Abstract

The causes of able-bodied gait asymmetries are unclear. Mild (< 3 cm) leg-length inequality (LLI) may be one cause of these asymmetries, however, this idea has not been thoroughly investigated. The purpose of this study was to investigate the nature of the relationship between LLI and able-bodied gait asymmetries. We hypothesized that subjects ($n = 26$) with greater LLI, quantified radiographically, would display less symmetrical gait than subjects with smaller LLI. Gait asymmetries were determined using standard gait analysis procedures. Symmetry coefficients were used to quantify gait symmetry for sagittal-plane hip, knee, and ankle joint angles, moments, and powers. A Pearson product-moment correlation coefficient (r) was used to evaluate the relationship between LLI and the aforementioned symmetry coefficients. Additionally, the symmetry coefficients were compared between subjects with relatively small LLI (< 1 cm; $n = 19$) and relatively large LLI (≥ 1 cm; $n = 7$). Statistically significant relationships were observed between LLI and the symmetry coefficient for knee moment ($r = -0.48$) and power ($r = -0.51$), and ankle moment ($r = -0.41$) and power ($r = -0.42$). Similarly, subjects with relatively large LLI exhibited significantly lower symmetry coefficients for knee moment ($p = 0.40$) and power ($p = 0.35$), and ankle moment ($p = 0.40$) and power ($p = 0.22$) than subjects with relatively small LLI. These results support LLI as a primary cause of able-bodied gait asymmetries. However, other factors must also contribute to these asymmetries, such as asymmetrical neuromuscular input to the lower limb muscles.

Introduction

Human able-bodied gait has been described extensively, but many fundamental aspects are still not well understood. For example, bilateral asymmetries, defined as a lack of perfect agreement between lower limbs [1, 2], have been documented during able-bodied gait for kinematic [3, 4], kinetic [1, 5], and electromyographic [6, 7] variables. The underlying causes of these asymmetries, however, remain unclear. An understanding of the causes of these asymmetries is important, as it could lead to enhanced rehabilitation programs for movement disorders characterized by asymmetrical gait, such as cerebral palsy and stroke. Several different explanations have been put forth as plausible causes of able-bodied gait asymmetries [2]. Most of these proposed explanations fall into one of two primary categories: 1) morphological asymmetry, and 2) asymmetrical neural input. Theoretically, if both legs are morphologically identical and receive the same neural input while in a controlled environment (e.g., a flat laboratory walkway), a symmetrical gait pattern should emerge. It is unlikely, however, that morphology or neuromuscular input are ever perfectly symmetrical, and both likely contribute to gait asymmetry. In this study, we focused on one possible morphological cause of gait asymmetry.

Mild leg-length inequality (LLI), defined as an anatomical LLI that does not exceed 3 cm [8], is a commonly suggested morphological cause of asymmetry in able-bodied gait [9-14]. The relationship between LLI and gait asymmetry, however, is not well understood. While it makes sense that bilateral differences in leg length would contribute to gait asymmetry, some prior research has contradicted this idea [15]. Among those who have suggested an association between LLI and gait asymmetry, some have concluded that any LLI greater than 1.0 cm will affect function [8, 16]. Others, however, have indicated that a LLI up to 2.5 cm will not affect gait mechanics [17, 18]. A weakness of the existing literature in this area is that there are no studies that have combined accurate measures of LLI (i.e., radiography) with quantitative measures of gait asymmetry. Consequently, the purpose of this study was to investigate the nature of the relationship between LLI, determined via X-ray, and able-bodied gait asymmetries, determined using standard gait analysis procedures. We hypothesized that subjects with greater LLI would exhibit a less symmetrical gait than subjects with smaller LLI. Specifically, we predicted that there would be significant negative correlations between LLI and measures of gait symmetry. In order to further investigate how LLI may influence gait asymmetries, we also compared subjects with relatively smaller LLI (< 1 cm) to subjects with relatively larger LLI (≥ 1 cm). We expected that subjects with greater LLI would exhibit significantly less symmetrical gait patterns. We chose 1 cm as the dividing point between relatively small and large LLI because 1 cm has been suggested by some investigators [8, 16] as the magnitude of LLI that will begin to affect biomechanical function during gait.

