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Stereotyped Pattern of Lower Limb Movement during Level and Grade Walking on Treadmill

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The effects of speed and gradient on stereotyped pattern of temporal-distance parameters of the lower limb in human gait were observed on five male subjects walking on a treadmill. Step length and step duration were consecutively determined by means of a computerized system. Step length increased approximately in proportion to the square root of the speed, and step duration decreased in proportion to the reciprocal of the square root of the speed. In grade walking, when compared with level walking, the subject had a tendency to take shorter steps at high speeds and longer steps at low speeds. Standard deviations of step length and step duration showed the minima at the speeds which were estimated to be about 90 and 95m/min for step length and step duration, respectively, although there were some variations of the speed with gradient. Coefficients of variation of these factors also showed the minima at particular speeds. These results suggest that when the subject is allowed to choose his own step length, there exists the speed at which the fluctuation of stereotyped movement of lower limb shows the minimum.

Key words : Stereotyped Movement, Level and Grade Walking, Step Length, Step Duration

INTRODUCTION

From the physiologic and anthropologic viewpoints, bipedal walking is one of the most interesting aspects of all human activities. Many investigators have analyzed various characteristic events occurring during walking. They have employed bioengineering techniques such as electrogoniometer, force plate, electromyography, accelerometer, and photography to aid in investigating human locomotion (Reviewed by Nakamura & Saito, 1979). However, these studies have been confined for the most part to the analysis of a few walking cycles. There is little information regarding the variability of stereotyped pattern in successive walking cycles.

We have investigated the fluctuation of step lengths measured in succession during treadmill walking, and suggested that series of step lengths do not fluctuate at haphazard but there are some systematic alternations in the fluctuation of step lengths. That is, autoregressive analysis of step lengths revealed a periodicity of two steps which might be considered as an endogenous mechanism (Yamasaki & Sasaki, 1982) and mental activities during walking reflected in time series of step lengths (Yamasaki, *et al.*, 1983). More recently, we also reported that there existed the walking speed at which the fluctuations of temporal-distance parameters show the minima, and the speed was estimated at about 90 m/min both for male and female ; in addition, the optimal step length and stride length, defined as the most suitable dimensions for gait, were calculated at 72cm and 145cm, respectively (Yamasaki, *et al.*, 1984). These results may be basically in agreement with the findings of Cotes and Meade (1960) and Beckett and Chang (1968) who observed the optimal cadence at which energy expenditure is minimal in walking at a constant speed.

The primary aim of the present study was to describe the effects of speed and gradient on stereotyped pattern of temporal-distance parameters in treadmill walking. For this purpose, step lengths and step durations measured in succession in level and grade walking on treadmill, and their means, standard deviations and coefficients of variance were calculated.

METHOD

Five healthy males of non-athletes volunteered as subjects in this investigation. The physical characteristics of the subjects in age, height and weight (mean±SE) were 25.2±2.4 years, 170.2±4.7cm and 66.0±5.2kg. During the experiment the subject wore walking shoes and gym clothes. The subjects walked on a motor-driven treadmill (Quinton 18-60) with inclination of 0, 5 and 10%, at different speeds between 60 and 120m/min with a stepwise increment of 10m/min. For the steepest gradient, the maximum speed was 10m/min slower. The belt speed of the treadmill was measured on a tachometer and calibrated, with and without an 83kg person walking on it, over the entire speed range, and it was confirmed that the belt speed was not affected by weight loading.

Step lengths and step durations of a thousand steps were successively measured. The last 200 steps for each of the three gradients at various speeds were used for analysis. Step length and step duration are defined as the linear distance and the time interval between successive heel strikes of alternate feet, respectively (Murray, *et al.*, 1964; Lamoreux, 1971).

