THE INFLUENCE OF SHOES ON HEALTHY SUBJECTS’ GAIT: A STATISTICAL ANALYSIS OF THE RELEVANT GAIT PARAMETERS.
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Abstract
In a previous study the main spatial and temporal parameters of gait in a population of about 600 healthy subjects were acquired while they were walking barefoot and with shoes. Barefoot data were used to set up a reliable reference data base for impairment assessment, at least for Western citizens aged 3-60. Natural asymmetries of bilateral parameters were also quantified. Statistical multiple linear regression models were applied to find eventual combinations among the above gait parameters and some of the relevant anthropometric characteristics of the subjects. In the present study extensive comparisons have been made to understand the effect of shoes on the absolute values of the gait parameters taken alone, and on the combinations among parameters themselves. Six classes were sorted on the basis of sex and age, and detailed comparisons are reported for each class. In general, the absolute values of the measured parameters confirmed a modulating effect of shoes; symmetries were improved in most cases but for toe-out angle; the fitting of the linear regression models was confirmed for all spatial parameters with the exception of contact area, while it was definitely bad for temporal phases. This suggests that data derived from gait with shoes should not be used for the construction of reliable reference data bases.

Introduction
The kinematic parameters of gait play an essential role in the functional assessment of the human locomotor system. Great attention has been paid – mainly in the past twenty years – to the development of reliable measurement instrumentation and effective assessment methodologies. The instrumentation issue has been satisfactorily solved, and nowadays reliable instruments for gait analysis range from simple foot-switches and electrogoniometers, to sophisticated, computer-managed pressure platforms, force platforms, and optoelectronic motion analysers. Many difficulties are, instead, still encountered in the standardisation of measurement protocols, analysis and interpretation of the acquired data. The difficulty in defining normal value ranges is partly due to the intrinsic variability of human gait - even in healthy subjects - which can be overcome only with the analysis of a wide population sample and by evaluating the mean values for each subject. In general, reliable data bases are scarce or altogether lacking. This still holds true for spatial and temporal parameters of gait, despite their wide use in clinical investigations. In addition, as recognised since the 1960s, normal ranges of single parameters do not constitute a sufficient reference, and it is essential to determine whether and how some parameters - i.e. velocity, gait cycle and swing phase - occur in normal combinations [1].

The data exploited in this study were obtained by examining the footprints of about 600 healthy subjects detected by means of a long pressure platform developed at the authors' laboratory ([2]-[4]). Subjects were acquired both barefoot and with shoes. For the sake of generality, and to avoid artifacts due to shoes, barefoot walking data were used to set up the reference data bases and to perform extensive statistical analyses, widely reported elsewhere [5]. Briefly, that paper dealt with the characterisation of data bases of spatial and temporal parameters of gait, the application of basic statistical concepts to establish relationships among them, and a procedure to exploit these relationships to estimate deviation from normality. The data bases were formed by the bulk of the measured values of the most relevant gait parameters (contact area, toe-out angle, step, stride breadth, swing phase, double support phase, stride, gait cycle, velocity, as defined in the standardisation protocol of the CEC CAMARC Project [6]) and the recorded values of significant anthropometric and general characteristics of the subjects (e.g. height, body mass, age, etc.), sorted by sex and age into six classes. The relationships were established by applying statistical multiple linear regression models to these data. In the models a few parameters were hypothesized as dependent on others and/or on the above characteristics. Those parameters were then predicted on the basis of the parameters and characteristics on which they depend. For each investigated parameter and for each subject class the distribution of the difference between the predicted and the measured value was settled as the reference normal distribution for that class (analysis of the residuals). Such reference distributions highlight the deviation from normality when analysing gait pathologies: the difference between the predicted and the measured value of a parameter of interest must be calculated and then compared with the related distribution. Normal symmetry indices between lateral sides of the body were also calculated to establish threshold values below which they should be interpreted as signs of pathology [7].
In the present paper the bulk of data collected from the same population sample while walking with shoes has been elaborated and analysed just as if it belonged to a pathologic population, for it can be regarded as homogeneous with respect to “deviation from normal”, in the sense that the only and common altering factor is the use of shoes. The distributions of absolute measured values have been compared with the reference distributions. Symmetry indices have been analysed to find whether and to what extent shoes can affect the natural asymmetry of human gait. This is extremely important in the diagnostic field when analysing certain pathologies characterised by asymmetry and variability such as the Chronic Fatigue Syndrome [8], since the already recognized modulating effect of shoes can mask the pathology itself. Statistical multiple regression models have been applied, and residuals evaluated and compared with the residual reference distributions: this is a fundamental issue to dissect, since the alteration of the absolute values of the parameters taken alone does not necessarily imply the alteration of the combinations that regulate the normal human gait.

