

Between-session reliability of skin marker-derived spinal kinematics during functional activities

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ABSTRACT

Background: Skin marker-based analysis of functional spinal movement is a promising method for quantifying longitudinal effects of treatment interventions in patients with spinal pathologies. However, observed day-to-day changes might not necessarily be due to a treatment intervention, but can result from errors related to soft tissue artifacts, marker placement inaccuracies or biological day-to-day variability.

Research question: How reliable are skin marker-derived three-dimensional spinal kinematics during functional activities between two separate measurement sessions?

Methods: Twenty healthy adults (11 females/9 males) were invited to a movement analysis laboratory for two visits separated by 7-10 days. At each visit, they performed various functional activities (i.e. sitting, standing, walking, running, chair rising, box lifting and vertical jumping), while marker trajectories were recorded using a skin marker-based 10-camera optical motion capture system and used to calculate sagittal and frontal plane spinal curvature angles as well as transverse plane segmental rotational angles in the lumbar and thoracic regions. Between-session reliability for continuous data and discrete parameters was determined by analyzing systematic errors using one sample T-tests as well as by calculating intraclass correlation coefficients (ICCs) and minimal detectable changes (MDCs).

Results and Significance: The analysis indicated high overall consistency for sagittal plane curvature angles during all activities, but lower consistency for frontal and transverse plane angles during walking and running. MDCs were mostly below 15° and generally higher in the lumbar than thoracic region. This study provides important information that can serve as a basis for researchers and clinicians aiming at investigating longitudinal effects of treatment interventions on spinal motion behavior in patients with spinal pathologies.

Keywords: Spine; curvature; longitudinal; ICC; MDC

1. INTRODUCTION

Optical motion capturing is an appropriate method to quantify the biomechanics of the spine during functional movement [1]. It provides an important basis for the longitudinal evaluation of treatment effects in patients with spinal pathologies. However, observed day-to-day changes might not necessarily be due to an administered treatment intervention, but can result from errors related to instrumental inaccuracies, soft tissue artifacts, marker placement inaccuracies or biological day-to-day variability [2-4]. While inaccuracies of current optical motion capture systems are relatively small (below 2 mm for dynamic experiments [5, 6]), errors emerging from soft tissue artifacts and marker placement inaccuracies are considerably higher (up to 10.7 mm and 21.0 mm, respectively [7, 8]). Most of these factors can only be partially controlled and therefore, it is important to know the extent of variability resulting from these factors. Researchers and clinicians need such information to determine whether an observed change can in fact be ascribed to a treatment intervention or is just a result of the aforementioned error sources. One possible way to quantify the reliability of repeated measurements is the three-layered approach by Weir [9]. Briefly, it includes the evaluation of systematic errors, relative consistency as well as trial-to-trial noise, which serves as a basis to calculate indices such as the minimal detectable change (MDC), a common measurand for determining the minimal difference required to be considered real.

This study aims at evaluating the between-session reliability of three-dimensional spinal kinematics (continuous data as well as discrete parameters) during various functional activities derived from marker-based optical motion capturing.

2. METHODS

2.1. Participants

Twenty healthy adults (11 females/9 males; height: 173 ± 10 (157-192) cm; mass: 69 ± 13 (45.5-91.7) kg; age: 31 ± 9 (20-53) years; body mass index (BMI): 22.6 ± 2.6 (18.5-27.5) kg/m²) participated in this study. The protocol was approved by the local ethics committee and written informed consent was obtained prior to the first measurement.

2.2. Measurement procedures and data collection

Participants were invited to the movement analysis laboratory for two visits separated by 7-10 days. At both visits, experienced physiotherapists equipped them with 58 retro-reflective markers according to a previously described configuration [1]. Participants were then asked to sit and stand quietly for 10 s and to perform four repetitions of the following activities (barefoot and at self-selected normal speed): walking and running on a 10-meter level ground, standing up and sitting down on a chair (chair rising), lifting up and putting down a 5 kg-box (box lifting), and performing a vertical counter movement jump (CMJ). Details on standardization and execution of the activities can be found elsewhere [10]. Data were recorded at a sampling frequency of 200 Hz using a 10-camera optical motion capture system (8x Bonita 3 and 2x Bonita 10; Vicon, Oxford, UK).

