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The Effects of Simulated Mild Leg Length Discrepancy on Gait Parameters and Trunk Acceleration

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Abstract

Background: Leg length discrepancy (LLD) leads to many musculoskeletal disorders and affects daily activities such as walking. In the majority of the population, mild LLD is a common condition. Nevertheless, it is still controversy among researchers and clinicians on the effects of mild LLD during gait, and available studies have largely overlooked this issue.

Objects: The purpose of the present study is to investigate the effects of mild LLD on the gait parameters and trunk acceleration.

Methods: A total of 15 female and male participants with no evidence of LLD of >.5 ㎝ participated in the present study. All participants walked under the following two conditions: (1) The non-LLD condition, where the participants walked in shoes of the same heel height; (2) A mild LLD condition induced by wearing a 1.5 ㎝ higher heel on the right shoe. The GAITRite system and tri-axial accelerometer were used to measure gait parameters and trunk acceleration. To compare the variation of each variable, a paired t-test was performed.

Results: Compared to the non-LLD condition, step time and swing phase were significantly increased in the mild LLD condition, while stance phase, single support phase, and double support phase significantly decreased in the short limb ($p<.05$). In the long limb of the mild LLD condition, single support phase significantly increased, while swing phase significantly decreased ($p<.05$). Furthermore, significant decrease in the gait velocity and cadence in the mild LLD condition were observed ($p<.05$). In the comparison between both limbs in the mild LLD condition, the step time and swing phase of the short limb significantly increased compared with the long limb, while step length, stance phase, and single support phase of the long limb significantly increased compared with the short limb ($p<.05$). Additionally, trunk acceleration of all directions (anterior-posterior, medial-lateral, vertical) significantly increased in the mild LLD condition ($p<.05$).

Conclusion: The results of the present study demonstrate that mild LLD causes altered and asymmetrical gait patterns and affects the trunk, resulting in inefficient gait. Therefore, mild LLD should not be overlooked and requires adequate treatment.

Key Words: Asymmetry; Gait analysis; Mild leg length discrepancy.

Introduction

Leg length discrepancy (LLD) is a common condition that occurs in 90% of the population due to asymmetry of both legs, of which 20% have LLD of above .9 ㎝ (Knutson, 2005). LLD is also classified by magnitude of the discrepancy: mild (<3 ㎝), moderate (3-6 ㎝), or severe (>6 ㎝) (Brady et al., 2003). Breakpoint of 2 ㎝ is often used to suggest treatment for individuals with LLD (Gurney, 2002). LLD affects daily activities, such as walking (Subotnick, 1981) or standing posture (Bloz and Davies, 1984), as well as leads to musculoskeletal disorders, such as low back pain (Defrin et al., 2005) or knee osteo-

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arthritis (Harvey et al., 2010).

In general, individuals with a LLD use compensatory movements to equalize the functional leg length of the short and the long limb during gait, which causes asymmetric gait patterns (Bhave et al., 1999). As compared to normal gait, asymmetric gait increases energy consumption, which leads to a decrease in gait efficiency (Khamis and Carmeli, 2017).

The control of trunk movement plays an important role in effective gait, providing a stable platform for the head and lower extremities by modulating the amplitude and structure of gait-related oscillations (Asai et al., 2013). Trunk acceleration during walking can suggestive of gait dysfunction (Latt et al., 2009), and has been identified as a possible measure of gait stability (Yack and Berger, 1993). LLD affects the trunk, which is the proximal part of the body, decreasing stability and efficiency during gait (Ku et al., 2014). Additionally, several studies have found that LLD causes compensatory movements of the trunk, such as lateral bending or rotation during gait (Kakushima et al., 2003; Resende et al., 2016b).

Many previous studies have demonstrated the effects of LLD above 2 ㎝ on gait. Discrepancy of less than 2 ㎝ was reported to have no significant effect on gait. For instance, Perttunen et al (2004) reported that LLD above 2.5 ㎝ could lead to asymmetric gait; particularly, higher quadriceps muscles activities were observed in short limbs than long limbs, which is a strategy to limit excessive drop of the pelvis. Furthermore, in their study using an artificial LLD, Gurney et al (2001) found that the study participants had a significantly increased energy consumption at the discrepancy of 2, 3, and 4 ㎝, as well as an increased heart rate and minute ventilation at 3 and 4 ㎝.