Materials and methods

The collection and elaboration of data from a large number of subjects usually face three main problems: i) excessive complexity of the measurement equipment; ii) inadequate potentiality of the software packages – at times related to the features of the instrumentation – that determine the increase in both elaboration time and complexity; iii) difficulty in getting the co-operation of a large number of subjects ranging from children to adults. The authors have overcome these difficulties by using a large-sized pressure platform developed at the authors’ laboratory [4]. The sensitive area of the pressure platform is large enough (2.5 x 0.5 m, corresponding to 512 x 96 sensors spaced 0.5 cm in both directions) to obtain at least 3 footprints per trial. The platform allows for the measurement of most spatial and temporal parameters of gait: contact area, toe-out angle, step, stride breadth, swing phase, double support phase, stride, gait cycle and velocity. The following anthropometric and general characteristics of the subjects were recorded: age, sex, height, body mass, leg length (measured from great trochanter to ground), and foot length. Sole material and heel height were recorded separately and added to the data related to gait with shoes. The platform length allows subjects to walk unconstrained, thus fulfilling the basic requirement of not influencing the subject’s way of walking. As gait parameters must be acquired when the subject’s velocity is at regimen, subjects were asked to start walking 2 m before and stop about 2 m after the platform surface. The accuracy of the instrument [4] is adequate for this study. Inaccuracies come mainly from the quantization intervals (resolution Δ) that are 5 mm and 10 ms for spatial and temporal quantities, respectively. According to the theory of digital signal analysis the corresponding standard deviations (σ) are given by the square root of the ratio between Δ and 12, and they are equal to 1.4 mm and 2.9 ms, respectively. For each measurement protocol (barefoot and with shoes), the subjects were asked to walk back and forth the platform three times at their own natural speed, because the number of steps thus obtained had already been proved sufficient to acceptably reduce the variability around the mean values of all the parameters of interest. The effect of the Gaussian noise, due to both the instrument and the intrinsic variability of the subject’s gait, is reduced correspondingly: the resulting standard errors due to the instrument were equal to or lower than 0.4 mm and 0.8 ms for spatial and temporal data, respectively. As already explained, the subjects were wearing their own shoes. This was a choice. Since the shoes have been adapted to suit the subjects’ gait, they are not to be regarded as a constraint, but rather as a familiar aid to walk more comfortably and, probably, to optimise energy consumption. The alternative could have been to furnish the same kind of shoes to all the subjects, but that would have affected gait as well, even if in a different way.

The sample was extracted from a population of healthy subjects screened at the Center of Sports Medicine “Le Naiadi” (Pescara, Italy). The anamnesis and an objective clinical examination excluded neuro-musculo-skeletal pathologies that could have influenced the volunteers’ gait.

The subjects were grouped into six classes according to sex and age ranges 3 to 10, 10 to 20, and 20 to 60. There were 266 females in all: 122 in the first age class IIF mean age 6.2; 71 in the second age class IIF mean age 13.7, and 94 in the third age class IIIF mean age 41.5. The males were 338 in all: 140 in the first age class IIM mean age 6.2; 71 in the second age class IIM mean age 13.7, and 107 in the third age class IIIM mean age 42.1.

For each class and parameter we verified that the two groups of values – the first related to the subject acquired barefoot and taken as a reference, the second related to the experiments with shoes – were significantly dissimilar (paired t-Student’s test with p=0.05). Mean values and standard deviations of the parameters acquired with shoes were finally calculated for each class and compared with those of the corresponding reference class [9], in order to analyse the shift of the mean values and the effect of shoes on the spread of the Gaussian distribution around the mean.

It is a fact that even healthy subjects show a certain degree of asymmetry between the right and the left side of the body, but in some people the left value of a certain parameter is higher than the right
one, and vice versa in other people. Thus, for the sake of generality, the bilateral parameters in [5] had been grouped as “higher values” and “lower values” and the symmetry index calculated accordingly [10]:

\[ SI_x = \frac{1}{N} \sum_{j=1}^{N} \frac{x_{lj}}{x_{hj}} \]

where \( SI_x \) = symmetry index of parameter \( x \); \( N \) = number of subjects; \( x_{lj} \) = lower value of parameter \( x \); \( x_{hj} \) = higher value of parameter \( x \) for the \( j \)th subject.

The same was done in this paper for the data collected with shoes. For each class the dissimilarity between the two groups was verified by applying the paired t-Student’s test, with \( p \leq 0.05 \).

