GAIT ANALYSIS OF HEMIPLEGIC PATIENTS BY MEASUREMENT OF GROUND REACTION FORCE

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ABSTRACT. Ground reaction force during walking was measured and analyzed in 58 patients who had been hemiplegic for more than 6 months. Utilizing the impulse (area between a component curve and the baseline) as an assessment value, several parameters were selected to represent the characteristics of each component curve (vertical, fore-aft and lateral) of the ground reaction force, and correlated with the degree of motor recovery in the patients. As a result, a high correlation was found between these parameters and the degree of motor recovery, indicating that ground reaction force well reflects the degree of motor recovery, which is highly correlated with the gait ability of hemiplegic patients. This evaluation method would also be very helpful for objective and quantitative estimation of the gait of hemiplegic patients.

Key words: gait, hemiplegia, cerebrovascular diseases, biomechanics.

INTRODUCTION

Analysis of the ground reaction force has a long history (6) and many reports on this topic have been published. Since recent technological developments have made the force plate method more reliable and less time-consuming, it has become a more feasible technique for evaluation of abnormal gait.

In the present study, ground reaction forces of hemiplegic patients were measured while the patients were walking using a large force plate. Since the severity of hemiplegic gait accurately reflects the degree of motor recovery of patients (2, 5), the subjects were evaluated for motor recovery, and its relationship with the characteristics of ground reaction force during walking was analyzed. In addition, an attempt was made to assess the usefulness of ground reaction force measurement for the evaluation of hemiplegic gait.

MATERIALS AND METHODS

The subjects of the study were 58 patients aged between 36 and 71 years (average 55.2 years) with hemiplegia due to cerebrovascular disease, who had been affected for a minimum of 6 months. In order to make the criteria for walking as uniform as possible, patients were selected on the basis of being able to walk, albeit unstably, without a cane. In addition they had no higher cortical dysfunction, ataxia or other particular complications which influenced their walking.

For each subject, motor recovery in the lower limb was evaluated using the Brunnström method (1), employing the following briefly defined criteria to define each stage. Stage 1: Flaccidity. No voluntary movement. Stage 2: Minimal voluntary movement. Developing spasticity evident. Stage 3: All joint movements synergistic, and spasticity often marked. Stage 4: Minimal non-synergistic movements. Stage 5: Selective control of non-synergistic movements. Stage 6: Isolated joint movements occurring in an integrated manner. The subjects were classified according to the above stages as follows: stage 6: 19 patients, stage 5: 14, stage 4: 14, stage 3: 11 (Table I).

The walkway employed was 10 m long, with a large force plate (10) (0.8 m × 4 m) set in its center. The force place was formed of four plates (0.4 m × 2 m) arranged parallel to the walkway. The subjects walked along the walkway twice with shoes, but without a cane or orthosis, at their most comfortable speed.

Ground reaction forces were recorded for the left and right limbs separately for more than 10 steps in each subject, and divided into three components perpendicular in direction to one another. The data for each component (vertical, fore-aft, lateral) were integrated into impulses, and these were averaged for all steps on each side. The impulse is defined as the change in momentum, and is also expressed as the area formed between the curve of each component and the baseline in the diagram. In calculating the impulse, each component was normalized according to the subject's body weight to produce values for "relative impulse" which were the basis for analysis.

Parameters

As the waveform of the ground reaction force in a hemiplegic gait is very complex (Fig. 1), some characteristic features found in the waveform were evaluated in this study and

Table I. *Classification of the patients*

Stage of motor recovery*	Number of patients	Side of Paralysis Right	Side of Paralysis Left	Age (average) (yr)
6	19	8	11	39–71 (56.2)
5	14	6	8	36–70 (51.2)
4	14	4	10	48–67 (60.1)
3	11	6	5	39–69 (52.2)
Total	58	24	34	36–71 (55.2)

* See text.

quantified using the impulse and the average height of the component curve (the value of the impulse divided by the duration of force) (Fig. 2).

