Communication

Gait analysis using a measuring walkway for temporal and distance factors

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1 Introduction

It may be wise for characteristic analysis of human gait to use specific measured discrete variables, representing its final output—the distance and temporal factors of foot-floor contact—because gait is typical of stochastic phenomena, which are very complex and highly different between individuals and also variable within an individual. A combination of several methods, for example radiography with force-plate data (Saleh and Murdoch, 1985; Winter *et al.*, 1974), can produce abundant and detailed analogous information. However, the more abundant it becomes, the more complex is the evaluation of its clinical relevance and essential characteristics, and the more costly is its application, even when considered on the basis of normalised patterns.

The measurement of distance and temporal factors has already been achieved by the application of pressure-sensitive sheets and instrumented shoes (Murray and Sepic, 1964; Winter *et al.*, 1974; Gabel *et al.*, 1979; Durie and Farley, 1980; Arenson *et al.*, 1983; Knight *et al.*, 1983). However, using these methods usually involved processing the measured data manually. Recently reported online systems may be relatively inadequate, complex and too expensive to be suitable for daily clinical use when compared with the system reported in a more recent study (Hirokawa and Ezaki, 1983). Using this latter system, some analysis has been performed to investigate temporal and distance factors in normal gait and temporal and distance factors in normal gait under some temporal or distance constraints.

2 Methods and materials

2.1 *Data acquisition*

The measuring apparatus (Figs. 1 and 2) consists of an instrumented walkway (constructed from several unit-walkways) for signal acquisition and a microcomputer for data processing and recording. Data acquisition can be performed while a subject walks only 12 m in arbitrary shoes or bare feet without any additional restriction. A unit-walkway consists of a 0·01 m × 0·01 m wire-latticed board 1·28 m long and 0·9 m wide, and designed to be connected with each other (Fig. 3). In this way any length can be made available, being typically 12 m long (eight units with start- and stop-mats) for an adult.

The wires were passed through urethane foam, through punched out round circles of 0·007 m diameter for each lattice, separated by 0·003 m vertical distance between the

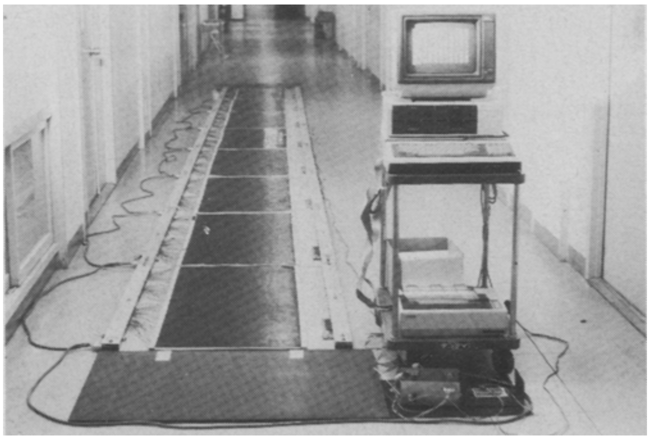

Fig. 1 *General view of our walkway system. Data acquisition and analysis can be done by a simple procedure: subjects must only walk 12 m in arbitrary shoes or bare feet without any additional restriction*

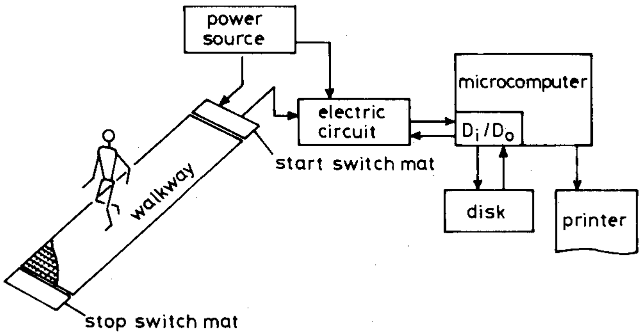

Fig. 2 *Schematic drawing of the walkway system, constructed with an instrumented walkway for signal acquisition and a microcomputer for data processing and recording*

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x- and y-axis wires. The separated wires between the crossing x- and y-axis wires come into contact with each other when a pressure in excess of 24 500 Pa is applied by a foot stamp on the walkway.

