Assessment of walking speed by a goniometer-based method

E. Maranesi, V. Barone and S. Fioretti

Abstract— **A quantitative gait analysis is essential to evaluate the kinematic, kinetic and electromyographic gait patterns. These patterns are strongly related to the individual spatio-temporal parameters that characterize each subject. In particular, gait speed is one of the most important spatio-temporal gait parameters: it influences kinematic, kinetic parameters, and muscle activity too. The aim of the present study is to propose a new method to assess stride speed using only 1-degree-of-freedom electrogoniometers positioned on hip and knee joints. The model validation is performed comparing the model results with those automatically obtained from another gait analysis system: GAITRite. The results underline the model reliability. These results show that essential spatio-temporal gait parameters, and in particular the speed of each stride, can be determined during normal walking using only two 1-dof electrogoniometers. The method is easy-to-use and does not interfere with regular walking patterns.**

I. INTRODUCTION

Gait analysis, more specifically the human gait analysis, is the systematic study of the locomotion. A quantitative gait analysis is essential to evaluate, in the right manner, the kinematic, kinetic and electromyographic gait patterns.

The majority of the recent studies on gait analysis are based on the comparison between a reference set of normal values and the individual ones. These kinematic, kinetic and electromyographic gait patterns are strongly related to the individual spatio-temporal parameters (like, f.i., step length, cadence and walking speed) [1,2]. In particular, gait speed is one of the most important spatio-temporal parameters [3]: it influences kinematic and kinetic parameters, such as hip and knee flexion/extension, ankle plantar/dorsi flexion, flexion/extension moment of the hip and knee during different gait phases [4], as well as muscle activity [5,6]. Intuitively, walking at faster steady-state speeds would necessitate an increasing muscular activity that contributes to forward propulsion. Conversely, walking at slower speeds may be mechanically less efficient (e.g. deviating more from natural frequency of the pendular movement so that additional muscular effort may be required) and less conducive to the storage and recovery of elastic energy in the musculotendon complex [6].

It is evident as the easy and fast estimation of the fundamental spatio-temporal parameters (i.e. stride length, stride duration and speed) should be a priory in the gait analysis. This is usually performed in a laboratory environment where only a few steps are analyzed, though with very high accuracy. Conversely for outdoor applications, the mean speed is computed very simply knowing the total distance traveled and the total time interval measured by a stopwatch. No information on the speed of each single stride in this case is obtained. However, this information is useful when analyzing very long walking trials performed in indoor environments when hundreds of steps are analyzed. This, for example, is the case of the statistical EMG analysis of walking [7,8], usually performed asking the subject to walk repeatedly in a ∞-shaped trajectory. In this case a control on the speed of each step is of paramount importance in order to distinguish steady-state walking patterns.

The aim of the present study is to propose a new method to assess walking speed by spatio-temporal gait parameters using only 1-degree-of-freedom (1-dof) electrogoniometers positioned on the hip and knee joints and based on a simple model that represents the lower limb modelled as two rigid segments: thigh and shank.

II. MATERIALS AND METHODS

A. Model description

The present method is based on a biomechanical model fed by signals acquired by two 1-dof electrogoniometers, positioned on the lateral side of the right lower limb and on the lateral side of the right pelvis, for measuring knee joint and hip joint angles in the sagittal plane, respectively. The availability of only two electrogoniometers led us to hypothesize gait symmetry between right and left lower limbs. This hypothesis can be relaxed if four electrogoniometers were available.

The model is designed to estimate the step length, as the sum of the length of two segments, d_1 and d_2, measured in two different gait-phases. To obtain the stride length, the step length is doubled. To this aim the symmetry between right and left steps is hypothesized. The model (Fig.1) defines d_1 during the stance-to-swing transition phase.

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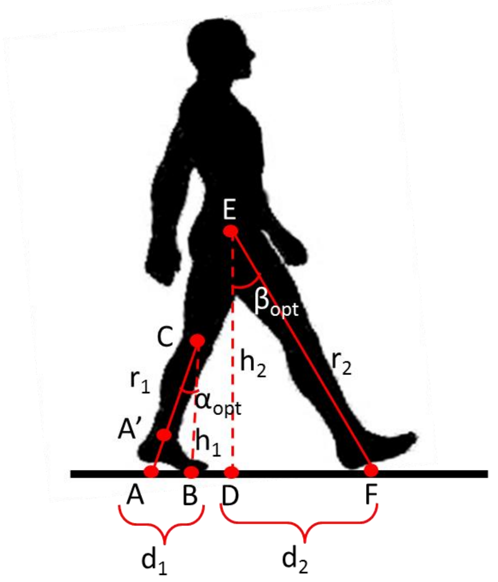

Figure 1. Model diagram.

