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What are the biomechanical consequences of a structural leg length discrepancy on the adolescent spine during walking?

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ABSTRACT

Background: Structural leg length discrepancy (LLD) is a common phenomenon. However, its effect on spinal gait kinematics remains unclear.
Research question: How does LLD affect spinal gait kinematics in patients with structural LLD and what is the immediate effect of a shoe lift?.
Methods: 10 adolescents with structural LLD (20–60 mm) and 14 healthy controls were included. All of whom were fitted with a trunk marker set and requested to walk barefoot as well as with an orthotic shoe lift (only patients). Data were collected using a 12-camera motion capture system. Group comparisons were conducted using one-dimensional Statistical Parametric Mapping (SPM).
Results: Patients with LLD showed statistically significant increased frontal plane lumbar bending angles to the longer side ($p = 0.007$), increased pelvic drop on the shorter side ($p < 0.001$) and increased hip adduction angles on the longer leg ($p < 0.001$) compared to the healthy controls. In the sagittal plane, patients demonstrated changed knee (shorter leg) and ankle joint (longer leg) motion. All gait deviations observed in patients with LLD could immediately be altered by correcting the LLD using a shoe lift.
Significance: Due to the LLD, patients showed a lateral pelvic drop on the shorter side, which appeared to be compensated for by a contralateral bending in the lumbar spine and a lateral shift of the pelvis towards the longer side. In addition, the use of an orthotic correction seems to be a suitable option to instantly normalize gait kinematics in patients with mild to moderate LLD.

1. Introduction

Leg length discrepancy (LLD) is a common phenomenon [1]. Discrepancies of over 20 mm are found in at least 1 out of every 1000 human beings [2]. Recent studies have stated associations between LLD and several diseases, such as lower back pain [3], lumbar disc herniation [4] or osteoarthritis (OA) of the knee, hip and lumbar spine [5].

Concerning the effects of LLD on walking, it is acknowledged that patients with LLD show changed gait patterns [1], and the most frequently seen gait deviation is a pelvic tilt in the frontal plane [6]. Most previous studies focused on changes in lower extremities due to LLD [7–9]. For instance, alterations in joint angles and torques of the ankle, knee and hip have been found [8]. A functional shortening of the longer leg can be achieved by increased dorsiflexion and increased hip or knee flexion [8,10]. On the shorter side, strategies to functionally lengthen the limb include equinus positioning of the ankle (toe walking), vaulting and increased knee extension [8,10,11]. Moreover, Kakushima et al. [12] measured significantly larger frontal plane bending angles in the lumbar, thoracolumbar and thoracic spine in subjects with artificially induced LLD during walking. The authors have concluded that the spinal compensatory maneuver for LLD consists of a double curve that is comparable to that observed in patients with scoliosis [12]. However, these results cannot be transferred directly to patients suffering true, structural LLD.

The most frequent treatment for LLD is the use of orthotic shoe lifts [1]. Differences not more than 20 mm can be equalized with an insert,

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while larger discrepancies require an elevation of the shoe sole [1].

The use of a standard full body marker set to quantify trunk movements using rigid segments is widespread, but it does not generate enough information to reliably assess spinal kinematics [13]. Recent studies have applied a more specific, validated trunk marker set (IfB marker set [14–16] to assess spinal kinematics across different populations [13,17,18]. Using the IfB marker set to quantify the effect of a structural LLD on spinal kinematics can provide useful information to clinicians, but may also contribute to more precise insights on investigating treatment effects (orthotic devices or surgical interventions). Investigations and evidence of spinal gait kinematics in patients with structural LLD and the immediate effect of an orthotic shoe lift are still unclear.

The aim of the current study was to investigate spinal kinematics in adolescents with structural LLD compared to healthy controls and evaluate the immediate effect of an orthotic shoe lift on spinal kinematics during walking in patients with LLD.

2. Methods

2.1. Study population

In total, 10 patients with structural LLD and 14 asymptomatic healthy controls took part in this observational study (Table 1). In collaboration with an orthopedic surgeon, specialized in the treatment of LLD, patients were recruited from the University of Basel Children's Hospital in Switzerland, amongst the adolescents aged 10 to 18 years with a structural LLD of greater than 1% of their body height and at least 20 mm. Selected patients were required to be capable of walking a distance of minimum 50 m barefoot without any assistive device. Exclusion criteria were a LLD due to or combined with a neurological etiology, diagnosed structural deformities of the spine, obesity (> 95th percentile BMI per age), and other pathologies, such as injuries or painful conditions that affected their walking ability. Healthy controls were between the age of 10 and 18 years, had no LLD of more than 1% of body height and did not suffer any disorders affecting gait [18]. The study protocol was approved by the Ethics Committee northwest/central Switzerland EKNZ. All participants and their legal guardians provided written informed consent.

2.2. Data collection

Prior to the gait analysis, participants' anthropometric data were assessed, and they underwent a standard clinical examination (measurement of joint mobility, strength and anthropometrics). Their LLDs were measured with a measuring tape (anterior superior iliac spine - patella - medial malleolus) [19,20]. A trained health care professional equipped the participants with 56 retro-reflective markers using a combination of the full body Plug-in Gait [21] and the IfB marker set [16,18] as previously described [14].