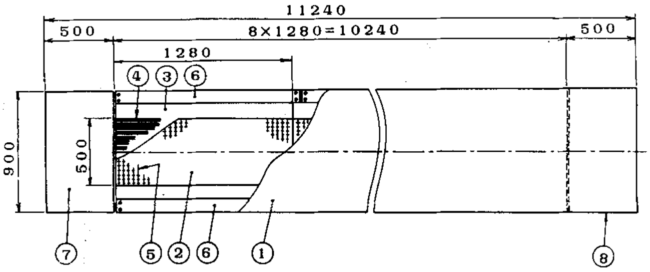

Fig. 3 *A unit-walkway; a grid 1·28 m long and 0·9 m wide, divided into 0·01 m² wiring networks to detect footprint patterns. Ordinarily eight units are connected to each other for investigating adults. In the figure, length is expressed in mm. ①: cover sheet, ②: urethane-foam, ③: base-plate, ④: y-axis, ⑤: x-axis, ⑥: side bar, ⑦: start-switch mat, ⑧: stop-switch mat*

This contacting state is electrically detected, for example, if one of the x-axis wires (to which an electric potential of 5 V is applied) makes contact with some of the y-axis wires. The contacting y-axis wires are easily identified from the currents, derived from the x-axis wire. Position data on the foot stamp and its temporal shift are acquired and traced as wire-cross points by sweeping and switching over between the x- and y-axis wires to search the wires for electric currents, derived from the separated cross-axis wires (Fig. 4). These procedures are performed by a combination of a digital multiplexer and demultiplexer (sweeping), a transistor comparator array (electric current detection) and a crystal oscillator for standard frequency excitation (Fig. 5). Then these data are sent to a microcomputer through a parallel interface (digital) bus. The sweep frequency can vary from 0·1 to 0·01 Hz to adjust to individual gait velocity.

2.2 *Data processing*

2.2.1 *Detection of footprint:* As shown in Fig. 4, a real foot stamp pattern ⑤ cannot be formed by wire-latticed switch matrices, but only as a square-shaped pattern ⑥. Moreover, a dummy area ⑧ appears if the opposite foot ⑦ stamps at the same time. Considering these conditions, logic to discriminate between single and double-support durations was constructed. First, a foot sole pattern was approximated to the shape in Fig. 6, and notations were introduced as:

W, D: pseudolengths of longitudinal and transverse foot axis on the walkway
W_f, D_f : true lengths of foot axis
r_a, r_b : parameters to correct the acquired square-shaped footprints to more accurate forms (ordinarily $r_a = W_f$, $r_b = W_f/2$).

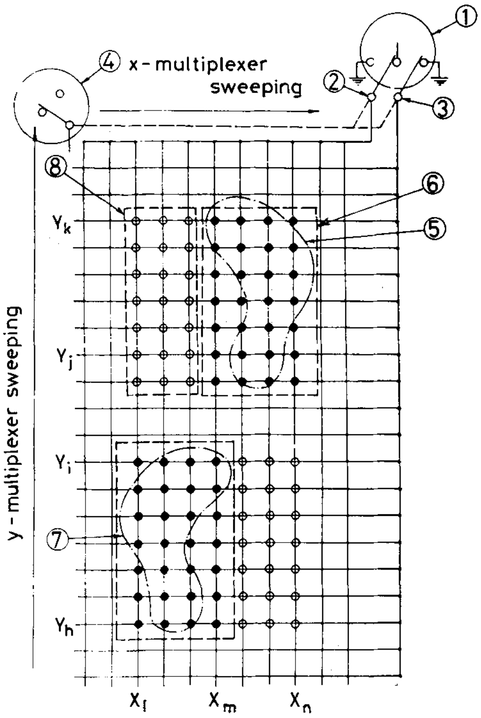

Fig. 4 *Wiring network to detect foorprint patterns. ①: multiplexer for switching to which axis is 5 V applied, ②: multiplexer for switching the electric current among the x-axis wires, ③: multiplexer for switching the electric current among the y-axis wires, ④: multiplexer for switching which axis is swept to detect electric current, ⑤: a real foot stamp pattern, ⑥: a square shaped pattern, ⑦: the opposite foot stamp at the same time, ⑧: a dummy area by ⑦*

