ORIGINAL ARTICLE

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Variability of gait patterns during unconstrained walking assessed by satellite positioning (GPS)

Abstract It is established that the ratio between step length (SL) and step frequency (SF) is constant over a large range of walking speed. However, few data are available about the spontaneous variability of this ratio during unconstrained outdoor walking, in particular over a sufficient number of steps. The purpose of the present study was to assess the inter- and intra-subject variability of spatio-temporal gait characteristics [SL, SF and walk ratio (WR = SL/SF)] while walking at different freely selected speeds. Twelve healthy subjects walked three times along a 100-m athletic track at: (1) a slower than preferred speed, (2) preferred speed and (3) a faster than preferred speed. Two professional GPS receivers providing 3D positions assessed the walking speed and SF with high precision (less than 0.5% error). Intra-subject variability was calculated as the variation among eight consecutive 5-s samples. WR was found to be constant at preferred and fast speeds [0.41 (0.04) m·s and 0.41 (0.05) m·s respectively] but was higher at slow speeds [0.44 (0.05) m·s]. In other words, between slow and preferred speed, the speed increase was mediated more by a change in SF than SL. The intra-subject variability of WR was low under preferred [CV, coefficient of variation = 1.9 (0.6)%] and fast [CV = 1.8 (0.5)%] speed conditions, but higher under low speed condition [CV = 4.1 (1.5)%]. On the other hand, the inter-subject variability of WR was 11%, 10% and 12% at slow, preferred and fast walking speeds respectively. It is concluded that the GPS method is able to capture basic gait parameters over a short period of time (5 s). A specific gait pattern for slow walking was observed. Furthermore, it seems that the walking patterns in free-living conditions exhibit low intra-individual variability, but that there is substantial variability between subjects.

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Introduction

Walking is the most common repetitive movement that humans perform. However, bipedal locomotion exhibits an inherent instability and requires complex motor control. The locomotor system is regulated by the cerebellum, the motor cortex and the basal ganglia, with feedback from proprioceptive, visual and vestibular sensors. The final output of the control segment modulates the spatial (step length, SL) and temporal (cadence or step frequency, SF) patterns of the gait. These parameters are directly related to walking speed (speed = SL·SF). At a given walking speed, a subject can theoretically adopt an infinite combination of SL and SF. However, in the late 1960s, investigators (Grieve and Gear 1966) highlighted the curvilinear relationship between walking speed and SF (SF = $\alpha V^{0.58}$); in other words, the ratio between SL and SF is constant over a large range of walking speeds. The common explanation for this phenomenon is that energetic considerations and stability constraints force a defined SF and SL combination (Holt et al. 1995).

In the mid 1990s, a research group (Nagasaki et al. 1996) defined the walk ratio (WR) as the ratio between SL and SF: WR is larger while walking with longer strides than with shorter steps. For these authors, WR was used as a simple index for describing temporal and spatial coordination. They suggested that aging or neuro-degenerative diseases (such as Parkinson's disease) modify the gait pattern and induce a smaller WR. Consequently, WR could constitute a useful tool for measuring pathological and aging walking patterns. Furthermore, it has been shown that WR exhibits low inter-subject variability in healthy young subjects (Sekiya et al. 1996) and an increase of WR at low walking speed was also described. Evidence was also demonstrated that WR is invariant during test-retest

experiments (Sekiya and Nagasaki 1998). These experiments were conducted in laboratory conditions over a short walking distance (about 10 m).

During the last decade, the group of Hausdorff thoroughly studied the variability of SF in terms of amplitude and dynamics (Hausdorff et al. 1995, 1996, 1998, 1999, 2001a, 2001b). They showed that aging and different neurodegenerative diseases (Parkinson's and Huntington's diseases) have a substantial impact on the variability of SF (Hausdorff et al. 1998). Their results were obtained for a large number of consecutive strides (duration ranging from 5 to 60 min). Their method, however, could not retrieve instantaneous walking speed and SL. Therefore, it seems that it would be interesting to assess not only the magnitude of the gait parameters (speed, SF, SL and WR) but also their variability in continuous, unconstrained walking.

WR provides an indication of the spatio-temporal adaptation of gait at a given speed. However, an index that describes how the gait pattern changes with speed would be valuable. In a study about the movements of the head during walking, Hirasaki et al. defined a new index, called the stride length index (SLI), which assesses the relative contribution of SL and SF to the change in walking velocity (Hirasaki et al. 1999). For treadmill walking, they found that SL contributes more to the speed increase than SF, except at high speed. Because these results seem inconsistent with the constant WR hypothesis, the assessment of both SLI and WR index during unconstrained walking would be valuable.

Recently, our research group used the Global Satellite Positioning System (GPS) to study the human locomotion. We demonstrated that the basic gait parameters (speed, SF and SL) could be retrieved with high-precision professional GPS receivers in differential phase mode (Perrin et al. 2000; Terrier et al. 2000, 2001). In the present study, the GPS technique was used in order to analyse the gait parameters outside the laboratory, with minimal constraint on the subject. It was possible to design walking experiments over a longer distance on the level than in a laboratory. The aim was to obtain basic gait parameters (speed, SF and SL) over several consecutive 5-s time windows.