The following statistical multiple linear regression model [11] had been applied in [5] to find relationships among the gait parameters themselves and, possibly, with some relevant anthropometric characteristics:

\[ y_i = \beta_0 + \beta_1 \cdot x_1 + \ldots + \beta_n \cdot x_n + \varepsilon \]

where \( y_i \) = predicted parameter \( i \); \( \beta_0 \) = intercept term; \( \beta_1 \ldots \beta_n \) = coefficients of the independent variables; \( x_1 \ldots x_n \) = independent variables; \( \varepsilon \) = error parameter.

In this paper the above coefficients have been used to estimate each parameter of each class; then the residual quantities, i.e. the differences between the measured and the estimated values, were calculated as

\[ \Delta y = y_m - y_e \]

where \( \Delta y \) = parameter \( y \) residual; \( y_m \) = measured value of parameter \( y \); \( y_e \) = value of the parameter \( y \) estimated by means of the corresponding statistical model. The above residual distributions were finally compared with those of the reference data.

Results
Since the following results depend on the varying stiffness of the sole material and on the heel height of the shoes we do not claim them to have a general validity. In general, children were almost homogeneous with regard to the sole material (rubber), the heel height was 0 mm for more than 50% of subjects, and the maximum heel height was about 15 mm. Young males wore rubber sport shoes with heel height from 0 mm (75%) to a maximum of about 15 mm. The same with young females but for two who wore shoes with leather soles; maximum heel height was 20 mm. Adult classes were more heterogeneous: about 20% of adult males wore shoes with leather soles, and heel height reached about 30 mm; more than 30% of adult females used leather soles with heel height up to 60 mm, and the rest used rubber soles that in few cases had heel height up to 50 mm.

The effect of shoes on the mean values of the measured parameters has been summarised in Table 1. Here the mean value of each parameter of each class has been compared with the corresponding reference mean value (barefoot reference data); the variations are expressed as percentage of reference mean values. Positive values indicate the increase in mean values while walking with shoes. On the whole, mean values significantly increase for spatial parameters but for toe-out angle, that clearly decreases for all classes, and for stride breadth, that varies according to sex and age: it significantly decreases for adult males only, and remains almost unchanged for the remaining classes. With regards to temporal parameters, a substantial increase is found for double support phase; swing phase always decreases, more for classes IIIF and IIM; gait cycle mainly increases for classes IF and IIF.
Table 1
Differences between gait-with-shoes mean values and barefoot reference mean values
(expressed as percentage of reference mean values)

<table>
<thead>
<tr>
<th>Class</th>
<th>Contact area</th>
<th>Toe-out angle</th>
<th>Step</th>
<th>Stride Breadth</th>
<th>Swing phase</th>
<th>Double support phase</th>
<th>Gait cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower</td>
<td>38.9%</td>
<td>-10.5%</td>
<td>10.1%</td>
<td>30.5%</td>
<td>0.5%</td>
<td>37.0%</td>
<td>4.2%</td>
</tr>
<tr>
<td>Higher</td>
<td>36.3%</td>
<td>-9.1%</td>
<td>10.2%</td>
<td>37.5%</td>
<td>-2.7%</td>
<td>37.0%</td>
<td>4.8%</td>
</tr>
</tbody>
</table>

Table 2 reports the variations of the symmetry indices calculated – for each bilateral parameter and for each class – as the difference between the symmetry index with and without shoes, and expressed as percentage of the reference symmetry index. For most parameters only slight per cent variations are found, since the symmetry indices are already very close to 1 for barefoot reference data. However, a general improvement can be noticed in subjects wearing shoes. The highest improvements are found for double support phase, in children more than in adults. Step, one of the most symmetric parameters, never shows significant variations. The same holds true for swing phase and stride breadth – apart from stride breadth of little girls -; even though they are somewhat more asymmetric. Special attention must be paid to toe-out angle. Barefoot reference data show that it is the most asymmetric of the measured bilateral parameters, with mean symmetry indices ranging from 0.646 to 0.734. The effect of shoes differs according to age and sex: there is a slight improvement for classes IF and IIF, a significant worsening for adult females, and a slight worsening for young males.

Table 2
Differences between gait-with-shoes symmetry indices and barefoot reference symmetry indices
(expressed as percentage of reference symmetry indices)

<table>
<thead>
<tr>
<th>Class</th>
<th>Contact area</th>
<th>Toe-out angle</th>
<th>Step</th>
<th>Stride Breadth</th>
<th>Swing phase</th>
<th>Double support phase</th>
<th>Gait cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower</td>
<td>1.75%</td>
<td>1.24%</td>
<td>-0.10</td>
<td>1.35%</td>
<td>0.51%</td>
<td>4.87%</td>
<td>4.74%</td>
</tr>
<tr>
<td>Higher</td>
<td>0.21%</td>
<td>0.75%</td>
<td>0.21%</td>
<td>0.10%</td>
<td>0.51%</td>
<td>2.74%</td>
<td>2.12%</td>
</tr>
</tbody>
</table>