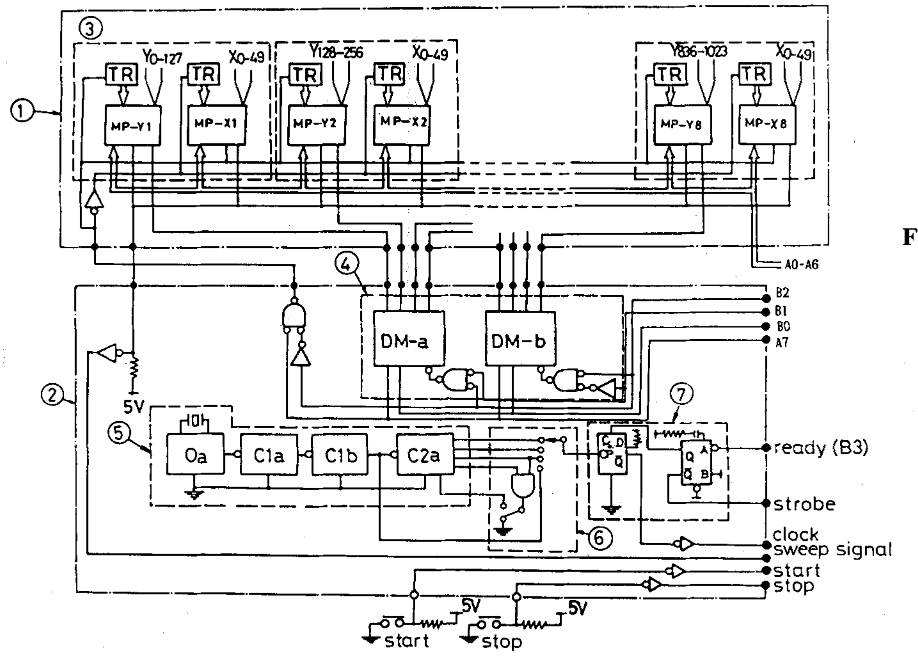

Fig. 5 *Electric circuit for footprint data. Sweep time: variable 0·1 to 0·01 Hz adjusted to objective gait velocity. ①: signal sensor, ②: controller for switching and sweeping, ③: unit block, ④: demultiplexer, ⑤: oscillator and frequency divider, ⑥: sweep time relay, ⑦: flip-flop*

Then the following equations were described (Fig. 6), using the definitions in Fig. 4:

$$W = X_n - X_1$$
$$= r_a + (D_f - r_a - r_b)\cos\theta + r_b(1 - \sin\theta)$$
$$D = Y_k - Y_h$$
$$= r_a \sin\theta + (D_f - r_a - r_b)\sin\theta + r_b(1 + \cos\theta)$$
$$r_a = W_f \quad r_b = W_f/2$$

Therefore a discriminant equation was derived by eliminating θ:

$$D(single) = W_f/2 - (W - 3W_f/2)W_f^2/(2K_f)$$
$$+ (D_f - W_f)^2\{K_f - (W - BW_f/2)^2\}^{1/2}/K_f$$
$$+ (K_f = D_f^2 - 3D_fW_f + 5W_f^2/2)$$