After the marker placement, all participants walked barefoot on a 10-meter pathway at a self-selected walking speed. Subsequently, patients walked a second time wearing shoes with the LLD corrected by an orthotic shoe lift. The amount of correction was individually determined, and the difference between the longer and shorter legs was kept below 1% of the individual's body height. For each condition, one static trial (upright standing) and five valid dynamic trials (walking) were recorded. Kinematic data were gathered using a 12-camera motion capture system (Vicon, Oxford, UK, MXT20, sample rate 200 Hz).

2.3. Data reduction

Data were pre-processed using the Nexus software (version 2.6, Vicon, Oxford, UK). The same software was used to filter the marker trajectories, define gait events and calculate Plug-in Gait angles (pelvis and lower extremities) as well as spatiotemporal gait parameters.

Spinal curvatures were generated with a custom-built MATLAB script (MathWorks Inc., Version R2017a, Natick, MA, USA). Frontal and sagittal thoracic (markers on spinous process T3, T5, T7, T9, T11), thoracolumbar (T9, T11, L1, L2, L3) and lumbar (L1, L2, L3, L4, L5, Sacrum) spinal curvatures were constructed using a second order polynomial and a circle fit function creating a curve fitting in the marker clouds [14]. In addition, rotation angles in the transverse plane were calculated for the thoracic, thoracolumbar and lumbar spine by the relative angle between the lines of markers Clavicle to spinous process C7 and right to left lower back marker, height of costal arch (thoracic); apex of sternum to spinous process T4 and right to left lower back marker, height of spinous process L4 (thoracolumbar); and right to left lower back marker height costal arch and the line connecting the two posterior superior iliac spines (lumbar), respectively; the marker descriptions have previously been described [15–17]. For the thoracic curvature angles, a dynamic coordinate system was used in order to obviate projection errors due to the axial rotation of the thorax during walking [17,18].

Kinematic data were normalized by time to one gait cycle (101 data points), which was specified as the time between two sequential foot strikes (both legs for patients, left leg for controls), and they were averaged for the five dynamic trials per subject [13,22].

Primary outcomes included lumbar, thoracolumbar and thoracic spinal curvature angles [°] in addition to pelvic angles [°] in the frontal, sagittal and transverse plane. Secondary outcomes included lower extremity joint angles [°] (ankle, knee and hip) in the sagittal and frontal plane (hip only) as well as spatiotemporal gait parameters (walking speed, cadence, stride length, stride time, step length, step time, stance phase [%], swing phase [%]). Spatiotemporal gait parameters were converted into non-dimensional values, as reported by Hof et al. [23]. All angles were evaluated during upright standing and during walking for the three conditions healthy control, LLD patients barefoot and LLD

Table 1
Subject characteristics of LLD patients and healthy controls. Shown are mean, standard deviation (SD) and range in brackets. Groups were compared using independent sample t-tests (alpha level was set to 0.05).

Parameters	LLD patients (n = 10)	Controls (n = 14)	p-value
Age [years]	15.1 SD 1.9 (13-18)	14.0 SD 1.7 (12-17)	0.142
Height [mm]	1696 SD 87.4 (1510-1810)	1617 SD 103.6 (1460-1840)	0.062
Mass [kg]	59.4 SD 11.3 (43.8-74.7)	54.2 SD 10.4 (40.3-70.4)	0.257
Gender [male/female]	7/3	8/6	–
Shorter side [left/right]	7/3	–	–
LLD [mm]	37.0 SD 15.3 (20-65)	5.7 SD 3.9 (0-10)	< 0.001
LLD [% of height]	2.19 SD 0.9 (1.15-3.84)	0.35 SD 0.23 (0-0.64)	< 0.001
Correction [mm]	26.9 SD 14.2 (10-60)	–	–
LLD after correction [mm]	10.1 SD 5.4 (0-17)	–	–
LLD after correction [% of height]	0.6 SD 0.3 (0-0.94)	–	–

Table 2
Mean and standard deviation (SD) of the kinematic outcome variables during upright standing (in degrees [°]) and spatiotemporal gait parameters (represented as non-dimensional values, as stated in Hof et al. [23]) are reported for the conditions CONTROL, LLD BAREFOOT and LLD CORRECTED. Moreover, results from the comparison of the three walking conditions using one-way ANOVA ($\alpha = 0.05$) and post-hoc pairwise comparisons (independent t-tests, two-tailed, $\alpha = 0.016$) are shown. Statistically significant differences are highlighted in bold. The asterisks (*) additionally indicate differences of greater than 5°.

