Heliyon 10 (2024) e29239

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Functional analysis of postural spinal and pelvic parameters using static and dynamic spinometry

Tobias Bode[a,*,1], Schima Zoroofchi[a,1], Eik Vettorazzi[f], Jan-Niklas Droste[b,c], Götz H. Welsch[a,d], René Schwesig[e,2], Robert Percy Marshall[b,e,2]

[a] Athleticum, University Medical Center Hamburg-Eppendorf, Martinistr. 52, 20246, Hamburg, Germany
[b] RasenBallsport Leipzig GmbH, Cottaweg 3, 04177, Leipzig, Germany
[c] BG Klinikum Hamburg-Boberg, Bergedorfer Str. 10, 21033, Hamburg, Germany
[d] Department of Trauma and Orthopedic Surgery, University Medical Center Hamburg-Eppendorf, Martinistr. 52, 20246, Hamburg, Germany
[e] Department of Orthopedic and Trauma Surgery, Martin-Luther-University Halle-Wittenberg, 06120 Halle (Saale), Germany
[f] Institute of Medical Biometry and Epidemiology, University Medical Center Hamburg-Eppendorf, Martinistr. 52, 20246, Hamburg, Germany

ARTICLE INFO

Keywords:
Spinometry
Posture
Video rasterstereography
Spino-pelvic dysfunction
Back pain
Motion analysis
Functional movement

ABSTRACT

Background: Spinometry is a radiation-free method to three-dimensional spine imaging that provides additional information about the functional gait patterns related to the pelvis and lower extremities. This radiation-free technology uses the surface topography of the trunk to analyze surface asymmetry and identify bony landmarks, thereby aiding the assessment of spinal deformity and supporting long-term treatment regimes. Especially reliable dynamic spinometric data for spine and pelvis are necessary to evaluate the management of non-specific back pain.

Research aim: This study aims to generate reliable dynamic spinometric data for spine and pelvis parameters that can serve as reference data for future studies and clinical practice.

Methods: This study assessed 366 subjects (185 females) under static and 360 subjects (181 females) under dynamic (walking on a treadmill at 3 km/h and 5 km/h) conditions. The DIERS Formetric 4Dmotion® system uses stripes of light to detect the surface topography of the spine and pelvis and identifies specific landmarks to analyze the spine during standing and walking.

Results: Relevant gender effects were calculated for lordotic angle ($\eta_p^2 = 0.22$) and pelvic inclination ($\eta_p^2 = 0.26$). Under static conditions, female subjects showed larger values for both parameters (lordotic angle: 41.6 ± 8.60°; pelvic inclination: 25.5 ± 7.49°). Regarding speed effects, three relevant changes were observed (sagittal imbalance: $\eta_p^2 = 0.74$, kyphotic angle: $\eta_p^2 = 0.13$, apical deviation: $\eta_p^2 = 0.11$). The most considerable changes were observed between static condition and 3 km/h, especially for sagittal imbalance and lordotic angle. For these parameters, relevant effect sizes ($d > 0.8$) were calculated between static and 3 km/h for males and females. Concerning clinical vertebral parameters, only lordotic angle and pelvic inclination were correlated with each other ($r = 0.722$).

Conclusion: This study generated a gender-specific reference database of asymptomatic individuals for static and dynamic spinometry. It demonstrated that the DIERS Formetric 4Dmotion® system could capture natural changes in static and dynamic situations and catalogue functional adaptations of spino-pelvic statics at different speeds. The lordotic angle is an indirect

* Corresponding author.
E-mail address: t.bode@icloud.com (T. Bode).

[1] The first two authors contributed equally to this project and should be considered co-first authors.
[2] The last two authors contributed equally to this project and should be considered co-last authors.

https://doi.org/10.1016/j.heliyon.2024.e29239
Received 13 September 2023; Received in revised form 2 April 2024; Accepted 3 April 2024
Available online 4 April 2024

marker of pelvic inclination, allowing spinometry to identify individuals at risk even under dynamic conditions.

1. Introduction

The pelvis is the central axis of human movement and is critical for upright posture, directly influencing the positioning of the upper and lower body [[1–3]]. Dysfunction of the spinal-pelvic complex is particularly relevant in lumbar pain syndromes [[4,5]]. In fact, non-specific back pain implies no known pathoanatomical cause and is the most common reason for chronic low back pain - approximately 90% of cases [[6]]. Unconscious movement patterns (such as lifting household items [[7]]) typically cause this pain, which can result in hypertonic, painful muscles and reduced joint mobility [[8,9]]. Conventional imaging methods such as X-ray or higher resolution imaging using Computed Tomography (CT) and Magnetic Resonance Imaging (MRI) [[10]] primarily cannot detect these conditions. However, surveys have shown that, despite medical guidelines, the diagnostic imaging of the lumbar spine remains subject to the personal preferences of the healthcare provider [[11]]. Static X-rays are still commonly performed in emergency departments [[12]].

For this reason, researchers and clinicians have developed clinical tests to detect functional deficits of the spino-pelvic complex [[13]]. These functional tests are often highly dependent on the clinical experience of the examiner and have low interrater reliability [[14,15]].

There is an urgent need to find a solution that can provide objective standards for the clinical examination of the spino-pelvic complex and minimize inter-rater variation to achieve better outcomes. We propose that spinometry can provide a much-needed adjunct tool for examining, monitoring, and prescribing therapy for patients with functional lumbar problems by functionally mapping the entire spinal-pelvic complex without harmful radiation. The primary objective of this study was to generate dynamic spinometry reference data for the spine in healthy subjects.

2. Materials and methods

2.1. Study population

Spinometric data from a total of 366 volunteers (185 female, 181 male) were analyzed in a static position. Of these, three hundred and sixty subjects (181 female, 179 male; age range: 20–40 years) were further examined in dynamic positions. The dynamic data of some subjects could not be used due to technical problems with the evaluation. This explains the difference (n = 6) between static and dynamic measurements.

Each subject was asked to complete a health questionnaire and then underwent a clinical examination to select suitable volunteers for this project. Subjects with one of the following criteria were excluded from the study: had reported episodes of back pain within the previous six months (> two days), had pre-existing spinal deformities, had musculoskeletal or neurological disorders, had a leg length difference of more than 0.5 cm, or were pregnant. Prior to participation, each individual involved in this study provided informed

Fig. 1. Schematic presentation of the Diers Formetric 4Dmotion® Lab: Patient is standing on a treadmill. Clothes have been taken of except underwear. Markers have been placed on distinct and defined anatomical landmarks of the back (vertebra prominens, both posterior superior iliac spines) and legs. Lateral cameras enable measurement of the leg axis from the side (with kind approval of Diers International, Wiesbaden, Germany).

consent. The local ethics committee approved this study (reference number: PV4960, local ethics committee of the Medical Chamber Hamburg).