2.3. Data reduction

Following data pre-processing with the software Nexus (version 2.9.2., Vicon UK, Oxford, UK), we used custom MATLAB algorithms (R2019a, MathWorks Inc., Natick, MA, USA) to calculate sagittal and frontal plane curvature angles as well as transverse plane segmental rotation angles for the lumbar and thoracic regions. Detailed information on event detection, angle calculations, marker placement accuracy and soft tissue artefacts have been reported elsewhere [8, 10-12]. Data were then low-pass filtered at 6 Hz (Butterworth, fourth order,

zero-phase), time-normalized to cycles consisting of 101 frames and parameterized into average and range of motion (RoM) values.

2.4. Statistical analysis

Statistical analyses were carried out using custom MATLAB algorithms (R2019a, MathWorks Inc., Natick, MA, USA). Data collected from the functional activities were averaged over the four repetitions. To evaluate between-session reliability, data was first analyzed for systematic errors by using one sample T-tests (alpha-level: 0.05) to compare the average of the individual differences to zero. For continuous data, T-tests were thereby implemented using one-dimensional Statistical Parametric Mapping (SPM; spm1d-package www.spm1d.org) [13]. Subsequently, relative reliability was determined using intraclass correlations coefficients (consistency formula ICC(C,1)), and absolute reliability was quantified by MDCs, calculated as $1.96 \times \text{SDd}$ (standard deviation of the differences) [14].

3. RESULTS

Some trials had to be excluded due to incomplete or missing marker data.

3.1. Continuous data

No systematic errors were found (Figures 1 and 2, left columns). ICC values for sagittal plane angles indicated high overall consistency (ICCs mostly >0.75), whereas values for frontal and transverse plane angles during walking and running showed only low to moderate consistency (ICCs mostly <0.6). MDCs for sagittal plane angles were 7.0° - 22.9° (other planes: 4.3° - 20.8°) in the lumbar and 3.9° - 10.8° (4.5° - 12.2°) in the thoracic region (Figures 1 and 2, right columns).

3.2. Discrete parameters

No systematic errors were found, except for lumbar RoM during sitting down on a chair ($p=0.025$) (Table 1). Most ICCs ranged from 0.52 to 0.96, except from a few frontal and transverse plane average angles during walking and running (ICCs of 0.11-0.35) as well as thoracic sagittal plane RoM values during walking, chair rising and box lifting (ICCs of 0.2-0.43). MDCs for sagittal plane average values were 9.0° - 13.3° (other planes: 4.7° - 16.8°) in the lumbar and 4.6° - 9.1° (4.6° - 9.0°) in the thoracic region, and for sagittal plane RoM values 8.3° - 19.2° (other planes: 2.7° - 11.4°) and 2.3° - 10.5° (4.6° - 5.9°), respectively.

4. DISCUSSION

This study aimed at quantifying the between-session reliability of continuous and discrete three-dimensional spinal curvature and rotation angles during various functional activities. The analysis indicated high overall consistency for sagittal plane curvature angles during all activities, but lower consistency for frontal and transverse plane angles during walking and running. MDCs were mostly below 15° and generally higher in the lumbar than thoracic region.

Compared to the literature, our results only partially agree with the recently published findings by Fernandes et al. [15] for walking. However, it should be considered that their marker configuration and definition of kinematic parameters were substantially different from ours, which complicates appropriate direct comparisons.

