Stride variability in human gait: the effect of stride frequency and stride length

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Abstract

This study focused on spatial and temporal variability of the stride in human gait. We determined the role of stride frequency (F) and stride length (L) on those parameters. Eight healthy subjects walked on a treadmill using 25 different FL combinations (0.95 < L < 1.5 m, and 0.8 < F < 1.26 Hz). The results showed that spatial and temporal variabilities tend to increase in concert with respect to change in stride parameters. In addition, stride variability was found (1) to be minimal at F = 1 Hz; and (2) to increase with smaller L. During additional trials, subjects walked freely at various speeds. Although it is generally hypothesized that freely chosen behaviors are optimal in terms of variability, our data show that this is not always the case in human gait.

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1. Introduction

Variability is inherent within all biological systems. In the particular case of human motor abilities, the fact that it seems impossible for a given individual to generate identical movements patterns on successive attempts is a strong testament to this observation [18]. Temporal and spatial intrasubject variability in kinematic variables is typically regarded as an important measure of motor skill and practice [23]. Therefore, the role that variability plays in the coordination and control of sensorimotor system is a central issue for the study of motor control. All theoretical accounts of motor control either implicitly or explicitly consider variability (for a review see [18]).

Despite the richness of the human motor repertory, the study of variability in movement has been mainly directed toward rapid single-aiming movements. The classical tasks were either the production of spatially oriented movements with the arm [22], or the production of force pulse in isometric [17]. Less attention has been paid to characterize variability in cyclical movements. The goal of this paper is to address variability of human gait, a very functional rhythmical movement. Note that in the particular case of gait, movement consistency is crucial, because it determines our ability to perform intentional modulations of the stride. Indeed, without a minimal steadiness of the locomotor pattern, humans cannot master modulations of the stride necessary, for example to avoid an obstacle [19,12].

Attempts have been formulated in order to characterize variability of human gait [26,15,23,8,14]. For instance, Sekyia et al. [23] have studied spatial variability in human walking, while Maruyama and Nagasaki [15] have investigated its temporal aspect. Surprisingly, although movements are performed simultaneously in the time and space domain, most researches focused on only one dimension at a time [7]. To our knowledge, the study of MacKay-Lyons [14] is the only one reporting both temporal and spatial aspects of gait variability, but this study was clinically oriented and only one walking speed was tested. The first goal of the present experiment is to provide a more complete description of variability in human gait. This means that both temporal and spatial variability will be used as dependent...
variables. In particular this will offer a chance to assess whether stride parameters induce similar changes in both types of variability.

Most stride parameters have been shown to affect the variability of human gait. There are reports showing that stride length affects spatial variability [23], as well as stride frequency (FREQ) affects the temporal variability [15]. However, the possibility that stride length (LENGTH) may affect the temporal variability, and/or that stride frequency may affect the spatial variability has been less investigated. The goal of the present study is to investigate whether or not these ‘cross over’ effects exist. This means that both FREQ and LENGTH will be used as independent variables. More specifically, we propose to monitor the temporal and spatial variability of the stride in a task in which subjects are asked to walk using a total of 25 stride frequency–length (FL) combinations (five stride frequencies being crossed with five stride lengths).

A third and last goal of this study is to determine whether gait variability is minimal when the FL combination is preferred. Indeed, gait is characterized by a preferred relationship between stride frequency and stride length. When a subject intends to walk at a given speed, that speed is attained with a specific stride frequency and length [11,26]. In addition, changes in walking speed have been shown to result in parallel changes in stride frequency and length [6,16]. However, under specific instructions, leg movement can be intentionally constrained. For example, stride frequency can be imposed [13,25], as well as stride length [13,20,24] or even both [3,4].

