors in sagittal alignment that may cause the exacerbation of imbalance.

Another limitation of the present study is that enrolled population included several races. Le Huec et al. [16] reported that pelvic parameters (PT, PI, SS) were comparable in comparative studies of Caucasian and Japanese subjects; however, the data showed that LL, TK, KF differed between the race groups. The standard values shown in this study may be slightly erroneous when the same values are applied to different races without adjustment. To address this problem, studies that include larger subjects or a more homogeneous group of subjects are needed. However, we believe that the correlation of these parameters that was shown in the present study will be useful for understanding the compensation mechanism.

Conclusions

We showed the normative values for comprehensive whole-body sagittal alignment in a standing posture based on a large asymptomatic population database. In both men and women, C2-7, T1 slope, KF, and SVA increased with age. In females but not males, age-related changes were found in pelvic parameters, including PT, PI and pelvic thickness. There is strong correlation between adjacent sagittal spinal parameters and KF, which was more associated with global parameters than local spinopelvic alignment. From the findings in the healthy population, several local alignment changes were found to occur with age, while changes in global parameters related to the center of gravity were kept relatively mild by the chain of compensation mechanisms, including the lower limbs.

Acknowledgements No funds were received in support of this work. No benefits in any form have been or will be received from a commercial party related directly or indirectly to the subject of this manuscript, either personally or institutionally.

Declarations

Conflict of interest The author's declare that they have no conflict of interest.

References

- Hasegawa K, Okamoto M, Hatsushikano S, Shimoda H, Ono M, Watanabe K (2016) Normative values of spino-pelvic sagittal alignment, balance, age, and health-related quality of life in a cohort of healthy adult subjects. *Eur Spine J* 25:3675–3686. <https://doi.org/10.1007/s00586-016-4702-2>
- Protopsaltis T, Schwab F, Bronsard N, Smith JS, Klineberg E, Mundis G, Ryan DJ, Hostin R, Hart R, Burton D (2014) The T1 pelvic angle, a novel radiographic measure of global sagittal deformity, accounts for both spinal inclination and pelvic tilt and correlates with health-related quality of life. *JBJS* 96:1631–1640
- Kim YC, Lenke LG, Lee SJ, Gum JL, Wilartatsami S, Blanke KM (2017) The cranial sagittal vertical axis (CrSVA) is a better radiographic measure to predict clinical outcomes in adult spinal deformity surgery than the C7 SVA: a monocentric study. *Eur Spine J* 26:2167–2175. <https://doi.org/10.1007/s00586-016-4757-0>
- Le Huec JC, Faundez A, Dominguez D, Hoffmeyer P, Aunoble S (2015) Evidence showing the relationship between sagittal balance and clinical outcomes in surgical treatment of degenerative spinal diseases: a literature review. *Int Orthop* 39:87–95. <https://doi.org/10.1007/s00264-014-2516-6>
- Hasegawa K, Okamoto M, Hatsushikano S, Watanabe K, Ohashi M, Vital J-M, Dubousset J (2020) Compensation for standing posture by whole-body sagittal alignment in relation to health-related quality of life. *Bone Joint J* 102:1359–1367
- Harroud A, Labelle H, Joncas J, Mac-Thiong JM (2013) Global sagittal alignment and health-related quality of life in lumbosacral spondylolisthesis. *Eur Spine J* 22:849–856. <https://doi.org/10.1007/s00586-012-2591-6>
- Schwab F, Lafage V, Patel A, Farcy J-P (2009) Sagittal plane considerations and the pelvis in the adult patient. *Spine* 34:1828–1833
- Takemoto M, Boissiere L, Novoa F, Vital JM, Pellise F, Perez-Gruoso FJ, Kleinstuck F, Acaroglu ER, Alanay A, Obeid I, Obeid I (2016) Sagittal malalignment has a significant association with postoperative leg pain in adult spinal deformity patients. *Eur Spine J* 25:2442–2451. <https://doi.org/10.1007/s00586-016-4616-z>
- Amabile C, Le Huec JC, Skalli W (2018) Invariance of head-pelvis alignment and compensatory mechanisms for asymptomatic adults older than 49 years. *Eur Spine J* 27:458–466. <https://doi.org/10.1007/s00586-016-4830-8>
- Hasegawa K, Okamoto M, Hatsushikano S, Shimoda H, Ono M, Homma T, Watanabe K (2017) Standing sagittal alignment of the whole axial skeleton with reference to the gravity line in humans. *J Anat* 230:619–630. <https://doi.org/10.1111/joa.12586>
- Obeid I, Hauger O, Aunoble S, Bourghli A, Pellet N, Vital J-M (2011) Global analysis of sagittal spinal alignment in major deformities: correlation between lack of lumbar lordosis and flexion of the knee. *Eur Spine J* 20:681
- Jalal CM, Cruz DL, Diebo BG, Poorman G, Lafage R, Bess S, Ramchandran S, Day LM, Vira S, Liabaud B, Henry JK, Schwab FJ, Lafage V, Passias PG (2017) Full-body analysis of age-adjusted alignment in adult spinal deformity patients and lower-limb compensation. *Spine* 42:653–661. <https://doi.org/10.1097/BRS.0000000000001863>
- Yukawa Y, Kato F, Suda K, Yamagata M, Ueta T, Yoshida M (2018) Normative data for parameters of sagittal spinal alignment in healthy subjects: an analysis of gender specific differences and changes with aging in 626 asymptomatic individuals. *Eur Spine J* 27:426–432. <https://doi.org/10.1007/s00586-016-4807-7>
- Barrey C, Roussouly P, Perrin G, Le Huec JC (2011) Sagittal balance disorders in severe degenerative spine: can we identify the compensatory mechanisms? *Eur Spine J* 20(Suppl 5):626–633. <https://doi.org/10.1007/s00586-011-1930-3>
- Lazennec JY, Folinis D, Bendaya S, Rousseau MA, Pour AE (2016) The global alignment in patients with lumbar spinal stenosis: our experience using the EOS full-body images. *Eur J Orthop Surg Traumatol Orthop Traumatol* 26:713–724. <https://doi.org/10.1007/s00590-016-1833-4>
- Le Huec JC, Hasegawa K (2016) Normative values for the spine shape parameters using 3D standing analysis from a database of