Vertical component

The ratio of the impulse of the affected limb divided by that of the unaffected one was used as a parameter, A, and the average component curve, which represents the impulse (force/subject's body weight × gravity) divided by the duration of force, was used as a parameter, B. Parameter B has two values which correspond to each limb of the patient. Fore and aft component:

The ratio of the impulse of the acceleration force to the sum of the impulses of the deceleration and acceleration forces (absolute value) was used as a parameter, C, which also has two values corresponding to each limb of the patient.

Lateral component

The average value of the lateral force of the affected limb divided by that of the unaffected one (absolute value) was adopted as another parameter, D.

Correlations between the above parameters for each component and recovery stage were calculated using the Pearson *r* coefficient, and differences between groups were examined using Student's *t*-test.

RESULTS

The value of parameter A increased with the stage of motor recovery from paralysis (improvement of stage) and approached 1.0 at stage 6 (Fig. 3). Upon examining the correspondence between parameter A and stage of motor recovery, a strong correlation ($r = 0.731$, $p < 0.001$) was seen, and there were significant differences between stages 6 and 5, and also between stages 5 and 4.

The value of parameter B also increased with the stage of motor recovery from paralysis on both sides

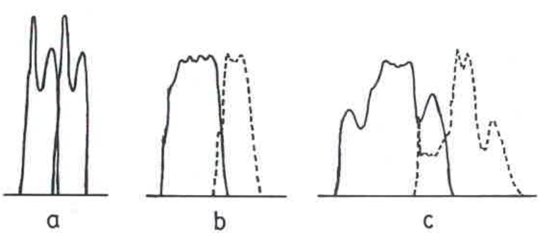

Fig. 1. Vertical component curve at free walking. a; normal gait. b and c; hemiplegic gait. *Solid lines* represent unaffected side and *dotted lines* represent affected side. As the component curves of hemiplegic patients are complex and the number of peaks differs between patients, evaluation on the basis of peak values is difficult.

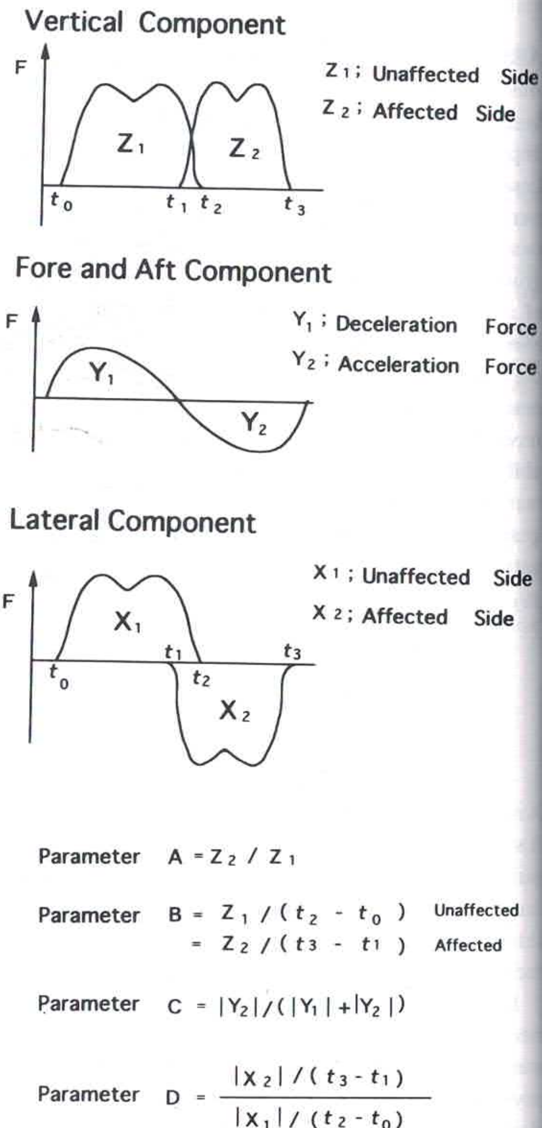

Fig. 2. Definition of parameters. Z_1, Z_2, Y_1, Y_2, X_1 and X_2 represent impulse of each component. Impulse is equivalent to the area formed between the component curve and the baseline. Parameters B and C for each patient have 2 values which correspond to the unaffected and affected sides.