			1) Controls	2) LLD barefoot	3) LLD corrected	p-values			
						ANOVA	post-hoc pairwise comparisons		
							1 vs. 2	1 vs. 3	2 vs. 3
Lumbar spine	Sagittal		−46.01 SD 10.11	−40.12 SD 13.70	−36.53 SD 10.97	0.142	0.238	0.040	0.526
	Frontal		−0.48 SD 3.31	10.90 SD 9.71	1.61 SD 10.78	**0.006**	**< 0.001***	0.499	0.058
	Transverse		0.06 SD 2.14	−0.74 SD 3.46	−0.77 SD 3.97	0.761	0.491	0.513	0.984
Thoracolumbar spine	Sagittal		−7.89 SD 6.00	−4.75 SD 14.09	−6.18 SD 13.85	0.796	0.461	0.682	0.821
	Frontal		−0.23 SD 3.58	6.35 SD 6.14	3.78 SD 8.29	**0.038**	**0.003***	0.119	0.441
	Transverse		1.00 SD 2.46	1.65 SD 4.08	2.27 SD 3.26	0.636	0.627	0.286	0.713
Thoracic spine	Sagittal		33.79 SD 9.39	29.37 SD 10.02	29.37 SD 10.36	0.448	0.281	0.288	1.000
	Frontal		4.05 SD 4.18	0.78 SD 7.59	1.92 SD 7.08	0.432	0.188	0.365	0.731
	Transverse		−1.68 SD 3.45	1.64 SD 4.07	2.35 SD 3.38	**0.022**	0.042	**0.009**	0.677
Pelvis	Sagittal		9.69 SD 2.75	11.73 SD 6.70	10.04 SD 6.82	0.649	0.314	0.864	0.582
	Frontal		−0.31 SD 1.81	−9.86 SD 5.69	−4.26 SD 4.44	**< 0.001**	**< 0.001***	**0.006**	0.025
	Transverse		0.24 SD 2.71	4.38 SD 6.03	2.86 SD 4.10	0.072	0.032	0.072	0.518
Hip	Sagittal	Shorter leg	3.29 SD 3.66	3.44 SD 9.09	1.57 SD 9.29	0.815	0.956	0.534	0.655
		Longer leg	4.17 SD 4.26	7.67 SD 9.58	5.75 SD 9.50	0.560	0.237	0.587	0.658
	Frontal	Shorter leg	−3.83 SD 2.73	−12.78 SD 6.34	−6.16 SD 4.83	**< 0.001**	**< 0.001***	0.146	0.017
		Longer leg	−2.72 SD 2.60	10.15 SD 7.30	3.69 SD 6.36	**< 0.001**	**< 0.001***	**0.002***	0.049
Knee	Sagittal	Shorter leg	−3.24 SD 4.35	−5.88 SD 5.41	−6.89 SD 4.21	0.152	0.199	0.052	0.648
		Longer leg	−2.40 SD 4.83	−0.01 SD 8.03	−0.55 SD 6.94	0.641	0.373	0.448	0.875
Ankle	Sagittal	Shorter leg	1.20 SD 3.27	1.22 SD 3.84	−0.72 SD 5.32	0.470	0.991	0.284	0.362
		Longer leg	1.73 SD 2.90	2.82 SD 3.38	3.17 SD 4.17	0.564	0.404	0.327	0.839
Walking speed			0.31 SD 0.03	0.29 SD 0.02	0.31 SD 0.03	0.059	0.027	0.797	0.050
Cadence			46.97 SD 2.02	46.29 SD 3.49	44.52 SD 2.93	0.115	0.552	0.024	0.235
Stride length			0.80 SD 0.05	0.74 SD 0.05	0.84 SD 0.06	**0.002**	**0.015**	0.123	**0.001**
Stride time			2.56 SD 0.11	2.61 SD 0.21	2.71 SD 0.19	0.117	0.473	0.025	0.274
Step length	Shorter leg		0.39 SD 0.02	0.36 SD 0.03	0.42 SD 0.03	**0.001**	**0.011**	0.055	**0.001**
	Longer leg		0.40 SD 0.04	0.38 SD 0.03	0.42 SD 0.03	**0.048**	0.113	0.305	**0.012**
Step time	Shorter leg		1.27 SD 0.05	1.34 SD 0.09	1.36 SD 0.09	**0.013**	0.019	**0.004**	0.628
	Longer leg		1.27 SD 0.07	1.24 SD 0.12	1.34 SD 0.11	0.076	0.477	0.057	0.069
Stance phase [%]	Shorter leg		58.90 SD 1.55	59.28 SD 1.06	61.36 SD 1.70	**0.001**	0.510	**0.001**	**0.004**
	Longer leg		59.07 SD 1.49	61.63 SD 1.68	62.04 SD 2.23	**< 0.001**	**0.001**	**0.001**	0.647
Swing phase [%]	Shorter leg		41.10 SD 1.55	40.72 SD 1.06	38.64 SD 1.70	**0.001**	0.510	**0.001**	**0.004**
	Longer leg		40.93 SD 1.49	38.37 SD 1.68	37.96 SD 2.23	**< 0.001**	**0.001**	**0.001**	0.647

Spine: frontal: positive values = lateral bending towards the longer leg (curvature convex to the shorter leg), negative values = lateral bending towards the shorter leg (curvature convex to the longer leg); sagittal: positive values = kyphosis, negative values = lordosis; transverse: positive values = rotation towards the shorter leg, negative values = rotation towards the longer leg. **Pelvis:** sagittal: positive values = anterior tilt, negative values = posterior tilt; frontal: positive values = lateral tilt to the longer leg, negative values = lateral tilt to the shorter leg; transverse: positive values = rotation towards the shorter leg, negative values = rotation to the longer leg. **Hip:** frontal: positive values = adduction, negative values = abduction; sagittal: positive values = flexion, negative values = extension. **Knee:** Positive values = flexion, negative values = extension. **Ankle:** Positive values = dorsiflexion, negative values = plantarflexion.

patients corrected.