and so it can be defined in Fig. 6 as

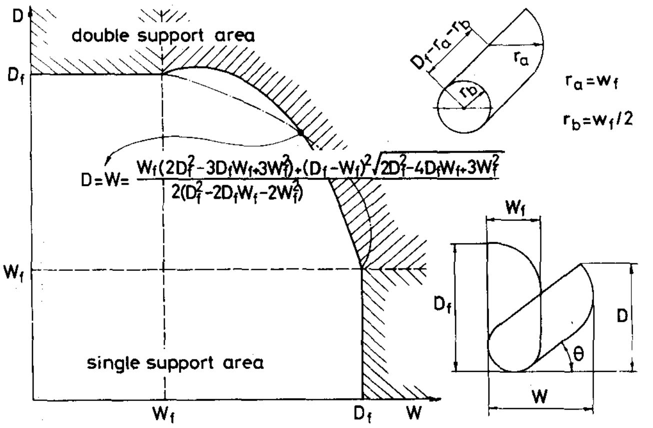

Fig. 6 *Logic for discriminating between single and double support durations*

single support duration: $W \geqslant W_f$ and D (single) $\geqslant D \geqslant W_f$ double support duration: other foot contact condition.

Distance factors were computed as in Fig. 7, where the squares ① – ⑤ are temporal footprints in a single support duration, and the square-shaped footprint ⑥ is formed by overlapping the squares ① – ⑤. Temporal factors of gait, i.e. single and double support durations, are acquired by counting the number of sweeping cycles through the multiplexer differently to obtain single and double support durations. In the present study foot angle is calculated by substituting inclination angle, derived from the following regression lines (Fig. 8) obtained from experimentally measured data.

$$\theta_s = 1{\cdot}37(180/\pi)\ \text{arc tan}\ \{(W^* - W_f)/D^*\}^\circ$$
$$\theta_f = (\theta_s + 4{\cdot}81)/0{\cdot}73^\circ$$

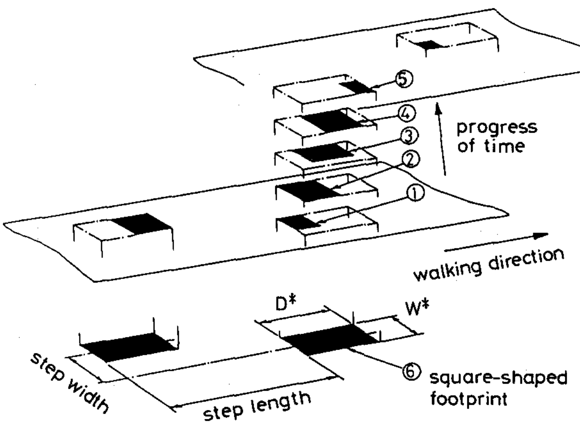

Fig. 7 *Visualised temporal shift of a square-shaped footprint. ①–⑤: temporal square-shaped footprints in a single support duration, ⑥: footprint formed by overlapping the squares ①–⑤*

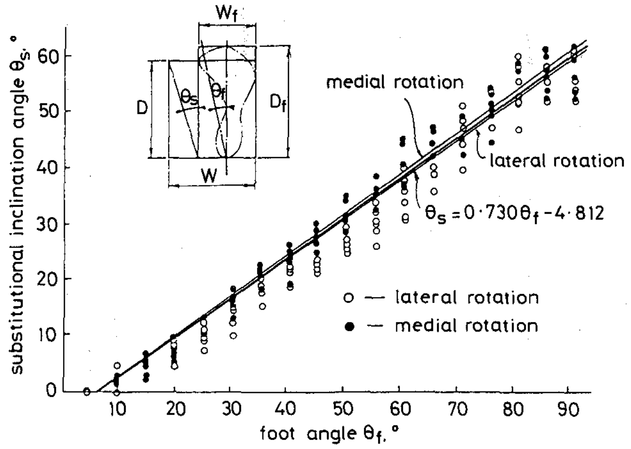

Fig. 8 *Correlation between foot angle and its substitutional inclination angle, derived from linear regression analysis*

2.2.2 *Successive moving of sweeping range:* To reduce the sweep cycle time the sweeping range was limited, from no more than 1 m forward to the foot contact point to 0·2 m backward in the subject's advancing direction, by specially written software (Fig. 9).