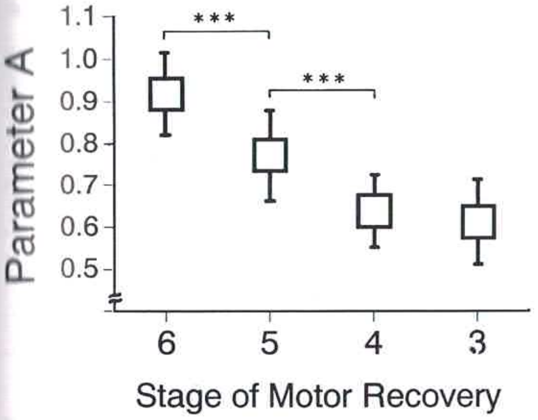

Fig. 3. Parameter A. The ratio of the impulse of the affected limb to that of the unaffected limb (vertical component). The *vertical bars* represent standard deviation for mean parameter values. Correlation coefficient is 0.731 ($p < 0.001$). *** = The difference in mean parameter value between recovery stages was significant ($p < 0.001$).

(Fig. 4), and was higher on the unaffected side than on the affected side at all stages. Coefficients of correlation between the parameters and the stage indicated a very significant relationship (unaffected side; $r = 0.507$, $p < 0.001$, affected side; $r = 0.816$, $p < 0.001$). Significant differences were seen between stages 5 and 4, and between stages 4 and 3 on the affected side.

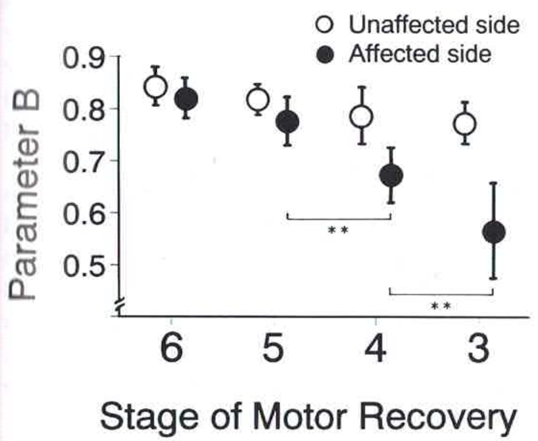

Fig. 4. Parameter B. The average height of the curve of a vertical component. Force is standardized according to the subject's body weight. The *vertical bars* represent standard deviation for mean parameter values. Correlation coefficients are 0.507 ($p < 0.001$) on the unaffected side and 0.816 ($p < 0.001$) on the affected side. ** = The difference in mean parameter value between recovery stages was significant ($p < 0.01$).

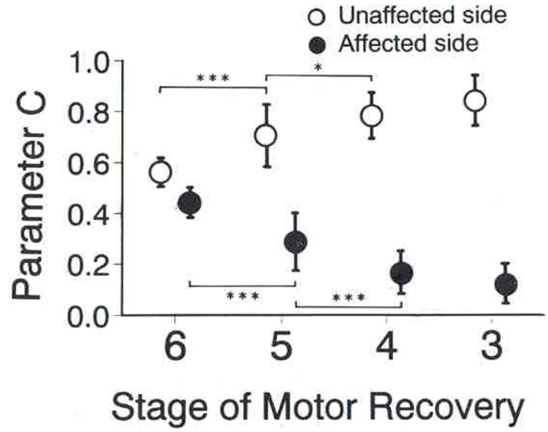

Fig. 5. Parameter C. The ratio of the impulse of an acceleration force to the sum of the impulses of deceleration and acceleration force (absolute value). The *vertical bars* represent standard deviation for mean parameter values. Correlation coefficients are 0.692 ($p < 0.001$) on the unaffected side and 0.787 ($p < 0.001$) on the affected side. * = The difference in mean parameter value between recovery stages was significant ($p < 0.05$). *** = $p < 0.001$.