The general purpose of the study was to explore the intra- and inter-subject variability of gait parameters at different speeds under unconstrained conditions. We did not seek to characterize the origin of the variability (i.e. anthropometric factors, gender, age, etc.), because the GPS method does not allow us to conduct the large-scale studies (i.e. substantial number of subjects) required for this purpose.

The first specific purpose of the present study was to highlight how the spatio-temporal walking parameters (SF, SL and WR) vary with walking speed or, in other words, how the subjects alter their gait style when they change speed. The hypothesis was that WR is constant at normal and high speeds and exhibits small inter-subject variations. The second purpose was to study the short-term intra-subject variability of the parameters of the gait (SF, SL, WR). The issue was whether subjects walk in a very repeatable manner, regardless of speed.

Methods

Material

Two high-precision GPS receivers were used (Legacy E, Javad Navigation Systems, San Jose, Calif., USA). One of the devices was the base station, and the other one (rover) was carried by the subject in a backpack (weight 1.2 kg). The rover's antenna was rigidly fixed onto a helmet (weight: 800 g).

General procedure

Twelve subjects [seven men, five women; age = 29.6 (12.7 years, mean (SD), body mass = 71.9 (13.9) kg, body height = 1.77 (0.08) m] provided informed consent to take part in the study. All were healthy and exhibited no orthopedic problems (assessed by a self report). The subjects freely walked three times along a 100-m athletic track (straight path, Tartan surface). The purpose was to give maximal freedom to the subject in selecting three different walking speeds. Hence, the instructions were to walk slower than their preferred speed during the first trial (slow trial), to walk at their habitual (preferred) speed during the second trial (preferred trial), and to walk faster than their preferred speed during the third trial (fast trial). Three subjects [three men; age = 27.6 (2.1) years, body mass = 81.1 (11.1) kg, body height = 1.86 (0.07 m)] performed the same test 2 months later to evaluate the repeatability of walking parameters. The aim was to highlight the inter-test differences, each subject being his own control.

Calculation of the gait parameters

The two GPS receivers were programmed to provide 3D positions 10 times per second (10 Hz, without interpolation or oversampling) by using the post-processing RTK (real-time kinematics) method.

The principle of high-accuracy positioning involves tracking the satellite carrier, i.e. the electromagnetic wave sent by the satellite to the receiver. By measuring at regular intervals (in our experiment, 10 times per second) the Doppler frequency between a carrier generated by an oscillator in the receiver and the satellite carrier, it is possible to follow with a high accuracy the relative displacement of the satellite and the moving receiver. By using a reference receiver (differential mode), most of the errors (clock errors, atmospheric errors, etc.) can be cancelled if the distance between this base station and the moving receiver is small.

The analysis was made in kinematics mode (trajectory and speed assessment). Because of the short baseline between the base station and the rover (150 m), centimetre accuracy was expected. Raw data were converted into the Swiss coordinates system, which provides 3D positions expressed in metric units, with the x axis in the West/East direction. The data corresponding to the first 5 s of each 100-m trial were not considered to avoid transition period and non steady-state. In order to obtain a similar sample size for each trial and for each subject, 40 s of data were kept for the subsequent analysis. These data were then divided into 8 samples of 5 s containing 50 3D-points. In order to express 3D coordinates (i.e. North, East and altitude) as "subjective" coordinates commonly used in biomechanics, an axis rotation around the z (vertical) axis was performed: the vector connecting the first and last position in the sample was defined as the new x-direction. The result, illustrated in Fig. 1, was that the main direction of the displacement was defined as the antero-posterior (x) axis; the other directions were the medio-lateral (y) and vertical (z) axes. The average speed of each 5 s sample was defined as the distance between the first and last position in the sample divided by the time (cf. Fig. 1). The average SF was assessed by analysing the frequency content of the

Fig. 1A–C Raw GPS data (10 Hz) of a subject walking at preferred speed (1.8 m/s) for 5 s (50 positions in 3D). **A** Lateral oscillation of the body (top view). **B** Vertical lift of the body (side view). **C** 3D walking speed oscillations at each step. Instantaneous speed (**C**) was computed by numeric derivation of the 3D position. *Solid line*: antero-posterior speed; *dash-dot line*: vertical speed; *dashed line*: lateral speed
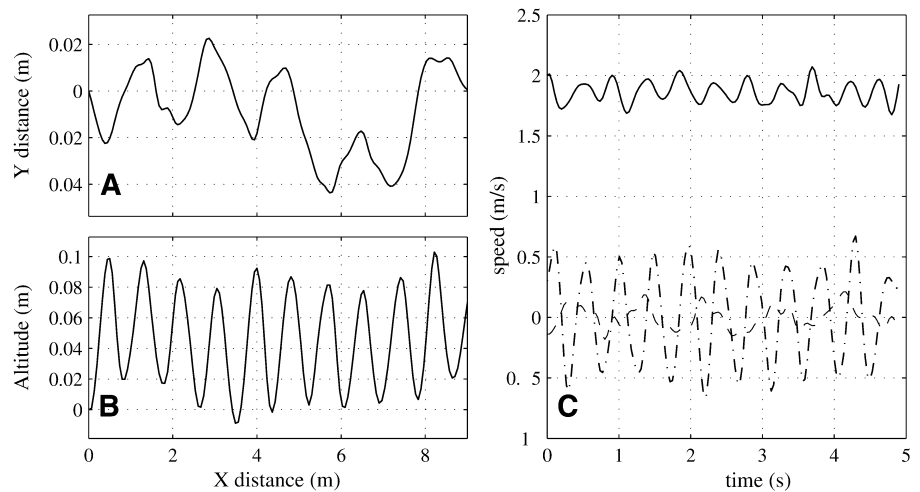
vertical axis signal (Fig. 1B) with a spectrum density algorithm (Welch's periodogram method). Because walking speed is the product of SF and SL, SL was then computed accordingly.

