Comparison of four methods of calculating the symmetry of spatial-temporal parameters of gait

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Although gait symmetry is being evaluated and reported in the literature with increasing frequency, there is still no generally accepted standard for assessing symmetry, making it difficult to compare studies and establish criteria to guide clinical decision-making. The purpose of this study was to ascertain whether gait symmetry in healthy subjects is consistent when assessed using various coefficients (RI, SI, GA, and SA), and if possible to identify a gait symmetry coefficient with the highest diagnostic utility. The study involved a group of 58 healthy university-level students of physical education and secondary school students aged 20.03 ± 0.97. Measurements of spatial-temporal gait parameters were conducted using the ZEBRIS platform. Our analysis supports existing recommendations that the symmetry index (SI) should be used as the most sensitive assessment of gait symmetry on the basis of spatial-temporal parameters in healthy subjects. Moreover, we developed normative values of individual features for diagnostic purposes.

Key words: *gait; symmetry; spatio-temporal parameters*

1. Introduction

In biomechanical terms, human gait is regarded as the motion of a complex mechanical system with a large degree of freedom and several driving forces. Because the two feet supporting the human body delineate small zones of support, and because a significant mass is carried in the upper part of the body, maintaining balance in standing posture and during gait poses a serious challenge to the central nervous system. 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 need to coordinate the work of a large number of skeletal muscles, and due to the large number of degrees 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 even surface. Slight asymmetry may reflect functional differences in the contribution of each limb to propulsion and control during walking [1]. As such, gait asymmetry is frequently used as a strong indicator in rehabilitation and clinical settings [2], [3].

Several kinematic and kinetic parameters, such as walking speed, stride length, foot rotation angle, maximum joint range of motion, duration of stance, and swing phases of gait, are frequently used to assess and monitor correctness of gait [4]–[7]. The most common approaches used to quantify gait asymmetry are the symmetry index (SI), the ratio index (RI), and several other, statistical approaches [8]. However, they are reported to have many disadvantages. Firstly, the SI needs to be normalized to a reference value [2]. Another limitation of the SI is its potential for artificial inflation [9]. Moreover, it cannot analyze motion through one complete gait cycle [6], [10]. More recently, Manal and Stanhope [11] proposed another method of examining asymmetric behavior. The method

was presented in the context of clinical gait analysis and it displays movement pattern deviations relative to normative data by color-coding the magnitude and the direction of the deviation. An advantage of this approach is that a single-page summary of all the deviation magnitudes can be displayed simultaneously, in a manner that is concise, visually effective and reduces complexity. However, this technique does not provide quantitative information for the comparison and analysis of complex movement patterns, and it does not examine changes in symmetry of bilateral parameters. Crenshaw and Richards [10] quantitatively examined joint angle symmetry and correspondence with the norm, using eigenvectors to compare waveforms of joint angle data. Their method does not make it possible to identify the point during the gait cycle at which deviations occur. Various statistical approaches are also, as we have noted, used to identify gait asymmetry. These include principal component analysis [1], regions of deviation analysis, and the paired *t*-test [6]. However, these methods require additional subjects and experiments, and may need normative data from able-bodied subjects as a reference.

Despite their shortcomings, these methods have been utilized in various clinical applications. Symmetry indices have been used to identify clinical related problems in stroke patients [4], [7], in amputees [12], and individuals with spinal cord injury [13]. As such, the aim of this study was to identify the indices with the highest diagnostic values in relation to kinematic data.

2. Materials and methods

2.1. Participants

The study included 58 healthy university-level students of physical education and secondary school students. Before commencing the study, the participants were informed of its purpose and methods, they were given the option to leave the study, and they signed a written agreement to participate in the study. Participants' age: 20.03 ± 0.97 years; height: 1.74 ± 0.81 m; weight: 72.4 ± 12.8 kg; BMI: 23.8 ± 3.2.