2.2. Spinometry

All subjects were examined statically and dynamically with spinometry-based devices (DIERS international, Schlangenbad, Germany). The device projects parallel light stripes onto the back of a standing patient. The distortion of the raster lines provides the basis for calculating the surface topography of the trunk to analyze surface asymmetry and identify bony landmarks [[16]]. The system can correlate surface topography with the position of the spine [[17]].

The DIERS Formetric 4Dmotion® system captures images of the back of the patient as they walk on a treadmill for 5 s at a rate of 50 frames per second. These images are converted into a three-dimensional (dynamic) reconstruction of the spine [[16]]. The fourth dimension, as implied by the name of the laboratory setup, refers to the measurement over 5 s. Therefore, this diagnostic examination method can be described as a four-dimensional diagnostic tool (4Dmotion® Lab; Fig. 1).

While performing static spinometry without markers, reflective markers must be attached to three pre-defined anatomical fixed points (the vertebra prominens and both posterior superior iliac spines), as soft tissue moves under dynamic conditions, making it difficult to detect these points automatically. These reflective markers are essential for calculating objective 4D values of the spine and pelvis. However, it is necessary to note that pelvic torsion and pelvic inclination can only be measured statically due to the experimental setup. The parameters analyzed in this study are defined and listed in Table 1.

Note that spinometry nomenclature of the DIERS Formetric 4Dmotion® system has changed. For better understanding, the parameters have been renamed according to widespread scientific nomenclature by the manufacturer. Trunk inclination, trunk imbalance and lateral deviation are now called sagittal imbalance, coronal imbalance and apical deviation. The terminology of the parameters is an integral part of the DIERS Formetric 4Dmotion® system. For a better understanding, Fig. 2a–i illustrates the spino-pelvic parameters used in this study, also pointing out their formerly used.

2.3. Measurement setup and protocol

Measurements were taken with the subject standing. The subjects were barefoot and wearing only underwear. They had their arms hanging down and looked forward. Long hair was tied back, and jewellery was removed. Reflective adhesive markers were placed on three anatomical landmarks: the vertebra prominens (the spinous process of the seventh cervical vertebra) and on both posterior superior iliac spines. The manufacturer uses these points as reference points for dynamic spinometry because they are considered classic topographical landmarks of the spino-pelvic complex. Their anatomical characteristics make them particularly easy to palpate and identify manually. The examination method was explained to the participants in an easy-to-understand manner in just a few minutes and was easy to perform. The static assessment was first performed standing on the treadmill. Before starting the dynamic measurement, the participants were allowed to familiarize themselves with the movement on the treadmill and the experimental setup according to their subjective needs, which usually took only a few minutes. Once the subjects felt confident and established homogeneous movements, the dynamic spinometry measurement was performed. For the dynamic assessment, the participants walked on the treadmill at 3 km/h and 5 km/h for 60–90 s at each speed level.

Table 1
Explanation of the spino-pelvic parameters.

Parameters	Interpretation
Kyphotic Angle (°)	The angle between the surface tangents on the two inflection points ICT and ITL.
Lordotic Angle (°)	The angle between the surface tangents on inflection points ITL and ILS.
Sagittal Imbalance (°) ***[formerly: Trunk Inclination]***	The angle between the connecting line VPDM and an external line of gravity n.i. Positive value signifies a forward inclination, negative value a rearward inclination of upper body.
Coronal Imbalance (°) ***[formerly: Trunk Imbalance]***	The angle between the direct connection VPDM and a line of gravity through the VP. Positive value signifies a shift of the VP to the right, negative value a shift to the left.
Surface Rotation rms (°)	The root mean square of the horizontal components of the surface normals on the symmetry line. In this calculation values get rectified before being averaged. (e.g.,: 3.0° R and −3.0° L build an average of 3.0°).
Pelvic Obliquity (mm)	The different height of the two lumbar dimples to each other in mm positive value = the right dimple is higher than the left
Pelvic Torsion (°)	The torsion of the surface normals on the two lumbar dimples. Notation: a positive pelvic torsion signifies that the right hip bone is oriented further forward (anterior) than the left one
Pelvic Inclination (°) ***[formerly: Pelvic Tilt]***	The mean vertical torsion of the two surface normals on the dimples. n.i. Notation: a positive pelvic inclination signifies a mean vertical component upwards
Apical Deviation (rms) ***[formerly: Lateral Deviation]***	The mean square deviation of the midline of the spine from the direct connection VPDM in the frontal plane. In this calculation values get rectified before being averaged (e.g.,: 3.0 mm R and −3.0 mm L build an average of 3.0 mm).

VP: **Vertebra Prominens** DM: **Dimple Middle** ICT: **Inflection point cervical thoracic** ITL: **Inflection point thoracic lumbar** ILS: **Inflection point lumbar sacral**.