Recent studies, however, found the biomechanical strategies used to compensate mild LLD of below 2 ㎝ during gait. For instance, in their study that simulated LLD of 1.45 ㎝ in healthy adults, Resende et al. (2016a) found that mild LLD results in compensatory changes during gait in order to equalize the functional length of the lower limbs. More specifically, the short limb compensated in stance phase with a greater ankle plantar flexion and rear foot inversion with the smaller knee and hip flexion angles and decreased hip adduction. The long limb compensated with a greater dorsiflexion and rear foot eversion with an increased knee and hip flexion angles during the stance phase. In addition, mild LLD affected pelvic motion in the frontal plane. In their study which simulated .5, 1, 1.5, 2, 3 and 4 ㎝ LLD in 7 healthy participants, Khamis and Carmeli (2017) found that, from mild LLD of .5 and 1 ㎝, biomechanical changes were observed. Specifically, the functional length of the short leg was lengthened, while the functional length of the long leg was shortened, causing asymmetric gait.

Due to the controversies in the literature, there is still no consensus on the effects of mild LLD on gait. Furthermore, there is a lack of research on how mild LLD affects the proximal part of body during gait. Therefore, the present study investigated the effects of mild LLD on the gait parameters and trunk acceleration. We hypothesized that participants would show altered and asymmetrical gait patterns and increased trunk acceleration.

Methods

Participants

A total of 15 healthy adults participated in this study, and the experiment was conducted from August 1 to 10, 2018. The inclusion criterion were structural or functional LLD smaller than .5 ㎝ (Resende et al., 2016a). Structural LLD was assessed by measuring the bilateral distance between the anterior superior iliac spine and the ipsilateral medial malleolus with a measuring tape, with the participants in the supine position. Functional LLD was measured by asymmetry in height of the iliac crests through a palpation meter. The exclusion criteria were (1) congenital deformities of lower extremities;

Table 1. General characteristics of the participants (N=15)

Parameters		Value
Gender (male/female)		6 / 9
Age (year)		22.9±2.2[a]
Height (㎝)		168.1±8.6
Weight (㎏)		63.5±9.9
Leg length (㎝)	Left	85.6±5.3
	Right	85.6±5.4
Leg length discrepancy (㎝)		.3±.2
Iliac crest height difference (㎝)		.3±.2

[a]mean±standard deviation.

(2) history of surgery or injuries to the lower extremities or to the lumbar-pelvic complex; (3) difficulty walking due to dizziness or hypotension, or reports of discomfort during procedures. The participants provided written informed consent to participate in this study. General characteristics of the participants are summarized in Table 1.

Instrumentation

GAITRite

Gait parameters were measured using the GAITRite system (CIR System, Easton, PA, USA). To compare the gait parameters of the participants between the experimental conditions and between both side of lower limbs, we measured gait velocity, cadence, step length, stride length, step time, and gait cycle; stance phase, single support phase, double support phase, swing phase. The system automatically measures gait parameters through 13,824 1 ㎝ -diameter sensors at a 5-inch center, arranged in a grid of 48 × 288 inches on a 144 × 24 inch mat. Gait parameters were measured three times under each condition, and the mean values of the three trials were used for data analysis.