2.2. Gait analysis

Analysis of spatial-temporal parameters of gait was conducted using the ZEBRIS FDM 3 (Zebris Medical GmbH, Germany) platform of dimensions $314 \times 62 \times 2.1$ cm with 17,024 sensors and registration frequency of 120 Hz. The platform was connected to the WinFDM software for analyzing gait, which records consecutive walks. Each participant walked across the platform three times at their own natural pace.

2.3. Data and statistical analysis

The gait cycles were analyzed, with the right and left lower limbs marked. Average values from three cycles were exported to Excel 2007 and Statistica v.10. WinFDM allowed us to obtain values for seven spatial-temporal parameters of gait [14], separately for the right and for the left lower limbs; they included step length (cm), step duration (s), stance phase (%), load response (%), single support (%), pre-swing, and swing phase (%). For each parameter, the symmetry factors RI, SI, GA, and SA were calculated [7]. Assuming that $X_R < X_L$, where X_R and X_L are the values of the specified parameter for the right and left limbs, the factors were calculated as follows:

- RI (Ratio Index): $\mathrm{RI} = \left(1 - \dfrac{X_R}{X_L}\right) \cdot 100\%$.

The factor indicates which of the variables has the highest value, and as such creates asymmetries. The value of RI = 0 indicates full symmetry, while RI ≥ 100% indicates asymmetry. Andres and Stimmel [15] used this factor effectively in their study of gait asymmetry in people with disabilities.

- SI (Symmetry Index): $\mathrm{SI} = \dfrac{|X_L - X_R|}{0.5 \cdot (X_L + X_R)} \cdot 100\%$.

The SI factor is a method of percentage assessment of the differences between the kinematic and kinetic parameters for both lower limbs during walking. The value of SI = 0 indicates full symmetry, while SI ≥ 100% indicates its asymmetry [8]. The SI index is the method most commonly used and cited in publications on gait symmetry.

- GA (Gait Asymmetry): $\mathrm{GA} = \ln\left(\dfrac{X_R}{X_L}\right) \cdot 100\%$.

This equation is a logarithmic transform of the RI factor. Plotnik et al. [16] used it to calculate asymmetry on the basis of the duration of the swing phase. GA = 0 and GA ≥ 100% denote symmetry and asymmetry, respectively.

- SA (Symmetry Angle): $SA = \dfrac{45° - \arctan\left(\dfrac{X_R}{X_L}\right)}{90°} \cdot 100\%.$

Symmetry angle is a factor calculated for the angle of the vector plotted from the right and left values of discrete gait parameters in relation to the OX axis [2]. As in the previous cases, SA = 0 indicates full symmetry, SA ≥ 100% asymmetry.

Statistical analysis was conducted using the Statistica v.10 software. Using the Shapiro–Wilk test, experimental data were compared to the normal distribution. Spearman's rank correlation coefficients were calculated. The correlation between experimental results and simple linear regression was analyzed.

To identify the coefficient with the highest diagnostic utility, ROC Curve analysis (Receiver Operating Characteristic Curve analysis) was used. ROC analysis investigates and employs the relationship between sensitivity and specificity of a binary classifier. Sensitivity (or true positive rate) measures the proportion of positives correctly classified; specificity (or true negative rate) measures the proportion of negatives correctly classified. These concepts are related to a positive likelihood ratio – the ratio between the probability of a positive test result given the presence of a phenomenon, and the probability of a positive test result in its absence, i.e. Sensitivity/(1–Specificity).

The sensitivity and specificity of a diagnostic test depend on more than just the quality of the test itself – they also hinge upon the definition of what constitutes an abnormal test. In practice, we seek to determine a decision threshold that minimizes the error rate or misclassification cost under given class and cost distributions. The decision threshold of a binary classifier that outputs scores, such as decision trees, is the value above which scores are interpreted as positive classifications. Decision thresholds can be either fixed (if the classifier outputs calibrated scores on a known scale) or learned from data (if the scores are uncalibrated). In our study, the RI factor was selected as a reference indicator and ROC analysis.