2.4. Statistical analysis

All statistics were implemented using one-dimensional Statistical Parametric Mapping [24] (SPM: spm1d-package, http://www.spm1d.org/index.html) in MATLAB. SPM allows to appropriately compare gait kinematics over an entire gait cycle without the necessity to preselect particular parameters, which therefore enables for a more explorative approach [24]. Normal distribution was confirmed using the function “spm1d.stats.normality.anova1”, whereas group comparisons (between the three conditions) for continuous and discrete data were conducted using one-way analysis of variance (function: “spm1d.stats.anova1”). To compare subject characteristic and for post-hoc comparisons independent sample T-tests (function: “spm1d.stats.ttest2”) were used. Because of multiple testing, the alpha level for post-hoc tests was Bonferroni corrected to $p = 0.016$ (two-tailed).

To address the issue of clinical relevance, statistically significant differences in spinal, pelvic and lower extremity angles were additionally evaluated using the previously adopted minimal clinically important difference (MCID) of 5° [18,25–27]. However, since this MCID was mainly based on expert opinions rather than distribution- or anchor-based approaches, it will only be used as a supplementary indication for the Tables and Figures, and not as a cutoff value for the statistical analysis.

3. Results

There were no significant differences between the LLD patients and healthy controls in terms of their age, height, mass (Table 1) and walking speed (Table 2).

3.1. Primary outcomes

In upright standing, LLD patients showed statistically significant larger frontal plane lumbar (barefoot: $p < 0.001$) and thoracolumbar (barefoot: $p = 0.003$) bending angles to the longer side, more thoracic rotation to the shorter side (corrected: $p = 0.009$) and an increased frontal plane pelvic drop on the shorter side (barefoot: $p < 0.001$; corrected: $p = 0.006$) compared to healthy controls (Table 2).

During walking, patients with LLD showed larger frontal plane lumbar bending angles to the longer side (convex on the short side) during initial contact and early mid-stance (barefoot: $p = 0.007$, 0–21% of gait cycle [%GC]; corrected: $p = 0.016$, 0–2%GC) and terminal

Table 3
Results of the comparison between the three walking conditions' calculations using one-way ANOVA (two-tailed, alpha level 0.05) for continuous spinal, pelvic and lower extremity angles using one-dimensional SPM [24].

			F-threshold	supra-threshold clusters	location [% of gait cycle]	p-value
Lumbar spine	Sagittal		4.858	–	–	–
	Frontal		5.260	2	0-17	0.037
					84-100	0.037
	Transverse		5.069	–	–	–
Thoraco-lumbar spine	Sagittal		4.350	–	–	–
	Frontal		5.204	–	–	–
	Transverse		6.060	–	–	–
Thoracic spine	Sagittal		4.249	–	–	–
	Frontal		4.920	–	–	–
	Transverse		5.648	2	12-19	0.046
					49-84	0.003
Pelvis	Sagittal		4.731	–	–	–
	Frontal		5.125	1	0-100	< 0.001
	Transverse		5.850	–	–	–
Hip	Sagittal	Shorter leg	5.328	–	–	–
		Longer leg	5.427	–	–	–
	Frontal	Shorter leg	5.204	–	–	–
		Longer leg	5.379	1	0-100	< 0.001
Knee	Sagittal	Shorter leg	6.519	2	40-52	0.013
					67-89	0.001
		Longer leg	6.431	–	–	–
Ankle	Sagittal	Shorter leg	5.928	1	57-67	0.036
		Longer leg	6.401	3	0-9	0.029
					52-65	0.014
					89-100	0.019

swing phase (barefoot: p = 0.009, 81–100%GC; corrected: p = 0.016, 96–100%GC) (Table 3 and Fig. 1). They also demonstrated increased pelvic drop on the shorter side (barefoot: p < 0.001, 0–100%GC; corrected: p = 0.016, 42–46%GC) and more thoracic rotation to the longer side in the push-off phase (corrected: p = 0.015, 52–58%GC and p = 0.011, 69–81%GC) compared to the controls. No other statistically significant differences were found for the primary outcome parameters. Results of all ANOVAs are presented in the Appendix, A1-A7.

3.2. Secondary outcomes

In upright standing, LLD patients demonstrated statistically significant increased frontal hip abduction angles on the shorter side (barefoot: p < 0.001) and higher adduction angles on the longer side (barefoot: p < 0.001; corrected: p = 0.002) in comparison with healthy controls (Table 2).

During walking, patients with LLD demonstrated increased frontal hip adduction angles on the longer side (barefoot: p < 0.001, 0–100%GC; corrected: p = 0.003, 40–66%GC and p = 0.016, 99–100%GC), increased knee extension on the shorter side in the midstance phase (barefoot: p = 0.014, 47–51%GC) and more dorsiflexion in the ankle joint of the longer side in the terminal stance phase (barefoot: p = 0.002, 52–66%GC) compared to healthy controls (Figs. 2 and 3).