Tri-axial accelerometer

Trunk acceleration during gait was measured using a tri-axial accelerometer (Fit Dot Life, Suwon, Korea). The accelerometer was 35 × 35 × 13 ㎜ in size and weighed 13.7grams. A sensor range of -8 g to +8 g was selected in the acquisition software (Fitmeter manager 2, ver. 1.2.0.14, Korea), and we used a sensor range of ±2 g. The raw data were measured using x, y, and z acceleration variables. The accelerometer was attached over the L3 spinous process using a double-sided adhesive tape (Tucker et al., 2008). Another accelerometer acting as a hand switch was used to obtain the acceleration data of the same period as the data obtained in GAITRite. When the participants pass the beginning and end points of the GAITRite walkway, the examiner press the switch (Shin et al., 2017). The data were collected with the sampling rate of 32 ㎐. Trunk acceleration in anterior-posterior (AP), medial-lateral (ML) and vertical (VT) directions was calculated using root means (RMS) for each direction (Eq. 1-3). The RMS values (AP, ML, and VT) were normalized to mean values (Helbostad and Moe-Nilssen, 2003).

$$AP = \frac{1}{n}\sum_{i=1}^{n}\sqrt{z_i^2} \qquad \text{(Eq. 1)}$$

$$ML = \frac{1}{n}\sum_{i=1}^{n}\sqrt{x_i^2} \qquad \text{(Eq. 2)}$$

$$VT = \frac{1}{n}\sum_{i=1}^{n}\sqrt{y_i^2} \qquad \text{(Eq. 3)}$$

Shoes

The shoes were prepared to fit the foot size of each participant. Mild LLD was induced by placing a 1.5 ㎝ external lift along the entire length of the shoe (from heel to toe). The external lift was made of a high-density ethylene vinyl acetate material and attached to the bottom of the shoes made of the same material (Resende et al., 2016a; Resende et al., 2016b). The long limb was defined as the right with the external lift and the left limb was defined as the short limb.

Experimental procedure

Before starting this experiment, the whole experi-

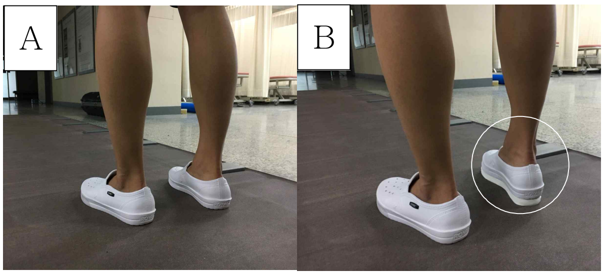

Figure 1. A: Non-LLD, B: Mild LLD condition (LLD: Leg length discrepancy).

ment procedure was explained to each participant. The examiner measured the participant's leg length and iliac crest height difference and then attached a 3-axis accelerometer at L3 level.

The participants then walked under 2 different conditions, wearing prepared shoes: (1) Non-LLD (control): The participants walked in shoes with no difference in the heel height (Figure 1A). (2) Mild LLD: The participants walked in the shoes with a 1.5 ㎝ external lift on the right side (Figure 1B).

Prior to the experiment, a preliminary practice was performed with a verbal instruction of "walk straight ahead and walk naturally" for inducing natural walk. After practice trials, the participants randomly completed two measured conditions. The participants were given 2 minutes to acclimate to external lift before the mild LLD condition trials start (Khamis and Carmeli, 2017). All participants walked the GAITRite walkway three times per condition with the instruction of "start" and "stop" with self-selective comfortable gait speed.

To avoid overlap and potential fatigue effects, each participant sat in a chair and had a 2-minute break between the measurements and between conditions. In order to exclude the acceleration and deceleration phase of the gait cycle from the measured values, the participants started 2 meters before the start line and stopped 2 meters after the finish line of the walkway.

Statistical analysis

PASW Statistics ver. 18.0 (IBM Corp., Armonk, NY, USA) was used to perform all statistical analyses. For inter-group comparisons, differences in gait parameters and trunk acceleration were analyzed using a paired t-test. It was also used to compare

Table 2. Comparisons of the gait parameters between conditions (N=15)