3. Results

Table 1 shows the mean, median, minimum, and maximum values of symmetry factors during free gait in healthy subjects. Symmetry was studied using the four factors described in the previous section.

The symmetry coefficients shown indicate differences both between the features and between the indicators. The lowest gait asymmetry was observed during the stance phase. Additionally, the lowest median values were observed for all variables where symmetry is assessed using the SA factor. In the next step an attempt was made to evaluate these differences. Compatibility with a normal distribution was examined. Using the Shapiro–Wilk test, it was found for all the variables studied that the distribution of these sets is significantly different from normal distribution, and is strongly skewed to the right.

Descriptive statistics (median and quartiles) were used for comparison. Figure 1 shows a box plot of the distribution of values for individual factors. Comparisons were conducted on a "round robin" basis. Using the outlier and extreme values, the SA factor was excluded from further analysis, giving very different results from the other indicators. Extreme values are the lowest and highest values in a given data set, while outliers are values that are significantly higher or lower than the remainder of the data. In order to be an outlier, the value must be:

- larger than quartile 3 by at least 1.5 times the interquartile range, or
- smaller than quartile 1 by at least 1.5 times the interquartile range.

Results of this analysis indicate that the SI, RI, and GA factors are similar in terms of their usefulness in the assessment of symmetry of gait in healthy subjects. Given that the distributions of all these factors are significantly different from the normal distribution ($p < 0.001$), we conducted a Spearman test analysis. As expected, correlation values between the RI, SI, and SA factors oscillate near the maximum value ($p < 0.001$). As such, it is more useful to analyze the compatibility of results for individual factors in the assessment of the symmetry of factors describing free gait in healthy subjects. Figure 2 shows simple regression coefficients of agreement between the listed factors.

The above graphs were drawn up for the eight coefficients ($n = 406$). The data presented in Fig. 2 show that there is a good agreement of results obtained using the SI and RI indicators. The line running at a 45 degree angle in Fig. 2a illustrates how significantly these two factors differ: in the case of perfect agreement between the results obtained by the two factors, the results should lay along this diagonal. Almost complete agreement of results is evident in Fig. 2b. The simple regression graphs indicate a very high correlation of results, $r^2 = 0.9984$.

It is important for clinical practice to evaluate the impact of individual factors (Table 2). To do so, we

Table 1. Mean, median, minimum, and maximum (%) values of symmetry factors (RI, SI, GA, SA)
for seven characteristic features of free gait in healthy subjects (*n* = 58)