- 268 asymptomatic Caucasian and Japanese subjects. *Eur Spine J* 25:3630–3637. <https://doi.org/10.1007/s00586-016-4485-5>
17. Iyer S, Lenke LG, Nemani VM, Albert TJ, Sides BA, Metz LN, Cunningham ME, Kim HJ (2016) Variations in sagittal alignment parameters based on age: a prospective study of asymptomatic volunteers using full-body radiographs. *Spine* 41:1826–1836
 18. Fairbank JC, Pynsent PB (2000) The Oswestry disability index. *Spine* 25:2940–2953
 19. Duval-Beaupere G, Schmidt C, Cosson P (1992) A Barycentremetric study of the sagittal shape of spine and pelvis: the conditions required for an economic standing position. *Ann Biomed Eng* 20:451–462
 20. Tardieu C, Hasegawa K, Haeusler M (2017) How did the pelvis and vertebral column become a functional unit during the transition from occasional to permanent bipedalism? *Anatom Record* 300:912–931. <https://doi.org/10.1002/ar.23577>
 21. Le Huec JC, Saddiki R, Franke J, Rigal J, Aunoble S (2011) Equilibrium of the human body and the gravity line: the basics. *Eur Spine J* 20(Suppl 5):558–563. <https://doi.org/10.1007/s00586-011-1939-7>
 22. Glassman SD, Berven S, Bridwell K, Horton W, Dimar JR (2005) Correlation of radiographic parameters and clinical symptoms in adult scoliosis. *Spine* 30:682–688
 23. Glaser DA, Doan J, Newton PO (2012) Comparison of 3-dimensional spinal reconstruction accuracy: biplanar radiographs with EOS versus computed tomography. *Spine* 37:1391–1397. <https://doi.org/10.1097/BRS.0b013e3182518a15>
 24. Amabile C, Pillet H, Lafage V, Barrey C, Vital JM, Skalli W (2016) A new quasi-invariant parameter characterizing the postural alignment of young asymptomatic adults. *Eur Spine J* 25:3666–3674. <https://doi.org/10.1007/s00586-016-4552-y>
 25. Le Huec J, Demezou H, Aunoble S (2015) Sagittal parameters of global cervical balance using EOS imaging: normative values from a prospective cohort of asymptomatic volunteers. *Eur Spine J* 24:63–71
 26. Yoshida G, Alzakri A, Pointillart V, Boissiere L, Obeid I, Matsuyama Y, Vital JM, Gille O (2017) Global spinal alignment in patients with cervical spondylotic myelopathy. *Spine*. <https://doi.org/10.1097/BRS.0000000000002253>
 27. Vialle R, Levassor N, Rillardon L, Templier A, Skalli W, Guigui P (2005) Radiographic analysis of the sagittal alignment and balance of the spine in asymptomatic subjects. *JBJS* 87:260–267. <https://doi.org/10.2106/jbjs.D.02043>
 28. Garagiola DM, Tarver RD, Gibson L, Rogers RE, Wass JL (1989) Anatomic changes in the pelvis after uncomplicated vaginal delivery: a CT study on 14 women. *Am J Roentgenol* 153:1239–1241
 29. Rousouly P, Gollogly S, Berthonnaud E, Dimnet J (2005) Classification of the normal variation in the sagittal alignment of the human lumbar spine and pelvis in the standing position. *Spine* 30:346–353. <https://doi.org/10.1097/01.brs.0000152379.54463.65>
 30. Ferrero E, Liabaud B, Challier V, Lafage R, Diebo BG, Vira S, Liu S, Vital JM, Ilharreborde B, Protopsaltis TS, Errico TJ, Schwab FJ, Lafage V (2016) Role of pelvic translation and lower-extremity compensation to maintain gravity line position in spinal deformity. *J Neurosurg Spine* 24:436–446. <https://doi.org/10.3171/2015.5.SPINE14989>

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