Gait parameters	Non-LLD[a]		Mild LLD		p
Step time (sec)	Left	.54±.03[b]	Short	.57±.04	.004*
	Right	.55±.03	Long	.55±.05	.697
Step length (㎝)	Left	70.05±7.31	Short	65.70±10.28	.056
	Right	70.62±7.25	Long	69.06±10.31	.481
Stride length (㎝)	Left	140.58±14.36	Short	138.55±14.36	.159
	Right	140.90±14.36	Long	139.68±16.61	.382
Stance (%)	Left	60.15±1.70	Short	58.34±1.56	<.001*
	Right	60.06±1.39	Long	61.83±4.05	.082
Single support (%)	Left	39.97±1.33	Short	39.06±2.01	.049*
	Right	39.44±1.42	Long	41.05±2.14	.039*
Double support (%)	Left	20.73±2.38	Short	19.29±2.82	.042*
	Right	20.74±2.46	Long	19.78±2.69	.167
Swing (%)	Left	39.54±1.42	Short	41.66±1.56	<.001*
	Right	39.92±1.30	Long	38.98±1.57	.017*
Velocity (㎝/sec)	129.34±13.88		123.19±16.36		.008*
Cadence (steps/min)	110.78±5.60		106.55±6.91		.002*

[a]leg length discrepancy, [b]mean±standard deviation, *p<.05.