Data analysis

In order to analyse the variation of SF and SL with walking speed, two complementary methods were used. First, the ratio between SL and SF, defined as walk ratio (WR), was calculated for each 5 s sample. Second, the step frequency index (SFI) was calculated to assess the relative contribution of SF to the change of walking speed:

$$\text{SFI} = \frac{\log \frac{\text{SF}_{i+1}}{\text{SF}_i}}{\log \frac{\text{Speed}_{i+1}}{\text{Speed}_i}} \qquad (1)$$

where SF_i and SF_{i+1} are the average step frequencies at adjacent walking speeds (Speed_i and Speed_{i+1} respectively). A SFI of 1 indicates that the subject changed his/her walking speed by varying his/her SF only. If the subject increased SF and SL in the same proportion in order to increase speed, then SFI is 0.5. This method of analysis was adapted from the study of Hirasaki et al. (1999). We chose to calculate SFI instead of SLI (step length index), because speed and SF were directly determined, while SL was derived from SF and speed. The SFI was calculated for each subject between the slow and preferred speed conditions and between the preferred and fast speed conditions.

Measurement errors

Because GPS is a relatively new technique for human applications, we paid special attention to evaluate the error of measurement. The time error was neglected: the receivers lock their internal clock to

Table 1 Estimation of the measurement error. Estimated relative error (absolute error/measured value × 100) of the different parameters were calculated from theoretical GPS accuracy (walking speed), numerical simulation (step frequency, see Methods for more details), or propagation of errors (step length and walk ratio)

Relative error (%)	Low speed	Preferred speed	High speed
Walking speed	0.43	0.30	0.21
Step frequency	0.01	0.08	0.10
Step length	0.44	0.38	0.30
Walk ratio	0.44	0.46	0.40

GPS time, which is controlled by a cluster of cesium clocks (namely, the accuracy is better than 50 ns). Consequently, taking into account a constant GPS error of 10 mm, the absolute speed error was 4 mm/s for a 5-s period [namely, (10mm + 10 mm)/5 s]. The relative error (RE = absolute speed error/speed) varied of course with walking speed (cf. Table 1).

Concerning SF, we assumed that the vertical oscillation of the head was close to a sine-wave at step frequency. This assumption was based on different results found in the literature (Hirasaki et al. 1999). The spectral analysis of the vertical GPS signal confirms this fact (cf. our previous study, Terrier et al. 2000). Therefore, we believe that 10 Hz sampling rate was sufficient to assess the SF. However, GPS errors superimposed a random, white noise on the actual trajectory of the head. In order to analyse the effect of this error on the determination of SF, we performed numerical simulation that mimicked the condition of the experiments: different sine waves (1.44 Hz, 1.81 Hz, 2.16 Hz, cf. Table 2) were generated. Each of these artificial signals contained 50 points (i.e. 5 s duration at 10 Hz sampling rate). A random white noise corresponding to the positioning error (i.e. 20% relative error for an average vertical lift of 50 mm, cf. Fig. 1B) was added to the signals. The simulation

Table 2 Walking parameters. Three times 12 subjects performed 100 m of walking at different freely selected speeds. Walking speed and step frequency (*SF*) were measured by high-precision GPS. Step length (*SL*) and walk ratio (*WR*) were calculated from speed and SF (SL = speed/SF, WR = SL/SF). The range is the lowest and highest value among subjects

Parameter		Low speed	Preferred speed	High speed
Walking speed (m·s^{-1})	mean (SD)	0.92 (0.17)	1.35 (0.23)	1.91 (0.18)
	range	0.72–1.23	1.05–1.82	1.68–2.21
Step frequency [steps·s^{-1} (Hz)]	mean (SD)	1.44 (0.11)	1.81 (0.16)	2.16 (0.14)
	range	1.28–1.59	1.57–2.16	1.99–2.52
Step length (m)	mean (SD)	0.63 (0.08)	0.74 (0.08)	0.89 (0.08)
	range	0.51–0.77	0.65–0.86	0.77–1.01
Walk ratio (m·steps^{-1}·s)	mean (SD)	0.44 (0.05)	0.41 (0.04)	0.41 (0.05)
	range	0.36–0.54	0.34–0.48	0.34–0.50

was repeated 100 times with different random noises for each sine wave, and the average relative error was calculated. By applying this method, we sought to illustrate that a random noise, which presents by definition a large spread in its spectrum, did not impair the detection of one particular frequency, provided the sampling rate is sufficiently high. The other parameters are derived from speed and SF, so their errors are estimated by the classical methods of the propagation of errors (i.e. the error on a product is the sum of the RE of each term of the product).

