Acta of Bioengineering and Biomechanics
Vol. 19, No. 3, 2017

Original paper
DOI: 10.5277/ABB-00770-2016-02

Assessing the asymmetry of free gait in healthy young subjects

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Purpose: The purpose of this study was to derive reference values for a four-level scale intended to evaluate variation in free gait asymmetry measurements in healthy subjects. *Methods*: This evaluation is based on kinetic values for the left and right lower limbs during gait, registered with advanced measurement systems and assessed using the symmetry index (SI) developed by Robinson. *Results*: For the majority of parameters, the SI does not follow normal distribution. As such, quartile values were used to create intervals for a four-step scale of assessing symmetry of free gait in healthy subjects for each gait parameter of interest. The SI rating intervals were from 0% (very good symmetry) to 21.2% (very poor symmetry) for kinetic parameters. The poorest symmetry was observed for horizontal force F3. *Conclusions*: The four-step scale of assessing symmetry in free gait in healthy subjects can be used in diagnosing gait disorders, devising surgical treatment strategies, and monitoring the rehabilitation process. Reference values for intervals of symmetry indicators in healthy subjects can be used as criteria for comparing individuals with/without disabilities.

Key words: *symmetry index, gait asymmetry, Zebris system*

1. Introduction

Gait symmetry serves as one of the important factors in gait analysis due to its significance in clinical applications and rehabilitation, and as such it has been studied for many years [16]. Various authors have assessed the symmetry of ground reaction force (GRF) components [2], [9], the orientation of the lower limb [17], [22], EMG activity [1] and angular rate of the lower extremity [20].

Gait involves a cyclical and laterally-alternating progression, from an unsteady balance during the single-limb stance phase to a quasi-stable balance during the dual-limb stance phase. In view of the coordinated work of a large number of skeletal muscles involved and due to the high degree of freedom in the entire locomotor system, each step varies slightly from the previous one. Therefore, human gait is not perfectly repetitive, even on a very flat surface. If the differences in kinematic and kinetic gait measurements are small and random, they should be treated as normal. However, if the left limb consistently takes shorter steps than the right limb, for instance, this is treated as symptomatic of asymmetric gait and may indicate gait pathology [7]. There are a number of causes of gait asymmetry; one group of causes includes pathologies of the musculoskeletal system [12], another includes pathologies of the motor system [5], [16].

The notions of symmetry and asymmetry are inextricably linked with a fundamental question in diagnostics: when is the free gait asymmetry observed in a given individual normal, and when should it start to be regarded as a pathology? In fact, the very notion of whether or not the lower limbs should normally be expected to behave symmetrically in the gait of subjects without impairments remains debatable [21].

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Received: July 27th, 2016
Accepted for publication: December 5th, 2016

Some authors [9], [10], [21] do assume gait variables to be symmetrical, whereas Sadeghi et al. [20], who completed an extensive literature review in terms of inherent symmetry or asymmetry of biomechanical gait parameters, report asymmetrical behavior of the lower extremities in able-bodied gait, observed using spatio-temporal, kinematic and kinetic parameters. Although many studies have been conducted in this area, different papers use different indicators for assessing the symmetry of gait parameters. There are also no reference values for intervals of symmetry indicators in healthy subjects which can be used as criteria for comparing individuals with/without disabilities.

As yet, there is no single general mathematical symmetry indicator for human gait. The development of increasingly sensitive methods of measuring and analyzing human movement continues to bring improvements to the assessment of gait symmetry. The most common methods used to define gait asymmetry are the Symmetry Index (SI), Symmetry Ratio (SR), and various statistical approaches [20]. The most common statistical methods are principal component analysis [21], regions of deviation analysis and paired *t*-tests [22]; these methods require additional subjects and experiments, and may need normative data from able-bodied subjects as a reference. SI and SR, in turn, are susceptible to potential artificial inflation (as can occur when a clinically irrelevant difference between sides is divided by a much smaller reference value, as noted by [8]), they require a reference zero which varies from case to case [25], and they are also unable to analyze motion in a single complete gait cycle [22]. However, the absolute values of parameters or units are not important for the Symmetry Index (SI); instead, the indicator is used to demonstrate side preference and to assess the symmetry of a number of parameters. As such, it is one of the most commonly used standards of symmetry, and it is used in this paper.

The objective of this study was to derive reference values for a four-level scale of evaluating variation in free gait symmetry measurements in able-bodied subjects. This evaluation is based on kinetic values for the left and right lower limbs during gait, registered using advanced measurement systems employed in biomechanics research.

2. Material and methods

2.1. Subjects

A total of 120 people took part in the study (M = 60, F = 60).