2.2.3 *Examination of measurement accuracy:* As a control study, a subject with painted soles walked on paper (width 0·5 m and length 10 m) placed over the walkway. The footprint data were then directly measured from the paper. Comparison between the data from the walkway and the footprint data revealed that both correlated well (distance difference: maximum 0·015, average 0·006 m). Accordingly it was concluded that the walkway could be put to clinical use (Fig. 10).

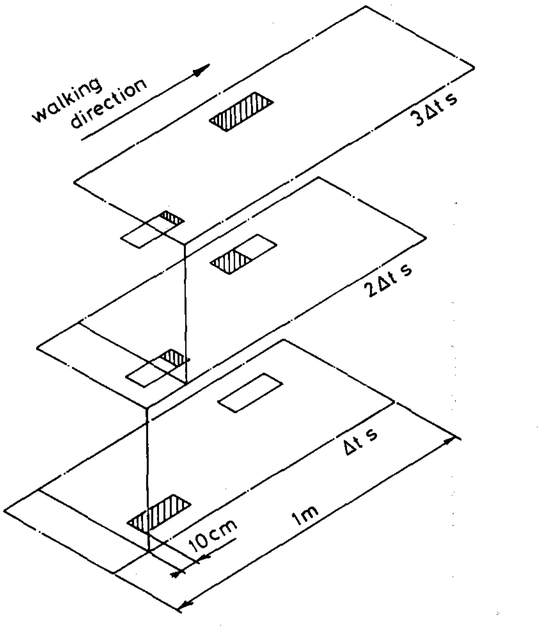

Fig. 9 *Successive removing states with sweep cycles. Each larger square (dotted line) represents one sweep range of one sweep cycle (cycle time: Δt s). Each smaller square (solid line) represents square-shaped footprints and shaded areas within them are the real sole contact places with the walkway. Temporal removing states are traced from the bottom larger square to the upper squares*

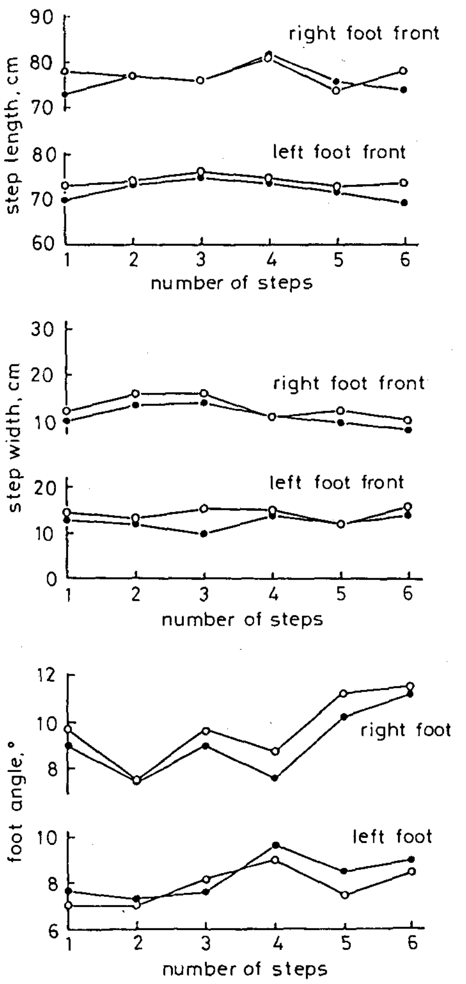

Fig. 10 *Measuring accuracy of the walkway system, compared with directly measured footprint data.*
–○– : *measured through the walkway*
–●– : *directly measured footprints*

3 Practical gait analysis of healthy subjects

3.1 *Normal gait at free velocity*

Healthy subjects (total 92: 53 males and 39 females) were asked to walk on the walkway barefoot without any additional constraints (normal gait). Data of temporal and distance factors concerning normal gait were assessed by considering the following relationships, based on the statistics.