Methods

Twenty six young adults (13 females; 13 males; age = 30 ± 6 yrs; height = 1.74 ± 0.10 m; mass = 73.9 ± 5.7 kg) who reported no lower-limb impairment participated in this study. Nineteen subjects exhibited a LLI that was less than 1 cm (11 females; 8 males; age = 30 ± 5 yrs; height = 1.73 ± 0.11 m; mass = 71.5 ± 16.8 kg). Seven subjects had a LLI that was greater than or equal to 1 cm (2 females; 5 males; age = 28 ± 8 yrs; height = 1.76 ± 0.07 m; mass = 74.6 ± 16.2 kg). Subjects gave informed consent in accordance with local ethical committee regulations.

LLI was determined using total body dual energy absorptiometry (DXA; Lunar DPX-IQ, Lunar Inc., Madison, WI, USA) scans. Total limb length was computed as the summed lengths of the tibia and femur [19] and was quantified using the ‘ruler’ function of the Lunar 4.3

software. Femoral length was the distance between the superior greater trochanter and most distal aspect of the lateral femoral epicondyles [19]. Tibial length was the distance between the distal lateral femoral epicondyle and most inferior aspect of the lateral malleolus [19]. LLI was the absolute difference between left and right total limb lengths.

During a separate lab visit, subjects underwent a standard gait analysis. Six high-speed video cameras (60 Hz; Motion Analysis Inc., Santa Rosa, CA, USA) and two force platforms (960 Hz; Kistler Instrument Corp., Amherst, NY, USA) were used to collect kinematic and kinetic data. Reflective markers were applied to anatomical landmarks in a modified Cleveland Clinic marker arrangement, and five successful walking trials were performed across a 10-m walkway at a self-selected pace. A trial was considered successful when the right foot and left foot each contacted a separate force platform during consecutive steps. Three-dimensional coordinates describing marker positions were determined using Motion Analysis EvaRT 4.0 software (Motion Analysis, Santa Rosa, CA, USA). Coordinate data were smoothed using a dual-pass Butterworth filter with a 6-Hz cutoff [20] in Motion Analysis EvaRT 4.0 software. Coordinate data were then exported into OrthoTrac 5.0.2 software (Motion Analysis, Santa Rosa, CA, USA) for the calculation of joint kinematics and kinetics.

Data Analysis. Bilateral sagittal-plane joint angles, net joint moments, and joint powers were calculated for the hip, knee, and ankle over five successful trials. For each successful trial, data were time normalized to one complete gait cycle. Bilateral ensemble average curves for joint angle, moment, and power were created by averaging the data across the five trials for each subject. A Pearson product-moment correlation coefficient was used to evaluate the degree of symmetry between limbs [6, 21] for the ensemble averaged joint angles, moments, and powers, for each subject. This measure of between-limb symmetry will be referred to as the "*symmetry* *coefficient*" to avoid confusion with the correlation coefficients later used as part of the statistical analysis, as described in the next section. Larger symmetry coefficient values indicated greater between-limb symmetry.

Statistical Analysis. The relationship between LLI (quantified via DXA) and gait symmetry (quantified via the symmetry coefficient) was evaluated using the Pearson product-moment correlation coefficient (*r*). Negative *r* values would indicate that subjects with greater LLI tended to exhibit less symmetrical gait. Additionally, the mean symmetry coefficients for hip, knee, and ankle joint angles, moments, and powers were compared between the group of subjects with relatively small LLI (LLI < 1 cm; n = 19) and the group of subjects with relatively large LLI (LLI $\geq$ 1 cm; n = 7). We used a nonparametric statistic (Mann-Whitney; *p* = 0.05) to make this comparison.

Results

For the entire sample (n = 26), the mean absolute value for LLI was 0.8 ± 0.7 (Mean ± SD) cm and ranged from 0.0 to 2.3 cm. Sample means and standard deviations for the symmetry coefficients are presented in Table 1, recalling that a larger symmetry coefficient indicates greater between-limb gait symmetry. Graphical examples of a variable that was very symmetrical (hip angle) and a variable that was less symmetrical (hip power) are shown in Figure 1A and 1B, respectively. Within each joint, angle tended to be highly symmetrical, while power was least symmetrical. The results for moment differed across joints (Table 1), with the ankle moment being most symmetrical and the knee moment the least symmetrical.

The strength of the correlations between LLI and gait symmetry are presented in Table 2. Significant moderate correlations existed between LLI and gait symmetry for knee moment (*r* = -0.48; *p* = 0.013), knee power (*r* = -0.51; *p* = 0.008), ankle moment (*r* = -0.41 *p* = 0.035), and ankle power ($r = -0.42$, $p = 0.032$). Figure 2A depicts the weakest relationship between LLI and gait symmetry (knee joint angle, not significant), while Figure 2B depicts the strongest relationship between LLI and gait symmetry (knee joint power, significant). The negative correlation coefficients for all variables indicate that subjects with greater LLI tended to exhibited less symmetrical gait, while the statistical significance tests revealed that joint moments and powers tended to be more strongly related to LLI than joint angles.