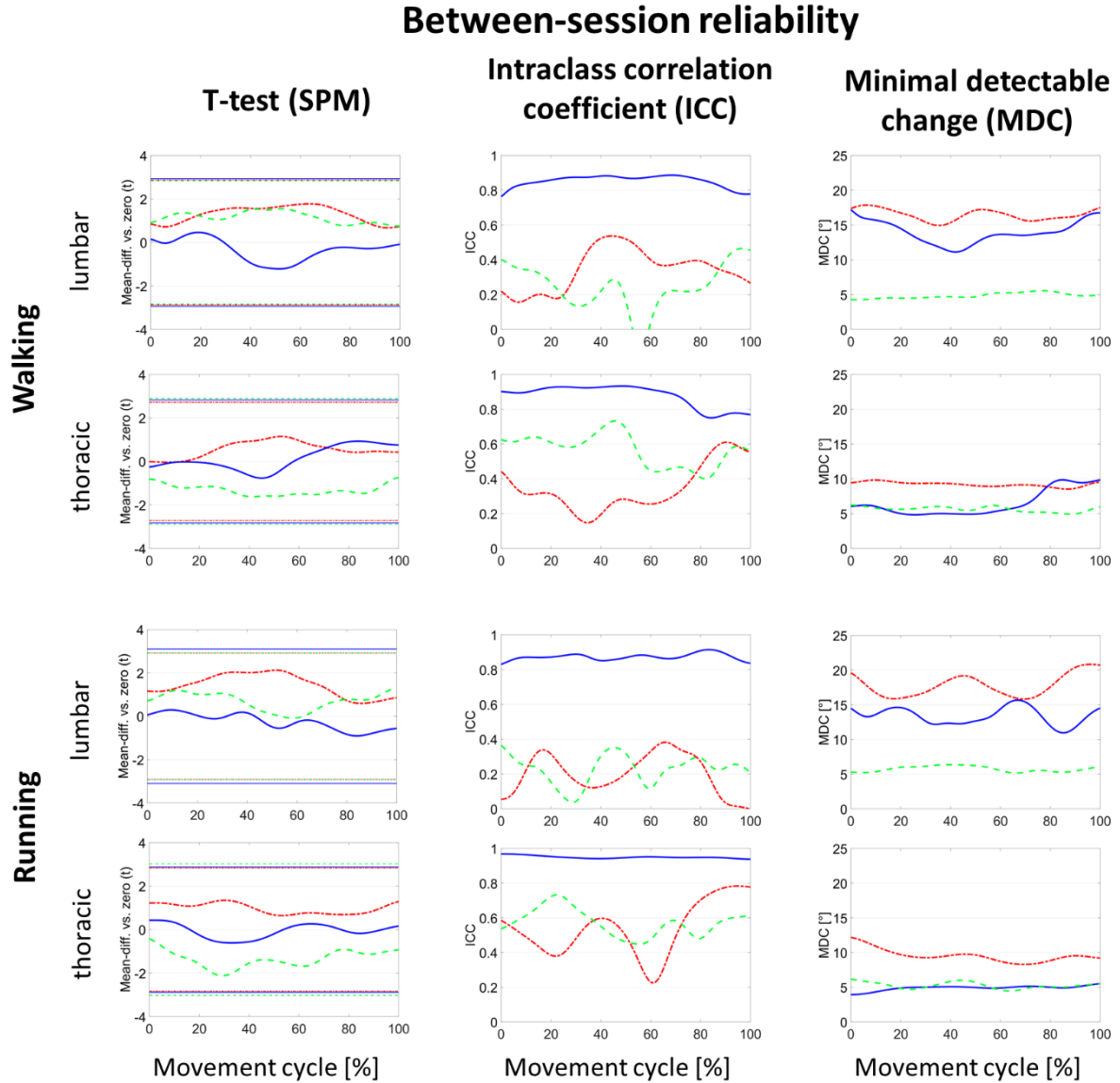


Figure 1: Between-session reliability for continuous lumbar and thoracic spine angles in the sagittal (blue), frontal (red), and transverse (green) planes for the activities walking and running. The left column shows results of the evaluation for systematic errors using independent samples T-test (implemented by means of one-dimensional Statistical Parametric Mapping, SPM), with the horizontal colored lines indicating the thresholds for statistical significance at the $p \leq 0.05$ level. Middle and right columns illustrate the intraclass correlation coefficient (consistency formula $ICC(C,1)$) for relative reliability and the minimal detectable change (MDC) for absolute reliability, respectively.