The correction of LLD with an orthotic shoe lift led to an increase in knee flexion on the patients' shorter side in initial and mid swing phase (p = 0.009, 69–76%GC) and to increased ankle dorsiflexion values on the longer side in initial contact (p = 0.016, 0–3%GC) and terminal swing phase (p = 0.014, 95–100%GC) when compared to the barefoot walking of LLD patients (Figs. 2 and 3). In contrast to the healthy controls, corrected LLD patients showed greater ankle dorsiflexion on the shorter side during the initial swing (p = 0.012, 58–67%GC) and on the longer side in the initial contact (p = 0.007, 0–9%GC) and terminal swing phases (p = 0.004, 88–100%GC).

The analysis of spatiotemporal gait parameters showed decreased stride and step length on the patients' shorter side compared to corrected (p = 0.001) and control (p = 0.015 and p = 0.001) condition (Table 2). Due to the correction, the stance phase on the shorter leg increased (p = 0.004). Although group comparisons of spatiotemporal parameters reached statistical significance, mean differences were small and should therefore be interpreted with caution.

4. Discussion

The aim of the current study was to investigate spinal gait kinematics in patients with structural LLD compared to healthy controls and to evaluate the immediate effect of an orthotic shoe lift.

The results demonstrated changed gait patterns in patients with LLD, including deviations in spinal, pelvic and lower extremity angles, which were instantly influenced upon correcting the LLD with a shoe lift.

It has been previously demonstrated that both joint angles and spatiotemporal gait parameters were seriously affected by walking speed in children [28]. In the current study, no group differences in walking speed were observed, and therefore the possibility of distorted results attributed to walking speed can be neglected.

As a reaction to the limb length inequality, patients showed a frontal pelvic drop on the shorter side when both walking and standing upright. These findings are in accordance with those of previously published papers, which have identified the pelvic drop as the most common isolated gait pattern in patients with true LLD [6]. According to a previously suggested classification of primary and secondary gait deviations [29], the frontal pelvic drop observed in LLD patients represents a passive secondary effect that results from the structurally shorter leg (primary pathology). This evaluation differs from many other studies, which identified the effect as a compensation mechanism [26].

Patients with LLD showed a larger frontal plane lumbar bending angle to the longer side (convex to the shorter leg). This alteration can be seen as an active compensation to balance out the pelvic deviations in the frontal plane and is in line with the findings of Kakushima et al. [12]. In contrast to their study, however, the current subjects did not show lateral bending of the thoracic spine as a counter-compensation for the lumbar spine deviations. It was therefore assumed that the