Statistical analysis

From the raw GPS data, two sets of data were formed. First, each 40-s trial was considered as a whole: a $12 \times 3 \times 4$ array was constituted (12 subjects $\times$ 3 trials (low, preferred, high speed) $\times$ 4 parameters (i.e. dependent variables: average speed, SF, SL, WR during the 40-s trial). This array was referred as *global* data, because we considered each trial without segmentation. Second, we computed 12 individual arrays (1 array per subject), i.e. 8 samples (8 samples of 5 s = 40 s) $\times$ 3 trials (low, preferred and high speed) $\times$ 4 parameters (speed, SF, SL, WR). These 12 arrays were referred as *individual* data, because the 3 trials of each individual were considered with a 5-s segmentation. Standard parametric statistical analysis {mean, SD, CV [= (SD/mean)$\times$100]} was performed. Different one-way ANOVA tests were computed in order to analyse the effects of speed. In order to take into account the difference of SDs between groups, the Welch's variance weighted ANOVA was used for the WR analysis. The differences between the slow/preferred/fast trials were analysed by using multiple comparisons (Tukey's procedure). Paired t-tests were also used to assess the similarity of the averages of different pairs of samples.

Results

GPS data

Figure 1 illustrates the type of data provided by the GPS technique for one representative subject. Position and speed data are shown in the "subjective" referential (x-axis in the direction of displacement). The plots represent 5 s duration, i.e. the basic duration for the calculation of the gait parameters. The intra-step variation of speed and position induced by the basic pattern of the gait can be clearly observed.

Measurement errors

Table 1 presents the theoretical RE. Speed RE decreased with speed, because a constant distance GPS error was assumed (1 cm). On the other hand, SF error (assessed by numerical simulation) increased with SF, because a higher SF approached Shannon's frequency (i.e. 5 Hz). The SL and WR errors represent the sum of the RE of speed and SF, and SF and SL respectively, because these parameters are computed from the others.

Basic gait parameters

Table 2 presents the average values ($n = 12$) of the different gait parameters (speed, SF, SL and WR). By design, average walking speed was significantly different between slow, preferred and fast speed conditions (global data, 3×12 one-factor ANOVA $p < 0.05$). The analysis of individual data confirmed that each subject selected a different walking speed during the different trials (12 one-factor ANOVA's 3×8, $p < 0.05$). When the subjects were asked to walk slowly, they selected a speed which was 31 (10)% lower than their preferred speed. When the instruction was to walk faster than their preferred speed, the subjects selected a speed 44 (16)% higher than preferred speed. It was found that SF and SL were significantly different between trials, either in the global data (one-factor ANOVA 3×12, $p < 0.05$) or in individual data (12 one-factor ANOVA's 3×8, $p < 0.05$).

Walk ratio

Despite the fact that a higher value at low speed was observed (0.44 vs. 0.41, cf. Table 2), this index did not change significantly between trials when global data were considered (one-factor ANOVA 3×12, $p > 0.05$). In addition, if WR is assumed constant over the entire range of speeds, SF should be proportional to the square root of walking speed (speed$^{0.5}$). SF and speed$^{0.5}$ were highly correlated ($R^2 = 0.88$, $p < 0.01$, $N = 288$, 8 samples, 3 different trials and 12 subjects). In contrast, a close analysis of individual data showed that 9 of the 12 subjects (three-quarters of them) exhibited a significant speed effect with respect to WR (12 one-factor Welch's ANOVA's 3×8). Tukey's analysis ($p < 0.05$) for assessing differences between pairs of samples demonstrated that three-quarters of the subjects had significantly different WR between slow and preferred trials, but that only one-third of the subjects had significantly different WR between preferred and fast trials.

The analysis of global data (i.e. the data averaged over 40 s) showed that the inter-subject variability of WR ($n = 12$), expressed as CV, was 11% at slow speed, 10% at preferred speed and 12% at fast speed (cf. Table 2). The individual results are presented in Fig. 2: average WR was plotted as a function of average speed for each subject. It can be observed that generally WR seemed higher at low speed than at preferred and high speed. However, two subjects exhibited a constant decrease of WR when speed increased, and one subject exhibited a substantial increase of WR between preferred and high speed.

Step frequency index

Figure 3 presents the individual results for SFI. Average SFI was 0.58 (0.09) (CV = 17%) between slow and preferred runs. This value is significantly different from 0.5 (two-tailed t-test for average SFI = 0.5: $p < 0.05$, one-tailed t-test for average SFI $\leq$ 0.5: $p < 0.01$). Therefore, SF contributed more to the speed increase than SL. This confirms the decrease of WR with speed observed in Fig. 2. Indeed, a lower WR indicates a higher SF. Between preferred and fast trials, SFI was 0.50 (0.13) (CV = 26%),