Despite the possibility that frontal and transverse plane angles during walking and running might simply be less reliable than sagittal plane angles, the lower consistency might be partially explained by the considerably smaller movement extent. It was shown that low levels of between-subjects variability can depress ICCs even if the differences between the sessions are low [9].

The fact that thoracic spine angles showed lower MDCs than lumbar spine angles with comparably high ICCs might be explained by a smaller and probably more controlled thoracic motion resulting from restrictions imposed by the rib cage as well as a larger amount of soft tissue in the lumbar region as previously discussed [11].

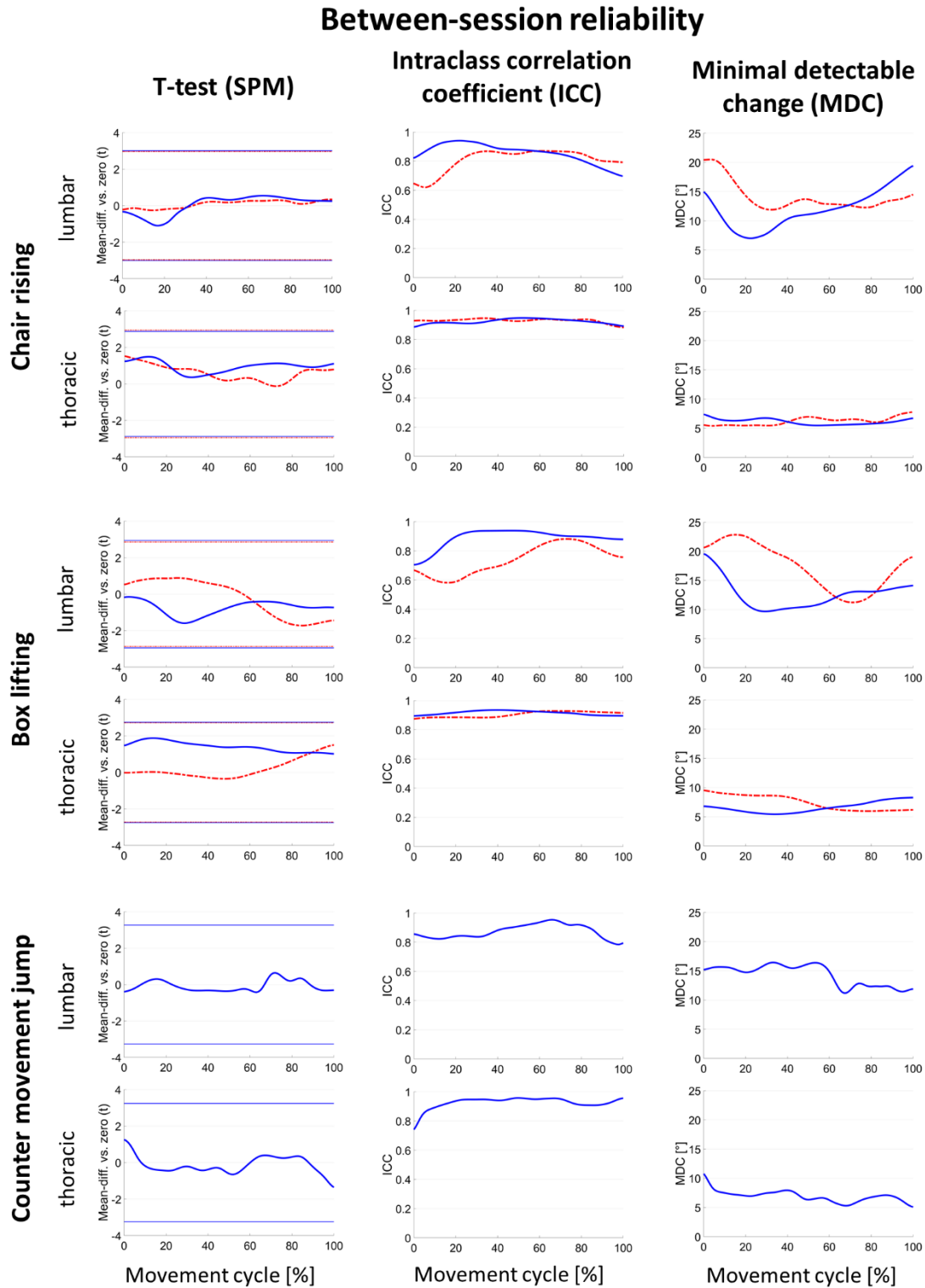


Figure 2: Between-session reliability for continuous lumbar and thoracic sagittal plane spine angles for the activities chair rising (i.e. standing up (blue) and sitting down on a chair (red)), box lifting (i.e. lifting up (red) and putting down a box (blue)) as well as counter movement jump. The left column shows results of the evaluation for systematic errors using independent samples T-test (implemented by means of one-dimensional Statistical Parametric Mapping, SPM), with the horizontal colored lines indicating the thresholds for statistical significance at the $p \leq 0.05$ level. Middle and right columns illustrate the intraclass correlation coefficient (consistency formula $ICC(C,1)$) for relative reliability and the minimal detectable change (MDC) for absolute reliability, respectively.

Table 1: Sagittal, frontal and transverse plane lumbar and thoracic spinal curvature angles (average over four repetitions) in degrees [°] as well as results of the between-session reliability analyses for average and range of motion (RoM) parameters.