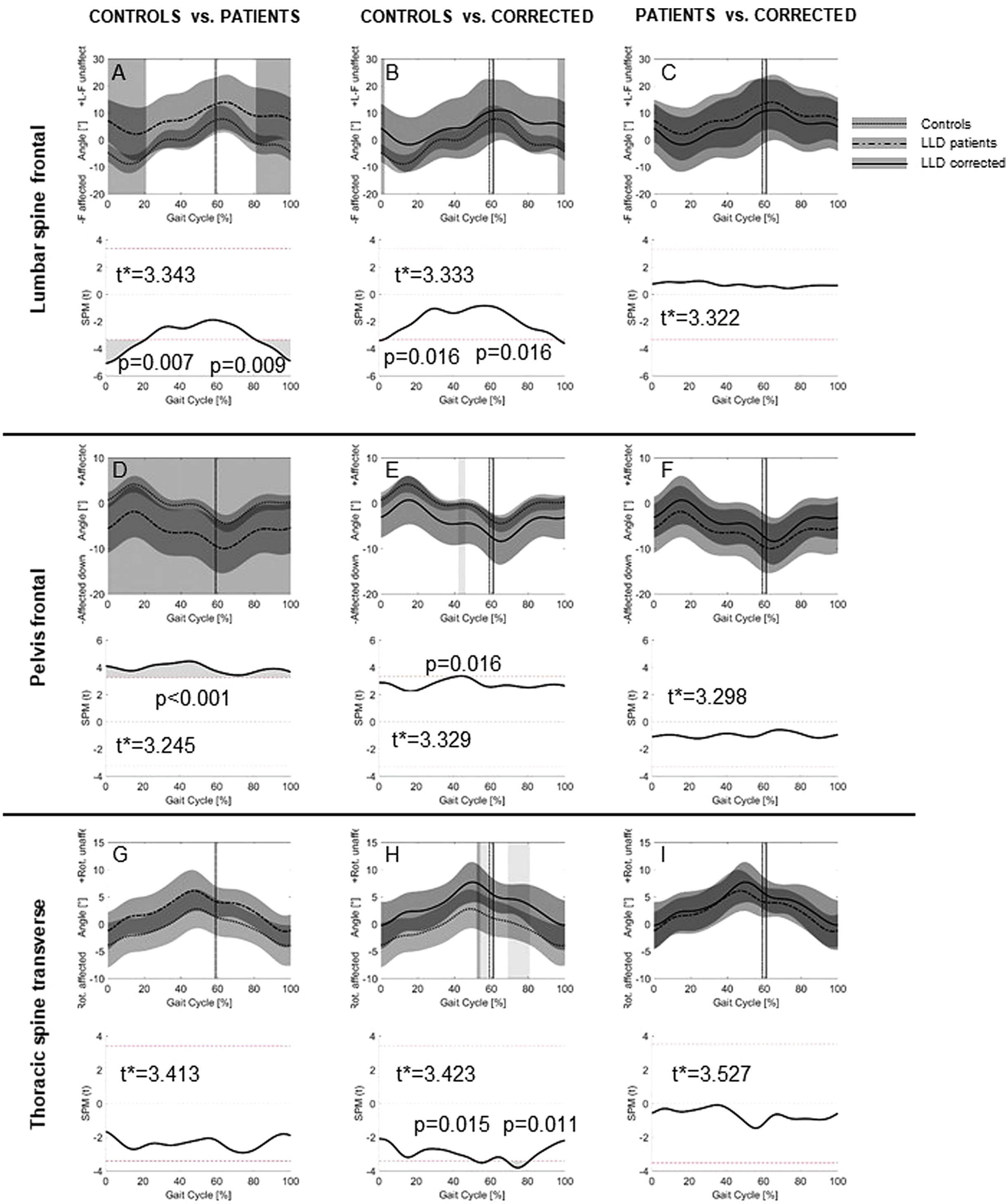

Fig. 1. Post-hoc group comparisons for spinal and pelvic angles between healthy controls and LLD patients (first column), healthy controls and corrected LLD patients (second column), as well as LLD patients and corrected LLD patients (third column). Mean values and one standard deviation (above and below) of the joint angles for healthy controls (dotted line), LLD patients (dash-dotted line) and corrected LLD patients (solid line) are represented (vertical axis) for one gait cycle (horizontal axis). The vertical lines around 60% of the gait cycle demonstrate the foot-off. The light grey shaded areas indicate any time points that show statistically significant differences ($p \leq 0.016$), whereas the dark grey shaded areas additionally indicate statistically significant differences of greater than 5°. The graph below displays the t-curve of the SPM. Horizontal dotted lines present the threshold for statistical significance (t*) and the corresponding p-values (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

current subjects counter-compensated with a lateral pelvic shift towards the longer side to preserve the normal path of the body's center of mass (COM). Frontal plane deviations in the hip (larger adduction angles) were thus probably not only due to the frontal pelvic tilt, but also resulted as a physical consequence of the lateral pelvic shift. The fact that the observed lumbar spine compensations predominantly occurred in terminal swing and initial contact phase can be explained by the patients' attempts to avoid unnecessary and excessive lowering of the COM when stepping onto the shorter leg and thereby reducing energy exertion [1,11,29].