| Variable		Mean	Median	Minimum	Maximum
Step length	RI	2.82	2.22	0	9.56
	SI	2.89	2.24	0	10.05
	GA	2.89	2.24	0	10.05
	SA	0.92	0.71	0	3.19
Step duration	RI	3.57	3.00	0	10.24
	SI	3.68	3.05	0	10.79
	GA	3.68	3.05	0	10.8
	SA	1.17	0.97	0	3.43
Stance phase	RI	2.3	1.83	0	8.72
	SI	2.38	1.85	0	9.11
	GA	2.38	1.85	0	9.12
	SA	0.75	0.59	0	2.9
Load response	RI	9.01	6.85	0.03	30.73
	SI	9.73	7.09	0.03	36.31
	GA	9.76	7.1	0.03	36.72
	SA	3.09	2.26	0.01	11.43
Single support	RI	4.48	3.4	0.03	19.83
	SI	4.67	3.45	0.03	22.01
	GA	4.67	3.45	0.03	22.1
	SA	1.48	1.10	0.01	6.98
Pre-swing	RI	7.55	6.15	0	25.04
	SI	8.08	6.34	0	28.62
	GA	8.09	6.35	0	28.82
	SA	2.56	2.02	0	9.05
Swing phase	RI	3.86	3.07	0	14.98
	SI	4.00	3.12	0	16.19
	GA	4.00	3.12	0	16.23
	SA	1.27	0.99	0	5.14
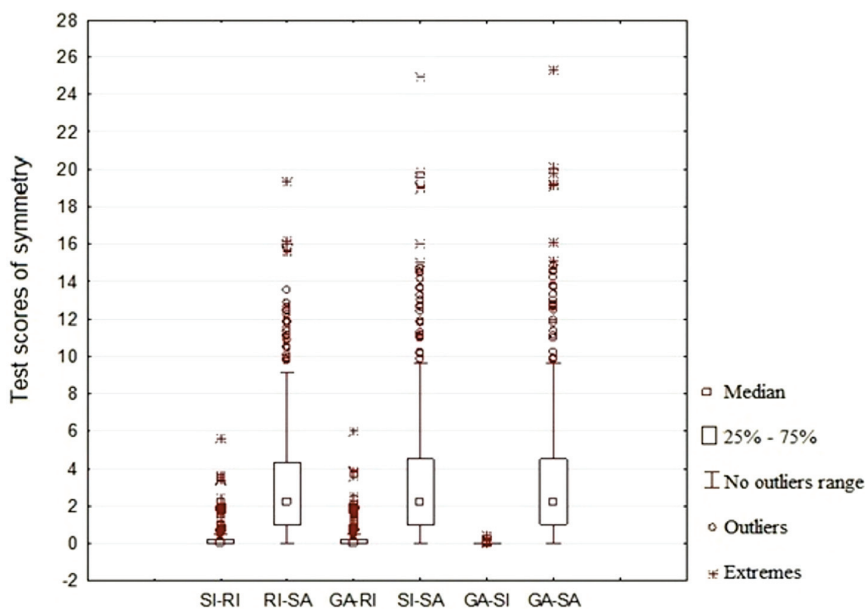
Fig. 1. Cage diagram of values of the RI, SI, SA and GA symmetry factors with outlier and extreme results

selected the RI factor as a reference indicator and performed ROC analysis.

The results show very similar diagnostic qualities of all the coefficients. However, it should be noted that the range of the SA indicator is much lower than that of the others, although that does not affect the possibility of a correct evaluation of symmetry during gait. For diagnostic purposes, normative values of
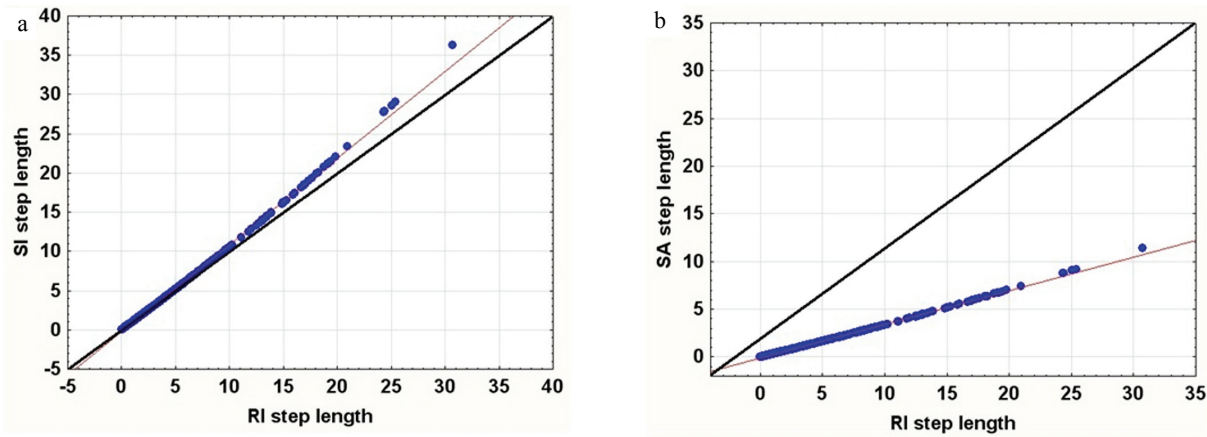
Fig. 2. Simple regression graphs of agreement between: (a) the RI and SA symmetry factors; (b) the RI and SI symmetry factors