Activity	Region	Plane	Parameter	Mean angle (SD) ^a		Between-session reliability		
				1. session [°]	2. session [°]	Syst. error (p-value)	ICC	MDC [°]
Standing	Lumbar	Sagittal	Average	-42.4 (14.6)	-44.3 (16)	0.098	0.80	12.1
	Thoracic			34.2 (8.2)	35.4 (7.5)	0.166	0.87	8.4
Sitting	Lumbar	Sagittal	Average	-19.6 (11.1)	-20.9 (8.4)	0.554	0.97	7.3
	Thoracic			30.1 (9.2)	31.3 (7.7)	0.250	0.89	7.2
Walking	Lumbar	Sagittal	Average	-42.3 (14.4)	-42.8 (11.3)	0.740	0.88	12.6
		Frontal		-3.2 (6.9)	-0.6 (6.5)	0.191	0.31	15.6
		Transverse		-0.2 (2.1)	0.5 (1.5)	0.248	0.17	4.7
	Thoracic	Sagittal		36.6 (6.9)	36.8 (6.5)	0.783	0.90	5.9
		Frontal		0.9 (4.1)	1.5 (3.6)	0.572	0.30	8.8
		Transverse		0.8 (2.7)	-0.1 (2.8)	0.177	0.52	5.3
	Lumbar	Sagittal	RoM	10.5 (6.4)	9.4 (5.4)	0.398	0.60	10.4
		Frontal		16.6 (6.2)	18.9 (6.1)	0.128	0.55	11.4
		Transverse		7.8 (2.1)	8.2 (2.2)	0.202	0.79	2.7
	Thoracic	Sagittal		3.7 (4)	2.6 (0.8)	0.200	0.20	7.1
		Frontal		12.1 (4.8)	12.6 (4.6)	0.391	0.88	4.6
		Transverse		11.8 (4.9)	11.3 (3.8)	0.177	0.52	5.3
Running	Lumbar	Sagittal	Average	-40.3 (13.5)	-40.7 (12.8)	0.792	0.89	12.1
		Frontal		-1.9 (7.1)	1.2 (6)	0.150	0.16	16.8
		Transverse		0.2 (2.1)	0.6 (2)	0.468	0.11	5.4
	Thoracic	Sagittal		33.6 (8)	33.6 (7.7)	0.931	0.96	4.6
		Frontal		0.4 (4.4)	1.5 (3.7)	0.316	0.35	9
		Transverse		1.5 (2.7)	0.7 (2.2)	0.148	0.55	4.6
	Lumbar	Sagittal	RoM	12.6 (7)	13.6 (7.6)	0.439	0.71	10.9
		Frontal		12.4 (3.7)	12.6 (4.4)	0.746	0.76	5.5
		Transverse		11.4 (2.6)	11.1 (2.6)	0.653	0.53	4.9
	Thoracic	Sagittal		5 (2.3)	5 (2)	0.815	0.86	2.3
		Frontal		22.2 (9.7)	22.1 (8.8)	0.922	0.95	5.6
		Transverse		14.7 (4.3)	13.9 (2.4)	0.317	0.63	5.9
Standing up from chair	Lumbar	Sagittal	Average	-19.6 (10.9)	-19.4 (11.1)	0.893	0.88	10.4
