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A Relevant Estimate to Assess Joint Asymmetric Gait

Leroy D.[1,2] & Grouin J. M.[3]

[1]*CETAPS laboratory EA 3238, UFR STAPS, Université de Rouen, Mont Saint Aignan, France*

[2]*GRHAL (Research Group on Gait Disorders), CHU Rouen, Rouen, France*

[3]*Psy.Co Laboratory EA 1780, Université de Rouen, Faculté de Psychologie, Mont Saint Aignan, France*

The aims of this study was to use a robust method not to compare the amplitude but all the measurements of the whole individual gait phases between the right and left sides for ankle, knee and hip flexion-extension during spontaneous gait. Twenty-seven male and absolute right-handed subjects (10 sedentary subjects and 17 soccer players) were equipped with markers and walked spontaneously. All variables were normalized. The standardized effect assessing the difference between both sides was first calculated on each cycle measurement. Then, the overall location parameter of the distribution of standardized effects over all cycle measurements was estimated by the robust semi-parametric Hodges-Lehmann method. Finally, a 95% two-sided confidence interval on the true location parameter was derived. It was planned a priori *in this experiment that an overall effect size larger than ¼ was considered as meaningful. Statistical significance (at the usual two-sided 5% level) was accepted whenever the null hypothesis value of 0 (*i.e.*, no effect) was not included in the 95% confidence interval (95% CI). First, this method revealed no differences for any of the variables, since the overall effect size was smaller than ¼ during an entire gait cycle. Second, the gait cycle was divided into four phases. No difference was found for any variable of the four phases between the right and left sides of the sedentary subjects. However, the right and left reception double-support phases of the ankle plantar-dorsiflexion [θ > ¼ with 95% CI (0.22; 0.34)] and the knee flexion-extension [θ > ¼ with 95% CI (0.10; 0.41)] were significantly different in the soccer group. This method may provide a useful sensitive tool for comparing kinematic and kinetic symmetry of normal human walking or running gait.*

Keywords: *gait, symmetry, method, statistics*

INTRODUCTION

Gait is continuous motor skill, where each step is related to the prior. Symmetry between the right and left lower limbs of a normal walking individual is usually taken for granted in both clinical and research settings. Inter-limb symmetry is generally assumed by researchers because less data need to be collected, which reduces the complexity of the overall analysis. However, a number of bilateral gait studies have analysed the symmetry between right and left body segments. When gait asymmetry has been noted, it has mainly been attributed to slight variations in measurements, limb dominance (Leavitt *et al.*, 1971) or differences in limb function (Õunpuu and Winter, 1989). Herzog *et al.* (1989) found that asymmetries in ground reaction force data were much larger than expected for a control group.

The symmetry index, SI(%) = $(X_R - X_L)/0.5\,(X_R + X_L) \times 100$ proposed by Robinson *et al.* (1987) has been widely used in studies of the symmetry of ground reaction forces and the evaluation of kinematic patterns (Karamanidis *et al.*, 2003; Liu *et al.*, 1998). Using this index, values are simply compared against the average value. Zifchock and Davis (2006) proposed to quantify the asymmetry using the symmetry angle (SA). The SA is related to the angle formed when two values (X_{right}, X_{left}) are plotted in two-dimensional space. The SA is a measure of the deviation of the vector (X_{right}, X_{left}) from the axis of symmetry (SA = (45° - arctan (X_{left}/X_{right}))/90°*100%). A SA value of 0% indicates perfect symmetry, and 100% indicates that the values are perfectly out-of-phase.

The ratio index, R = X_R/X_L, was also created to quantify gait symmetry or asymmetry (Andres and Stimmel, 1990; Ganguli *et al.*, 1974). According to Wall and Turnbull (1986), however, the ratio index has a major limitation: it fails to provide information on the location of the asymmetry. Statistical approaches have also been developed to determine the similarities or dissimilarities between the lower limbs in order to avoid the limitation of the ratio index (Allard *et al.*, 1996; Hershler and Milner, 1978; Gundersen *et al.*, 1989; Pierroti *et al.*, 1991; Sadeghi *et al.*, 1997; Vagenas and Hoshizaki, 1992). However, none of these comparison techniques is able to take into account all of the measurements of a variable, but instead can account for either the whole curve (average) or only two measurements extracted from the curve (amplitude). Moreover, these ratios only allow relatively small asymmetry with unknown location of asymmetry and low sensitivity.

Recently, for the very first time, Crenshaw & Richards (2006) have used an eigenvector approach to

correspondence author: *E-mail: david.leroy@univ-rouen.fr*

determine joint symmetry and normalcy of gait pattern. This method assessing joint symmetry utilises the entire selected waveform. Their method involves calculating five distinct measures for the time-normalised right and left limb waveforms of the hip, knee and ankle joints in each of the three planes of motion.