Table 2. Characteristics of diagnostic parameters of the seven features of gait in healthy subjects ($n = 58$)

	Boundary (%)	Sensitivity (%)	Specifity	Diagnostic precision (%)	Likelihood of positive result (%)
RI	13.5				
SI	14.1	92.4	92.6	92.3	7.6
GA	14.1	92.4	92.6	93.3	7.6
SA	4.5	92.6	93.1	92.3	7.4

Table 3. Normative values for SI indicator for seven features of gait
in healthy subjects ($n = 58$)

Features	Height 0–25	Normal		Low 75–100
		25–50	50–75	
Step length	<0.81	0.82–2.24	2.25–4.21	4.22<
Step time	<1.57	1.58–3.04	3.05–5.21	5.22<
Stance phase	<0.82	0.83–1.84	1.85–3.27	3.28<
Load response	<3.85	3.86–7.09	7.10–14.95	14.96<
Single support	<1.70	1.71–3.45	3.50–6.67	6.68<
Pre-swing	<2.38	2.39–6.34	6.35–11.77	11.78<
Swing phase	<1.39	1.40–3.12	3.13–5.31	5.32<

individual features have been developed. The SI indicator was adopted as recommended.

4. Discussion

Quantifying the differences and finding a single discrete value describing right/left asymmetry for spatial-temporal, kinematic, and kinetic parameters during gait is a common clinical and research objective. The purpose of this work was to compare the most common symmetry equations – RI (ratio index), SI (symmetry index), GA (gait asymmetry), and SA (symmetry angle) – with the goal of achieving a recommendation for standardized practice.

The ratio index (RI) is a common method of analyzing gait symmetry, and has been used to compare peak velocity of below-knee amputees [17], to reflect the degree of asymmetry in each of the support phases of the gait cycle for 25 patients with residual stroke symptoms [18], and to assess subjects with osteoarthritis of the knee [19]. The greatest limitations of this index are its low sensitivity, relatively low asymmetry, and failure to provide information regarding the location of the asymmetry [8]. However, it should be noted that this simple index is indicative of a reciprocal gait pattern, while higher and lower values reflect asymmetries. In this paper, the average results obtained by the RI for all spatial-temporal parameters analyzed varied between the results obtained using the SA and SI (while the SI produced the same results as the GA index).

To represent perfect gait pattern symmetry on the basis of ground reaction forces, Robinson et al. [20] defined a new index – the symmetry index (SI) – which has been used to analyze symmetry in long distance runners, chronic stroke patients, and subjects with leg length discrepancy [8]. Unfortunately, as in the case of the previous ratio, there are some disadvantages. The SI must be normalized to a reference value whose selection depends on the question being asked. Assessing asymmetry in the healthy population, where there is no obvious side to use as a reference (such as in this study), can be difficult, therefore the average for the two sides is frequently used. Herzog et al. [21] described asymmetry values for ground reaction forces. They reported SI values in the range of 4%–13%. These inflated values can occur when a clinically irrelevant difference between sides is divided by a much smaller reference value. This happens when the difference between a positive value on one side and a negative value on the other may be referenced to the average of the two values, which will be close to zero. In spite of these limitations, Becker et al. [22] were able to show that for forty young adults the successful surgical treatment of ankle fractures resulted in improved gait symmetry in terms of plantar pressure distribution. In our study, to avoid this situation in calculating the SI, the absolute values were used for each side.