Preferred behaviors have been often viewed as the most efficient (i.e. economical). Indeed, when subjects have to walk at a given speed using different FL combinations, non-preferred FL combinations required more energy than that spontaneously adopted, whatever this amount of energy was estimated through oxygen consumption measures [28,10] or inverse dynamics techniques [5,10]. Therefore, it is likely that spontaneously adopted behaviors minimize the involvement of the muscular system in gait production. Because muscular forces produce movements, and variability in muscular forces produces variability in movements [22,21], one can expect that, in the lack of external perturbations, movement variability should be less for spontaneous behaviors than for non-preferred behaviors. On the one hand, the study of Maruyama and Nagasaki [15] suggests that walking is optimized in terms of temporal variability when the subjects walk with freely chosen step rate at a given speed. On the other hand, Sekiya et al. [23] found that the step frequency (120 steps per min) leading to minimal spatial variability remained similar across different walking speeds. In order to investigate further this question, all subjects performed additional trials in which he or she was asked to walk freely at five different speeds, that is without any constraint in their FL combination. This allowed us to determine which of the 25 FL combinations tested earlier were the most preferred.

2. Method

2.1. Subjects

Eight subjects participated in this experiment, two men and six women. The mean subject age, height, and mass, were 28.5±5.2 years, 165±6 cm, 58.5±8.7 kg, respectively. None of the subjects had any known history of postural or skeletal disorders. All subjects gave informed consent according to the procedures approved by Mediterranean University.

2.2. Set-up

Subjects walked on a treadmill driven by their own locomotor activity (Gymroll, sprint 1800, 0–8 km/h, walking surface 0.6 m wide and 1.80 m long, with lateral protective bars). The treadmill motor was a torque servomotor. This setup left subjects entirely free to adopt the walking speed that they wished, as well as the FL combination. The treadmill belt slid along a very smooth supporting surface, which enabled the subject to feel the usual plantar sensations while walking. The subjects were fixed to the treadmill by a weight lifter’s belt connected to a rotating axle by a bar. With this bar arrangement, the subjects could exert the propulsive forces allowing them to overcome the treadmill belt friction—the higher the subject’s mass, the greater the friction. This friction could be regulated by a motor generating a constant torque (which helps the subject to move the treadmill belt), whose magnitude determined the effort required to walk: the higher the torque, the lower the effort. For a given torque value, the subjects could modulate their walking speed by modifying the traction forces that they exerted on the belt. For each subject, the magnitude of the motor torque was maintained constant throughout the experiment.

The horizontal front-to-back displacement of the tip of each foot was recorded by connecting each one separately to a precision potentiometer by means of non-extensible thread. The thread was attached by an adhesive tape surrounding the tip of foot at the level of the fifth metatarsal. The potentiometer (10 kΩ, ten revolutions) transduced the foot displacement in voltage, moving clockwise when the foot moved forward and counter clockwise when the foot moved backward. The measurement system was initially calibrated by establishing the correspondence between 1 m of pulled thread and the modification in voltage. Typical signals recorded with this apparatus are shown in Fig. 1. All
signals were collected on-line on a PC 386, with a sampling rate of 100 Hz.

2.3. Procedure

In each trial the subject had to walk at a given FL combination. Each subject performed a total of 25 trials of 120 s each. Five lengths (in m, L1 = 0.95, L2 = 1.05, L3 = 1.20, L4 = 1.35, L5 = 1.50) were crossed with five frequencies (in Hz, F1 = 0.80, F2 = 0.89, F3 = 1, F4 = 1.14, F5 = 1.26). Overall the conditions, the changes in L and F were comparable (L5 = 1.57 × L1, F5 = 1.57 × F1) such that their contribution to the change in speed was similar. We designed this experimental plan having two objectives in mind. First, the range of resulting walking speed (from 0.7 to 1.8 m/s) should be typically observable [1,23]. Second, because we wanted to assess the effect of decoupling the FL relationship, we made sure that the expected speeds would be very similar for the combinations F1L5, F2L4, F3L3, F4L2, and F5L1 (one diagonal of our experimental plan). For this set of combinations the expected speed was 1.2 m/s. This speed was likely to be close from the preferred walking speed [10].