In particular d_1 is the distance between the extension to the floor (A) of the segment joining the knee (C) and ankle (A') joint centres, and the orthogonal projection (B) of the knee joint on the ground, measured when the hip angle assumes the zero value, immediately preceding the peak of the knee trajectory. The knee joint (C) is the point of application of the knee electrogoniometer, and the shank length (r_1) is measured as the distance between C and the ground, in the subject standing position. Thus, ABC is a right-angled triangle where the shank is the hypotenuse, and d_1 and h_1 (height of the knee joint in the stance-to-swing transition) are the other two sides. For this reason, d_1 is computed as:

$$d_1 = AB = r_1 \sin \alpha_{opt} \tag{1}$$

In the same way, d_2 is defined as the distance between the orthogonal projection (D) of the hip joint (E) on the ground, measured in the heel strike instant, and the point of heel strike (F). The hip joint (E) is the point of application of the hip electrogoniometer, and the leg length (r_2) is measured as the distance between E and the ground, in the subject standing position. Thus, DEF is a right-angled triangle where the leg (r_2) is the hypotenuse, and d_2 and h_2 (height of the hip joint, in the heel strike instant) are the other two sides. For this reason, d_2 is computed as:

$$d_2 = DF = r_2 \sin \beta_{opt} \tag{2}$$

In this configuration, the model provides the step length as the sum of the estimated values of d_1 and d_2:

$$\text{step length} = d_1 + d_2 \tag{3}$$

Stride length has been assumed to the twice the step value:

$$\text{stride length} = 2*\text{step length} \tag{4}$$

Stride duration has been estimated from hip electrogoniometer data, as the time interval between two consecutive HF points.

Stride speed has been computed as the ratio between the estimated stride length and duration, in the same stride:

$$\text{stride speed} = \text{stride length} / \text{stride duration} \tag{5}$$

A sensitivity analysis was performed to assess, from the electrogoniometer data, the optimal value of model parameters α and β, able to provide a suitable assessment of d_1 and d_2. The optimal α_{opt} was identified as the value of the knee-joint angle in correspondence of the time instant when the thigh segment is perpendicular to the ground. This time event is identified as the instant when the hip angle assumes the zero value (H), immediately before the peak of the knee trajectory (point K in Fig. 2). The maximum angle of hip flexion (HF) corresponding to heel strike was selected as the optimal value for β_{opt} (Fig. 2).

Thus, the optimal α_{opt} and β_{opt} estimates, together with the further assumption that points B and D are coincident, allow to achieve the optimal configuration for the biomechanical model.