Table 3 presents the mean symmetry coefficients for hip, knee, and ankle angle, moment, and power for the two subsamples of subjects (LLI < 1 cm and LLI $\geq$ 1 cm). No significant between-group differences for symmetry coefficients were observed for hip joint angle (p = 0.285), moment (p = 0.174), or power (p = 0.069). There were significant between-group differences, however, in symmetry coefficients for knee joint moment (p = 0.040) and power (p = 0.035), but not for knee joint angle (p = 0.418). Similar to the knee, significant between-group differences for the asymmetry coefficients existed for ankle joint moment (p = 0.040) and power (p = 0.022), but not for ankle joint angle (p = 0.064). These differences at the knee and ankle joints indicate that joint moment and power were less symmetrical for subjects with a relatively large LLI ($\geq$ 1.0 cm). While not quite reaching statistical significance, hip joint power (p = 0.069) and ankle joint angle (p = 0.064) also exhibited a tendency towards being less symmetrical for subjects with relatively large LLI.

Discussion

Bilateral able-bodied gait asymmetries have been well documented [1-3, 5-7, 22, 23], yet their causes have not been fully explained. LLI may be one cause of gait asymmetries [9-14], and the purpose of this study was to investigate the nature of the relationship between LLI and able-bodied gait asymmetries. This was accomplished by accurately quantifying LLI and gait asymmetries within a relatively large sample of subjects. Our results showed that LLI is not strongly related to the degree of bilateral symmetry for joint angles during gait. Our results do, however, support the idea that LLI influences gait symmetry for hip, knee, and ankle joint moments and powers. Each of the correlations for moments and powers were negative (*r* values ranged from -0.36 to -0.51), and nearly all of them met statistical significance. The two *p* values that exceeded 0.05 (0.053: hip moment, and 0.072: hip power) did so only by small margins. These moderate negative correlations indicate that in able-bodied walking, subjects with larger LLI tend to exhibit a greater degree of asymmetry in joint kinetics. It should be emphasized, however, that the highest *r* value was -0.51, meaning that no more than 26% of the observed gait asymmetries can be explained by LLI. Other morphological asymmetries, such as segment mass or moment of inertia, or neuromuscular factors, must also contribute to the observed gait asymmetries.

The results from the comparisons between subjects with relatively small and large LLI also supported the idea that LLI influences joint moment and power symmetry during gait. Subjects with relatively large LLI showed less symmetry for knee and ankle moment and power than subjects with relatively small LLI (Table 3). In combination, the moderate negative correlations described in the previous paragraph, and the between-group (large vs. small LLI) differences described here, indicate that gait symmetry for joint moments and powers is related to LLI..In contrast, our results provided little evidence that joint angle asymmetries are strongly influenced by LLI. Particularly at the hip and knee, the joint angles were so bilaterally symmetrical that there was little variance to be explained by LLI, or any other variable. This may reflect a tendency for humans to maintain stable and consistent kinematics, by varying their joint kinetics. A similar phenomenon, referred to as kinematic invariance, has been reported in both normal [24] and amputee gait [25].

Our data are consistent with previous research regarding gait symmetry and LLI for impaired subjects [12, 13]. Conclusions from this prior research also indicated that gait symmetry decreases with increases in LLI. The present data are consistent with one previous report [9] that showed that various components of the ground reaction force become less symmetrical with increases in LLI. However, the present data differ from the results of another study concerning the relationship between LLI and symmetry for quadriceps and plantarflexor muscle electromyographic (EMG) activity [10]. It was reported that quadriceps and plantarflexor EMG activity are symmetrical in subjects with a LLI up to 3 cm [10]. This difference in results may be partially explained by the different variables considered. EMG data tend to be more variable than joint kinetics and kinematics, which would make asymmetry more difficult to identify.

The present study was the first to quantify LLI and gait asymmetries, using radiography and high-speed videography respectively, in an attempt to better understand the relationship between LLI and able-bodied gait symmetry. An important strength of this study is the use of radiography to determine LLI. Previous evaluations of the relationship between LLI and gait symmetry used less accurate methods for quantifying LLI, including the tape measure [9] and a wooden block [26] method. When considering LLI that is relatively small in magnitude, it is especially important to use radiography [27], as other methods may be unreliable [8] and lack the precision necessary to accurately detect small LLI. One limitation of the present study is the exclusion of the foot in the consideration of limb length. Unlike the femur and tibia, it is difficult to accurately assess the contribution of the foot to limb length using DXA, and it has generally been excluded from such measures [19, 27]. In principle, a gross foot deformity could result in a LLI that would not be captured using the current approach. Therefore, we screened prospective subjects to minimize the risk of this potential confound.