Table 1. Characterization of healthy participants

Group		Height [m]	Body mass [kg]	Age [years]
F (n = 60)	$x \pm$ SD min-max	1.66 ± 0.06 1.53–1.78	59.3 ± 6.4 46.1–78.4	23.5 ± 1.8 20.6–28.6
M (n = 60)	$x \pm$ SD min-max	1.81 ± 0.06 1.7–1.93	76.5 ± 9.2 58.6–99.8	23.1 ± 1.8 20.4–29.7

Before the study began, each participant was informed of the course and aim of the research, and signed a declaration stating their willingness to participate. The reasons for exclusion from the study included permanent or temporary disorders of the musculoskeletal system, serious injury, or taking medication that might affect motor skills. None of the participants exhibited any disorders of gait. The groups showed no difference in terms of age or variance around the mean value. There were significant differences ($p < 0.001$) between the men and women in terms of height and body mass at homogenous standard deviation values. The coefficient of variation (% CV) of the participants' heights was very low (3.3% for men and 3.6% for women), while variation in body mass for each group was moderate (11.1% and 13.3%, respectively).

Approval was obtained from the Institute's Research Ethics Commission and additional informed consent was obtained from all subjects for whom identifying information is included in this article.

2.2. Experimental setup

The experiment required the subjects to walk along a 15-meter walkway at self-selected speed, without shoes. Each subject repeated the walk six times, with three measurements taken for each of the lower limbs. Although the walkway was fitted with two independent platforms, we took measurements separately for each lower limb. Pilot studies show that even healthy subjects experience a certain difficulty in stepping on both platforms in a single walk cycle, with the gait becoming unnatural as a result. Only attempts without any random mistakes, with the subjects performing the task naturally, were used in the analysis.

2.3. Data collection

The components of GRF during free gait were measured using a piezo-dynamometric platform made by Kistler, Switzerland (type 9281E). The GRF measuring platform also includes an amplifier and calculation unit. Signal processing, data collection, and report generation were carried out using the proprietary BioWare®-System v.4.0 software for four platforms, with a PC application (type 2812A-03-S424). The error of GRF measurements taken with the Kistler platform was below 1% in all directions. This includes sensor errors and errors resulting from the conversion of the analogue system into digital.

2.4. Statistical analysis

The mean values (x), mean error ($\pm Sx$), standard deviation (±SD), coefficient of variation (CV%), symmetry index, and distribution kurtosis were calculated. These were compared against normal distribution with the Shapiro–Wilk test. The Mann–Whitney U test was used to check for statistically-significant differences between the limbs, and the Anova–Manova model to assess the main effects of and interactions between individual factors. Spearman's coefficient was used to assess linear correlation. All calculations were conducted using the STATISTICA software, v.9. Symmetry indexes were calculated following Robinson's formula [18]

$$SI = 2 * \frac{X_R - X_L}{X_R + X_L} \cdot 100\% .$$

For comparison, GRF values were normalized for the body mass of each subject, and the durations of the support phase were normalized for the total duration of the support phase during each walk. For statistical analysis, the processes were parameterized following Nolan et al. [15]. The description of the vertical component includes two local maxima (F1, F2), and the horizontal component two extremes (F3, F4). Determination of the local minima and maxima proceeded as follows: within the stance phase of the gait cycle, the values of local extremes F1 and F2 were determined, assuming that vertical and antero-posterior components of ground reaction force with the values in the ordered set, defined on the topological space, have a local minimum (maximum) at point xo of this space if there is an open neighborhood U of the point xo so that for each $x \in U f(x) \leq (\geq)\ f(xo)$ (see Fig. 1). It was assumed that these parameters would constitute the set of statistical attributes of the model describing the asymmetry of the GRF in the given set.

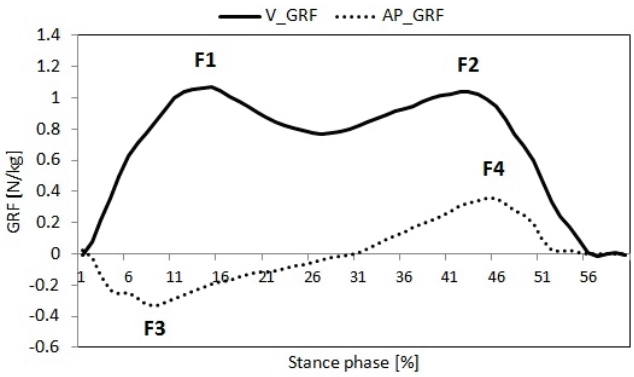

Fig. 1. Antero-posterior and vertical Ground Reaction Forces during gait. The peaks marked are as follows: the weight-acceptance peak (F1) and the push-off peak (F2) for vertical ground reaction force, and negative braking force peak (F3) and positive propulsive force peak (F4) for horizontal force

Since symmetry indicators do not follow normal distribution for all parameters, the parameters describing the course of GRF during gait were normalized on the basis of median and quartile values. The data were used to prepare intervals for qualitative and quantitative assessment of gait symmetry on the basis of GRF.

