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VARIABILITY OF GAIT PATTERN AND ITS RELEVANCE TO GAIT MEASUREMENTS AND EVALUATION

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Abstract

The stochastic nature of measurements of the biomechanics of gait and its relevance to data interpretation is discussed. It was found that in the case of the dynamic variables of gait (vertical components of ground reaction and its point of application) their variability significantly prevails over that of the applied instrumentation. Significant differences in the variability of gait of unilaterally impaired patients pertaining to the normal and pathological side were found. Interpretation of the phenomenon observed is also given.

Introduction

There are many reasons for gait pattern variability. Two of them are the variability due to the measuring equipment, and the variability due to gait itself.

Both of them can significantly influence the measured results and thus also judgements about the process studied, but neither of them is treated in the literature. Many authors have incidently remarked on this phenomenon but without further explanations, probably because the characteristics of the measuring instruments, their precision and consistency, are not usually known. In (1,2) the variability of gait parameters as a function of velocity was studied with no reference to the measuring equipment. The purpose of this paper is to prove the existence of variability in the gait process, and to highlight its relevance to evaluation criteria, as well as to the definition of the experimental conditions.

Statistical character of gait variables

The main reason for gait measurements is the need for evaluation of orthoses and prostheses. To obtain bias free data measuring methodology have to consider:

a) the quality of the instruments (precision and accuracy)

b) the dynamic characteristics of gait (stochastics, stationarity and time variation of parameters);

c) evaluation criteria.

Because they are strongly interrelated in the process of evaluation, all the three items need to be considered carefully. For example, to make a decision about the influence of some means of rehabilitation (e.g. functional electrical stimulation) on gait, one has to test the null hypothesis for the variables describing gait under different conditions according to the selected criteria.

At a certain precision of the instruments and with the supposition that gait is in the stationary, condition the measured data can be characterized by the following expressions:

$$\bar{x} = \frac{1}{n-1} \sum_{i=1}^{n} x_i^{(1)}, \qquad S = (\frac{1}{n-1} \sum_{i=1}^{n} (\bar{x} - x_i)^2)^{1/2} \tag{2}$$

In (1), (2) $\bar{x}$ represents the average value of the measured variable x_i and s its standard deviation.

According to the points a) and b) above the standard deviation can be expressed by:

$$S = (S_p^2 + S_i^2)^{1/2} \tag{3}$$

where S_p and S_i represent the mutually independent variations of the process and the instruments. Supposing that S_i is known (the characteristics of the instruments), the variations of the process S_p can be calculated. The vertical component of ground reaction F_z and its point of application (POA) were measured during the stationary gait to test the statistical character of the gait. Measurement was made using force measuring shoes (3). The variability of the shoes was estimated by comparing the data obtained by a standard (Kistler) force plate during the same gait process. S_1 and S_2 in Eqs. (4) and (5) represent standard deviations (variabilities) of the gait measured by the force plate and shoes, respectively.

$$S_1 = (S_p^2 + S_{fp}^2)^{1/2} \tag{4}$$

$$S_2 = (S_p^2 + S_{fs}^2)^{1/2} \tag{5}$$

The variability of the force plate S_{fp} = 1.2 N was estimated by repetitive weighing of a known mass, W = 558 N, many times and by computing the standard deviation according to $S_{fp}^2 = (\frac{1}{n-1} \sum_{i=1}^{n} (w - w_i)^2$. Sp is obtained by substituting S_{fp} in (4) and then S_{fs} (the force shoes variability) from (5). For an experimental subject of body weight = 600 N walking over fp with force shoes, n = 20 steps, at a cadence of 70 step/min, an average S_{fs} = 12 N and an average S_p = 22 N was found. These data we need later for the analysis of variability of gait. Beside this the F test was applied to a clarified hypothesis about differences of variation between samples measured on the left and right leg of pathological gait.

Namely, it is supposed that unilateral damages to gait have an influence on the redistribution of the control mechanism of walking to assure stable motion which in reflected in the gait parameters variability. In this way, two samples can be simultaneously obtained under the same experimental conditions.