Among the fore and aft components, the value of parameter C in the unaffected limb was larger than 0.5, and became closer to 0.5 as motor recovery progressed. On the other hand, in the affected limb, the value of C was less than 0.5, and became closer to 0.5 as the stage of motor recovery increased (Fig. 5). Significant correlations between the parameters and the stage were also seen (unaffected side; $r = 0.692$, $p < 0.001$, affected side; $r = 0.787$, $p < 0.001$). Significant differences were observed between stages 6 and 5, and between stages 5 and 4 on both sides.

The value of parameter D exceeded 1.0, and approached 1.0 as the stage of motor recovery increased (4, 5, 6). The value of this parameter for stage 3 was smaller than that at stage 4 (Fig. 6). Significant correlations between parameter D and stage were seen ($r = 0.465$, $p < 0.001$) but the degree of correlation was lower than those between the other parameters and the stage. Significant differences were seen between stages 6 and 5, and between stages 5 and 4.

DISCUSSION

In order to clarify the characteristics of human gait, analysis should be conducted from many viewpoints using electromyography, electrogoniometry, videorecording and so on, and the data obtained should be synthesized to form a complete picture.

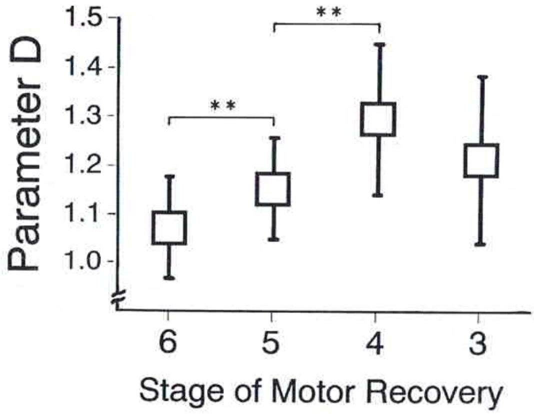

Fig. 6. Parameter D. The ratio of the average height of a lateral component curve for the affected limb to that for the unaffected limb (absolute value). The *vertical bars* represent standard deviation for mean parameter values. Correlation coefficient is 0.465 ($p < 0.001$). ** = The difference in mean parameter value between recovery stages was significant ($p < 0.01$).

Measurement of ground reaction force is useful for studying the dynamics of gait as a whole, and a variety of data processing methods have been developed and applied for this purpose (3, 7). The type of data processing that should be employed depends on the characteristics of the abnormal gait studied. A hemiplegic gait is considerably different from a normal gait, and the waveform of the ground reaction force is very complex (Fig. 1). For example, in methods using characteristic features (such as the peak), the determination of these features is fraught with difficulties and the results tend to be obscure. Therefore, it is impossible to make an accurate evaluation. Accordingly, we adopted a method using impulse (area) as a means of analysis. Although this method also has a drawback in that fine data on ground reaction force are likely to be omitted, it allows not only an accurate understanding of the characteristics of the original waveform, but also makes it possible to quantify them.

By reducing differences between data obtained for various subjects, some parameters of gait can be made uniform at measurement. Although hemiplegic patients have difficulty in walking with a fixed cadence or step length, the characteristics of their gait can only be deduced sufficiently upon free walking, and therefore in this study the subjects were directed to walk freely at their most comfortable speed. On calculation, force was divided by body weight, and then parameters B and D were divided by time in order to achieve standardization. However,

Table II. *Significant correlations between the parameters and walking speed*

	Correlation coefficient	
Parameter*	Stage of motor recovery**	Walking velocity
A	0.731	0.444
B (unaffected)	0.507	0.265
B (affected)	0.813	0.306
C (unaffected)	0.692	0.489
C (affected)	−0.787	−0.582
D	−0.465	−0.325

* See Fig. 2. ** See text.

complete normalization which abolished the variation in cadence or walking speed was impossible because of the large differences in the waveform of the reaction force at different velocities.