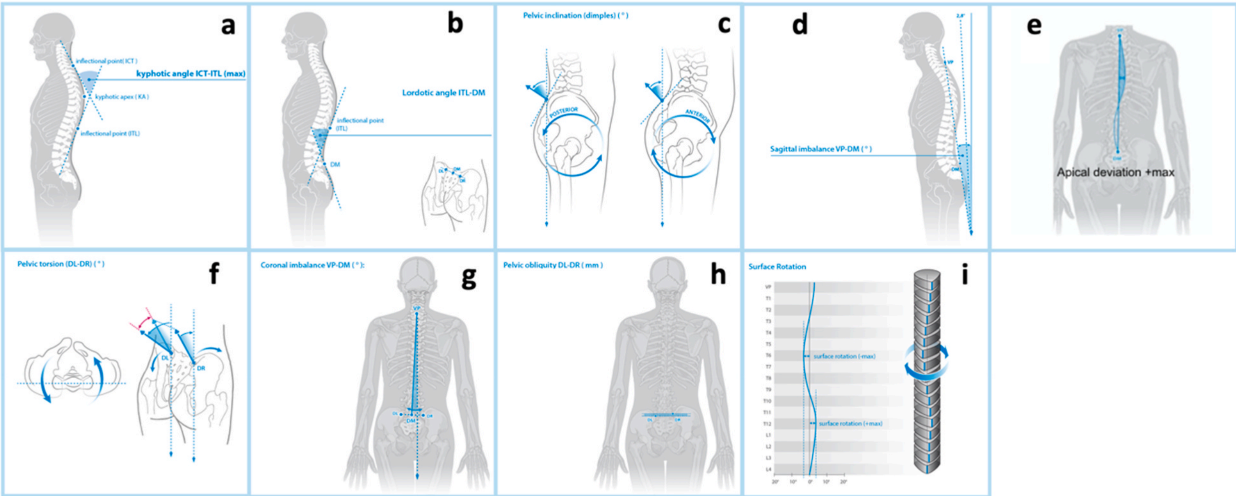

Fig. 2. a–i: Illustrations of the spino-pelvic parameters analyzed (with kind approval of Diers International, Wiesbaden, Germany): **a)** *kyphotic angle*: formed by the surface tangents of the upper Thoracic-Lumbar-Inflection Point (ICT) in the vicinity of the seventh cervical vertebra (veterbra prominens; VP) and the Cervico-Thoracic-Inflection Point (ITL), **b)** *lordotic angle*: formed by the surface tangents of the ITL and DM (midpoint of the two dimples), **c)** *pelvic inclination*: calculated mean torsion angle of the left dimple (DL) and right dimple (DR) surface, **d)** *sagittal imbalance*: angle formed by the perpendicular (vertical) line and the line connecting the seventh cervical vertebra (vertebra prominens, VP) and DM. >2.8° is referred to as "inclination", <2.8° "reclination", **e)** *apical deviation + max:* the maximum deviation distance of the spinal midline from the line connecting the vertebra prominens to the midpoint of the two dimples (VPDM) to the right, **f)** *pelvic torsion*: calculated angle from the reciprocal torsion of the surface normal on the two lumbar dimples (vertical components), **g)** *coronal imbalance*: angle formed by the perpendicular midline originating from VP and the connection line VPDM (positive value means VP is shifted to the right, negative value indicates a shift to the left), **h)** *pelvic obliquity*: difference in height of the lumbar dimples based on a horizontal plane, **i)** *surface rotation* (with kind approval of Diers International, Wiesbaden, Germany).

3. Statistics

Descriptive statistics were reported for all variables, including means, standard deviations (SDs) and 95% confidence intervals (95% CIs). Normality was tested using the Shapiro-Wilk test prior to data analysis. Sagittal Imbalance ($p = 0.125$), Coronal Imbalance ($p = 0.150$) and Lordotic Angle ($p = 0.613$) showed a normal distribution for static measurement.

A two-factor (gender and speed: static or dynamic at 3 or 5 km/h) univariate general linear model was used to examine the mean differences [[18]]. Differences between the means were considered significant if $p < 0.05$ and $\eta_p^2 > 0.10$ [20]. Due to the large sample size (n = 366 or n = 360), the partial eta squared is more important than the alpha error level ($p < 0.05$) to avoid an overestimation of the mean differences within the analysis of variance.

The effect size d (the mean difference between scores divided by the pooled SD) was also calculated between adjacent speed levels depending on gender for all parameters [[19]]. The interpretation is based on the recommendations of Cohen: small: $d < 0.5$, moderate: $d \geq 0.5$, large: $d > 0.8$ [21].

Relationships between variables were analyzed using Pearson's product-moment correlation (r) and interpreted as negligible (<0.1), weak (0.1–0.4), moderate (0.4–0.7), strong (0.7–0.9), and very strong (>0.9) [21]. A correlation of $r^2 > 0.5$ (explained variance >50%) was considered relevant and only reported.

Statistical analyses were performed using SPSS version 28.0 for Windows (IBM, Armonk, NY, USA).

4. Results

The anthropometric data is summarized in Table 2.

The study was completed by 360 participants (age: 26.2 ± 5.06 years, weight: 70.7 kg ± 13.5 kg). Female participants (61.5 ± 9.15 kg; 1.68 ± 0.06 m) were significantly (weight: $\eta_p^2 = 0.46$; height: $\eta_p^2 = 0.54$) lower in height and weight than males (79.8 ± 10.7

Table 2
Demographic and anthropometric data of the investigated sample for the static measurement.

	Female (n = 163–180)	**Male (n = 166–180)**	Variance analysis (p/η_p^2)
Age (years)	26.3 ± 4.99	26.1 ± 5.14	0.640/0.01
Weight (kg)	61.5 ± 9.15	79.8 ± 10.7	<0.001/0.46
Height (m)	1.68 ± 0.06	1.83 ± 0.07	<0.001/0.54
BMI (kg/m^2)	21.7 ± 2.86	23.8 ± 2.48	<0.001/0.14

kg; 1.83 ± 0.07 m). Table 3 gives a detailed overview of all spinometry data measured during standing and moving, broken down by gender and speed.

Two relevant gender effects (Lordotic angle: $\eta_p^2 = 0.22$; pelvic inclination: $\eta_p^2 = 0.26$) and three relevant speed effects (Sagittal imbalance: $\eta_p^2 = 0.74$; Kyphotic angle: $\eta_p^2 = 0.13$; Apical deviation: $\eta_p^2 = 0.11$) were calculated. No interaction effects (gender x speed) were observed for examined the parameters. As shown in Table 3, females (41.6 ± 8.60°) had a significantly larger lordotic angle ($p < 0.001$, $\eta_p^2 = 0.22$) than males (34.2 ± 8.23°) in static measurements. In addition, the sagittal imbalance angle (3.21 ± 2.19°) and pelvic torsion angle (0.13 ± 2.30°) were significantly smaller in females. Pelvic inclination was significantly larger in females (25.5 ± 7.49°).

4.1. Comparison depending on velocity

Independent of gender, we found three main speed effects (Table 3). A relevant difference was detected for the apical deviation between 3 and 5 km/h ($\eta_p^2 = 0.27$) and for the lordotic angle between static measurement and 3 km/h ($\eta_p^2 = 0.63$). Only for sagittal imbalance were two relevant differences between adjacent velocities (static vs. 3 km/h: $\eta_p^2 = 0.75$; 3 vs. 5 km/h: $\eta_p^2 = 0.24$).

Relevant effect sizes ($d > 0.8$) between any two adjacent velocity levels were calculated solely for lordotic angle and sagittal imbalance (Fig. 3a–g).

All four relevant effect sizes (each for males and females; d range: 0.86–1.66) were detected between static and 3 km/h (Fig. 3).