For measurement and computation of data we employed the computerized system consisting of a minicomputer (JEC-6, JEOL), a position sensitive device, PSD, (C1373-16, Hamamatsu T.V.) and foot switches (Ribbon switch 102-B, Tapeswitch Corp. Amer.). The requirements of the system are: (1) consecutive measurement of step length and step duration, (2) accuracy of step length within 1cm, (3) on-line collection and storage of data. The details on the method of data collection has been described in our previous paper (Yamasaki, *et al.*, 1981),

RESULT

Time series data samples of step lengths from one subject for each of three gradients at two speeds of 60 and 110m/min are shown in Fig. 1. Step lengths were distributed at random around the mean values. The deviation seemed to be somewhat related to gradient. In grade walking, fluctuations of step lengths tended to be slightly larger than those in level walking, particularly in the steepest grade walking. There was a wide variation in absolute values of step lengths reached by different individuals, but they all showed the same pattern of response, as illustrated in Fig. 1.

Mean values and standard deviations were calculated for 200 step lengths and for 200 step durations for each of three gradients at various speeds. With an increase of speed from 60 to 120m/min, the step length increased from 60 to 90cm (150%), and the step duration decreased from 620 to 430 msec (70%). The relationship of step length (L, cm) or step duration (D, sec) to walking speed (V, m/min) appeared to be curvilinear rather than linear. Assuming the relationship to be L (or D)=

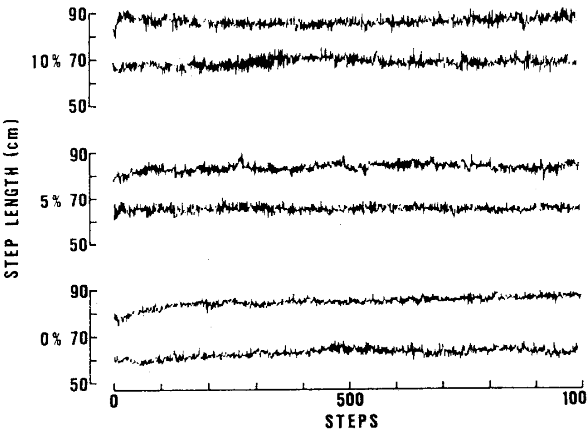

Fig. 1 Time series data samples of step lengths for one subject at 60 m/min (lower) and 110 m/min (upper) for each of three gradients.

Table 1 Values of the constants, α and β, and correlation coefficients(r), from the relation L(or D)$=\alpha V^{\beta}$ of step length L(or step duration D) and walking speed V, derived by plotting results for all subjects.

Inclination	Step length			Step duration		
%	α	β	r	α	β	r
0	5.72	0.57	0.955	3.40	−0.43	0.919
5	9.51	0.46	0.851	5.33	−0.52	0.876
10	10.51	0.43	0.831	5.89	−0.55	0.886

αV^{β}, the constants, α and β, were estimated and given in Table 1. Although in no case the linearity of the regression could be rejected, the correlation coefficients obtained were somewhat lower when compared with those in Table 1. The step length increased approximately in proportion to the square root of the speed, while the step duration decreased approximately in proportion to the reciprocal of the square root of the speed. This is also confirmed by the fact that the sum of absolute exponents (β) of step length and step duration makes unity for each of three gradients. From this table it is also evident that α increased with gradient both for step length and for step duration.

Fig. 2 illustrates the relation between standard deviation of step length and walking speed at each of three gradients. Significant differences existed between the standard deviations of step length in the steepest grade walking and those in other grade walking ($p<0.001$). In any case the standard deviation of step length seemed to increase exponentially at speeds slower and at speeds greater than a particular speed. Best-fit polynomial of degree 3 was estimated for evaluation of standard deviation of step length with respect to the speed, and the polynomial constants were found significant, except in the steepest grade walking ($p<0.1$).

Standard deviation of step duration increased remarkably at the slowest speed (Fig. 3). As well as standard deviation of step length, there were significant differences between the standard deviations of step duration in the steepest grade walking and those in other grade walking ($p<0.001$). In addition, the polynomial regression line of standard deviation of step duration against walking speed could also be obtained for each gradient.