There is no absolute method for evaluating hemiplegic gait, but motor recovery from paresis is considered to correspond to overall gait ability (2, 5). In our study, the gait speed, cadence (number of steps per minute) and stride length of each patient during free gait, which represent one aspect of gait ability (8, 11), were measured simultaneously and found to be dependent on the stage of motor recovery from paralysis (Fig. 7). Therefore we adopted the Brunnström method (1), which indicates the stage of motor recovery from paralysis as a standard, and analyzed its correspondence with formulated parameters of ground reaction force. We found that these parameters corresponded closely to the stage of motor recovery. Since the degrees of correlation were larger than those between the parameters and walking speed (Table II), the parameters reflected not only gait speed but also some other factors related to walking.

The vertical component is the load imposed on the stance leg in the vertical direction while walking, and hence the parameter A expressed by this component (affected limb impulse/unaffected limb impulse) is considered to reflect mainly load ability. In this study, the better the motor recovery from paralysis, the greater the load on the patient's affected limb during walking. As hemiplegic patients probably exert more load on the unaffected limb while walking than healthy individuals, the load on the unaffected limb becomes smaller and approaches the normal level with motor recovery.

Parameter B, which is the average height of the curve for the vertical component, is influenced by the slope of the curve. If patients have a foot deformity or

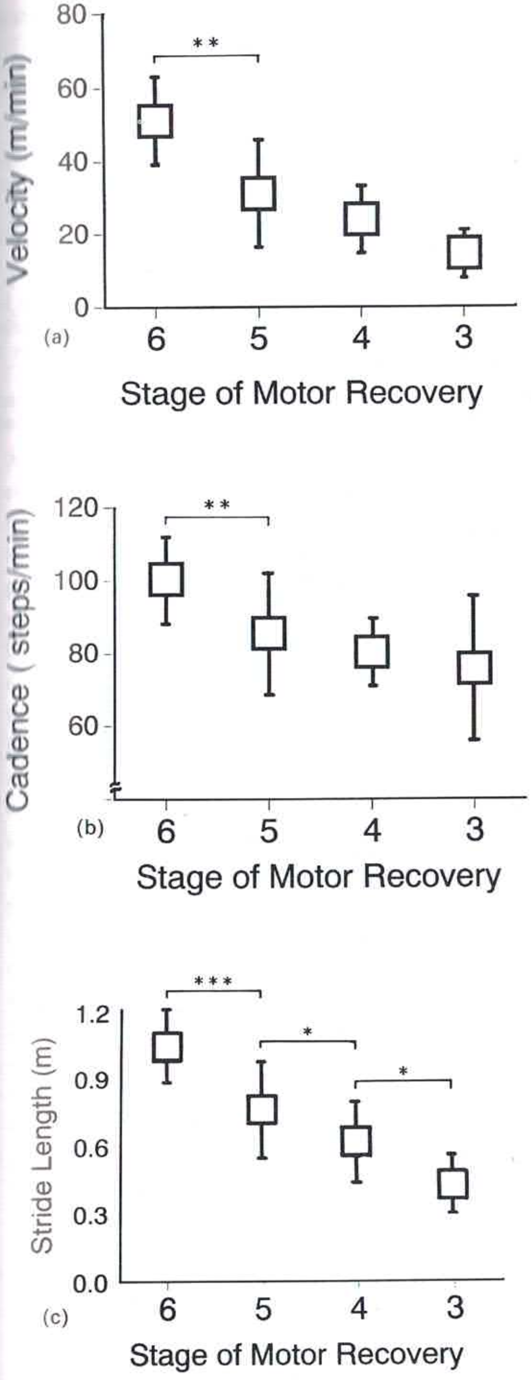

Fig. 7. (a) Walking velocity. (b) Cadence. (c) Stride length. Recovery from paralysis was well reflected in each factor during free walking. The *vertical bars* represent standard deviation for mean parameter values. Correlation coefficients are 0.623 ($p < 0.001$) in 7a, 0.543 ($p < 0.001$) in 7b and 0.787 ($p < 0.001$) in 7c. * = The difference in mean parameter value between recovery stages was significant ($p < 0.05$). ** = $p < 0.01$. *** = $p < 0.001$.

lower limb instability, they cannot allow their affected limb to support their body weight suddenly (i.e. perform weight shift) at heel strike. As a result, the slant of the curve of the ground reaction force becomes gentle. Generally, if the shift of weight from the affected to the unaffected limb or vice versa cannot be performed smoothly, the gradient of the component curve at heel strike and toe raising becomes small. Also, in a gait which has a relatively high ratio of the double support phase, parameter B also becomes small. Accordingly, this parameter B reflects the smoothness of weight shift as a whole. This study showed that hemiplegic patients were able to walk more smoothly with the progress of motor recovery.