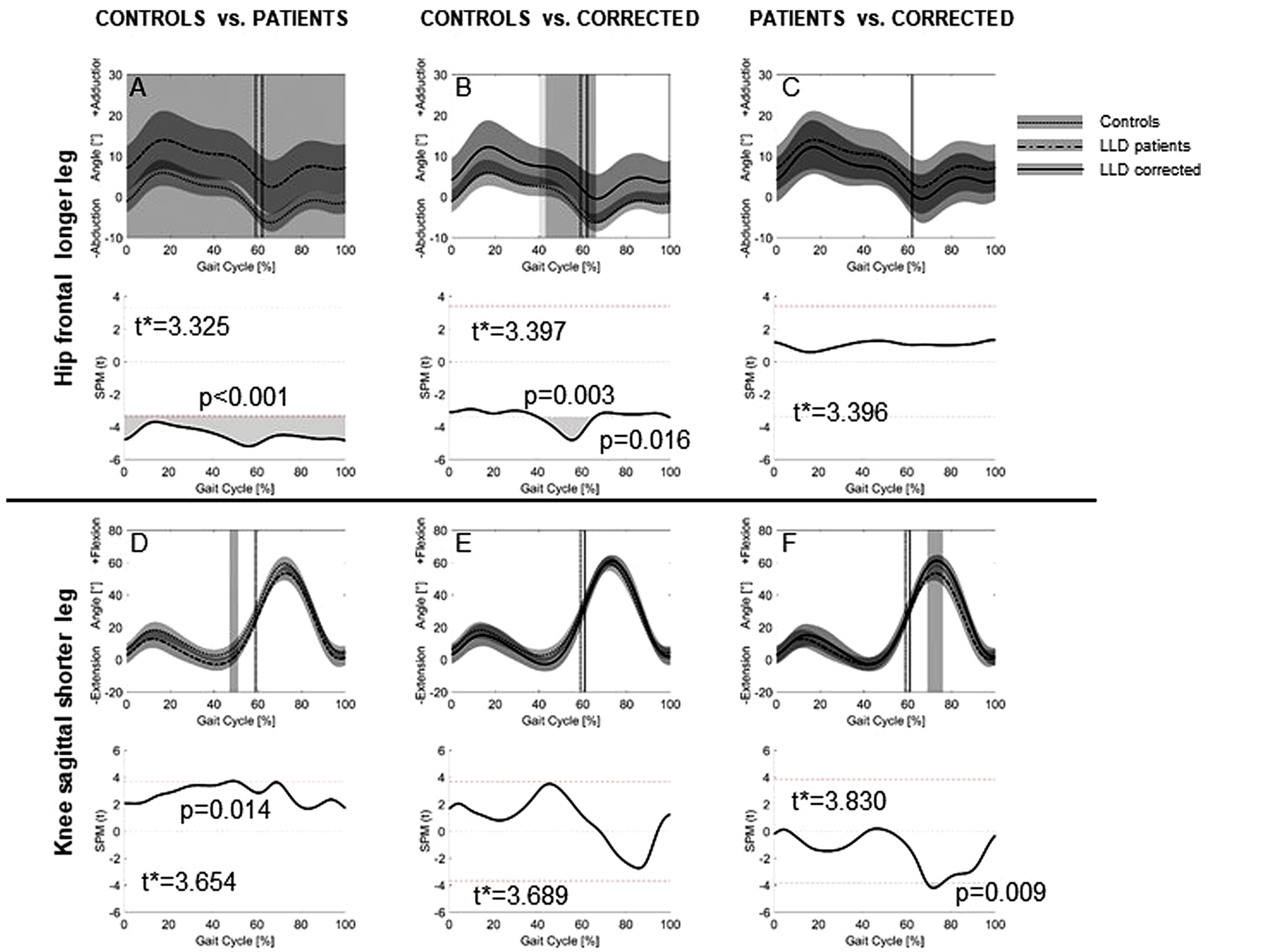

Fig. 2. Post-hoc group comparisons for hip and knee angles between healthy controls and LLD patients (first column), healthy controls and corrected LLD patients (second column), as well as LLD patients and corrected LLD patients (third column). Mean values and one standard deviation (above and below) of the joint angles for healthy controls (dotted line), LLD patients (dash-dotted line) and corrected LLD patients (solid line) are represented (vertical axis) for one gait cycle (horizontal axis). The vertical lines around 60% of the gait cycle demonstrate the foot-off. The light grey shaded areas indicate any time points that show statistically significant differences ($p \leq 0.016$), whereas the dark grey shaded areas additionally indicate statistically significant differences of greater than 5°. The graph below displays the t-curve of the SPM. Horizontal dotted lines present the threshold for statistical significance (t*) and the corresponding p-values (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

A possible explanation for the different compensatory strategies between the current study and the study of Kakushima et al. [12] could be the different study populations. In their study, participants were distinctly older (range 19–45 years, mean 26.2 years) and walked with artificially induced LLD, whereas subjects in the present study were under the age of 18 years and suffered from true LLD. Considering that both long-standing LLD and a younger age enable patients to better cope with LLD [1], it can be hypothesized that the applied compensation strategies logically differ between the two samples.

Furthermore, differences in thoracic spine rotation angles between corrected LLD patients and healthy controls during walking were found in the present analysis (Table 1). These distinctions can be attributed to the thoracic deviation of the control subjects, who showed noticeable thoracic frontal plane bending (4.05°) and axial rotation (1.68°) angles in standing position and during gait (Table 1), rather than be seen as a compensation strategy for LLD.

Alterations in the knee and ankle joint can be classified as active compensatory mechanisms with the intention to equalize leg length in order to limit the pelvic drop. The increase in dorsiflexion on the longer side in the terminal stance phase is evidence of a strategy to functionally shorten the longer leg, whereas the increased knee extension on the shorter side during the mid-stance phase causes a functional lengthening of the shorter leg [8,10,11].

Once LLD was corrected, all aforementioned differences in gait kinematics were distinctly (pelvis, knee and ankle) or partially (lumbar spine and hip) eliminated. Due to the reduction of the pelvic drop, active compensations of the spine were less necessary.

A somewhat unexpected outcome in patients walking with correction were the increased dorsiflexion values in the longer leg during the terminal swing and initial contact phases. These findings can be attributed to the previously observed increased ankle dorsiflexion at heel strike in shod walking compared to barefoot walking [30].

Moreover, the increased knee flexion and ankle dorsiflexion on the shorter side in the initial swing phase when walking with the orthotic device represent a strategy to ensure that the foot does not bump into the ground.

Furthermore, the decrease in plantarflexion during push-off on patients' shorter side may be justified by the automatized movement pattern, which insinuates that push-off activity in order to raise the COM is no longer necessary since the shoe lift lengthens the limb and lifts the COM. Then again, it must be considered that the ability to move the ankle toward plantarflexion was diminished due to the shoe lift (placed under the entire sole of the shoe).

Due to the previously disclosed limitations for spinal kinematics measurements that use standard marker configurations [14,18], the application of an enhanced marker-based approach can be considered a