The present data indicate that reasonable kinematic symmetry can be maintained by young asymptomatic individuals, despite varying degrees of LLI. Several of our subjects exhibited LLI that were greater than thresholds that have been deemed pathologic by some researchers [11, 28], yet our subjects were all healthy and asymptomatic. This supports the conclusions of Gurney [27] and Reid and Smith [29], which stated that it is difficult to identify a single LLI threshold as generally pathologic and necessitating intervention. The threshold of LLI that may cause asymmetry or even impairment likely varies between individuals and depends upon various factors including anthropometrics, age, and activity level [27, 29]. Also, as walking is a relatively benign activity, it may be important to consider the relationship between LLI and between-leg symmetry during more dynamic activities that involve greater ground reaction forces, like running or landing. LLI may be more strongly related to between-limb symmetry during these more dynamic activities.

In summary, the key findings of this study were that the degree of symmetry for knee and ankle joint kinetics were significantly related to LLI in able-bodied gait. Although all of our subjects had LLI that were relatively mild (< 3 cm), knee and ankle joint moments and powers were less symmetrical for the subjects with relatively larger LLI. This primary finding was substantiated through two approaches. First, moderate negative relationships were observed between LLI and the symmetry coefficient for knee and ankle moment and power. Second, subjects with relatively large LLI ($1 \text{ cm} \leq \text{LLI} < 2.3 \text{ cm}$) exhibited significantly less gait symmetry for knee and ankle joint moment and power than subjects with relatively small LLI

(LLI < 1 cm). The results for hip joint kinetics were similar to the knee and ankle, but failed to reach statistical significance. No similar relationships were found between joint angles and LLI, as the joint angles were highly symmetrical across subjects. This knowledge of the relationship between LLI and gait asymmetry for joint kinetics increases our understanding of able-bodied gait mechanics and may lead to better rehabilitation protocols for gait pathologies that are related to LLI.

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Table 1. Means and standard deviations for the symmetry coefficients that were used to quantify the degree of between-limb gait symmetry for sagittal-plane joint angle, moment, and power at the hip, knee, and ankle (n = 26). Lower coefficient values indicate less symmetrical gait. Joint moments and powers were generally less symmetrical than joint angles.

Table 2. Pearson product-moment correlation coefficients (*r*) that were used to quantify the relationship between leg-length inequality and degree of gait symmetry for a sample of healthy subjects (n = 26). Degree of symmetry for sagittal-plane knee and ankle joint moment and power were moderately and negatively related to leg-length inequality, indicating that as leg-length inequality increased, gait symmetry for knee and ankle joint moment and power decreased.

Table 3. Means and standard deviations for degree of gait symmetry, quantified via the symmetry coefficient, for two groups of subjects: 1) leg-length inequality less than 1 cm (n = 19), and 2) leg-length inequality equal to or greater than 1 cm (n = 7). Lower symmetry coefficients indicate less gait symmetry. The degree of gait symmetry was significantly less for sagittal-plane knee and ankle joint moment and power for subjects with a leg-length inequality that was greater than or equal to 1 cm.