Subjects were given a visual feedback on their actual step length. The signal of the right locometer was displayed on-line on a screen located in front of the subject. The subject was instructed to maintain the oscillation of the signal between two marks delimiting the correct amplitude. In addition, the subjects had to follow the step frequency imposed by the beep of a metronome. They kept time to the metronome by making the heel strike of the foot coincide with the metronome beat. At the beginning of each trial we waited for the subject to feel comfortable with the task (typically less than 30 s), then data acquisition was performed for the next 2 min.

In addition to this protocol, subjects performed five additional trials in which they were asked to walk at a given speed in their comfortable way. Under each speed condition, they had no instructions on stride frequency and stride amplitude. The five walking speeds tested were S1 = 0.75, S2 = 0.90, S3 = 1.15, S4 = 1.45, S5 = 1.75 (in m/s). These values were chosen to cover the range of walking speeds experienced by the subjects in the previous protocol. In fact these speeds were very similar to the ones imposed by the combinations F1L1, F2L2, F3L3, F4L4, and F5L5. Like in the previous experimental design, each trial lasted 2 min, and the order of presentation of the speed was randomized across subjects. In order to let the subjects as free as possible, they were only warned verbally by the experimenter when their speed deviated from more than 0.05 m/s of the intended value. No metronome was involved.

2.4. Data processing

The first 65 strides of each trial were kept for further analysis. Each stride was described by two parameters:

![Figure 1: Data processing of the locometer signals. The longitudinal displacement of the right (thick line, top signal) and left foot (thin line, bottom signal) are shown as a function of time. While walking on the treadmill, the foot moves backward during the stance phase (St), and forward during the swing phase (Sw). The duration of the stride (T) was computed based on the time interval between two successive peaks (i.e. heel contacts). The frequency of the stride was taken as 1/T. The stride length (L) was computed as the distance covered by one foot during the swing phase (d1) plus the distance covered by the other foot during this time interval (d2). An example is illustrated in the figure.](image-url)
its length \((L)\) and its frequency \((F)\). The method used to compute \(L\) and \(F\) from the raw signals is illustrated by Fig. 1. For each trial, the within-subject variability of each parameter was calculated over the 65 strides. In order to facilitate comparison with previous studies, the within-subject variability has been expressed in absolute and relative units. Standard deviations (S.D.) were used for the absolute units, while coefficients of variation (CV = S.D./Mean) were used for the relative units. A total of four dependent variables were extracted from each trial (S.D. spatial, CV spatial, S.D. temporal, and CV temporal).

2.5. Statistical analysis

Two types of statistical analysis were performed. First, we assessed the general effects of stride length (LENGTH) and frequency (FREQ) on spatial and temporal variability. This was achieved using two-way analysis of variance (ANOVA) with LENGTH and FREQ as within-subject factors (five levels each). Second, we investigated the possible differences in variability for the five FL combinations resulting in a similar walking speed. One-way ANOVAs were used to assess the effect of the FL combination (COMB factor, five levels). Post-Hoc Newman Keuls analyses were used whenever necessary. Because S.D.s are often not normally distributed, we used a logarithmic transformation before conducting any ANOVA procedure. A similar transformation was used for the CV data as well.

In order to assess if spatial and temporal variability followed/did not follow the same pattern with respect to change in stride parameters, we performed a linear regression analysis across the 25 experimental conditions. The group averaged data were used for this analysis. For all statistical purposes, the threshold of significance of 0.05 was kept constant.

3. Results

Among the 200 trials, four trials had to be rejected for technical problems. Missing values were replaced by the mean performance of the group in the same experimental condition.

3.1. Spatial and temporal variability of the stride

The mean group stride length and frequency were never different from more than 5% of the intended value.