The variations we have seen so far with respect to the measured parameters taken alone do not necessarily imply an alteration of the relationships among them, which need to be studied separately. The multiple linear regression models have been applied to the data collected with shoes by using the coefficients estimated for the barefoot reference data. In order to confirm or reject the validity of the models, and the ensuing relationships among parameters, we estimated and compared the parameters with the corresponding measured values. The residual quantities, obtained by subtracting the measured value from the estimated one, have been compared with the residual reference 95% confidence intervals. Interestingly enough, spatial models continue to estimate the parameters well for all classes; the only exception was contact area, obviously dependent on sole material and heel height. The most important finding regards the alteration of the relationships involving the temporal phases of the gait, which is highlighted by the residual distributions of the swing and double support phases. This is true for all classes, even though in different ways: for classes IF, IIF, IM, IIM more than 70% of the residuals were found outside the 95% confidence intervals; about 50% for class IIM and about 30% for
class IIF. The rest, however, was always strictly distributed around the boundaries of the intervals, i.e. far from the mean values, in all classes. As an example, fig. 1 shows the residual distributions of the higher values group for class IF; fig. 1a shows swing phase, that is overestimated by the model; fig. 1b shows double support phase, that is underestimated, instead.

![Figure 1](image)

Residual distributions for class IF. a) swing phase (expressed as percentage of gait cycle); b) double support phase (expressed as percentage of gait cycle).

**Discussion and conclusions**

The acquisition of spatial and temporal gait parameters from a wide population of about 600 healthy subjects walking with their own shoes allowed for the analysis of the effect of shoes on normal gait. The use of a simple, reliable, high-resolution, long-sized pressure platform and the application of a standardised measurement protocol avoided the alteration of the collected data due to the intrinsic variability of human gait. Therefore, we can conclude that the use of shoes was actually the only altering factor. From the analysis of the mean values of the most relevant gait parameters, an overall increase of the step, stride and contact area can be seen. With regard to the temporal quantities, there is a general, significant increase of the double support phase and a minor decrease of the swing phase. These results account for a steadier gait with shoes; in fact, a reduction of swing time accompanied by an increase in stride can be obtained with a more smoothed leg movement, similar to a ballistic movement in which neural control, temporally speaking, is reduced to a minimum. Gait cycle in normal walking greatly depends on the geometrical distribution of the body masses; this is immediately evident if we take the inverted pendulum as the mechanical model of the human body. Given the minor influence of shoes on the gait cycle — minimum for little and young girls and neglectable for the other classes —, the increase of the double support phase is therefore a direct consequence of the decrease in swing phase. Toe-out angle and stride breadth account for equilibrium; the fact that the former decreases even though the latter remains unchanged is a further sign that subjects feel safer when walking with shoes. This may be a characteristic common to the citizens of industrialised countries. The narrower distribution of some parameters around their mean values, namely toe-out angle, swing phase and gait cycle, may have the same cause. The effect of shoes on the symmetry of the gait differs among the classes, and is particularly evident for double support phase, in children more than adults. Even though part of this effect is due to the specific measurement instrumentation - whose response is influenced by the stiffness of the sole material - the major improvement of the symmetry in children’s gait is probably due to the greater variability of their barefoot gait: they are still searching for an optimal use of their locomotor system, that is in continuous modification as their body segments grow and their neuro-muscular system evolves. In their case, shoes bring about a more stabilising effect than in adults. The most asymmetric among the analysed parameters, toe-out angle, greatly worsens for adult females, and this should be read as a clear effect of an unnatural way of walking resulting from high heeled shoes. Interesting conclusions can be drawn by applying the multiple linear regression models and by comparing the residual distributions with those of the reference data. Spatial parameters are well fitted by the models for all classes, which means that the relationships they hold with stride, body mass, leg length, and age are preserved. The only exception is, once again, contact area. This is particularly evident in the adult females residuals distribution: the model significantly underestimates the parameter...
in the presence of low heels and rubber soles, and overestimates it in the presence of high heels and leather soles. Significant alterations of the relationships are found for the temporal parameters swing phase and double support phase, independently of age and sex. This means that, when walking with shoes, subjects differently correlate swing and double support phase to body mass, stride and velocity, which are the main independent variables appearing in the models. A final conclusion should be drawn from this finding. In order to set up a reliable reference data and establish relationships for the gait with shoes of healthy subjects, it will be essential to analyse a wide healthy population wearing homogeneous shoes (same stiffness and material of the sole, same heel height, same wear level) and to find the related reference intervals, symmetry indices, and coefficients of the linear regression models.

References