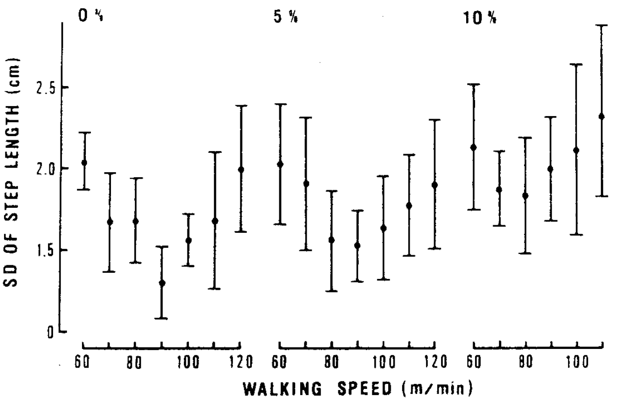

Fig. 2 Relation between standard deviation (SD) of step length and walking speed in level (0%) and grade (5 and 10%) walking. The vertical lines represent standard deviation about the mean values obtained for the five subjects.

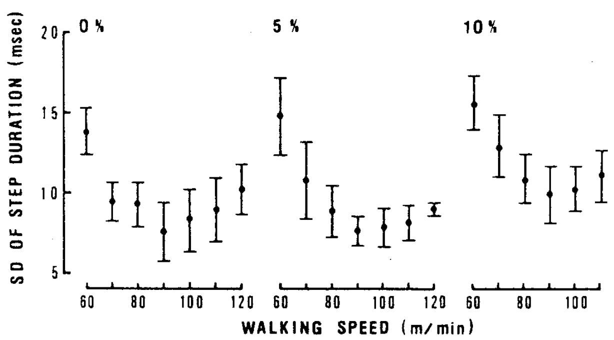

Fig. 3 Relation between standard deviation (SD) of step duration and walking speed in level (0%) and grade (5 and 10%) walking. The vertical lines represent standard deviation about the mean values obtained for the five subjects.

It is naturally expected that the longer the step length, the greater the movement of the body with each step. Therefore, we must take the ratio of standard deviation to the mean value into consideration. Fig. 4 shows relation between coefficient of variation (CV) of step duration and walking speed at each of three gradients. Apparently a polynomial regression line of degree 3 was fitted for each of three gradients, as with other measurements. Table 2 shows the walking speeds with minimal SD and CV of step length and step duration

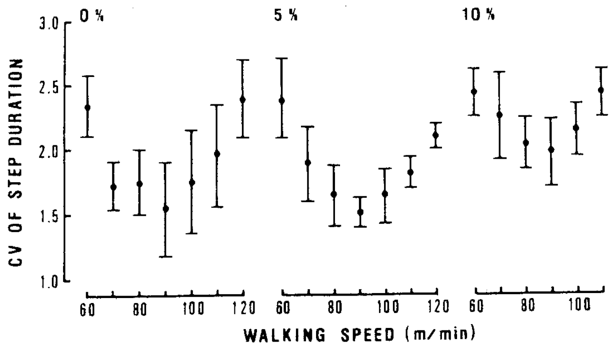

Fig. 4 Relation between coefficient of variation (CV) of step duration and walking speed in level (0%) and grade (5 and 10%) walking. The vertical lines represent standard deviation about the mean values obtained for the five subjects.

Table 2 Walking speeds(m/min) at minima of standard deviations(SD) and coefficients of variation(CV) at each of three gradients. Values in parentheses are estimated by substituting the speeds at minima for V in equations L (or D) $= \alpha V^{\beta}$ in Table 1.