4.2. Relationships between multiple parameters and dimensions

A relevant correlation ($r = 0.722$) was computed exclusively between pelvic inclination and lordotic angle (Fig. 4).

This means that the pelvic inclination explains 52% of the variance in the lordotic angle ($r^2 = 0.52$). The second largest correlation was found between the kyphotic angle and the lordotic angle ($r = 0.407$). Consequently, the explained variance is only 17% ($r^2 = 0.17$), much less than the unexplained variance (83%).

4.3. Comparison of own results with comparable results of the literature

Previous studies on defining reference values for static and dynamic spinometry have been published, as shown in Table 4.

5. Discussion

Static upright radiographs are frequently used for diagnosing spinal deformities in back pain despite frequent lack of indication [[20]]. Possible harmful consequences of excessive radiation exposure (especially to the primary sex glands) have been discussed extensively in the past [[21,22]].

Spinometry has been developed as a possible radiation-free assessment based on video-rastersterography [[23]]. Initially validated in scoliosis patients, it can reconstruct three-dimensional spino-pelvic posture with an accuracy comparable to anterior-posterior radiographs [[16]]. However, unlike radiography, which relies on the accurate positioning of the patient to avoid systematic measurement errors, spinometry provides consistent and reproducible results regardless of position, facilitating re-examination by different operators [[24]]. Spinometry has demonstrated good reliability, validity and reproducibility of clinically relevant postural

Table 3
Descriptive comparison depending on gender and velocity for rasterstereography and analysis of variance (relevance criteria: $p < 0.05$ and $\eta_p^2 > 0.10$). Relevant differences and maxima marked in bold. M = male (n = 168); f = female (n = 167); standard deviation = SD.

parameter	gender	velocity (km/h) Mean ± SD			variance analysis (p/η_p^2); effects		
		0	3	5	gender	velocity	gender x velocity
Sagittal Imbalance (°)	m	3.92 ± 2.16	7.72 ± 2.41	**8.29 ± 2.60**	<0.001/0.04	**<0.001/0.74**	0.612/0.01
	f	3.21 ± 2.19	6.82 ± 2.46	7.44 ± 2.63			
Coronal Imbalance (°)	m	−0.58 ± 0.94	**−0.48 ± 1.02**	−0.49 ± 0.95	0.006/0.02	0.003/0.02	<0.001/0.05
	f	−0.53 ± 1.05	−0.88 ± 1.03	−0.96 ± 1.14			
Pelvic Obliquity (mm)	m	0.18 ± 3.93	−0.98 ± 3.52	−1.03 ± 3.44	0.310/0.00	<0.001/0.06	0.632/0.00
	f	**0.38 ± 3.80**	−0.55 ± 4.06	−0.60 ± 4.08			
Kyphotic Angle (°)	m	**49.0 ± 9.19**	46.9 ± 7.89	46.2 ± 8.26	<0.001/0.04	**<0.001/0.13**	0.720/0.00
	f	45.6 ± 8.71	43.9 ± 8.27	43.1 ± 8.59			
Lordotic Angle (°)	m	34.2 ± 8.23	26.4 ± 7.12	25.9 ± 7.28	**<0.001/0.22**	<0.001/0.06	0.016/0.01
	f	**41.6 ± 8.60**	34.4 ± 8.13	34.4 ± 8.66			
Surface Rotation rms (°)	m	3.27 ± 1.22	3.16 ± 0.99	3.16 ± 0.99	0.945/0.00	<0.001/0.03	0.076/0.01
	f	**3.45 ± 1.28**	3.08 ± 0.92	3.08 ± 0.95			
Apical Deviation rms (mm)	m	4.23 ± 2.01	4.78 ± 1.78	5.09 ± 1.69	0.733/0.00	**<0.001/0.11**	0.205/0.01
	f	4.38 ± 2.06	4.63 ± 1.46	**5.25 ± 1.40**			
Pelvic Torsion (°)	m	**0.75 ± 2.41**	–	–	0.017/0.02	–	–
	f	0.13 ± 2.30	–	–			
Pelvic Inclination (°)	m	16.7 ± 6.77	–	–	**<0.001/0.26**	–	–
	f	**25.5 ± 7.49**	–	–			