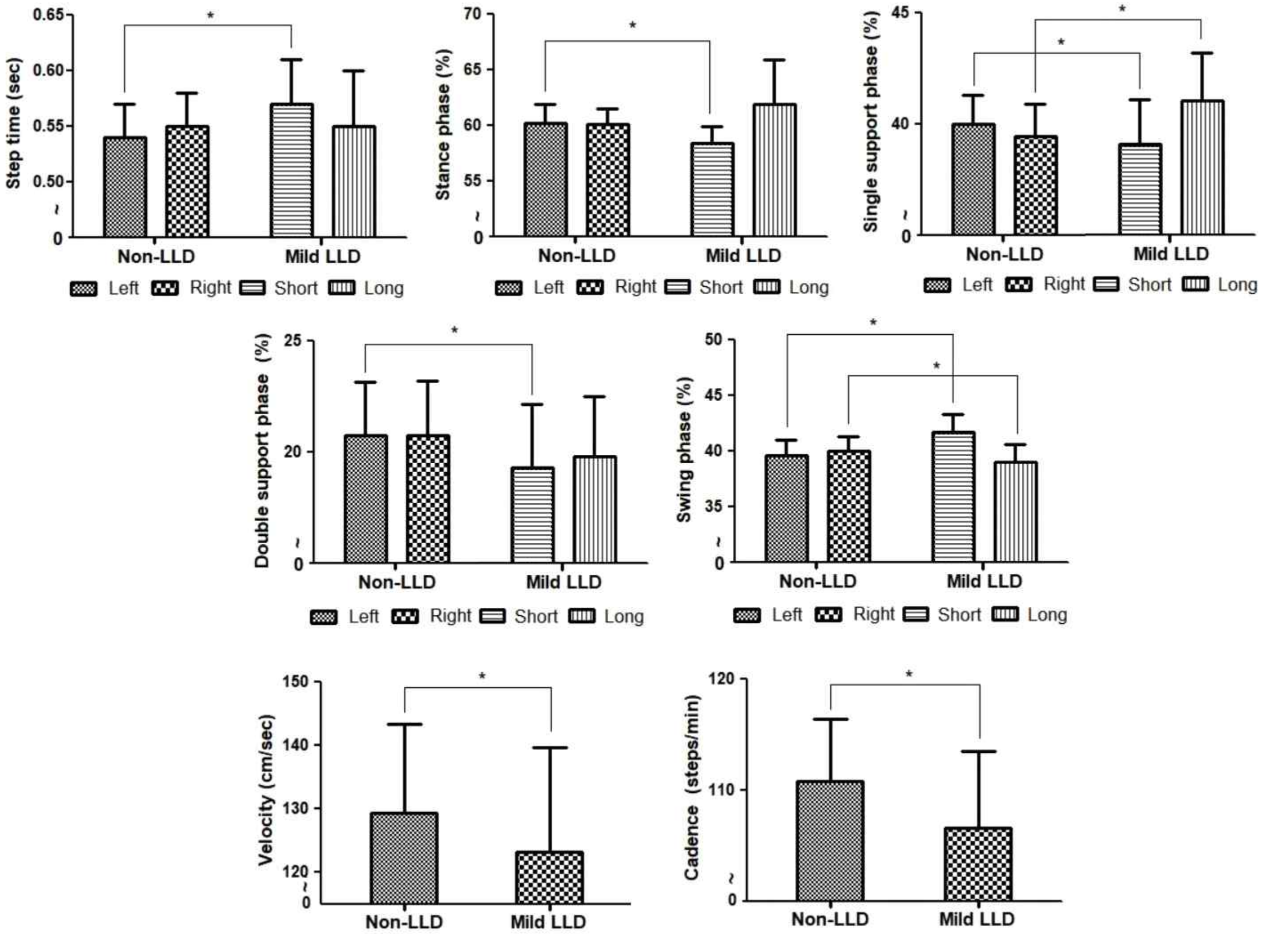

Figure 2. Comparisons of gait parameters between conditions (LLD: Leg length discrepancy) (*p<.05).

between limbs in each condition. The level of significance was set at p<.05.

Results

Comparisons of gait parameters between conditions

Comparisons of gait parameters between the non-LLD and mild LLD conditions are reported in Table 2 and Figure 2. Compared to the non-LLD condition, in the short limb, the step time and swing phase increased significantly, whereas a significant decrease in stance phase, single support phase, and double support phase was observed (all comparisons: p<.05). In the long limb, the single support phase significantly increased, while swing phase significantly decreased (all comparisons: p<.05). Additionally, velocity and cadence significantly decreased in the mild LLD condition vs. the non-LLD condition (both comparisons: p<.05). No significant differences in step length and stride length between two conditions were observed.

Comparisons of gait parameters between limbs

Comparisons of gait parameters between left and right limb in the non-LLD condition are reported in Table 3. No significant differences in any gait parameters between left and right limbs were observed.

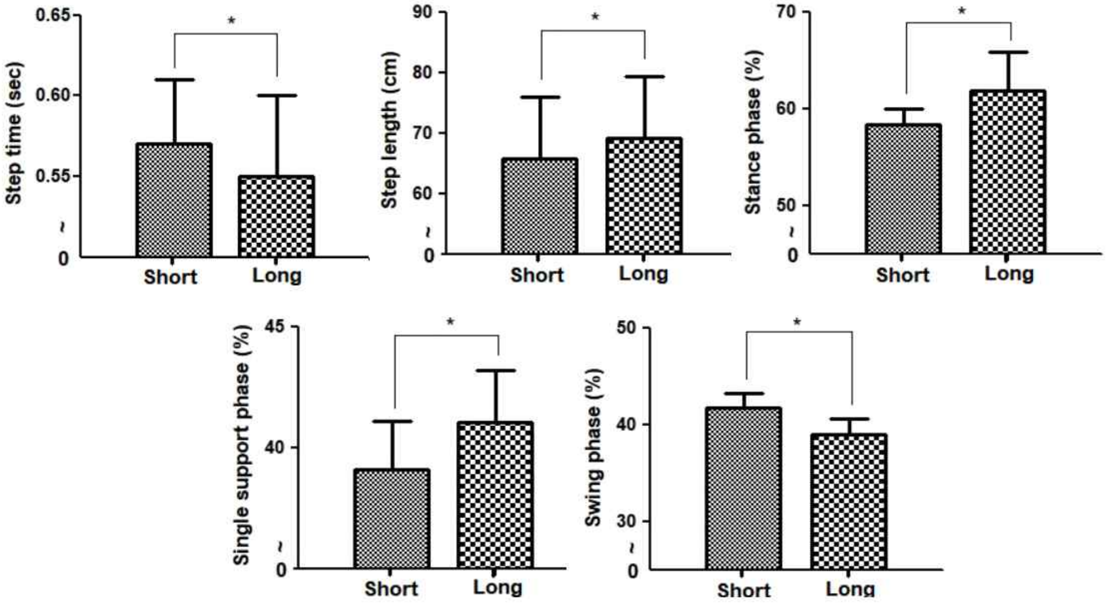

Figure 3. Comparisons of gait parameters between limbs in the mild LLD condition (LLD: Leg length discrepancy) (*p<.05).