Fig. 2 Individual walking speed vs. walk ratio (WR = step length/step frequency) in 12 subjects. Average WR values for slow (*circles*), preferred (*triangles*) and fast (*squares*) runs are presented for each subject. *Dashed lines* connect data of each subject. *Vertical* and *horizontal lines* are SD of WR and speed respectively
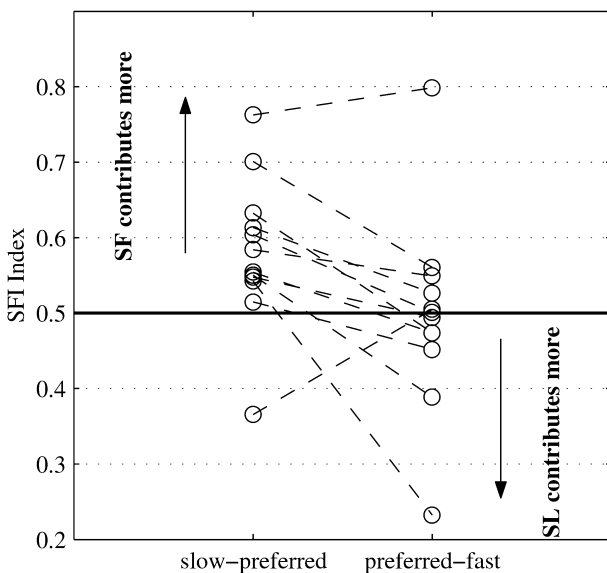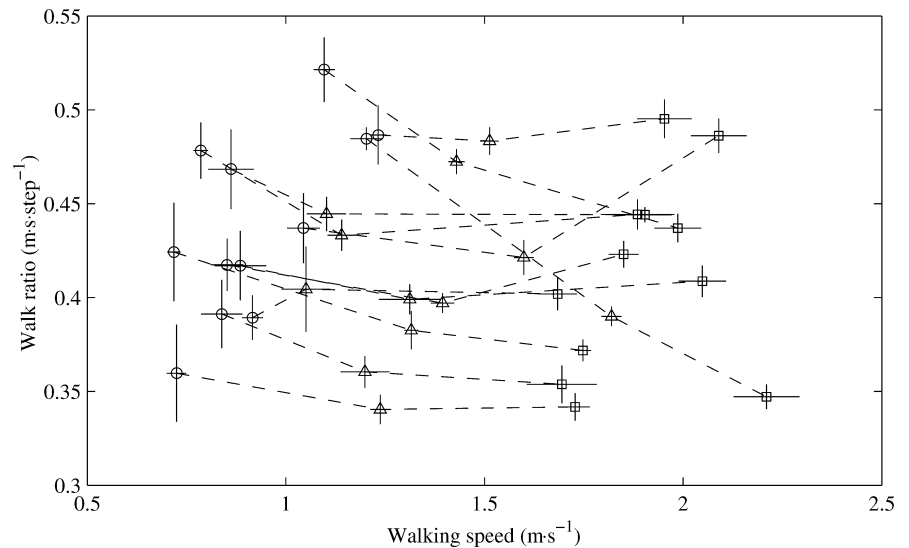

Fig. 3 Relative contribution of stride frequency (*SF*) to walking speed changes in 12 subjects. Stride frequency index (*SFI*, defined in Eq. 1) was calculated between slow and preferred trials (0.92–1.35 m/s) and preferred and fast trials (1.35–1.91 m/s). The *bold horizontal line* indicates an equal contribution of SF and SL. *Dashed lines* connect the subjects' values to highlight the trend of the variation

indicating that SF and SL contributed equally to the speed increase. The substantial inter-subject variability of WR shown in Fig. 2 was confirmed.

Intra-subject variability

The intra-subject (5 s to 5 s) variability of the different gait parameters was computed from individual data, and expressed as CV ($n = 8$ samples). These individual results are presented as box plots in Fig. 4. This figure highlights the average sample-to-sample variability during each 40-s trial across subjects. The variability is low (less

than 5%) for all parameters. Furthermore, no significant difference was found between the different trials for speed and SL. However, a significant difference was observed for SF and WR (3×12 single factor ANOVA, $p > 0.05$). WR variability was particularly low in all subjects (with one exception) during preferred and fast speed trials: the average CV's were 1.9% and 1.8% respectively. On the other hand, the intra-subject variability of WR was higher under slow speed conditions (average CV = 4.1%). The 5-s to 5-s variations exhibited substantial differences among subjects; for instance, at preferred speed (Fig. 4, middle), the speed variability ranged from 1.3% to 6%, the SL variability from 0.7% to 4.7%, the SL variability from 0.5% to 3.7% and the WR variability from 0.6 to 2.7% (outlier at 5.7%).

Test re-test experiment

The three subjects who repeated the experiment selected a different preferred walking speed (paired *t*-test, $p < 0.05$). One of them selected a similar speed during a slow run and a second one a similar speed during a fast run (paired *t*-test, $p > 0.05$). Figure 5 illustrates the changes of WR between the two sessions. WR was not systematically similar between sessions. However, the general pattern of the adaptation of WR to speed change was conserved for each subject.