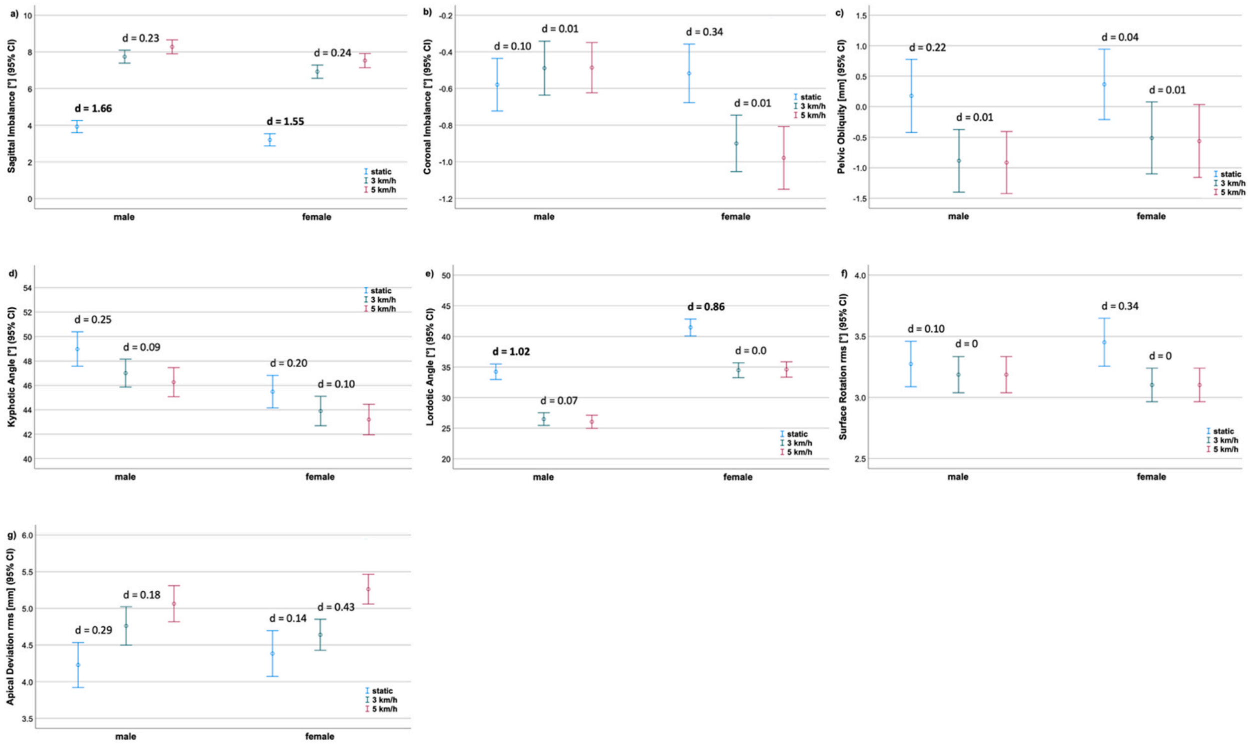

Fig. 3. a–g Results of rasterstereography under static and dynamic (3 and 5 km/h) conditions: **a)** Sagittal Imbalance [°], **b)** Coronal Imbalance [°], **c)** Pelvic Obliquity [mm], **d)** Kyphotic Angle [°], **e)** Lordotic Angle [°], **f)** Surface Rotation [°], **g)** Apical Deviation [mm]. Partial effect sizes (d) between adjacent velocity levels depending on gender are reported. Relevant effect sizes (d > 0.5) marked in bold.

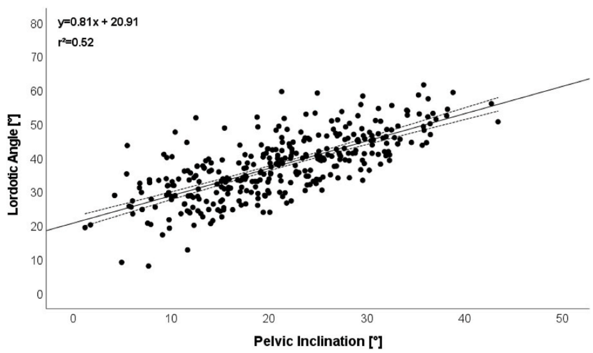

Fig. 4. Relationship between lordotic angle and pelvic inclination. Please note that one dot can represent several subjects.

parameters under dynamic conditions, making it a helpful examination tool for long-term follow-up [[25]]. Its high accuracy and reproducibility compared to radiographs were later demonstrated in patients with and without spinal deformities [[26–28]]. Spinometry offers advantages in terms of speed and cost-effectiveness compared to MRI imaging, although both methods share the advantage of not emitting ionizing radiation.

Initially, spinometry served as a static imaging tool. Following further development of the methodology, it is now able to analyze the movement of the subject during walking and performing clinical tests, providing deeper insights into the functional behaviour of spinal segments in musculoskeletal disorders [[29]]. Previous research has demonstrated that dynamic spinometry can detect reflective markers with an accuracy of ±1 mm, considered as equally accurate as the “gold standard” of dynamic imaging VICON [[30]]. Thus, clinicians can measure compensatory movements due to disability, pain, or functional deficits in a realistic context for the first time.

Under static conditions, the data generated show significant gender differences in lordotic angle and pelvic inclination, which are greater in females than males. Females typically have a higher lordotic angle than males [[31]]. Researchers have discussed that the higher lordotic angle in women may be due to greater lordotic wedging of the lumbar vertebrae, upper body mass distribution

Table 4
Comparative table – comparison of own results with comparable results of the literature. g = gender, m = male, f = female.

parameter	g	velocity (km/h) [mean ± SD]											
		0				3				5			
Sagittal Imbalance (°)	m	3.92 ± 2.16	–	1.89 ± 1.88	3.3 ± 2.2	7.72 ± 2.41	–	–	–	8.29 ± 2.60	–	6.76 ± 2.24	–
	f	3.21 ± 2.19	–	2.12 ± 2.4	2.8 ± 2.1	6.82 ± 2.46	–	–	–	7.44 ± 2.63	–	6.72 ± 2.62	–
Coronal Imbalance (°)	m	−0.58 ± 0.94	–	−0.08 ± 0.96	−0.2 ± 0.7	−0.48 ± 1.02	–	–	–	−0.49 ± 0.95	–	−0.17 ± 0.86	–
	f	−0.53 ± 1.05	–	−0.07 ± 0.91	−0.03 ± 0.8	−0.88 ± 1.03	–	–	–	−0.96 ± 1.14	–	−0.27 ± 1.00	–
Pelvic Obliquity (mm)	m	0.18 ± 3.93	3.1 ± 2.5	−0.32 ± 3.34	–	−0.98 ± 3.52	–	–	–	−1.03 ± 3.44	–	−0.51 ± 2.61	–
	f	0.38 ± 3.80	3.8 ± 2.7	−0.42 ± 2.79	–	−0.55 ± 4.06	–	–	–	−0.60 ± 4.08	–	−0.29 ± 2.04	–
Kyphotic Angle (°)	m	49.0 ± 9.19	49.2 ± 9.3	44.6 ± 7.84	46.5 ± 7.1	46.9 ± 7.89	–	–	–	46.2 ± 8.26	–	39.9 ± 7.72	–
	f	45.6 ± 8.71	47.1 ± 8.6	44.0 ± 8.64	46.9 ± 6.9	43.9 ± 8.27	–	–	–	43.1 ± 8.59	–	39.3 ± 8.51	–
Lordotic Angle (°)	m	34.2 ± 8.23	35.8 ± 6.6	29.0 ± 7.67	34.5 ± 6.5	26.4 ± 7.12	–	–	–	25.9 ± 7.28	–	21.9 ± 7.67	–
	f	41.6 ± 8.60	42.7 ± 8.2	37.4 ± 9.79	43.0 ± 8.7	34.4 ± 8.13	–	–	–	34.4 ± 8.66	–	30.3 ± 8.82	–
Surface Rotation rms (°)	m	3.27 ± 1.22	3.1 ± 1.5	3.54 ± 1.56	2.2 ± 0.8	3.16 ± 0.99	–	–	–	3.16 ± 0.99	–	3.45 ± 0.93	–
	f	3.45 ± 1.28	3.6 ± 1.8	3.64 ± 1.62	2.4 ± 0.9	3.08 ± 0.92	–	–	–	3.08 ± 0.95	–	4.23 ± 1.03	–
Apical Deviation rms (mm)	m	4.23 ± 2.01	5.8 ± 2.5	5.07 ± 2.13	3.6 ± 1.6	4.78 ± 1.78	–	–	–	5.09 ± 1.69	–	4.60 ± 1.30	–
	f	4.38 ± 2.06	5.5 ± 2.3	5.59 ± 2.32	3.45 ± 1.6	4.63 ± 1.46	–	–	–	5.25 ± 1.40	–	5.52 ± 1.72	–
Pelvic Torsion (°)	m	0.75 ± 2.41	2.5 ± 2.0	–	–	–	–	–	–	–	–	–	–
	f	0.13 ± 2.30	1.8 ± 1.4	–	–	–	–	–	–	–	–	–	–
Pelvic Inclination (°)	m	16.7 ± 6.77	17.6 ± 4.4	–	–	–	–	–	–	–	–	–	–
	f	25.5 ± 7.49	21.9 ± 4.8	–	–	–	–	–	–	–	–	–	–
references		our data	Schröder et al. (2011)	Michalik et al. (2020)	Huthwelker et al. (2022)	our data	Schröder et al. (2011)	Michalik et al. (2020)	Huthwelker et al. (2022)	our data	Schröder et al. (2011)	Michalik et al. (2020)	Huthwelker et al. (2022)
comments			only static measured		young participants (18–30 yr)		only static measured		young participants (18–30 yr)		only static measured		young participants (18–30 yr)