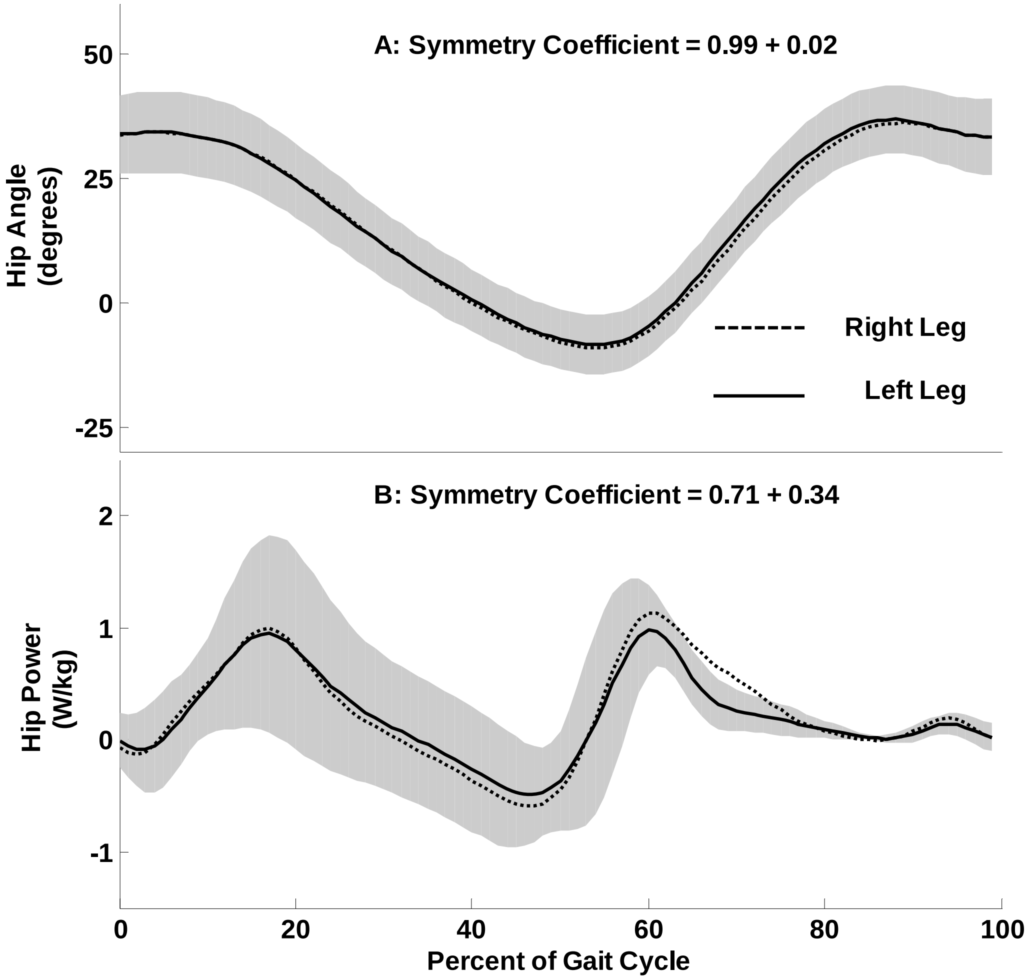
Figure 1. Means and standard deviations (shaded area) for sagittal plane hip joint angle (A) and power (B) over the full gait cycle (n = 26). To increase clarity of the figure, only standard deviations for the left leg are shown, as standard deviations were bilaterally similar. The mean symmetry coefficient was higher for hip joint angle than for hip joint power, indicating that hip joint angle was generally more symmetrical than hip joint power.