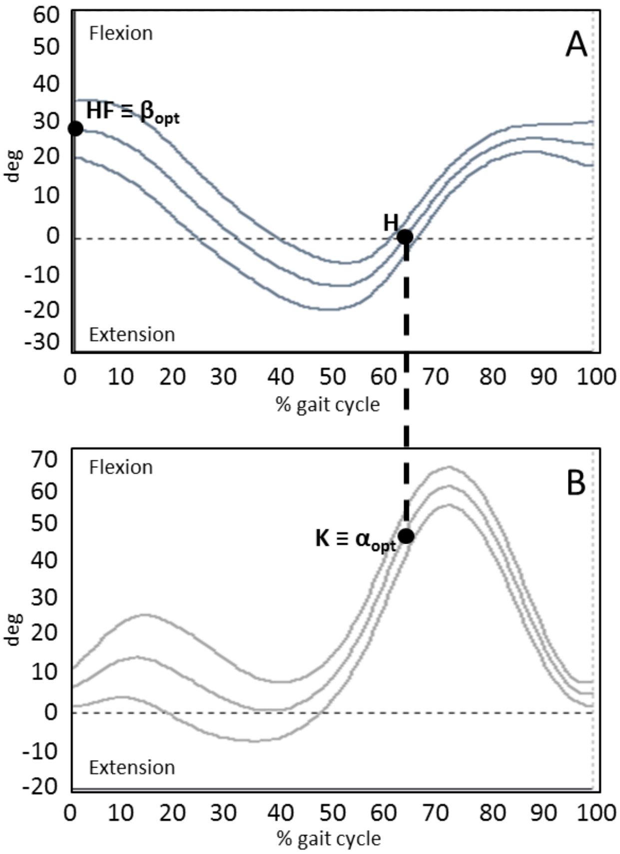

Figure 2. Typical hip (panel A) and knee (panel B) angle trajectories during a stride. Outer curves delimit the normality band. Point K is the optimal value of the α_{opt} angle. Point HF is the optimal value of the β_{opt} angle.

B. *Recording system signal acquisition and processing*

One healthy female adult volunteer (age 26 years; height 165 cm; shank length, r_1, 40 cm; leg length, r_2, 83 cm; weight 59 kg; body mass index 21.6 kg m^{-2}) was recruited for the validation procedure. Exclusion criteria included history of neurological disorders, orthopedic surgery within the previous year, acute or chronic knee pain or pathology, BMI>25, or abnormal gait. Before the beginning of the test, the volunteer signed informed consent.

Signals were acquired by means of a multichannel recording system for statistical gait analysis (Step32, DemItalia, Italy). The subject was instrumented with two electrogoniometers (accuracy 0.5°). The first electrogoniometer was applied to the lateral side of the lower limb for measuring the knee joint angles in the sagittal plane (Fig. 3). The second electrogoniometer was applied to the lateral side of the pelvis for measuring the hip joint angle in the sagittal plane (Fig. 3). After positioning the sensors, subject was asked to walk barefoot at three different self-selected speeds: natural, fast and slow. Electrogoniometric signals were low-pass filtered with a cut-off frequency of 15 Hz.

C. *Model validation*

Model validation has been performed using GAITRite Electronic Walkway System (CIR Systems Inc, USA). Data from GAITRite and electrogoniometers were acquired contemporaneously while the subject walked on the GAITRite's electronic walkway.

Results estimated by the model and those automatically obtained from GAITRite system were compared in each stride. The GAITRite system consists of a portable electronic walkway embedded with pressure-activated sensors. The electronic mat detects the timing of sensor activation as well as the relative distances between the activated sensors, and feeds this information into application software that computes spatial and temporal gait parameters for individual footfalls as well as an overall average for each parameter.

Figure 3. Experimental set-up.

The GAITRite system active area is 61 cm wide and 732 cm long. The sensors are placed 1.27 cm apart (total of 27648 sensors). The sampling rate of the system is 80 Hz [9]. GAITRite has been assumed, in this paper, as gold-standard instrumentation.

D. *Statistical analysis*

The spatial and temporal parameters of gait (stride length, stride duration and speed) were computed for each single stride within each walking trial. Mean and standard deviation (SD) were computed over all the steps of each walking task (at natural, fast and slow speed). The Mann-Whitney U test was applied to test statistically significant differences ($p<0.05$) between parameters computed by the model and the GAITRite system.

III. RESULTS

Actual hip and knee angular trajectories of one stride, expressed in percentage of gait cycle duration, are reported in Fig. 4.

Table I shows mean values and standard deviation of the spatial and temporal parameters computed for the three walking tasks performed. No statistically significant differences (at a p level of 0.05) were found between estimated values of the parameters, provided by the present model and the GAITRite system.