To test whether there is evidence that one leg is more consistent than the other, we set up the null hypothesis that there is no difference in consistency. In other words, we assume that the samples are from populations of the same variance Fisher's test $F = S_1^2/S_2^2$, where $S_1^2 > S_2^2$ and S_1^2, S_2^2 are the sample variance of the left and right leg at the same degree of freedom was applied.

The results of experiments tested by the null hypothesis are shown in Figs. 1, 2, 3, 4, 5.

In Fig. 1 two measurements of a left side hemiplegic patient are shown. The full line represents the vertical component of force (F_z) and its POA obtained from the measurement of 25 steps without stimulation, and the dashed line represents the measurement of 28 steps with stimulation of the n. peroneus. There is no significant difference between the POA trajectories and between the forces on the right (normal) for stimulated – nonstimulated gait. The only significant correction can be observed in the POA trajectory for the left stimulated leg.

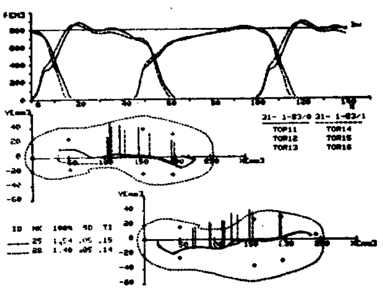

Fig. 1

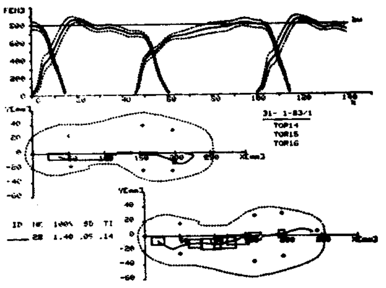

Fig. 2

From Fig. 1 it could be concluded that the measuring shoes were very consistent in the experiments.

In Fig. 2 the same measurements as in Fig. 1 but without stimulation are shown with the corresponding standard deviations. Even by graphical inspection it is evident that the variations on the right side are much bigger than the left over almost the whole stance phase. The results of the null hypothesis testing of F (F = S_n^2/S_p^2 ; $S_n > S_p$, n = normal, p = pathological, $H_o(S_n = S_p)$) at times defined by 30 % and 40 % of the gait period for hemiplegic, amputee and normal gait are shown in Table I. The critical value of F at the 1 % confidence level is much less than the F value obtained for the variation of the Y_c coordinate of POA for the hemiplegic and amputee gait, while for the normal gait, the F value is below the critical one. Therefore it can be concluded that there is a large difference between the variation of the coordinates of POA of pathological and normal legs at the 1 % confidence level. But for normal gait there is no reason to reject the null hypothesis.

TABLE I. The results of F test evaluation for $t_1 = 30\ \%$, $t_2 = 40\ \%$ of gait period T for subjects: hem pat. = Fig. 2, amputee = Fig. 4 and normal = Fig. 5. F_c = critical value of F at 1 % confidence level, df = degree of freedom

Subjects	Variables	$F(t_1)$	$F(t_2)$	$d_f = v_1 = v_2$	F_c (P = 1 %)
hemiplegic	F_z	4.0	1.77	24	2.66
Fig. 2	J_c	36.2	25.0		
amputee	F_z	1.5	9.0	29	2.49
Fig. 4	J_c	18.7	10.5		
normal	F_z	1.0	1.4	29	2.49
Fig. 5	J_c	1.0	1.4		