The aim of our study is to propose another method using the measurements throughout the gait cycle or throughout its individual phases, in order to asses the symmetry with one relevant estimate.

METHOD

Sample

Twenty-seven male subjects (10 sedentary subjects and 17 soccer players) were selected for the study during routine medical check-ups. A sports physician verified that none of the subjects had any disorders of the musculoskeletal system. The sedentary subjects (i.e. not practising any sport) were aged 20.2 ± 2.2 years and the soccer players, 19.4 ± 2.7. The soccer players competed at a national level. All subjects were male and absolute right-handed according to the "Edinburgh Handedness Inventory" (Oldfield, 1971). The soccer players all preferentially kicked with their right foot (being on a left stance). All subjects gave informed written consent to participate in the experimental protocol. The experiments have been carried out according to the ethical guidelines laid down by the University ethics committee.

Paired Student t tests failed to indicate any significant difference in age, height or weight between the soccer players and the sedentary subjects.

Material

The angular variation of the ankle, knee, and hip were measured with a ViconTM (Oxford's MetrixTM, Oxford, UK) using optoelectronic markers. The markers were placed on the spineous process of S1, anterosuperior iliac spines, lateral malleoli and fifth metatarsi, and double-markers on the lateral femoral condyles. The subject equipped with markers made three runs in free walk in order to adopt his own usual spontaneous comfortable gait. Recordings were thus obtained in an automatic phase of free walk, excluding the gait initiation phase. The three-dimensional trajectories of the markers were smoothed using Fourier transforms with a cut-off frequency at 10 Hz. All the variables of the gait cycles for each side were extended to yield a normalised gait cycle with 100 equally spaced points (Kadaba *et al.*, 1990). Zero percent (0%) corresponded to the heel strike and 100% corresponded to the next heel strike of the same limb. Variables were thus normalised into a 100% cycle and then averaged for each group.

Statistical Methods

Since vertical variations in the marker positions on the left and right sides might have biased the results, the measurements were adjusted with the following method: the difference in the means of both sides was calculated from a Romberg posture made just before the walking trials began and was then systematically added to each measurement of the left side. Cycles of the 100 adjusted measurements were divided into gait's phases of interest: the reception double-support phase, the single-limb stance phase, the propulsion double-support phase and the swing phase. Each phase consisted of the appropriate consecutive measurements of the 100 whole-cycle measurements. Both the whole cycle and the individual phases were analysed. The analysis was performed within each subgroup of interest, that is for soccer players and sedentary subjects separately. The methodological issue arisen in this context was to propose a relevant estimate to assess the overall difference based on all the 100 cycle measurements between left and right sides. Even if there is no optimal choice, the key principles underlying the building of the overall estimate were as follows:

1. Each cycle measurement should be given the same weight in the building process. Therefore, in order to achieve this, a standardised effect denoted e_i ($1 \leq i \leq p = 100$) defined as the mean over the standard deviation of within subject differences between both sides, was assessed for each measurement as follows: let $d_{ik} = x_{ikL} - x_{ikR}$ denote the difference in values between both sides (Left and Right) for the k_{th} subject and the i_{th} measurement. Let $\bar{d}_i$ and s_i denote respectively the mean and the standard deviation of these differences in the subgroup of interest. Then $e_i = \frac{\bar{d}_i}{s_i}$. It is worth noting that each standardised effect may be positive or negative. Standardised effects are thus normalised quantities which makes their comparison among cycle measurements easier.
2. This method proposes a single overall estimate of all the standardised effects (e_i; $1 \leq i \leq p$). That summarises their distribution in a relevant manner. As the distribution of standardised effects over the p = 100 measurements turned out to be quite asymmetric, an overall robust estimate of the location parameter was given by the semi-parametric Hodges-Lehmann method (Hodges and Lehmann, 1963): if e_i and e_j are denoted as the standardised effects based on the i^{th} and j^{th} measurements respectively (i = 1, p; j=1, p), then the Hodges-Lehmann estimate $\hat{\theta}$

is given by the median of the p(p+1)/2 Walsh averages denoted as W_{kl}:

$$\hat{\theta} = \text{med}_{1 \le i \le j \le p} \{W_{ij}\} \text{ with } W_{ij} = (e_i + e_j)/2$$

3. The 95% confidence interval can be derived (Hettmansperger and McKean, 1998) using the ordered Walsh averages denoted as $W_{\{1\}}$,…, $W_{\{p(p+1)/2\}}$. Then, the confidence interval for q is given by [$W_{\{k\}}$; $W_{\{p(p+1)/2\ -k\}}$] with k defined by the usual Wilcoxon signed-rank test T for the one-sample or paired samples context: under the null hypothesis (H_0) that there is no difference between right and left sides, then k is given by Pr (T under $H_0 \le k$) = 2.5%. Since the number of measurements is large enough, k can be approximated using the asymptotic normal distribution of T under H_0 by

$$k = \frac{n(n+1)}{4} - 1.96\sqrt{\frac{n(n+1)(2n+1)}{24}} - \frac{1}{2}$$

Statistical significance (at the usual two-sided 5% level) will be accepted whenever the null hypothesis value of 0 (*i.e.* no effect between right and left sides) is not included in the 95% confidence interval (95% CI).