	Thoracic			28.4 (8.1)	29.1 (7.7)	0.306	0.94	5.5
	Lumbar	Sagittal	RoM	28.4 (7.9)	27.6 (8)	0.551	0.75	11.2
	Thoracic			6.7 (2.4)	7.3 (3.5)	0.486	0.43	6.2
Sitting down on chair	Lumbar	Sagittal	Average	-21.9 (10.3)	-21.8 (11.9)	0.944	0.83	12.6
	Thoracic			31.1 (8.3)	31.5 (8.4)	0.516	0.94	5.5
	Lumbar	Sagittal	RoM	26.3 (8.4)	28.8 (8.9)	0.025*	0.88	8.3
	Thoracic			6.5 (2.3)	7 (3.7)	0.464	0.59	5.5
Lifting up a box	Lumbar	Sagittal	Average	-15.5 (10.5)	-15.5 (12)	0.997	0.82	13.3
	Thoracic			29 (8.8)	29.1 (8.3)	0.886	0.92	6.7
	Lumbar	Sagittal	RoM	34.9 (9.9)	35.9 (10.4)	0.551	0.72	14.8
	Thoracic			5.2 (2.4)	5.4 (3.4)	0.860	0.33	6.6
Putting down a box	Lumbar	Sagittal	Average	-15.9 (12.7)	-17 (14.1)	0.923	0.53	9
	Thoracic			31.2 (8.3)	32.2 (7.8)	0.429	0.76	9.1
	Lumbar	Sagittal	RoM	35 (11.5)	35.2 (8.7)	0.949	0.54	19.2
	Thoracic			5.8 (2.7)	5.6 (3.2)	0.765	0.37	6.6
Counter movement jump	Lumbar	Sagittal	Average	-25.1 (13.2)	-25.3 (14.6)	0.906	0.92	10.9
	Thoracic			29.8 (9.4)	29.7 (8.9)	0.888	0.96	5.3
	Lumbar	Sagittal	RoM	39 (10.5)	39.1 (11.5)	0.966	0.63	18.6
	Thoracic			12.9 (4.2)	12.9 (6.3)	0.959	0.50	10.5

Abbreviations: ICC = Intraclass correlation coefficient; MDC = Minimal detectable change.

^a Negative average values in the sagittal plane represent a lordotic posture of the lumbar and thoracic back region, negative average values in the frontal plane represent a left lateral bending and negative average values in the transverse plane represent a left rotation.

The asterisks (*) indicates a statistically significant systematic error at a p≤0.05 level.

Momentary ICC and MDC fluctuations such as observed in beginning of the chair rising and box lifting activities might be ascribed to movement standardization and event detection issues.