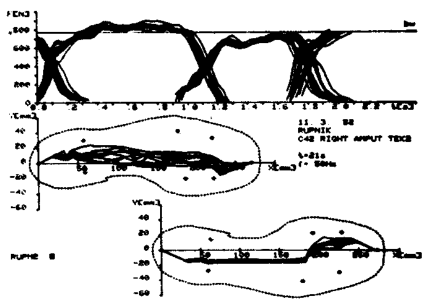

Fig. 3

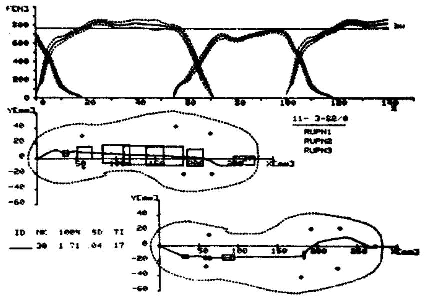

Fig. 4

Figs. 3 and 4 show F_z and its POA of the right amputee's gait with an above – knee prothesis. Fig. 3 shows forces and trajectories of the POA for each step separately, and Fig. 4 mean values and standard deviations of the same data. The results of the F test, shown in TABLE I, prove that the differences in the variations of the measured variables of the right and left are not accidental but caused by some consistent reason. As an illustration a pattern of normal gait is shown in Fig. 5. Close symmetry between the right and the left leg can be seen both in the mean values and in the standard deviations.

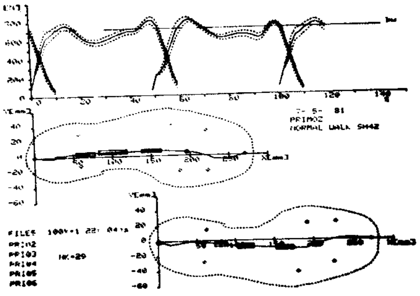

Fig. 5

A possible meaning of gait parameter variability

Regardless of the source of gait variation, the standard deviation, as a measure of data variation, is a useful tool for the estimation of the confidence limits of the population mean of the sample, according to

$$\bar{x} - t_c s/\sqrt{n-1} < r < \bar{x} + t_c s/\sqrt{n-1} \qquad (6)$$

This last expression represents the certain interval of the true value r which is proportional to S and inversely proportional to the square root of n, the number of measurements. From a biomechanical point of view, variability of gait variables could be interpreted in the following way. The more variable is a process (higher st. deviation), the more energy is required for stable motion, and the worse its efficiency (1). This statement can be partially verified by a simplified model of the ankle joint moment about the x and y axes:

$$\begin{aligned} M_x &= F_z y_c \\ M_y &= F_z (x_c - x_a) \end{aligned} \qquad (7)$$

where x_a represents the x coordinate of the ankle joint. For the results in Fig. 2 the mean value of F_z and its y_c of the POA at 30 % of the stance phase lie within the interval : $F_z \in$ (697 N, 743 N) and $y_c \in$ (14 mm, 23 mm) at the 95 % confidence level and n = 28 steps, while under the same conditions and n = 5 steps, the intervals are: $F_z \in$ (659 N, 781 N) and $y_c \in$ (7 mm, 30 mm). What these intervals actually mean with respect to the system performance remains to be discovered through experiments. Ankle moments M_x, M_y directly depend on variable F_z and y_c, x_c. Referring to Fig. 4, it seems that POA (and therefore also M) has an almost uniform distribution about zero over the whole range. This means that the agonist and antagonist muscle groups must be engaged to prevent rotation of the foot about its y axis, which requires a certain amount of metabolic energy. Additional analysis could be carried out for other segments. Owing to the lack of complete information about the biomechanical variables of gait, it is highly speculative to write certain mathematical expressions relating changes in mechanical energy to variations of gait variables. Nevertheless, it is evident that the efficiency of strongly stochastic gait is worse than that of a rather deterministic one. The control aspect of gait variability was studied in (1). It was shown that certain relations exist between variability of gait, control information, goodness of the system, and energy consumption. The results here confirm this relationship at least qualitatively. Namely, some measured dynamic variables of the impaired extremity (without control information) are much more steady than those of the normal one. The reason for that is the criterion for a person's stability.

Conclusion

The existence of variability in the vertical component of ground reaction F_z and its POA was discussed. The nature of the gait process, especially pathological gait, owing to its variability, requires a statistical approach. Different biodynamical variables should be characterised at least by their mean values and standard deviations. It is suggested that energy consumption in the process of gait should be proportional to the variability of some important dynamic variables and parameters. In certain respects, the variability could also be a measure of the quality of control of the gait process. When a sufficient set of biomechanical data become available to design a satisfactory mathematical model of gait, it would be an appealing task to verify experimentally the relations between the mechanical and methodological energy of gait motion and its variability.

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