At the spatial level, no significant effect of LENGTH was found when the variability of stride length was expressed in meters \((F(4,28) = 0.71, P > 0.05);\) see black diamonds in Fig. 2A). As a matter of fact, expressed in percent, these fluctuations were increased for shorter steps \((F(4,28) = 32.87, P < 0.001);\) see black diamonds in Fig. 2C). We found an effect of FREQ \((F(4,28) > 2.79, P < 0.05)\), such that both absolute and relative variability tended to be minimal at the intermediate frequency F3 (see black diamonds in Fig. 2B and D). Post-Hoc analysis actually confirmed that variability was smaller at the frequency F3 than at the frequency F1 and F5 \((P < 0.05)\). Whatever variability was expressed by S.D.s or CVs, we did not find any significant interaction between LENGTH and FREQ \((F(4,28) < 0.87, P > 0.05)\).

At the temporal level, the variability of stride frequency was influenced by the stride frequency. The effect of FREQ was significant for both S.D.s and CVs \((F(4,28) > 6.35, P < 0.001)\). In both cases, the temporal variability tended to be minimal for the intermediate frequencies (see hollow squares in Fig. 2B and D). Post-Hoc analysis confirmed that the relative variability was smaller at the frequency F3 than at the frequency F1 and F5 \((P < 0.05)\). There was also a significant effect of LENGTH, indicating that the temporal variability was dependent on stride length. Absolute and relative variability in timing was smaller for the larger stride \((F(4,28) > 7.94, P < 0.001);\) see hollow squares in Fig. 2A and C). Post-Hoc analysis showed that the relative and absolute variability were larger at the lengths L1, L2, and L3, than at the amplitudes L4, and L5 \((P < 0.05)\). There was no significant interaction between LENGTH and FREQ \((F(4,28) < 1.12, P < 0.05)\).

At a more general level, we found that, across all experimental conditions, spatial and temporal variability increased (or decreased) in concert. This is illustrated by Fig. 3, where data pooled across subjects are presented. Coefficients of regression are significant for both S.D.s (Fig. 3A) and CVs (Fig. 3B). Regression analyses performed with individual data showed a similar trend. All subjects had significant coefficients of regression, except one for S.D.s. At last, a signed-test also showed that temporal CVs were smaller than spatial CVs \((P < 0.001);\) see also Fig. 2C and D).

3.2. Effects of stride frequency and length at a given walking speed

The comparison of the mean walking speed in the following conditions, F1L5, F2L4, F3L3, F4L2, and F5L1, revealed no significant differences \((F(4,28) = 2.06, P > 0.05)\). The average walking speed across these five conditions was \(S = 1.15 \pm 0.01\) m/s (S.D. is across conditions).

Despite similar walking speeds, we observed clear differences in stride variability depending on the FL combination (see Fig. 4). For most parameters we observed a significant effect of COMB. At the spatial level, relative variability was increased when subjects walked with small strides at a high frequency \((F(4,28) =\)
6.49, \( P < 0.001 \); see black diamonds in Fig. 4B). Post Hoc analyses showed smaller variability for the combinations F1L5, F2L4, and F3L3, than for the combinations F4L2, and F5L1 (\( P < 0.05 \)). We observed a tendency for smaller S.D.s at the intermediate combinations F3A3, but this effect was not significant (\( F(4,28) = 1.36, P > 0.05 \); see black diamonds in Fig. 4A). We also observed a main effect of COMB at the temporal level for both the absolute (\( F(4,28) = 6.13, P < 0.01 \); see hollow squares in Fig. 4A) and relative variability (\( F(4,28) = 10.81, P > 0.001 \); see hollow squares in Fig. 4B). Post Hoc analyses showed that CVs for the intermediate combinations F2L4, F3L3, and F4L2 was smaller than CVs for the extreme combinations F1L5, and F5L1 (\( P < 0.05 \)).