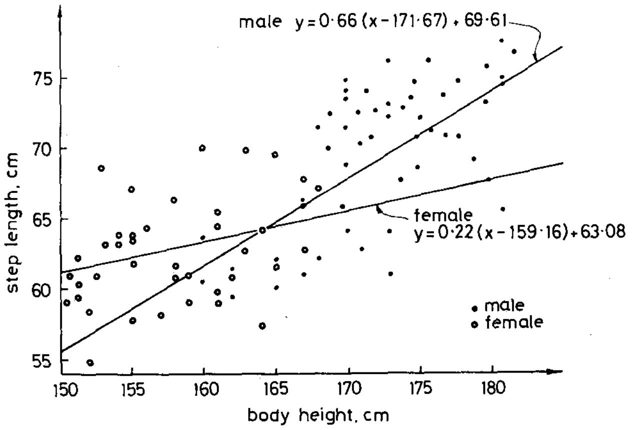

Fig. 11 *Scatter diagram and regression lines between body height and step length. Females showed lower coefficients than males. In the case of the males, the velocity seemed to depend on stride length, whereas that of the female depended on cadence*

3.1.1 *Relationship between subject's physical characteristics and gait variables:* Only body height showed a strong correlation with step length (Fig. 11), possibly supported by the lower limb-pendulum theory (Grieve, 1968). Females exhibited a lower coefficient than males, which might indicate that, in the case of the male, velocity depended mainly on stride length, whereas the velocity of the female seemed to depend on cadence (possibly to conserve energy expenditure through elongation of the step length).

Table 1 Coefficient of variation for the gait parameters

Variable parameters	Mean	Min	Max
Step length	0·019	0·005	0·060
Step width	0·103	0·014	0·318
Single support duration	0·049	0·010	0·099
Double support duration	0·123	0·001	0·239
Foot angle	0·170	0·013	0·351

92 subjects: 53 males and 39 females

3.1.2 *Variation (reproducibility) of gait parameters:* (Tables 1 and 4.) The reproducibility of the gait parameters was evaluated by examining the coefficient of variation. The results (Table 1) indicated that the highest reproducibility was observed in step length, followed in order by the single support duration and width of step. The highest reproducibility of step length at all velocities (Table 4) and high sensitivity to corresponding physical states, for example body height, might mean that it is *the* fundamental and stable parameter of gait.

3.1.3 *Symmetry of right and left limbs:* (Tables 2 and 3.) Both the orthodox symmetry analysis (Table 2) and the significance (Table 3) were computed to evaluate which method is suitable for clinical use (Table 1).

The symmetry ratio was very individual, varying between 0·8 and 1·0, and showed no predominant symmetrical tendency. The significance tests (Table 3) were also sensitive to asymmetry within individuals. Although certain sports physiologists and anatomists have reported functional asymmetry similar to that found on the upper limbs, no predominant right-left symmetrical or functional difference (Table 2 and 3) was found at free velocity in the present study, but significant asymmetry was found during our line-stepping constraint (not shown) in the distance factor (the step lengths of left-line stepping were longer than those of right-line stepping, a difference not found in the temporal factors). These facts may suggest that, although functional asymmetry exists, it is concealed

Table 2 Symmetry ratio of right and left limb's sampling mean values

k	Variable parameters	Mean	Min	Max	W_k
1	Step length	0·980	0·945	1·000	0·183
2	Step width	0·931	0·780	0·981	0·192
3	Single support duration	0·965	0·850	1·000	0·185
4	Double support duration	0·900	0·750	1·000	0·199
5	Foot angle	0·743	0·606	1·000	0·241

$$S_k = \left\{ \sum_{m=1}^{N} (X_{k|m}/X_{kRM}) \right\} \Big/ N$$

$$= \left\{ \left(\sum_{i=1}^{N_L} X_{kLi} \right) \Big/ N_L \right\} \Big/ \left\{ \left(\sum_{i=1}^{N_R} X_{kRi} \right) \Big/ N_R \right\} = X_{kL}/X_{kR}$$

R, L: Distinguishing sign for right or left foot in front
k: type of variables, W_k : weight coefficient