In the fore and aft components, we found that the value of parameter C for a normal gait (constant velocity) was about 0.5 in 25 healthy adults we examined. There was a clear tendency for the impulse of the acceleration force to be larger than that of the deceleration force in the unaffected limb (parameter $C > 0.5$), whereas in the affected limb the former was smaller than the latter. The possible causes of such a gait include restriction of hip extension and ankle dorsiflexion on the affected side, or synergistic motion and limited kicking power (acceleration) of the whole affected limb during walking. These abnormalities would be manifested as asymmetry of two successive steps (9). Our results showed that the push-off force of the affected limb became large and that the asymmetry characteristic of gait disturbance improved with recovery from palsy.

The peak value of the lateral component of the affected limb tended to be higher than that of the unaffected limb. Therefore, parameter D exceeded a value of 1 in most patients. The lateral component is considered to be related to gait stability and step width (3). We speculate that the height of the component curve during a single stance would increase as the distance from the body's centre of gravity to the stance leg increases. In other words, in patients where the body's center of gravity moves near to the unaffected limb, and body weight does not depend on the affected limb, the curve of the lateral component for the affected limb is thought to be higher than that of the unaffected limb.

We have thus analyzed the ground reaction force of a hemiplegic gait and demonstrated that it reflects accurately the degree of recovery from paralysis, being a useful parameter for evaluating the gait of hemiplegic patients. The parameters described above have a high correlation with the gait ability of hemiplegic patients with respect to motor recovery. This method of evaluation can thus provide an objective and quantitative estimate of hemiplegic gait.

REFERENCES

1. Brunnström, S.: Movement therapy in hemiplegia: a neurophysiological approach. Harper & Row, New York, 1970.
2. Brandstater, M. E., de Bruin, H., Gowland, C. & Clark, B. M.: Hemiplegic gait: analysis of temporal variables. Arch Phys Med Rehabil *64:* 583–587, 1983.
3. Carlsöö, S., Dahllöf, A. G. & Holm, J.: Kinetic analysis of the gait in patients with hemiparesis and in patients with intermittent claudication. Scand J Rehabil Med *6:* 166–179, 1974.
4. Cavagna, G. A. & Margaria, R.: Mechanics of walking. J Appl Physiol *21:* 271–278, 1966.
5. Dettmann, M. A., Linder, M. T. & Sepic, S. B.: Relationships among walking performance, postural stability, and functional assessments of the hemiplegic patient. Am J Phys Med *66:* 77–90, 1987.
6. Elftman, H.: The force exerted by the ground in walking. Arbeitsphysiologie *10:* 485–491, 1939.
7. Jacobs, N. A., Skorecki, J. & Charnley, J.: Analysis of the vertical component of force in normal and pathological gait. J Biomechanics *5:* 11–34, 1972.
8. Mizrahi, J., Susak, Z., Heller, L. & Najenson, T.: Variation of time-distance parameters of the stride as related to clinical gait improvement in hemiplegics. Scand J Rehabil Med *14:* 133–140, 1982.
9. Perry, J.: The mechanics of walking in hemiplegia. Clin Orthop *63:* 23–31, 1969.
10. Takami, M., Okumura, S., Morita, S., Aikawa, T., Fujita, T. & Ishigami, S.: Development and features in clinical application of a new three-dimensional force plate capable of continuous gait measurement. Jpn J Rehabil Med *21:* 161–170, 1984 (in Japanese).
11. Wade, D. L.: Walking after stroke. Measurement and recovery over the first 3 months. Scand J Rehabil Med *19:* 25–30, 1987.

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