3.3. Preferred relationship between stride frequency and amplitude

During free walking, the mean speed in the following conditions, S1, S2, S3, S4, S5, were, respectively, 0.75, 0.91, 1.14, 1.44, and 1.77 m/s. Fig. 5 shows the average FL combinations used by the group to achieve those walking speeds (see the hollow circles). As in other studies [11,26], we found a linear relationship between \( F \) and \( L \). The correlation between stride frequency and length was highly significant (\( r = 0.999, P < 0.001 \)). The slope and the intercept of this linear relationship were, respectively, 1.664 m/Hz and \(-0.302\) m. Based on those results, we tried to evaluate which of the 25 FL combinations tested earlier were potentially the most
preferred; the 25 FL combinations are plotted in the background of Fig. 5 (see the black dots). For each stride length (L1, L2, L3, L4, and L5), we searched for the stride frequency (F1, F2, F3, F4, and F5) potentially preferred (i.e. leading to a minimal distance from the preferred FL relationship). The results are the following: F1 for L1 and L2, F2 for L3, F3 for L4, and F3/F4 for L5. In other words, within the earlier experimental design, the preferred frequency depended on the stride length to produce. If we assume that stride variability is minimal when the FL combination is preferred, we have to expect an interaction between the factors FREQ and LENGTH. However, as reported earlier, no significant interaction was found, and F3 appeared as the optimal frequency in terms of variability for all stride lengths. This means that a preferred FL combination is not necessarily optimal in terms of spatial and temporal variability.

4. Discussion

The goal of this study was to investigate the role of stride frequency, and stride amplitude in the generation of stride variability in human gait. At this stage, we can formulate the following remarks (1) temporal and spatial variability tends to increase in concert with respect to changes in stride parameters; (2) stride length and stride frequency are two fundamental parameters affecting both the spatial and temporal variability of the stride; and (3) walking with a preferred FL combination does not always guarantee the lowest variability. Let us now discuss those issues more extensively.

4.1. Relationship between temporal and spatial variability

In most studies, temporal and spatial variabilities of human gait have been treated separately [15,23]. Because methodology, subjects characteristics, and data processing could vary across earlier studies, it was rather complicated to assess whether there could be any specific relationship between temporal and spatial variability. The present experiment provides a clear answer to this issue. Our regression analyses showed if a change in stride parameter is followed by an increase in spatial variability, it is also accompanied by an increase in temporal variability. Somehow, this suggests that one type of variability may eventually be sufficient to assess the steadiness of human gait. However, one should keep in mind that, when compared in terms of relative units, the variability of the stride was generally smaller in the time domain than in the space domain.

4.2. The effect of stride frequency

The present set of data showed a clear effect of stride frequency. Both spatial and temporal variability appeared to be minimal for the intermediate frequency F3 (1 Hz), as illustrated by the U-shape of the curves presented in Fig. 2B and D. Similar U-shape functions have been previously reported in locomotion studies. Hoyt and Taylor [9], by measuring the rate of oxygen consumption in horse under a wide variety of speeds found that there is a speed minimizing energy consumption for each mode of locomotion. Using the same technique with human subjects walking at a constant speed (1.25 m/s) under different frequencies, the results of Holt et al. [10] indicates that energy consumption was minimal for a stride frequency of about 0.98 Hz. They found rather similar results by analyzing the variability of the vertical head trajectory, or the phase relationship between the joints of the lower limb. Even more resembling, in a plan crossing three walking speeds with five frequencies, Sekiya et al. [23] found that the variable error in step length was minimal at 120 steps per min (i.e. 1 Hz for the stride frequency). All together,
these results argue in favor of a particular frequency for which energy consumption and motion variability are both minimal. The main contribution of our study is the extension of this statement to both the spatial and temporal domains of gait variability.

However, the following question emerges: Why would 1 Hz represent the optimal stride frequency? A parsimonious explanation can be formulated in the context of mechanical oscillators. Every mechanical system possesses an ‘eigen’ or ‘reasoning frequency’, for which the amount of energy needed to sustain its oscillation is minimal. Using a hybrid-pendulum spring model, Holt et al. [10] determined that the reasoning frequency of the lower limb of their pool of subject was about 0.92 Hz. Therefore, we expect that at this particular frequency the movement of the neuro-muscular synergy sustaining the leg oscillation is minimal. Consequently, if less internal forces are needed, self-induced (internal) perturbations are less likely to occur, and the more consistent is expected the movement.