3. Results

In order to define asymmetry for GRF values, we calculated the values of parameters F1, F2, F3 and F4 for both men and women (Table 2). The data indicate a close correlation between mean values of F1 and F2 for both lower limbs in both groups. Multivariate analysis shows that the factors of male or female sex ($p < 0.001$) and left or right lower limb ($p < 0.001$) have a significant impact on the difference in values of the studied parameters. There is also an interaction between the "limb" and "sex" factors ($p < 0.004$).

Table 2. Selected statistical values for parameters describing the ground reaction force during free gait

		Left leg				Right leg			
		F1 [–]	F2 [–]	F3 [–]	F4 [–]	F1 [–]	F2 [–]	F3 [–]	F4 [–]
F (n = 60)	$\bar{x}$	1.16	1.16	–0.21	0.25	1.15	1.16	–0.21	0.26
	±SD	0.11	0.09	0.06	0.06	0.10	0.10	0.06	0.06
	%CV	9.5	7.8	–28.6	24.0	8.7	8.6	–28.6	23.1
M (n = 60)	$\bar{x}$	1.10	1.12	–0.18	0.23	1.11	1.10	–0.19	0.24
	±SD	0.10	0.08	0.05	0.04	0.11	0.07	0.05	0.04
	% CV	9.1	7.1	–27.8	17.4	9.9	6.4	–26.3	16.7

Tukey's HSD test revealed the greatest number of differences between factors F3 and F4.

The most important observation made on the basis of data in Table 2 is the low scattering of results for factors F1 and F2 (moderate variance), and the high scattering around the mean for factors F3 and F4 (high variance).

Using Robinson's equation [18], we calculated the SI values for each of the given parameters for mean values achieved by participants in both groups. The results are shown in Table 3.

Table 3. Gait symmetry index (SI) values for mean (±SD), median, and quartile values of parameters describing the GRF component for men and women (n = 120)

Group	Parameter	Mean	±SD	Q25	Median	Q75
F (n = 60)	F1	5.9	4.5	2.0	5.0	9.4
	F2	2.2	1.1	1.4	2.2	3.1
	F3	15.9	19.7	0.0	8.7	21.1
	F4	3.0	2.6	0.0	2.9	4.6
M (n = 60)	F1	4.9	4.0	1.8	4.4	7.8
	F2	2.1	1.2	1.3	2.1	2.9
	F3	12.3	13.3	0.0	10.3	19.6
	F4	2.7	2.2	0.0	3.2	4.4

Apart from factor F3, SI values for the other factors calculated for the entire group show small percentage differences between the left and the right leg. Goodness-of-fit between individual GRF values for both limbs during free gait can be verified using methods such as linear regression and simple correlation. Linear correlation coefficients are high (the highest for factor F4 in women; r = 0.7249) and statistically significant ($p < 0.001$), which reveals a notable similarity between the values for both legs. However, results obtained for individual participants do not follow a straight line, while regression curves do not cross at a 45 degree angle, indicating that the factors are not fully symmetrical for both limbs.

The data were used to prepare intervals for qualitative and quantitative assessment of gait symmetry on the basis of GRF (Table 4).

Table 4. Gait symmetry index (SI) intervals for gait based on parameters describing the GRF component for men and women (n = 120)

Parameter	Quartile	Rating	SI [%]	
			F	M
F1	I	v. good	0 < 2.0	0 < 1.8
	II	good	2.1–5.0	1.9–4.4
	III	poor	5.1–9.4	4.5–7.8
	IV	v. poor	9.5<	7.9<
F2	I	v. good	0 < 1.4	0 < 1.3
	II	good	1.5–2.2	1.4–2.1
	III	poor	2.3–3.1	2.2–2.9
	IV	v. poor	3.2<	3.0<
F3	I	v. good	0	0
	II	good	0–8.7	0–10.3
	III	poor	8.8–21.1	10.4–19.6
	IV	v. poor	21.2<	19.7<
F4	I	v. good	0	0
	II	good	0–2.9	0–3.2
	III	poor	3.0–4.6	3.3–4.4
	IV	v. poor	4.7<	4.5<

The data reveal that, on average, the asymmetry for factor F1 in free gait of healthy men and women falls between 1.9% and 9.4%, factor F2 between 1.4% and 3.1%, factor F3 between 0% and 21.1%, and factor 4 between 0% and 4.6%.