I_s : index of symmetry $= \sum_{k=1}^{5} W_k S_k^*$

for $S_k \leqslant 1$ then $S_k^* = S_k$, for $S_k > 1$ then $S_k^* = 1/S_k$

Table 3 Significant test results of difference between right and left sampling mean values (double-sided test for null hypothesis)

		$\lvert\bar{X}_L - \bar{X}_R\rvert/\sqrt{S_L^2/N_L + S_R^2/N_R}$		
Subject	N	Step Length	Single support duration	Double support duration
Male S.O.	32	2·797**	0·382	0·731
F.T.	32	1·620	4·400**	1·001
Y.N.	29	2·908**	2·533*	3·438**
Female T.E.	36	4·624**	0·158	2·600*
K.Y.	40	1·239	4·194**	3·703**
C.A.	36	3·075**	4·591**	2·286*

$\lvert X_L - X_R\rvert > Z\alpha(\sigma_L^2/n_L + \sigma_R^2/n_R)^{1/2}$
level of significance $\alpha = 0{\cdot}05, 0{\cdot}01$
*:significant at the level of $\alpha = 0{\cdot}05$
**:significant at the level of $\alpha = 0{\cdot}01$

during daily activities by the excellence of human motor control.

3.2 *Normal gait under constraints*

There are many reports of gait analyses using certain constraints, which are not designed to observe the consequences of restricted gait, but which arise inevitably from the measuring conditions themselves. These may consist of rhythm constraint applied with a metronome, stepping on a force-plate during the gait cycle and changes in initiating and ending the gait. However, these various effects have not been exhaustively investigated. Accordingly, in the present study, two constraints were examined and the results indicated that they have a considerable influence on the gait characteristics. Investigators who study gait must therefore take account of these constraints. We believe that these constraints should not be avoided but should be required for gait analysis, because gait is too complex to study by itself in its natural form.

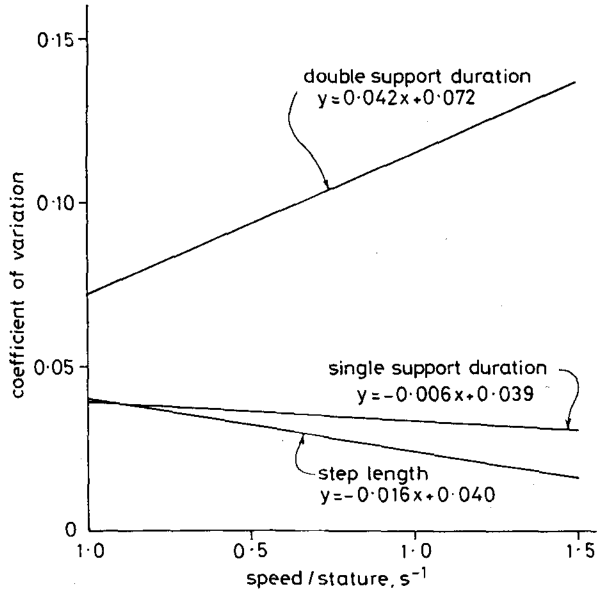

Fig. 12 *Regression analysis between velocity and gait parameters concerning normal gait under the velocity constraints—fast, free and slow*

The temporal and distance factors of normal gait were examined under the following temporal or distance constraints (total six: three males and three females: all were college students).

3.2.1 *Velocity constraints—fast, free and slow:* (Fig. 12, Table 4). The results of this study indicated that the coefficients of variation of step length were inversely correlated with the velocities, single support durations were non-correlated, and double support durations were positively correlated. The coefficients of variation (Table 4) were lowest walking at free velocity, a finding which may be due to an optimised efficiency of energy consumption at the velocity of choice.