An important limitation of this study is that our motion capture system was not always able to identify and distinguish all lumbar spine markers, especially in smaller individuals and individuals with a pronounced lumbar lordosis. We therefore suggest that future studies include more cameras and/or cameras with a higher resolution to overcome such issues.

This study provides important information that can serve as a basis for researchers and clinicians aiming at investigating longitudinal effects of treatment interventions on spinal motion behavior in patients with spinal pathologies.

5. CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

6. ACKNOWLEDGMENTS

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6. REFERENCES

- [1] Schmid S, Bruhin B, Ignasiak D, Romkes J, Taylor WR, Ferguson SJ, et al. Spinal kinematics during gait in healthy individuals across different age groups. *Hum Mov Sci*. 2017;54:73-81.
- [2] Chiari L, Della Croce U, Leardini A, Cappozzo A. Human movement analysis using stereophotogrammetry. Part 2: instrumental errors. *Gait Posture*. 2005;21:197-211.
- [3] Della Croce U, Leardini A, Chiari L, Cappozzo A. Human movement analysis using stereophotogrammetry. Part 4: assessment of anatomical landmark misplacement and its effects on joint kinematics. *Gait Posture*. 2005;21:226-37.
- [4] Leardini A, Chiari L, Della Croce U, Cappozzo A. Human movement analysis using stereophotogrammetry. Part 3. Soft tissue artifact assessment and compensation. *Gait Posture*. 2005;21:212-25.
- [5] Merriau P, Dupuis Y, Bouteau R, Vasseur P, Savatier X. A Study of Vicon System Positioning Performance. *Sensors (Basel)*. 2017;17.
- [6] Eichelberger P, Ferraro M, Minder U, Denton T, Blasimann A, Krause F, et al. Analysis of accuracy in optical motion capture - A protocol for laboratory setup evaluation. *J Biomech*. 2016;49:2085-8.
- [7] della Croce U, Cappozzo A, Kerrigan DC. Pelvis and lower limb anatomical landmark calibration precision and its propagation to bone geometry and joint angles. *Med Biol Eng Comput*. 1999;37:155-61.
- [8] Zemp R, List R, Gulay T, Elsig JP, Naxera J, Taylor WR, et al. Soft tissue artefacts of the human back: comparison of the sagittal curvature of the spine measured using skin markers and an open upright MRI. *PLoS One*. 2014;9:e95426.
- [9] Weir JP. Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. *J Strength Cond Res*. 2005;19:231-40.
- [10] Suter M, Eichelberger P, Frangi J, Simonet E, Baur H, Schmid S. Measuring lumbar back motion during functional activities using a portable strain gauge sensor-based system: A comparative evaluation and reliability study. *J Biomech*. 2020;100:109593.
- [11] Schmid S, Studer D, Hasler CC, Romkes J, Taylor WR, Brunner R, et al. Using Skin Markers for Spinal Curvature Quantification in Main Thoracic Adolescent Idiopathic Scoliosis: An Explorative Radiographic Study. *PLoS One*. 2015;10:e0135689.

- [12] Bangerter C, Romkes J, Lorenzetti S, Krieg AH, Hasler CC, Brunner R, et al. What are the biomechanical consequences of a structural leg length discrepancy on the adolescent spine during walking? *Gait Posture*. 2019;68:506-13.
- [13] Pataky TC. One-dimensional statistical parametric mapping in Python. *Comput Methods Biomech Biomed Engin*. 2012;15:295-301.
- [14] Bland JM, Altman DG. Applying the right statistics: analyses of measurement studies. *Ultrasound Obstet Gynecol*. 2003;22:85-93.
- [15] Fernandes R, Armada-da-Silva P, Pool-Goudzwaard AL, Moniz-Pereira V, Veloso AP. Three dimensional multi-segmental trunk kinematics and kinetics during gait: Test-retest reliability and minimal detectable change. *Gait Posture*. 2016;46:18-25.