Table 3. Comparisons of the gait parameters between limbs the non-LLD condition (N=15)

Gait parameters	Left	Right	p
Step time (sec)	.54±.03[a]	.55±.03	.161
Step length (㎝)	70.05±7.31	70.62±7.25	.427
Stride length (㎝)	140.58±14.36	140.90±14.36	.488
Stance (%)	60.15±1.70	60.06±1.39	.835
Single support (%)	39.97±1.33	39.44±1.42	.261
Double support (%)	20.73±2.38	20.74±2.46	.968
Swing (%)	39.54±1.42	39.92±1.30	.393

[a]mean±standard deviation.

Table 4. Comparisons of the gait parameters between limbs in the mild LLD condition (N=15)

Gait parameters	Short	Long	p
Step time (sec)	.57±.04[a]	.55±.05	.005*
Step length (㎝)	65.70±10.28	69.06±10.31	<.001*
Stride length (㎝)	138.55±14.36	139.68±16.61	.103
Stance (%)	58.34±1.56	61.83±4.05	.003*
Single support (%)	39.06±2.01	41.05±2.14	.031*
Double support (%)	19.29±2.82	19.78±2.69	.216
Swing (%)	41.66±1.56	38.98±1.57	<.001*

[a]mean±standard deviation, *p<.05.

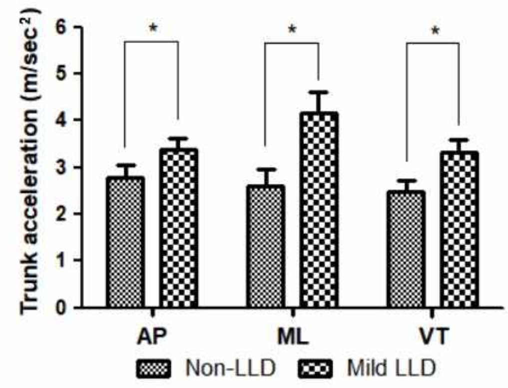

Figure 4. Comparisons of trunk acceleration between conditions (AP: anterior-posterior, ML: medial-lateral, VT: vertical, LLD: Leg length discrepancy) (*p<.05).

Comparisons of gait parameters between short and long limb in the mild LLD condition are summarized in Table 4 and Figure 3. There were significant differences in step time, step length, step time, stance phase, single support phase, and swing phase (all comparisons p<.05).

Comparisons of trunk acceleration between conditions

Comparisons of trunk acceleration between conditions are shown in Table 5 and Figure 4. All directions (AP, ML, and VT) of trunk acceleration under the mild LLD condition were significantly faster than in the non-LLD condition (p<.05).

Discussion

The present study aimed to investigate the effects of mild LLD on gait parameters and trunk acceleration. Compared to the non-LLD condition, step time and swing phase significantly increased, while stance phase, single support phase, and double support phase significantly decreased in the short limb of the mild LLD condition. In the long limb of the mild LLD condition, single support phase significantly increased, while swing phase significantly decreased. This altered gait pattern was observed as a means of compensating for mild LLD, as the short limb and long limb needed to minimize the center of mass (COM) displacement and to reduce energy consumption. Additionally, compared to the non-LLD condition, velocity and cadence in the mild LLD condition significantly decreased. These results indicate that mild LLD can cause a decrease in gait ability.

In the comparison between both limbs in the mild LLD condition, step time and swing phase of the short limb significantly increased as compared to the long limb, and the step length, stance phase, and single support phase of the long limb were significantly increased as compared with the short limb. However, no significant differences in any gait parameters between both limbs in the non-LLD condition were found, which suggests a symmetrical gait pattern. These results indicate that mild LLD causes asymmetric gait patterns of both limbs, and repetition of this asymmetric gait can lead to an increase the risk of musculoskeletal disorders (Carabello et al., 2010).