differences, and gender-related variations in lumbar intervertebral statics [[32]].

Our data show no significant difference in pelvic inclination between males and females in standing positions, in contrast to previous studies that found a higher pelvic inclination in males [[33]]. Nevertheless, our results consistently show no difference in pelvic inclination in cohorts without back pain. Age is a confounding factor affecting pelvic inclination [[34]] rather than gender [[35]].

The transition from static to dynamic imaging revealed the most significant change in postural parameters while increasing speed did not show comparable significance. Our data show that the lordotic and kyphotic angles decrease under dynamic conditions for both genders. This is concordant with previously published scientific data recorded using spinometry and the VICON system [[36,37]]. It has been discussed that humans straighten their backs to look forward to improve vision and avoid falling [[38,39]]. At the same time, for energy conservation during walking as a physiological process, the centre of mass is shifted forward [[40]], resulting in increased sagittal imbalance as walking speed increases, matching previous research using video analysis alone [[41,42]].

All subjects showed an apical deviation and surface rotation to the right, which increased with increasing walking speed, which is in agreement with two previous publications for reasons that are still unknown [[29,43]]. Possible explanations have been discussed, with most people being right-handed or, alternatively, the left anterolateral pulsatile force of the thoracic aorta causing an asymmetric effect with surface rotation to the right [[44]].

Most importantly, we demonstrated a relevant correlation between pelvic inclination and lordotic angle in static spinometry. Previous research has suggested a significant correlation between pelvic inclination, lumbar lordosis, thoracic kyphosis and sagittal imbalance [[45,46]]. Pelvic inclination and lumbar lordosis are of particular clinical interest as both have been reported to correlate [[45]] and increase with the incidence of back pain [[47–49]]. As dynamic spinometry is unable to analyze pelvic tilt under dynamic conditions, this correlation could lead to the hypothesis that lumbar lordosis is a valid indirect marker of pelvic posture for identifying patients at higher risk of future back problems even under dynamic conditions.

Schroeder et al. [[27]], however, only used static spinometry measuring people aged 25.4 ± 5.5 years with similar anthropometrics, but the number of subjects was limited to 20 (9 females, 11 males). Probably the most comprehensive spinometric data collected and published by the working group surrounding Huthwelker et al. [[43]] and Wolf et al. [[50]] have not yet published dynamic data. Only Michalik et al. [[29]] dynamically measured 121 subjects (56 females, 65 males; age 24.1 ± 2.16 years) to investigate gender differences in spinal posture between static and dynamic spinometry. However, they did not include pelvic parameters in their interpretation. Regarding static conditions, it should be noted that the proportion of the SD around the mean (coefficient of variability, CV) for the parameter pelvic obliquity is exceptionally high in all reported studies (Table 4). Comparable with other investigations [[28,30]], the CV in our study ranged from 71% to 2083%. The same is true for the parameter pelvic torsion. According to our data and Schroeder et al. [[27]], the CV ranged from 78% to 1669%. Hence, one should discuss these parameters with great caution. From a statistical point of view, the measurement of pelvic parameters should be improved to allow a valid interpretation of these data. Further development of this examination method enabling detection of dynamic pelvic parameters would be helpful its clinical relevance even more.

Consequently, the validity of the measurement for both parameters (pelvic obliquity and pelvic torsion) should be (im)proved. In contrast, the pelvic inclination is the only pelvic parameter with a reasonable relationship between mean and SD. The CV from our study (60 and 29%) and Schroeder et al. [[27]] (25 and 22%) was at a similar and much lower level compared to pelvic obliquity and pelvic torsion. Therefore, pelvic inclination and lordotic angle (Fig. 4) should be used as spino-pelvic parameters that are measured at a much higher level of accuracy. It has been shown in previous studies that dynamic testing is more informative about the risk of back pain than static testing methods [[48]], making dynamic spinometry particularly interesting for clinicians. As already discussed, the lordotic angle could be used as a possible indirect dynamic (pelvic) marker for patients at risk of lumbar syndromes. However, this hypothesis needs further investigation in future studies comparing asymptomatic with symptomatic subjects.

Overall, this work can be seen as a logical continuation of previous research to establish a conclusive link between pelvic and spinal parameters. This research provides a rationale for static and dynamic spine measurement as spino-pelvic parameters demonstrate gender and kinematic differences during movement. The data collected in this study can be used as reference data for dynamic spinometry performed on healthy males and females at speeds of 3 and 5 km/h.

As mentioned above, pelvic inclination has been found to vary with age, and our age group does not appear to have a wide enough age range to show significant differences in pelvic inclination. In addition, the technical limitations of spinometry do not allow dynamic measurement of pelvic inclination and torsion. In order to measure pelvic inclination dynamically, it would be necessary to detect both the posterior superior iliac spine and the anterior superior iliac spine. This is not possible with the DIERS Formetric 4Dmotion® system.

It should be added that there is scientific evidence of differences in spino-pelvic parameters not only due to gender but also due to racial differences [[51]]. Therefore, it is essential to point out that this study was only carried out on Caucasian subjects. Further research is needed to establish similar reference data for different ethnic backgrounds.

Increasing walking speed changes our gait pattern and upper body movement. A limitation of the methodological approach of our study is that walking on a treadmill is different from physiological movement patterns. The subjects' limited experience with treadmill walking may have altered physiological movement patterns inversely. Previous research analysis has shown in cadence and stride length differences between treadmill and free running [[52]]. Skin markers and lack of palpation skills may be another source of error [[53]]. In addition, patients with back pain may have difficulty walking and may be afraid of treadmills [[54]].