It is also meaningful to assess the magnitude of the observed overall difference between right and left sides. An *a priori* decision was planned in this experiment to declare an overall difference (estimated by the Hodges-Lehmann method) as still worthwhile whenever the size of the overall estimate is larger than ¼ . This cut-off of ¼ is obviously partially subjective, but it is common to regard in other experimental contexts, such as in clinical trials for example, a standardised effect smaller than ¼ as an effect which is not meaningful. On the contrary, a standardised effect larger than ¼ could be considered as already interesting on an experimental basis.

RESULTS

The curves of the ankle plantar-dorsiflexion and the knee and hip flexion-extension angles were characterised (Figure 1). The entire gait cycle between the right and left sides in each group were first compared. The statistical method revealed no difference for any variables, since the absolute median was never higher than ¼ for each joint motion in the sedentary subjects' and the soccer players' groups.

Next, the gait cycle was divided into the reception double-support phase, the single-limb stance phase, the propulsion double-support phase and the swing phase. For the sedentary subjects, no difference was found for any variable in any phase between the right and left sides (all $\theta < ¼$). However, in the soccer group, the right and left reception double-support phases of the ankle plantar-dorsiflexion ($\theta > ¼$ with 95% CI [0.22; 0.34]) and the knee flexion-extension ($\theta > ¼$ with 95% CI [0.10; 0.41]) were significantly different (Figure 1).

DISCUSSION

We had to evaluate the difference between right and left sides based on the whole 100 cycle measurements for ankle, knee and hip flexion-extensions. Usual methods for assessing this difference are based on indices which use either a single point (maximum or minimum over the measurements) or a limited set of points (e.g., the amplitude) and thus do not take into account all the measurement points (except means). Pure multidimensional methods usually yield a set of estimates which may not be interpreted easily. We proposed a single and robust overall estimate to assess the gait symmetry which uses all the measurement points. Noticing that there is an inconsistency among the measurement dispersions and as there is no reason to overweight a measurement with respect to another, we decided to give each measurement the same weight. This is why, for each measurement separately, a standardised effect was first derived to normalise the heteroscedasticity of the measurements. Another crucial choice was to take into account the possible opposite directions of the standardised effects. The proposed method is based on an aggregation of the standardised effects and therefore as positive and negative effects may nullify, only overall (positive or negative) trends will possibly be detected. Another possible choice would have been to consider absolute standardised effects. In this case, all the absolute standardised effects are positive by definition and therefore add up. A resulting overall difference would not express a trend towards a particular direction, and hence this would not reflect a true gait asymmetry. To summarise the standardised effect,- it was decided to define the overall estimate as the location parameter of the distribution of all these 100 standardised effects. As this distribution turned out to be quite asymmetric, we proposed the robust semi-parametric Hodges-Lehmann estimate to assess its location parameter.

Second, we selected a frequency of 10Hz for the filtration cut-off. The disadvantage of this frequency is that it eliminates the elements of the signal with a higher frequency. This disadvantage seems to be negligible in the study of gait. According to Kawate *et al.* (1992), the significant signal harmonics, obtained in optoelectronic studies of human gait in various situations, normal or pathological, are included in a spectrum of frequencies quite lower than 10 Hz; the frequency of most fundamental harmonics is in fact less than 2 Hz. Therefore, a cut-off frequency of 10 Hz produces a smoothing effect that may be considered as 'light' when compared with the fundamental frequencies of the signal