Discussion

The GPS technique seems to offer a good alternative to the classical laboratory method of analysing gait parameters of unconstrained walking. The advantage is to be close to a ''physiological'' situation with minimal constraint for the subject. In addition, this technique permitted us to record longer walking periods. It was possible to follow the variation of the gait pattern over a

Fig. 4 Relative intra-subject variability of speed, step frequency (*SF*), step length (*SL*) and walk ratio (=SL/SF) at three different speed conditions (presented as whiskers-box plots)
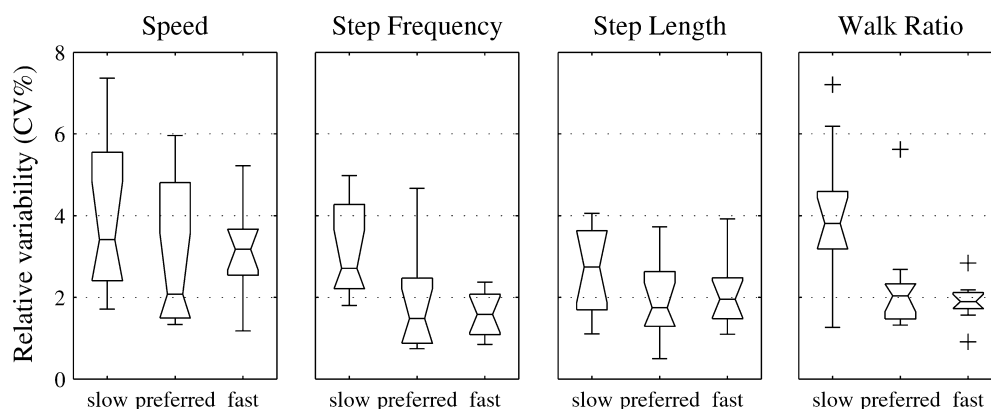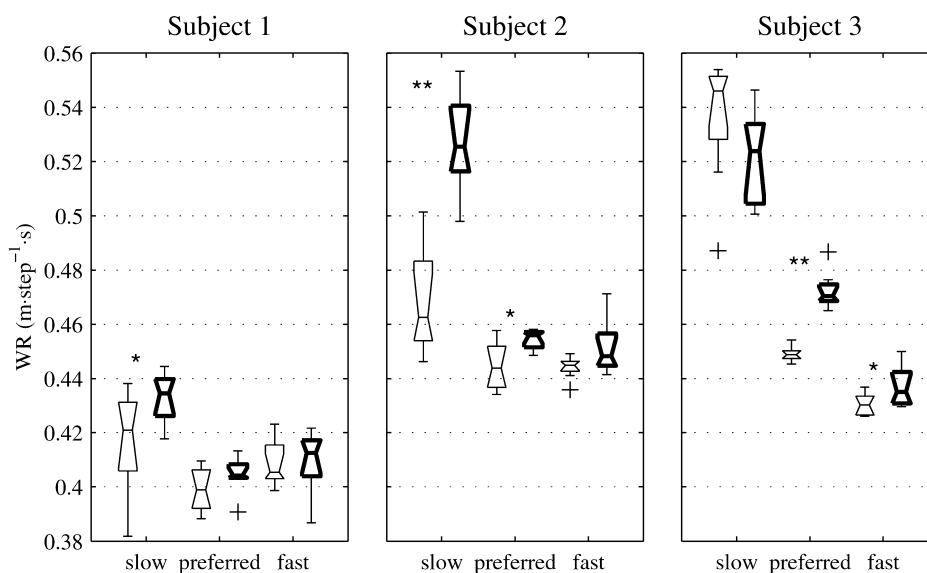

Fig. 5 Test-retest of walk ratio in three subjects (2-month interval). *Bold boxes* are retest results. Whiskers-boxes present the intra-subject variability (*n*=8 samples of 5 s duration). *Significant difference between tests, *t*-test *p*<0.05. **Significant difference, *t*-test, *p*<0.001

distance of 100 m, under free walking conditions. This is very difficult to realize under laboratory conditions with classical methods such as video analysis.

In our previous GPS studies (Terrier et al. 2000, 2001), the gait parameters were assessed from a substantial number of consecutive strides, and then averaged. In the present study, the purpose was to reduce the number of strides from which the gait parameters were averaged. A 5-s interval seemed ideal in terms of compromise between minimizing measurement errors and optimizing the time interval for studying intra-subject variability. Indeed, we chose to calculate SF from the power spectrum of the vertical signal: as demonstrated with the numerical simulation, this method constitutes a good solution for detecting a frequency from a noisy signal. With the new GPS receiver we used, the sampling rate (10 Hz) was therefore sufficient for the assessment of SF with minimal error (0.01–0.1%, cf. Table 1). This confirms the result we obtained in our previous study (Terrier et al. 2000): average SF assessed from the GPS data was comparable to average SF assessed from a portable accelerometer (40 Hz). With regard to the error

of walking speed, the 5-s window induced low theoretical errors (0.2–0.4%). If the errors of speed and SF are both low, SL and WR also must exhibit low errors.

Nowadays, it seems that the high-accuracy GPS technology is difficult to implement in bio-medical applications. Indeed, high-precision positioning requires many satellites (seven and more), with a wide distribution in the sky (low dilution of precision): such an ideal configuration occurs in a narrow time window during the day and reduces the time frame for conducting experiments.

However, future technical developments will undoubtedly increase the practicality of the technique; for example, the size of the receivers will be reduced with a higher computation power (new 100 Hz GPS chips are already available). With regard to GPS satellites, a challenging modernization program will offer a third civilian frequency (L5) for better availability and accuracy. To increase coverage, additional Russian GLONASS satellites will be also launched in the near future. Finally, the European positioning system (Galileo) is planned for the next decade: it will provide a third independent system. Consequently, the accuracy and

availability of satellite positioning have a substantial potential of growth.