4. Discussion

In all available publications, the degree of gait asymmetry in a given group of participants is defined using the mean and standard deviation [4], [17], [20]. However, no information is available about the distribution of experimental data. In our study, analysis using the Shapiro–Wilk test did not support the null hypothesis of normal distribution. A similar observation was made by Nolan et al. [15] (obtaining SI = 8 ± 4.19% for the F1 value) and McCrory et al. [13] (SI = 0.94 ± 0.85% for F1 and SI = 0.15 ± 1.94% for F2). Such high standard deviations are an important sign of potential differences between the distribution of experimental data and normal distribution, which suggests that it is impossible to create a standard for assessing asymmetry on the basis of the mean and standard deviation. In our experiment, the data tended to follow right-skewed distribution. This may be due to the fact that a higher number of our participants are closer to the value of SI = 0, therefore exhibiting very low or no asymmetry. As such, we normalized the data using medians and quartiles for each of the parameters. Each quartile was assigned a verbal assessment of asymmetry to simplify the interpretation of individual results. Normalizing gait symmetry using factors describing the kinematics and kinetics of free gait in healthy subjects, based on median and quartile values, provides a good interpretation of this phenomenon. However, such an approach has not been applied in the literature.

A number of definitions of symmetry have been used in literature. Herzog et al. [8] define symmetry as the "perfect agreement of the external kinetics and kinematics of the left and right leg". Sadeghi et al. [20] suggest that symmetry is achieved if no statistical differences exist between parameters that are measured bilaterally. In turn, Liikavainio et al. [11] describe values that deviate by less than 10% from perfect symmetry as symmetrical. Burnett et al. [4] confirm that GRF "perfectly agrees" with the definition given above. However, the authors assess symmetry using points F1 and F2 only. White et al. [24], who mark symmetry for both the vertical and horizontal components, show that F3, F4 and the time of occurrence of F3 are characterized by asymmetry of over 10%. In our study, the mean of only one parameter (F3) exceeded 10%.

Asymmetry of GRF component values for the left and right legs may be in part due to differing degrees of strength developed by individual muscle groups. This is illustrated by the effects of loss of muscle strength following injury, as well as being present in people with temporary and permanent disabilities. Loss of strength in just a single muscle may affect the overall value of global muscle strength and momentum of muscle strength in individual muscles, which in turn has a direct impact on GRF components. The cause–effect relationship between the loss and change during the course of GRF in relation to normal is frequently compensated. Compensation usually presents as stimulation of muscles other than those activated in the standard pattern of muscle activity in gait. The compensation mechanism may also change the sequence of muscle activation in individual phases of the gait cycle, or put a greater strain on muscles that are fully functional [14], [23].

As noted in the introduction, most authors do not use a single indicator of symmetry. Patterson et al. [17] and Błażkiewicz et al. [3] verify the practical implications of using various symmetry indicators. It should be noted that most authors use SI% since it is easy to interpret, independent of the absolute size of the trait under investigation, and independent of the measurement units; it also makes it possible to compare different traits against a value standardized to 100%, and it clearly indicates the direction of asymmetry. However, it does not take into consideration the weight of the natural distribution of values for a given trait in a healthy population.

Using available methods and analytical indicators to assess asymmetry is undoubtedly important as a diagnostic and screening tool in children and young people. Monitoring gait asymmetry is also essential during rehabilitation following surgery, for example, reconstruction of the anterior cruciate ligament [19]. However, the usefulness of gait asymmetry analysis on its own may be debatable in children with cerebral palsy, who present with significant changes in joint anatomy, as well as in subjects with other types of palsy, spasticity, and antagonist muscle disorders. In such instances, biomechanical gait analysis should at least be combined with EMG or perhaps replaced by personalized gait modeling and optimization. The criteria for optimizing gait in healthy subjects are very different to those used for assessing people with disabilities. One classic example is the "energy criterion", which in healthy subjects entails minimizing the energy cost of gait, which may be supplanted in people with disabilities by a criterion of "reaching the goal above all else".

5. Conclusion

This study has yielded several new findings regarding the symmetry of free gait in healthy subjects, quantifying symmetry with respect to kinetic variables measured bilaterally in healthy individuals. The proposed intervals on the four-step scale of assessing symmetry in free gait in healthy subjects can be used in diagnosing gait disorders, devising surgical treatment strategies, and monitoring the rehabilitation process. These reference values for intervals of symmetry indicators in healthy subjects can be used as criteria for comparing individuals with/without disabilities.

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