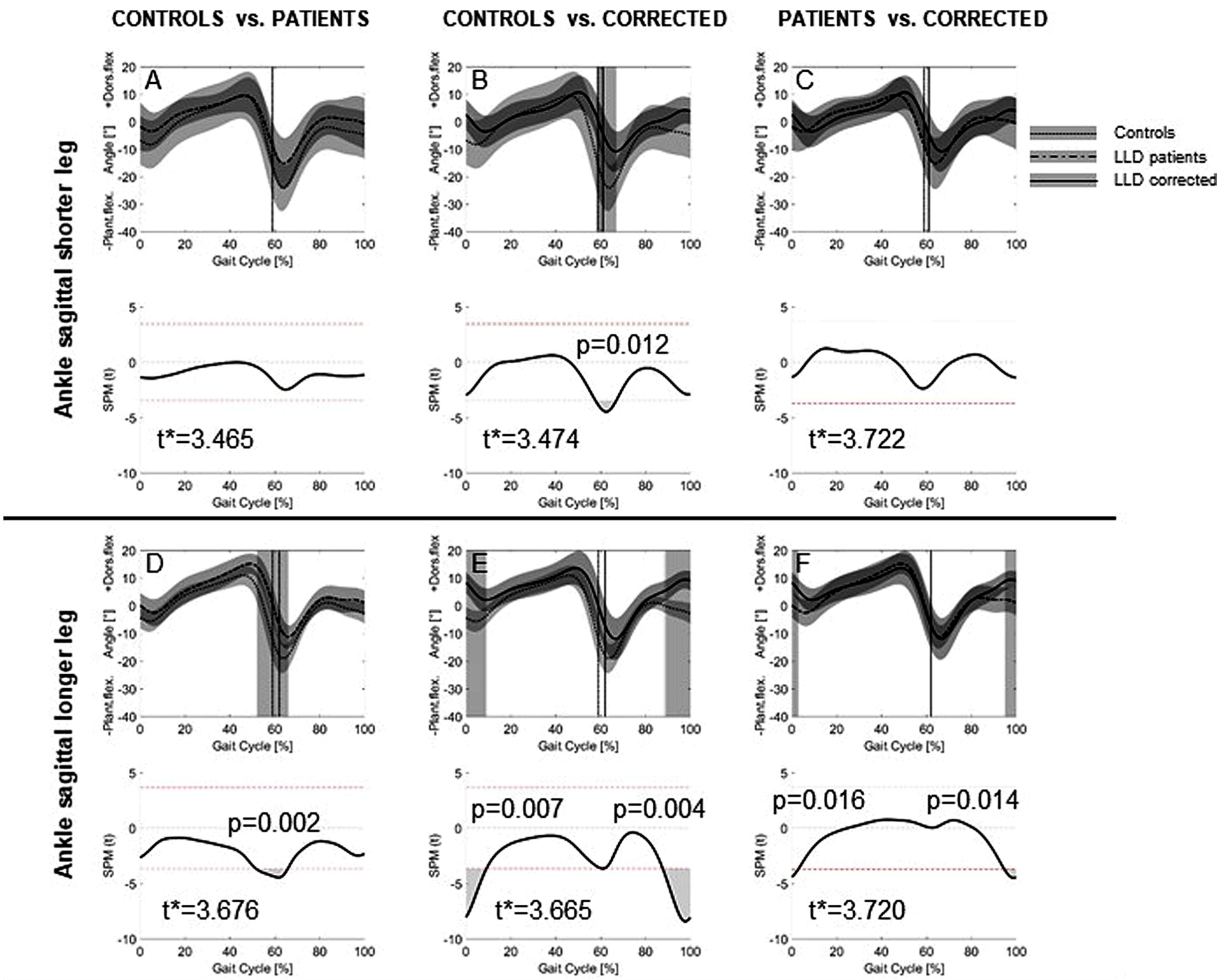

Fig. 3. Post-hoc group comparisons for sagittal ankle angles between healthy controls and LLD patients (first column), healthy controls and corrected LLD patients (second column), as well as LLD patients and corrected LLD patients (third column). Mean values and one standard deviation (above and below) of the joint angles for healthy controls (dotted line), LLD patients (dash-dotted line) and corrected LLD patients (solid line) are represented (vertical axis) for one gait cycle (horizontal axis). The vertical lines around 60% of the gait cycle demonstrate the foot-off. The light grey shaded areas indicate any time points that show statistically significant differences ($p \leq 0.016$), whereas the dark grey shaded areas additionally indicate statistically significant differences of greater than 5°. The graph below displays the t-curve of the SPM. Horizontal dotted lines present the threshold for statistical significance (t*) and the corresponding p-values (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

strength of this study. Furthermore, the use of SPM [24] for the statistical analysis is another positive aspect of the current paper.

A limiting factor of the present study was the small number of subjects with the possible lack of power for some comparisons, which might have increased the chance of error type 2. Moreover, the inclusion of patients with discrepancies between 20 and 60 mm led to a considerable mean variation. Averaging all values from these subjects might have washed out different compensatory mechanisms depending on the amount of LLD.

Up to date, there remains disagreement in academic literature concerning not only the role LLD plays in the development process of several musculoskeletal disorders [1,5], but also the amount of LLD necessary to cause problems, alter gait patterns or warrant treatment interventions [1]. This is the first study investigating spinal gait kinematics in patients with structural LLD. Further studies are needed to conclusively clarify the cause-effect relationship between LLD and musculoskeletal disorders so that tangible recommendations concerning the treatment of LLD can be made.

In conclusion, LLD patients in the current study showed a pelvic drop on the shorter side, which they appeared to compensate for with a lateral bending in the lumbar spine and a lateral shift of the pelvis towards the longer side. In addition, all observed gait deviations in LLD patients were immediately influenced by an orthotic shoe lift.

This study contributes to a better understanding of both secondary gait deviations seen in patients with structural LLD and the immediate effect of an orthotic correction on spinal, pelvic and lower extremity kinematics. A possible approach to provide further insights into dynamic joint loading patterns and neuromuscular control mechanisms in patients with LLD is the future application of complex computer-simulated musculoskeletal models. In this context, the collected data could serve as the basis for the development of a corresponding computer program.

Conflict of interest statement

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.gaitpost.2018.12.040.

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