In the past, different studies highlighted that humans spontaneously select gait patterns that require a minimum energy cost of walking (Minetti et al. 1995). The invariant relationship between step length and step rate seems to be a constraint for optimal energy economy: Zarrugh showed, for instance, that more energy was expended with a deviated walk ratio (Zarrugh et al. 1974; Zarrugh and Radcliffe 1978). In parallel, other authors showed that gait patterns with invariant WR require minimal attentional demand and are optimal in terms of movement stability (Kurosawa 1994; Holt et al. 1995). Recently, a study showed that the relationship between walking speed and SF was obtained by the assumption that a person optimizes an underlying objective function of speed and SF that has a minimum at preferred gait: a reasonable approximate candidate for this function is the metabolic cost of displacement (Bertram and Ruina 2001). Consequently, WR seems to be an important factor for studying both energetic and psychomotor aspects of human locomotion.

The value of WR at preferred speed (0.41 m·s·steps^{-1}) was comparable to the values described in literature for laboratory experiments [0.40 m·s·steps^{-1} (Sekiya et al. 1996), 0.37 m·s·steps^{-1} (Sekiya and Nagasaki 1998)]. By studying the non-segmented data (global data), we observed that WR remained constant when the subjects varied their walking speed, as demonstrated by the high correlation between SF and speed$^{0.5}$ ($R^2 = 0.88$, $p < 0.01$). However, this constancy was not confirmed by a closer analysis of the individual segmented data. Indeed, as in the previous study of Sekiya et al. (1996), we observed that WR was higher at low speed for the majority of subjects. This finding is corroborated by the SFI analysis (Fig. 3): in order to increase walking speed from slow to the preferred speed, the subjects increased their cadence more than their step length. It seems that slow walking requires a different spatial and temporal adaptation of the gait, compared to preferred or fast walking. In contrast, SFI index analysis confirmed that speed change was mediated by SF to the same extent as SL between preferred and fast speeds. Our results are different from those obtained by Hirasaki et al. (1999): these authors described that speed increase was mediated preferentially by an increase of SL between 1.0 and 1.6 m/s. This may be due to the difference in perception between the use of the treadmill in his study and unconstrained walking in our study, but this remains to be further investigated.

The inter-subject variability of WR was substantial (CV = 10–12%) as compared to short-term intra-subject variability (CV = 1.8–4.1%). Past studies observed that body height increases WR, especially at preferred and fast speeds: tall subjects walk with longer steps because of the standard compass gait model (Sekiya et al. 1996). This is probably the main factor influencing WR. However, this factor or other anthropometric parameters do not easily explain why some subjects substan-

tially modified their WR with speed while most of the subjects kept a constant WR between the preferred and fast speed trials (cf. Figs. 2 and 3). It can be assumed that each person develops his/her own walking habits during childhood and has a personal strategy for adapting gait patterns according to speed. This remains to be further investigated.

We observed that slow speed walking not only induced a different gait pattern (higher WR), but also exhibited substantial variability. Indeed, under low speed conditions, the average intra-subject variability (5-s to 5-s segmentation) of WR was relatively high (CV = 4.14%). In contrast, under preferred and fast speed conditions, average WR variability was more than two times lower (CV = 1.9% and 1.8%). In addition, it should be noted that the low variability of WR is a relatively constant feature among subjects; for instance, all subjects except one walked at preferred speed with a variation of WR ranging from 0.58% to 2.68%.

The test re-test experiment (Fig. 5) demonstrated that the constancy of WR should not be considered as a systematic rule. Indeed, under the same experimental conditions, a subject (for instance, subject 3) may adopt a significantly different gait pattern (i.e. a different WR) if the test is repeated. However, the general pattern of the adaptation of WR to speed was mostly conserved. Further studies with a larger number of subjects are warranted to confirm these findings.

The stride-to-stride variability of stride duration (the inverse of SF) has been thoroughly studied by Hausdorff et al. during the last decade (Hausdorff et al. 1995, 1996, 1998, 1999, 2001a, 2001b). Despite a different experimental design, our data can be compared with the long-term variability found in these studies. In 12-year-old children, a stride-time variability of 2.1% (CV) was described for preferred walking speed (Hausdorff et al. 1999). During a 1-h walking test in healthy young subjects, the variability of stride time was lower than 3% (Hausdorff et al. 1996), whereas in 70-year-old adults, they described a slightly higher value averaging 3.6 (1.8)% (Hausdorff 2001a). In the present study, the variability of SF was 3.07 (1.25)% at low speed, 1.79 (1.17)% at preferred speed and 1.51 (0.52)% at high speed. Because in our study we assessed average SF variability from 5-s segmented values and because the duration of the measurement was shorter, lower values were expected. However, our results agree with Hausdorff's findings. The low intra-subject variability of SF is in accordance with the neuro-motor hypothesis of central pattern generators, i.e. specialized neural networks generating a constant frequency that maintain a constant SF (Hausdorff et al. 1995). In addition, an important difference in methodology can be outlined: the GPS method allowed us to retrieve simultaneously three parameters, i.e. speed, SF and SL data. In contrast, the footswitch method (force-sensitive insoles) used by Hausdorff et al. can monitor stride time series only. We believe that our approach opens new perspectives in the analysis of long-term variability of walking with a

better spatio-temporal description of the gait (i.e. simultaneous assessment of speed, SL, and SF) over a prolonged period of time.