However, the simplicity of the examination tool and the importance of the functional aspects outweigh the disadvantages. One possible solution to reduce such anxiety would be to teach patients how to walk correctly on treadmills, leading to a higher degree of familiarization [[55–57]]. We believe dynamic functional examination methods such as spinometry will hopefully help to effectively plan treatment of patients with spino-pelvic problems.

6. Conclusion

This study provides gender-specific reference data of asymptomatic individuals for dynamic spinometry. The DIERS Formetric 4Dmotion® system was shown to be able to capture natural changes in both static and dynamic situations, as well as functional adaptations of spino-pelvic statics to different speeds. The lordotic angle may be an indirect marker of pelvic inclination. It seems, that the spinometry could therefore be able to identify individuals at risk even under dynamic conditions. Thus, spinometry might be a promising technology for analysing spino-pelvic pathologies.

Establishing reliable and accurate reference data will assist in the effective measurement and detection of functional pathologies of the spine thus enabling individual therapeutic intervention and closely monitor long-term therapy.

Funding

DIERS International GmbH provides funding for open access charges.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors without undue reservation.

CRediT authorship contribution statement

Tobias Bode: Writing – review & editing, Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Schima Zoroofchi:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Eik Vettorazzi:** Visualization, Validation, Software, Resources, Formal analysis. **Jan-Niklas Droste:** Writing – review & editing, Validation, Supervision, Project administration. **Götz H. Welsch:** Validation, Supervision. **René Schwesig:** Writing – review & editing, Formal analysis. **Robert Percy Marshall:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Rene Schwesig reports was provided by Martin Luther University of Halle Wittenberg Faculty of Medicine. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] C.J.C. Lamoth, P.J. Beek, O.G. Meijer, Pelvis–thorax coordination in the transverse plane during gait, Gait Posture 16 (2002) 101–114.
[2] A.A. Shah, J.V. Lemans, J. Zavatsky, et al., Spinal balance/alignment - clinical relevance and biomechanics, J. Biomech. Eng. 141 (7) (2019) 070805.
[3] J. Otayek, A.J. Bizdikian, F. Yared, et al., Influence of spino-pelvic and postural alignment parameters on gait kinematics, Gait Posture 76 (2020) 318–326.
[4] A. Wieczorek, E. Campau, E. Pionk, et al., A closer look into the association between the sacroiliac joint and low back pain, Spartan Med. Res. J. 6 (2021) 21971.
[5] G. Barros, L. McGrath, M. Gelfenbeyn, Sacroiliac joint dysfunction in patients with low back pain, Fed. Pract. 36 (2019) 370–375.
[6] C. Mattiuzzi, G. Lippi, C. Bovo, Current epidemiology of low back pain, J. Hosp. Manag. Health Policy 4 (2020) 15.
[7] C. Maher, M. Underwood, R. Buchbinder, Non-specific low back pain, Lancet 389 (2017) 736–747.
[8] W.-D. Kim, D. Shin, Effects of pelvic-tilt imbalance on disability, muscle performance, and range of motion in office workers with non-specific low-back pain, Healthcare 11 (2023) 893.
[9] E. Al-Eisa, D. Egan, K. Deluzio, et al., Effects of pelvic asymmetry and low back pain on trunk kinematics during sitting: a comparison with standing, Spine 31 (2006) E135–E143.
[10] B.W. Koes, MW van Tulder, S. Thomas, Diagnosis and treatment of low back pain, BMJ 332 (2006) 1430–1434.
[11] G.S. Logan, A. Pike, B. Copsey, et al., What do we really know about the appropriateness of radiation emitting imaging for low back pain in primary and emergency care? A systematic review and meta-analysis of medical record reviews, PLoS One 14 (2019) e0225414.
[12] A.C. Traeger, G.C. Machado, S. Bath, et al., Appropriateness of imaging decisions for low back pain presenting to the emergency department: a retrospective chart review study, Int. J. Qual. Health Care 33 (2021) mzab103.
[13] B.W. Koes, M. van Tulder, C.-W.C. Lin, et al., An updated overview of clinical guidelines for the management of non-specific low back pain in primary care, Eur. Spine J. 19 (2010) 2075–2094.
[14] R. Gajdosik, R. Simpson, R. Smith, Intratester reliability of measuring the standing position and range of motion, Phys. Ther. 65 (1985) 6.
[15] W.H. Suits, Clinical measures of pelvic tilt in physical therapy, Int. J. Sports Phys. Ther. 16 (2021) 1366–1375.
[16] M. Mangone, P. Raimondi, M. Paoloni, et al., Vertebral rotation in adolescent idiopathic scoliosis calculated by radiograph and back surface analysis-based methods: correlation between the Raimondi method and rasterstereography, Eur. Spine J. 22 (2013) 367–371.
[17] J.M. Frerich, K. Hertzler, P. Knott, et al., Comparison of radiographic and surface topography measurements in adolescents with idiopathic scoliosis, Open Orthop. J. 6 (2012) 261–265.
[18] J. Bortz, Basic principle of one-factorial analysis of variance, Stat. Soc. Sci. (1999) 237–249.
[19] A. Hartmann, T. Herzog, A. Drinkmann, Psychotherapy of bulimia nervosa: what is effective? A meta-analysis, J. Psychosom. Res. 36 (1992) 159–167.
[20] M.R. Nouh, Imaging of the spine: where do we stand? World J. Radiol. 11 (2019) 55–61.