Inclination	Step length		Step duration	
%	SD	CV	SD	CV
0	90.69 (74.7cm)	98.22	93.56 (483ms)	86.73
5	90.85 (75.7cm)	98.70	95.05 (499ms)	89.52
10	76.53*	85.60	91.44 (491ms)	86.19

* There is no significant correlation between SD of step length and speed($p < 0.1$)

derived from the best-fit polynomials. The speeds ranged from 90 to 100m/min and the slowest speed was seen in the steepest grade for each measurement. Table 2 also gives both the step lengths and the step durations obtained by substituting the speeds at minima for V in equation L (or D) $= \alpha V^{\beta}$. For the two gradients (0 and 5%) there were no essentially differences in step length and step duration evaluated by the equation, which were estimated to be about 75cm and 490msec, respectively. Theoretically the values might be able to be regarded as the optimum step length and the optimum step duration.

DISCUSSION

The variability of walking pattern from step to step exists even at a constant speed. The variability could be considered as the physiological response to walking (Yamasaki, *et al.*, 1984). Wall and Charteris (1980, 1981) pointed out that the variability was dependent on the process of habituation to treadmill walking and concluded that a stable walking pattern was achieved after 1 hour's habituation on a treadmill and temporal components should not be measured within the first 2 min of walking. Our subjects were well accustomed to treadmill walking, and both step length and step duration could be regarded as a steady state, because the first 200 and the last 200 steps of a thousand steps showed no significant differences in both step lengths and step durations of the same subjects.

Milner & Quanbury (1970) showed that both step length and cadence increased with the square root of speed. We also found the exponentials of about 0.5 for step length and about -0.5 for step duration which is linearly in inverse proportion to cadence. The exponentials for both step length and step duration decreased with inclination, whereas constants in Table 1 increased with inclination, which means that in grade walking, subjects took shorter steps at high speeds and longer steps at low speeds as compared with level walking. A few authors have examined the relationships of step length on gradient (Erickson, *et al.*, 1946; Bobbert, 1960). They observed that step length was not systematically influenced by gradient. However, they could not estimate the slight variation of step length because this conclusion was elicited from dividing the walking distance by step frequency.

The curves of standard deviation and coefficient of variation of temporal-distance parameters, plotted as ordinate against speed as abscissa, were concave upward. Walking speeds at minima of standard deviations of temporal-distance parameters tended to decrease for the steepest grade. In level and gentle grade walking, the speed at minimum of standard deviation of step length was estimated to be about 90m/min. This result is in accordance with the finding of our previous study (Yamasaki, *et al.*, 1984), which described the speeds at minima of standard deviation of step length as 88.3 and 91.6m/min for male and female, respectively. Although the optimum step length obtained (about 75cm) was also consistent with the previous report (about 72cm), these values were calculated by means of two regression equations. Therefore, it is not evident whether this optimum step length was essential for the Japanese adult man.

In walking, the movement of the body components would be made in such a way as to minimize the amout of mechanical work that is done (Beckett and Chang, 1968). It seems reasonable, therefore, to expect that the speed at minimum of standard deviation of temporal-distance parameters might be directly related to the optimal speed at which the energy cost per unit of distance moved is minimal. Since many authors have found the optimum speed to be between 60 and 90m/min (e.g. Cotes and Meade, 1960; Zarrugh, *et al.*, 1974), the optimum speed seems to be a little greater than the speed at minimum of standard deviation of temporal-distance parameters. However, a large value of the standard deviation of step length can be regarded as an increment of sway in the antero-posterior direction during treadmill walking. In such a case, there also is a possible increase of lateral and vertical sway, as well as antero-posterior sway. It migth be warranted, therefore, to assume any correlation between the fluctuation of body movement during walking and the optimal speed.

In this study we can also calculate both stride length and stride time which are defined as the linear distance and the time interval between successive heel strikes of the same foot, respectively. Thus it can be deduced that the trends of the stereotyped patterns of these factors are similar with those of step length and step duration, so long as there is no remarkable laterality of walking pattern (Yamasaki, *et al.*, 1984).

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