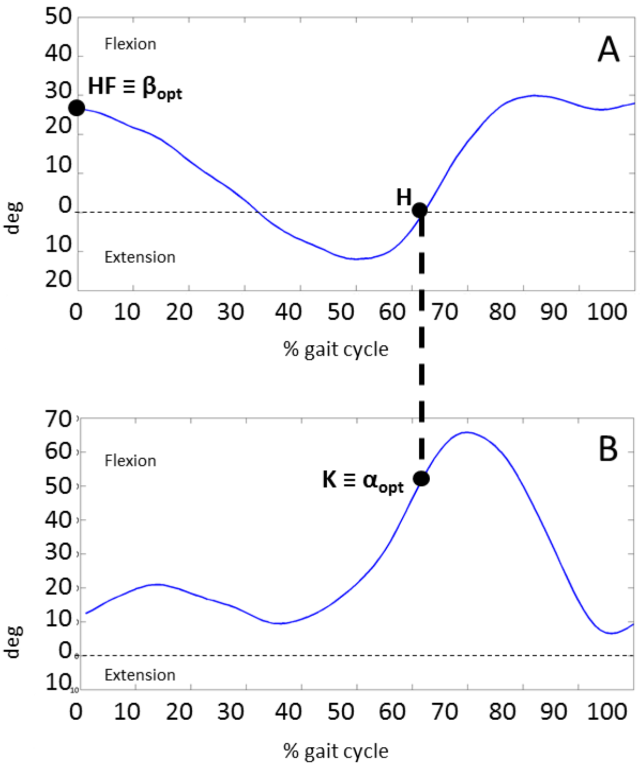

Figure 4. Experimental trajectories of hip (panel A) and knee (panel B) joint angles, expressed in percentage of gait cycle duration for one stride.

Table I. MEAN±STANDARD DEVIATION SPATIO-TEMPORAL PARAMETERS VALUES.

A. NATURAL SPEED	**New Model**	**GAITRite**	**Statistics**
Stride length (m)	1.34±0.05	1.33±0.34	NS
Stride time duration (s)	1.11±0.05	1.12±0.02	NS
Stride speed (m s^{-1})	1.20±0.1	1.21±0.49	NS
B. FAST SPEED	**New Model**	**GAITRite**	**Statistics**
Stride length (m)	1.61±0.07	1.62±0.89	NS
Stride time duration (s)	0.81±0.01	0.81±0.001	NS
Stride speed (m s^{-1})	1.98±0.05	1.98±0.92	NS
C. SLOW SPEED	**New Model**	**GAITRite**	**Statistics**
Stride length (m)	1.26±0.03	1.25±0.36	NS
Stride time duration (s)	1.33±0.02	1.32±0.01	NS
Stride speed (m s^{-1})	0.94±0.007	0.94±0.19	NS

NS=not statistically significant

IV. DISCUSSION

This study was designed to develop a new method to assess single stride speed by spatio-temporal gait parameters, using only 1-dof electrogoniometers, positioned on the hip and knee joints. Stride length, stride duration and stride speed are provided by means of a suitable choice of α and β angles derived from measured knee and hip joint angle trajectories.

The reliability of the goniometer-based model results was tested by direct comparison with GAITRite system, in one healthy subject during walking tests at three different speeds. The absence of statistically significant differences, detected between the values estimated by the two systems (Table I), highlights the reliability of the model in the assessment of spatio-temporal gait parameters. A further support for the reliability of the model lies in its capability of providing the same accuracy in the parameter estimates in the three different walking speeds (normal, high and low), adopted by the subject.

The underlying hypothesis of symmetry between right and left strides was due to the availability of only two electrogoniometers. Despite this simplifying hypothesis, results show a very good correspondence with the gold-standard ones. This is due to the fact that the analyzed subject had a normal walking. Though the method proposed in this study has been validated only on one healthy subject, nonetheless it showed an elevated accuracy in the assessment of stride speed. Having at disposal two further electrogoniometers, the symmetry assumption can be released and the method could be tested on subjects with pathological gait, too.

The model input data are acquired by means of reliable, low-cost, and easy-to-use sensors, such as electrogoniometers. This makes the present approach suitable to be integrated in systems, like pure EMG recorders, that are not able to obtain spatio-temporal gait parameters, without employing also other instrumentation like force platforms, inertial measurement units (IMU), or stereo-photogrammetric systems. For example, the method may be integrated as a supplementary tool for Step32 (DemItalia) system, the system used in the present study to acquire kinematic data by electrogoniometers, in order to provide the essential spatial gait parameters on very long walking trials (hundreds of steps), in addition to the statistical EMG analysis performed by that system. Further validation of the method is being performed not only with GAITRite system but also with a 6-camera stereophotogrammetric system (SMART-D, BTS) on a higher number of subjects.

V. CONCLUSION

The usefulness of the method is guaranteed by the fact that results are provided by the model using only simple and low-cost instrumentation like 1-dof electrogoniometers. Thus, the results of the present study candidate this goniometer-based model as a reliable tool for an easy and flexible assessment of stride speed and in general of spatio-temporal gait parameters in normal subjects, and propose it as a valid alternative to the traditional methods that use foot switches, ground reaction forces, IMU or stereo-photogrammetric systems.

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