[21] C.L. Nash, E.C. Gregg, R.H. Brown, et al., Risks of exposure to X-rays in patients undergoing long-term treatment for scoliosis, J. Bone Joint Surg. Am. 61 (1979) 371–374.
[22] C.M. Ronckers, M.M. Doody, J.E. Lonstein, et al., Multiple diagnostic X-rays for spine deformities and risk of breast cancer, Cancer Epidemiol. Prev. Biomark. 17 (2008) 605–613.
[23] B. Drerup, E. Hierholzer, Automatic localization of anatomical landmarks on the back surface and construction of a body-fixed coordinate system, J. Biomech. 20 (1987) 961–970.
[24] V. Asamoah, H. Mellerowicz, J. Venus, et al., Oberflächenvermessung des Rückens, Orthop 29 (2000) 480–489.
[25] N.L. Krott, M. Wild, M. Betsch, Meta-analysis of the validity and reliability of rasterstereographic measurements of spinal posture, Eur. Spine J. 29 (2020) 2392–2401.
[26] P. Knott, S. Mardjetko, M. Rollet, et al., Evaluation of the reproducibility of the formetric 4D measurements for scoliosis, Scoliosis 5 (2010) O10.
[27] J. Schroeder, R. Reer, K.M. Braumann, Video raster stereography back shape reconstruction: a reliability study for sagittal, frontal, and transversal plane parameters, Eur. Spine J. 24 (2015) 262–269.
[28] Mohokum M, Schülein S, Skwara A. The validity of rasterstereography: a systematic review. Orthop. Rev.;7:5899.
[29] R. Michalik, J. Hamm, V. Quack, et al., Dynamic spinal posture and pelvic position analysis using a rasterstereographic device, J. Orthop. Surg. 15 (2020) 389.
[30] M. Betsch, M. Wild, B. Johnstone, et al., Evaluation of a novel spine and surface topography system for dynamic spinal curvature analysis during gait, PLoS One 8 (2013) e70581.
[31] O. Hay, G. Dar, J. Abbas, et al., The lumbar lordosis in males and females, revisited, PLoS One 10 (2015) e0133685.
[32] J.F. Bailey, C.J. Sparrey, E. Been, et al., Morphological and postural sexual dimorphism of the lumbar spine facilitates greater lordosis in females, J. Anat. 229 (2016) 82–91.
[33] F. Laouissat, A. Sebaaly, M. Gehrchen, et al., Classification of normal sagittal spine alignment: refounding the Roussouly classification, Eur. Spine J. 27 (2018) 2002–2011.
[34] K. Sasaki, M. Hongo, N. Miyakoshi, et al., Evaluation of sagittal spine-pelvis-lower limb alignment in elderly women with pelvic retroversion while standing and walking using a three-dimensional musculoskeletal model, Asian Spine J 11 (2017) 562–569.
[35] R. Vialle, N. Levassor, L. Rillardon, et al., Radiographic analysis of the sagittal alignment and balance of the spine in asymptomatic subjects, J. Bone Jt. Surg. 87 (2005) 260–267.
[36] E. Simonet, B. Winteler, J. Frangi, et al., Walking and running with non-specific chronic low back pain: what about the lumbar lordosis angle? J. Biomech. 108 (2020) 109883.
[37] D. Levine, M.A. Colston, M.W. Whittle, et al., Sagittal lumbar spine position during standing, walking, and running at various gradients, J. Athl. Train. 42 (2007) 29–34.
[38] S. Imagama, Z. Ito, N. Wakao, et al., Influence of spinal sagittal alignment, body balance, muscle strength, and physical ability on falling of middle-aged and elderly males, Eur. Spine J. 22 (2013) 1346–1353.
[39] F. Prince, D. Winter, P. Stergiou, et al., Anticipatory control of upper body balance during human locomotion, Gait Posture 2 (1994) 19–25.
[40] L. Tesio, V. Rota, The motion of body center of mass during walking: a review oriented to clinical applications, Front. Neurol. 10 (2019) 999.
[41] J. Crosbie, R. Vachalathiti, R. Smith, Age, gender and speed effects on spinal kinematics during walking, Gait Posture 5 (1997) 13–20.
[42] A. Thorstensson, J. Nilsson, H. Carlson, et al., Trunk movements in human locomotion, Acta Physiol. Scand. 121 (1984) 9–22.
[43] J. Huthwelker, J. Konradi, C. Wolf, et al., Reference values for 3D spinal posture based on videorasterstereographic analyses of healthy adults, Bioengineering 9 (2022) 809.
[44] J.-W.M. Kouwenhoven, L.W. Bartels, K.L. Vincken, et al., The relation between organ anatomy and pre-existent vertebral rotation in the normal spine: magnetic resonance imaging study in humans with situs inversus totalis, Spine 32 (2007) 1123–1128.
[45] C. Boulay, C. Tardieu, J. Hecquet, et al., Sagittal alignment of spine and pelvis regulated by pelvic incidence: standard values and prediction of lordosis, Eur. Spine J. 15 (2006) 415–422.
[46] D. Levine, M.W. Whittle, The effects of pelvic movement on lumbar lordosis in the standing position, J. Orthop. Sports Phys. Ther. 24 (1996) 130–135.
[47] A. Król, M. Polak, E. Szczygieł, et al., Relationship between mechanical factors and pelvic tilt in adults with and without low back pain, J. Back Musculoskelet. Rehabil. 30 (2017) 699–705.
[48] R.A. Laird, J. Gilbert, P. Kent, et al., Comparing lumbo-pelvic kinematics in people with and without back pain: a systematic review and meta-analysis, BMC Muscoskel. Disord. 15 (2014) 229.
[49] E. Cha, J.H. Park, Spinopelvic alignment as a risk factor for poor balance function in low back pain patients, Global Spine J. 13 (2023) 2193–2200.
[50] C. Wolf, U. Betz, J. Huthwelker, et al., Evaluation of 3D vertebral and pelvic position by surface topography in asymptomatic females: presentation of normative reference data, J. Orthop. Surg. 16 (2021) 703.
[51] B.S. Lonner, J.D. Auerbach, P. Sponseller, et al., Variations in pelvic and other sagittal spinal parameters as a function of race in adolescent idiopathic scoliosis, Spine 35 (2010) E374.
[52] A. Matsas, N. Taylor, H. McBurney, Knee joint kinematics from familiarised treadmill walking can be generalised to overground walking in young unimpaired subjects, Gait Posture 11 (2000) 46–53.
[53] S.M. Bruijn, O.G. Meijer, J.H. van Dieën, et al., Coordination of leg swing, thorax rotations, and pelvis rotations during gait: the organisation of total body angular momentum, Gait Posture 27 (2008) 455–462.
[54] C.J.C. Lamoth, A. Daffertshofer, O.G. Meijer, et al., How do persons with chronic low back pain speed up and slow down? Gait Posture 23 (2006) 230–239.
[55] B. Hanley, A.K. Mohan, Changes in gait during constant pace treadmill running. *J. Strength cond*, Res. 28 (2014) 1219–1225.
[56] J.T.E. Richardson, Eta squared and partial eta squared as measures of effect size in educational research, Educ. Res. Rev. 6 (2011) 135–147.
[57] J. Cohen, Statistical Power Analysis for the Behavioral Sciences, second ed., Routledge, New York, 1988.