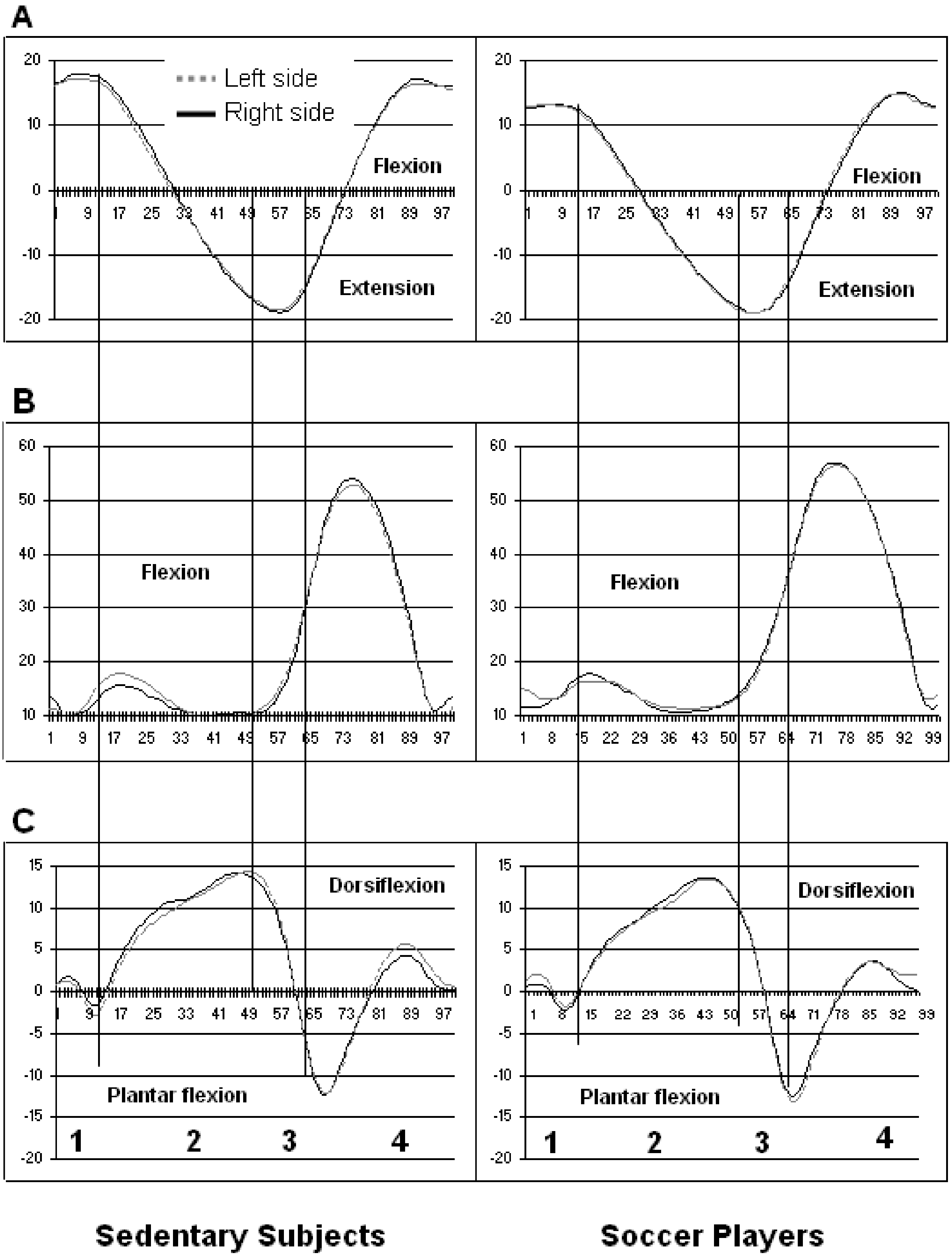

Figure 1: Sagital plane joint angles for the hip (A), knee (B) and ankle of the sedentary subjects and soccer players. Numbers 1, 2, 3 and 4 represent respectively the reception double-support phase, the single-limb stance phase, the propulsion double-support phase and the swing phase

under study, and makes it possible to totally eliminate the noise affecting our experimental data.

In our study, each subject was recorded three times at their spontaneous gait speed, excluding the initial phases. Fifteen cycles were then averaged for each subject. Collection of non-consecutive foot strikes has been considered a limitation of gait studies (Vagenas and Hoshizaki, 1989). However, Zifchock and Davis (2007) found that normal gait is sufficiently repeatable to sum gait cycles from different trials. By comparing the variability within a side to the variability between sides, they found that the majority of variables exhibited low variability between trials.

To conclude, functional gait asymmetry is often apparent in lateralised sports. In soccer, a preferentially unilateral sport, the right double-support phase was found to be longer than that of the left side (Leroy *et al.*, 2000; Leroy *et al.*, 2003). However, this was not observed in normal unathletic subjects (Murray *et al.*, 1964; Richard *et al.*, 1995) nor was it seen in swimmers (Leroy *et al.*, 2000). It is thus of practical interest to quantify the degree of symmetry that occurs in normal human walking or running gait, and this method may provide a useful tool for comparing kinematic and kinetic symmetry. Moreover, it is worth noting that a gait asymmetry individual estimate can be derived on the same methodological basis. For each subject and given a measurement, the standardized individual difference would be estimated as the ratio of the within subject difference between both sides by its group standard deviation. Then the gait asymmetry individual overall estimate would be calculated as the Hodges-Lehmann estimate among all the measurements. From a clinical viewpoint, the individual estimate of a subject could then be compared to a reference group overall estimate. This would allow clinicians to detect gait changes over time or changes caused by a therapeutic intervention.

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