These altered and asymmetric gait patterns also affected the trunk, so that the trunk acceleration in the mild LLD condition increased in the directions of the AP, ML, and VT significantly more than in the non-LLD condition. Likewise, Hsue et al. (2009) found that the COM was in an unbalanced state during the transition from single support to double support phase due to the LLD and that, with an increase of LLD, a larger displacement occurred. Interruption of the normal gait cycle and the energy-conserving characteristics of trunk and limb motion result in increased energy expenditure (Saunders et al., 1953).

Table 5. Comparisons of trunk acceleration between conditions (N=15)

	Non-LLD[a]	Mild LLD	p
AP[b] (㎨)	2.78±.27[c]	3.38±.23	.015*
ML[d] (㎨)	2.61±.35	4.15±.45	.003*
VT[e] (㎨)	2.48±.25	3.32±.27	.006*

[a]leg length discrepancy, [b]anterior-posterior, [c]mean±standard deviation, [d]medial-lateral, [e]vertical, *p<.05.

The results of the present study demonstrated that the mild LLD caused an abnormal and asymmetric gait pattern, which affected the proximal part of the body and increased the trunk acceleration, which may cause ineffective gait.

In general, individuals with LLD have abnormal gait, such as vaulting and hiking, which leads to an increase in the vertical movement of the COM. The body's center of mass falls excessively downwards on the short limbs in the stance phase and there is a relative rise upwards on the long limb, resulting in a greater energy expenditure (Gurney et al., 2002). Compensatory mechanisms against LLD aim to minimize the sway of the body and to reduce energy expenditure during gait by functionally equalizing leg lengths (Bhave et al., 1999). These common gait characteristics for LLD of greater than 2 ㎝ have been consistently reported in previous research. Previous studies demonstrated that LLD greater than 2 ㎝ affects gait deviations. Perttunen et al. (2004) and Gurney et al. (2001) studied the effects of the LLD on muscle activity, minute ventilation, heart rate, et al, during gait. However, the present study investigated the effects on spatio-temporal gait parameters, showed that mild LLD lead to altered gait pattern.

Friberg (1992) suggested that a relatively small LLD could be clinically important in certain conditions, such as persistent loading or repeated walking. Recent studies by Resende et al. (2016a) and Khamis and Carmeli (2017) have reported the effect of mild LLD of less than 2 ㎝ on gait, suggesting that compensatory strategies can induce various musculoskeletal disorders (Resende et al., 2016b). In the present study, mild LLD showed the asymmetric gait patterns of both limbs and affected the trunk acceleration. This results may support previous studies that mild LLD may be clinically significant.

The present study explored the hypothesis that the mild LLD of less than 2 ㎝ would result in altered and asymmetrical gait patterns due to compensatory movements, which would then result in increased trunk acceleration. The results demonstrated that, similarly to the LLD of 2 ㎝ or higher, mild LLD also leads to an asymmetric and ineffective gait. Therefore, mild LLD should not be neglected as it can have a negative influence on the body. In this context, it is necessary to apply appropriate evaluation and intervention for mild LLD, recognizing that abnormal gait pattern due to mild LLD may lead to various musculoskeletal disorders.

Our study has several limitations. First, the number of participants in this study was small. Second, since we induced mild LLD to investigate its effects on gait parameters and trunk acceleration, the gait patterns observed in this study may slightly differ from those observed in individuals with a true mild LLD. However, we provided the participants with adaptation time to induce mild LLD. Third, because we measured walking through a specified section, the results might deviate from what would have been observed in the participants' walking in their everyday environment. Future studies should investigate the effects of mild LLD on long-distance walking patterns of individuals with true LLD.

Conclusion

This study demonstrated that mild LLD causes altered and asymmetrical gait patterns, as well as affects the trunk resulting in inefficient gait. Contrary to several previous studies suggesting that mild LLD is naturally compensated for and does not need treatment, the findings of the present study emphasize that mild LLD can cause significant changes in normal gait pattern and efficiency of gait. Therefore, the potential impact of mild LLD should not be overlooked in clinical practice.

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