The third index tested in this paper, gait assymetry (GA), is a simple log-transformed symmetry ratio index (RI). Plotnik et al. [16] used this ratio to assess gait symmetry in healthy elderly adults, healthy young adults, and patients with Parkinson's disease. Gait asymmetry was assessed by comparing the swing time performed by one leg, against that performed by the other. GA values were significantly higher in subjects with Parkinson's disease than the elderly subjects, and higher in the healthy elderly subjects than the young adults. No other special applications of this index have been found in literature. Patterson et al. [7] used GA to compare the most common expressions of spatial-temporal gait symmetry to describe post-stroke gait and make recommendations of the most suitable standardization method. In our study, symmetry calculation using the SI and GA coefficients yielded the same mean results for all spatial-temporal parameters (Table 1), therefore further analysis was performed without the GA index.

Zifchock et al. [2] proposed a novel method for quantifying asymmetry – the symmetry angle (SA) – which does not require a reference value to be selected, as is the case of SI. Symmetry angle values tend to be lower than symmetry index values, although the measures are very highly correlated. This suggests that the symmetry angle is a good substitute for the symmetry index. In our study, we obtained similar findings. For all analyzed parameters, the SI values obtained were three times higher than the SA values. A very high correlation (0.9984) was obtained for RI, SI, and SA. However, the results of box plot analysis indicated a high similarity between RI and SI in their ability to assess gait symmetry in healthy young adult subjects (Fig. 1). All symmetry and asymmetry terms, causes, symptoms, types, and assessment methods based on kinematic and kinetic parameters during gait and standing (posturography) can be found in [23].

Petterson et al. [7] is the only paper to have compared the most common four expressions of spatial-temporal gait symmetry for describing post-stroke gait. They concluded that no symmetry equation demonstrated a clear advantage in terms of discriminative ability; however, all ratios (RI, SI) faciliate interpretation. Our analysis of common expressions of gait symmetry in the literature revealed that the individual equations do not appear to provide any unique differences: the four equations were similar in their distribution, and the SI, RI, GA, and SA values were highly correlated and strikingly similar in discriminative ability. However, our box plot analysis indicated a high similarity between RI and SI, and their clear advantage over SA. Next, using ROC analysis, we have found the SI ratio to be superior, thus supporting existing recommendations that SI should be used as the most sensitive assessment of gait symmetry on the basis of spatial-temporal parameters in healthy subjects.

Overall, in recent years there has been a tendency in the literature to seek a single indicator best describing gait abnormalities, symmetry, or differences between curve shapes. As shown in this paper, there are several functions in the literature which describe symmetry; however, none is precise enough. We observed the same problem when comparing curve shapes [24]. The aim of that paper was to compare group homogeneity with respect to dispersion around the reference curve and to compare waveforms of normal and pathological gait data based on joint angle curves in 5 groups: healthy men, women, children, and patients with drop foot and Trendelenburg's sign. Waveform parameterizations, RMS (Root Mean Square), IAE (Integral Absolute Error) and correlation coefficients were used to compare joint angles with reference curve. The sample scores obtained in that work provide important information about closeness in the shape of two curves.

Most research studies using gait analysis have relied on comparing a limited number of specific gait characteristics to evaluate traits such as outcomes of surgical procedures, or compare normal and pathological gait. In 2000, Schutte et al. [25] proposed a normalcy index, which shows potential as a useful tool for objectively quantifying overall changes in gait. The Gillette Gait Index (GGI) quantifies gait deviation from the norm by a single number. It can be considered as a measure of the distance between the set of selected variables describing the patient's gait and the average of these variables in healthy subjects. The GGI is a summary measure incorporating 16 clinically important kinematic and temporal parameters. However, it only appears to have been validated in children with cerebral palsy. Nevertheless, the parameters used to compute GGI are not specific to children. Cretual et al. [26] demonstrated that GGI can also be used to evaluate gait abnormalities in adults. It seems pertinent to ask whether it is possible to find a single indicator which describes asymmetry for any given research group, in a manner similar to GGI, with results related to a standard scale. The results presented in the present paper may possibly represent a step in that direction.

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