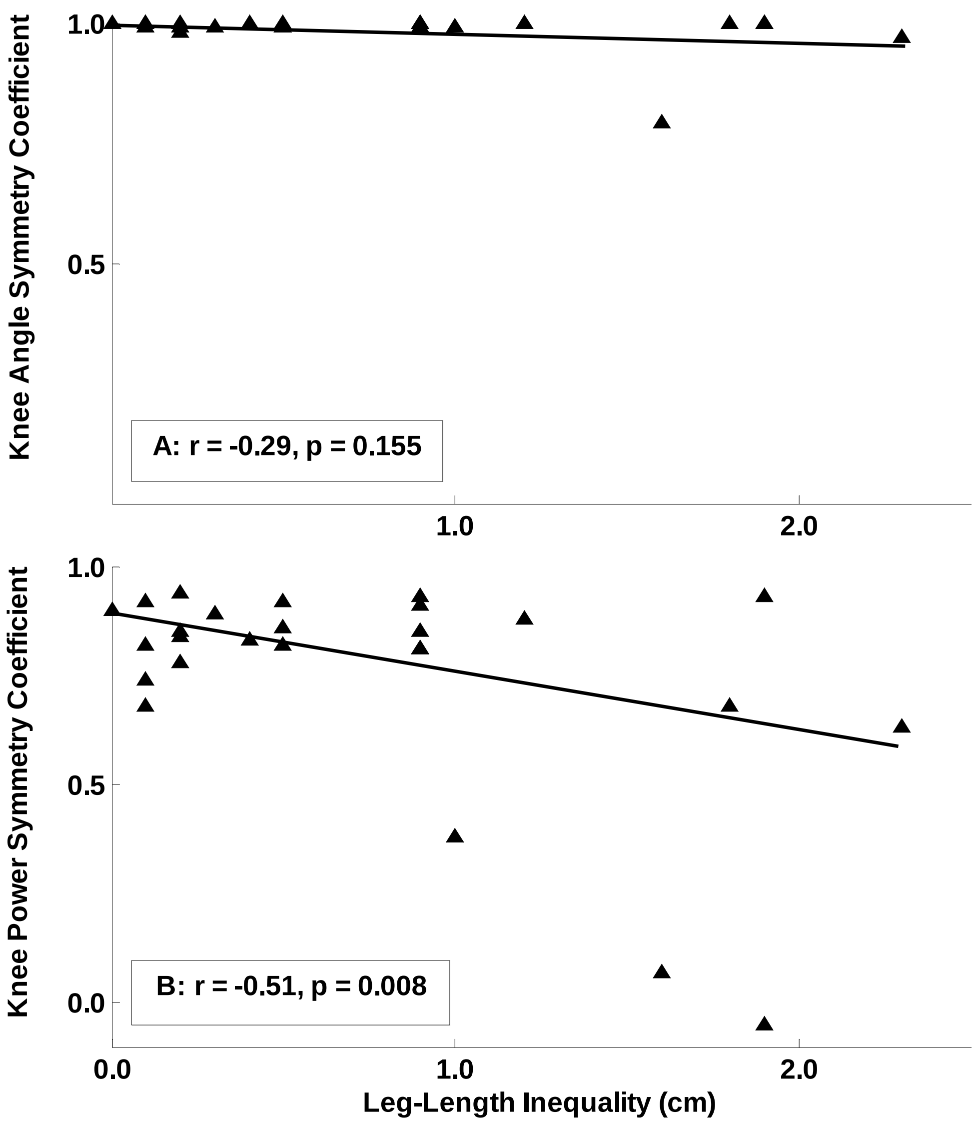
Figure 2. Scatter plots (n = 26) that depict the linear relationship (*r*) between leg-length inequality and degree of between-limb gait symmetry, quantified via the symmetry coefficient, for sagittal-plane knee joint angle (A) and power (B). Greater symmetry coefficients indicate more gait symmetry. The negative relationship between leg-length inequality and gait symmetry for knee power was statistically significant, indicating that gait was less symmetrical for knee joint power decreased for subjects with relatively larger leg-length inequality. There was also more between-subject variability with larger leg-length inequality.

Joint	Measure	Mean Symmetry Coefficient
Hip	Angle	0.99 ± 0.02
	Moment	0.87 ± 0.23
	Power	0.71 ± 0.34
Knee	Angle	0.99 ± 0.04
	Moment	0.77 ± 0.26
	Power	0.75 ± 0.25
Ankle	Angle	0.94 ± 0.12
	Moment	0.95 ± 0.09
	Power	0.87 ± 0.19

Joint	Measure	*r* value	*p* value
Hip	Angle	-0.30	0.135
	Moment	-0.38	0.053
	Power	-0.36	0.072
Knee	Angle	-0.29	0.155
	Moment	-0.48	0.013
	Power	-0.51	0.008
Ankle	Angle	-0.34	0.094
	Moment	-0.41	0.035
	Power	-0.42	0.032

Joint	Measure	LLI < 1 cm	LLI ≥ 1 cm	*p* value
Hip	Angle	0.99 ± 0.01	0.98 ± 0.04	0.285
	Moment	0.94 ± 0.06	0.66 ± 0.37	0.174
	Power	0.81 ± 0.14	0.41 ± 0.52	0.069
Knee	Angle	0.99 ± 0.01	0.96 ± 0.08	0.418
	Moment	0.85 ± 0.11	0.55 ± 0.41	0.040
	Power	0.85 ± 0.07	0.50 ± 0.38	0.035
Angle	Angle	0.97 ± 0.02	0.87 ± 0.22	0.064
	Moment	0.98 ± 0.02	0.86 ± 0.15	0.040
	Power	0.94 ± 0.04	0.69 ± 0.31	0.022


A: Symmetry Coefficient = 0.99 + 0.02
Hip Angle (degrees)
50
25
0
-25
Right Leg
Left Leg
B: Symmetry Coefficient = 0.71 + 0.34
Hip Power (W/kg)
2
1
0
-1
0
20
40
60
80
100
Percent of Gait Cycle



Knee Angle Symmetry Coefficient
1.0
0.5
A: r = -0.29, p = 0.155
1.0
2.0
Knee Power Symmetry Coefficient
1.0
0.5
0.0
B: r = -0.51, p = 0.008
0.0
1.0
2.0
Leg-Length Inequality (cm)