As suggested in the Section 1, preferred behaviors are generally considered to be the most efficient [5,10,28]. We hypothesized that, if the involvement of the muscular system is minimized for preferred behaviors, walking with a preferred FL combination should result in lower spatial and temporal variability. On the one hand, this study shows that the frequency minimizing stride variability does not depend on the stride length. On the other hand, during free walking at various speeds, we observed parallel changes in stride frequency and length. We conclude that (1) in human gait,
preferred behaviors are not necessarily optimal in terms of movement variability; and (2) the relationship between movement efficiency and movement consistency is certainly less trivial than we proposed.

4.3. The effect of stride length

The effect of stride length on gait variability was also demonstrated by the present study. However, this effect was clearly different from the one described for stride frequency. First, the effect of stride length seems more specific to relative variability. Indeed, when the variability of the stride was expressed in absolute units, we found an effect of stride length at the temporal level, but not at the spatial level. By contrast, when the variability of the stride was expressed in relative units, we found a significant effect for both levels. A second difference lies in the nature of the effects. While we observed a U-shape effect for stride frequency, the effect of stride length was rather monotonic (see Fig. 2A and C): larger steps were associated with smaller fluctuations in the temporal, and spatial domains (if expressed in percent). What can be the reason(s) leading to higher consistency for longer steps? We would like to propose a biomechanical explanation based on the movements of the joints. In order to make larger steps, angular motion at the knee, hip and ankle, has to be increased [27]. As the joints get closer from their full flexion or extension position, antagonist muscles becomes more and more stretched, and there starts to be little room for overshoot. The passive resistance created by the antagonist muscles, and the limited range of the joints can certainly help to erase some of the irregularities of the stride. At this stage, this explanation is just a proposition, and other studies are encouraged to offer alternative explanations.

4.4. Is there a specific effect of walking speed

By manipulating stride length and stride frequency, we clearly influenced the consistency of the stride. As a first attempt to provide an explanation, one could suggest that gait variability is in fact only influenced by the walking speed, since changes in stride frequency or stride length result obligatory in changes in walking speed. Nevertheless, this hypothesis needs to be rejected for the following reasons. First, increases in stride length and stride frequency did not lead to similar changes in stride variability. Second, differences in gait variability were found when the walking speed was maintained constant, and the FL combination manipulated (i.e. COMB effect). In fact, the effect of walking speed can simply be decomposed as separate effects of stride frequency and stride amplitude. However, because changes in speed during free walking result more from a change in length than in frequency (slope of the FL relationship = 1.664 m/Hz), the effect of walking speed resembles more to the effect of stride length.

4.5. Concluding remarks

We conclude that stride frequency and length are two fundamental parameters determining the variability of human gait. Even though the spatial and temporal variabilities of the stride relate to each other, stride length and stride frequency have distinct effects on gait variability. Somehow, analyses dealing with gait variability that do not integrate these two contributions (by focusing on the effect of walking speed) may give a rather incomplete picture. Indeed, we clearly showed through the effect of COMB, that, for a given speed, the spatial and temporal variability can change depending on the FL combination. This may have direct implications for studies aiming to compare groups, like for instance the clinical studies assessing the level of impairment of Parkinsonian patients [2,8]. As proposed by Sekiya et al. [23], we would like to stress the possibility that some discrepancies between normal and pathological populations might not only originate from the usage of different walking speeds, but also from the usage of different FL combinations if the walking speed is similar.

At last, we would like also to stress that, even though modulations in stride variability exist with respect to change in stride parameters, human gait is a very consistent behavior. Indeed, the present study showed that, across all experimental conditions, CVs were rarely over 3%. We think that this consistency is a fundamental property of human gait that needs to be considered by researchers, especially when their protocols require intentional modulations of the stride.

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