Taken together the different results of the present study permit us to discern three parameters of interest in order to give a general description of the gait pattern of a subject:

- The WR at preferred speed
  This index indicates the spatiotemporal adaptation of the gait to preferred speed condition. It mainly depends upon body height (Sekiya et al. 1996).
- The SFI between slow, preferred and fast walking speed
  This index indicates the adaptation of the gait to speed changes. It assesses whether the subject keeps a constant WR when he/she modifies his/her walking speed, or adopts a different strategy.
- The WR variability at preferred speed
  This index indicates whether the subject walks with a constant pattern. Because WR is the ratio between SL and SF, this is an average index of the spatio-temporal mid-term gait stability.

It is concluded that the GPS method, using a professional receiver, can measure basic gait parameters with a 5-s time frame, what enables assessment of the variability of continuous walking. Furthermore, in free-living conditions, gait parameters and WR in particular exhibited low intra-subject variability, but substantial inter-subject variability. In other words it seems that the gait parameters and their adaptation to speed changes constitute an individual characteristic that makes it difficult to determine what a normal and "healthy" gait is. Further investigations using GPS technology may contribute to delineate, with a much larger group of subjects, the effect of different parameters (such as age, gender, obesity, leanness, chronic diseases and pharmacological treatment) on gait characteristics.

References

Bertram JE, Ruina A (2000) Multiple walking speed-frequency relations are predicted by constrained optimization. J Theor Biol 21:445–553

Grieve DW, Gear RJ (1966) The relationships between length of stride, step frequency, time of swing and speed of walking for children and adults. Ergonomics 9:379–399

Hausdorff JM, Peng CK, Ladin Z, Wei JY, Goldberger AL (1995) Is walking a random walk? Evidence for long-range correlations in stride interval of human gait. J Appl Physiol 78:349–358

Hausdorff JM, Purdon PL, Peng CK, Ladin Z, Wei JY, Goldberger AL (1996) Fractal dynamics of human gait: stability of long-range correlations in stride interval fluctuations. J Appl Physiol 80:1448–1457

Hausdorff JM, Cudkowicz ME, Firtion R, Wei JY, Goldberger AL (1998) Gait variability and basal ganglia disorders: stride-to-stride variations of gait cycle timing in Parkinson's disease and Huntington's disease. Mov Disord 13:428–437

Hausdorff JM, Zemany L, Peng C, Goldberger AL (1999) Maturation of gait dynamics: stride-to-stride variability and its temporal organization in children. J Appl Physiol 86:1040–1047

Hausdorff JM, Nelson ME, Kaliton D, Layne JE, Bernstein MJ, Nuernberger A, Singh MA (2001a) Etiology and modification of gait instability in older adults: a randomized controlled trial of exercise. J Appl Physiol 90:2117–2129

Hausdorff JM, Rios DA, Edelberg HK (2001b) Gait variability and fall risk in community-living older adults: a 1-year prospective study. Arch Phys Med Rehabil 82:1050–1056

Hirasaki E, Moore ST, Raphan T, Cohen B (1999) Effects of walking velocity on vertical head and body movements during locomotion. Exp Brain Res 127:117–130

Holt KG, Jeng SF, Ratcliffe R (1995) Energetic cost and stability during human walking at the preferred stride frequency. J Mot Behavior 27:164–178

Kurosawa K (1994) Effects of various walking speeds on probe reaction time during treadmill walking. Percept Mot Skills 78:768–770

Minetti AE, Capelli C, Zamparo P, di Prampero PE, Saibene F (1995) Effects of stride frequency on mechanical power and energy expenditure of walking. Med Sci Sports Exerc 27:1194–1202

Nagasaki H, Itoh H, Hashizume K, Furuna T, Maruyama H, Kinugasa T (1996) Walking patterns and finger rhythm of older adults. Percept Mot Skills 82:435–447

Perrin O, Terrier P, Ladetto Q, Merminod B, Schutz Y (2000) Improvement of walking speed prediction by accelerometry and altimetry, validated by satellite positioning. Med Biol Eng Comput 38:164–168

Sekiya N, Nagasaki H (1998) Reproducibility of the walking patterns of normal young adults: test-retest reliability of the walk ratio (step-length/step-rate). Gait Posture 7:225–227

Sekiya N, Nagasaki H, Ito H, Furuna T (1996) The invariant relationship between step length and step rate during free walking. J Hum Mov Stud 30:241–257

Terrier P, Ladetto Q, Merminod B, Schutz Y (2000) High-precision satellite positioning system as a new tool to study the biomechanics of human locomotion. J Biomech 33:1717–1722

Terrier P, Ladetto Q, Merminod B, Schutz Y (2001) Measurement of the mechanical power of walking by satellite positioning system (GPS). Med Sci Sports Exerc 33:1912–1918

Zarrugh MY, Todd FN, Ralston HJ (1974) Optimization of energy expenditure during level walking. Eur J Appl Physiol 33:293–306

Zarrugh MY, Radcliffe CW (1978) Predicting metabolic cost of level walking. Eur J Appl Physiol 38:215–223