3.2.2 *Rhythm and velocity constraint applied with a metronome:* (1·3–3·0 Hz), (i.e. synchronised gait, with a regular rhythm (Fig. 13). This constraint produced a linear relationship between the cadence and step length, and

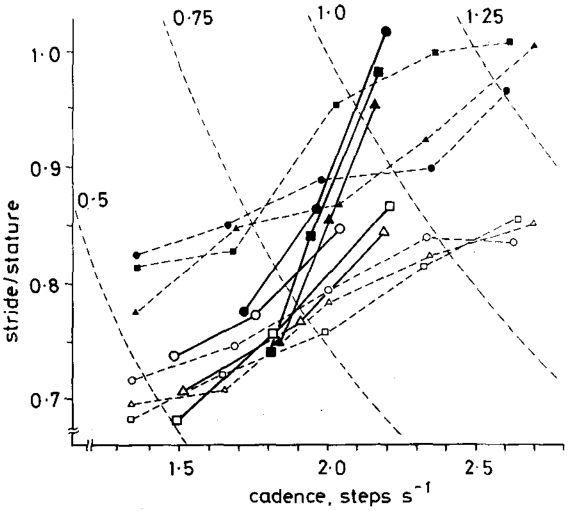

Fig. 13 *Relationship between cadence and relative stride (absolute stride/body height) under rhythm constraint—synchronised gait with a regular rhythm using a metronome (chained line, 1·3–3·0 Hz). The difference between males and females disappeared under this constraint. Solid symbols: male, hollow symbols: female*

Table 4 Coefficient of variation shift by velocity. The free velocity frequency showed the lowest variation

Parameters	Slow	Normal	Fast
Step length	0·04(0·02–0·06)	0·03(0·02–0·05)	0·04(0·02–0·07)
Step width	0·29(0·18–0·34)	0·21(0·09–0·32)	0·19(0·14–0·24)
Single support duration	0·09(0·07–0·14)	0·08(0·07–0·10)	0·08(0·06–0·13)e
Double support duration	0·29(0·18–0·34)	0·19(0·14–0·24)	0·21(0·09–0·32)
Foot angle	0·45(0·20–0·65)	0·37(0·26–0·35)	0·34(0·20–0·41)

mean (min-max)

there was a reduced difference between male and female subjects.

4 Discussion

The advantages of this present system compared with the previously reported systems are

(*a*) the simplicity of the procedure for data acquisition and analysis—a subject must only walk about 10 m in arbitrary shoes or bare feet without any restriction.
(*b*) low cost (under US $3000) and simple hardware which can be easily constructed
(*c*) much digital information—length, width and angle of the step, and durations of each phase of the gait cycle—all of which are suitable parameters for statistical analysis
(*d*) high sensitivity of switching and an adjustable rate of signal sweeping (0·1–0·01 Hz).

This low-cost system, which can obtain the gait parameters automatically without any additional constraints, may be very valuable for daily clinical practice and, furthermore, in the laboratory, not only when used on its own but also when synchronised with certain gait monitoring systems.

The measuring accuracy appeared to be limited by the size of wire lattice of the walkway, 0·01 m in the present study. This accuracy (average difference: 0·006 m) may be sufficient for adults even with pathological gaits, although it is probably not adequate for the analysis of paediatric gait. The optimal size of the lattice must be investigated in a future study.

Using discrete gait parameters—distance and temporal factors of foot-floor contact—facilitates the study of quantitative characteristics of gait which essentially possess severe complexity and individuality. This quantitative statistical analysis is important, not only for studying normal gaits but also pathological ones, since all gait parameters of pathological subjects ordinarily deviate from the normal range in variation and symmetry, and the level and interrelation of this deviation is the most important information in the evaluation of pathological gait.

5 Summary

We have reported a new type of automatic gait analyser which requires no subject constraint and have shown some results concerning the temporal and distance factors associated with normal gait as well as the influences of some ordinary experimental constraints not reported fully in previously published observations on gait.

The symmetry of right and left limbs was very individual, varying between 0·8 and 1·0. The highest reproducibility was observed in step length. The difference between male and female in the relationship between body height and step length indicated that, in the case of the male, velocity depended most on stride length, whereas that of the female depended most on cadence.

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