(1) Title : An Evaluation System of Dynamic Postural Controllability of Hemiplegic Patients

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Summary

A system for evaluating dynamic controllability of moving of center of gravity to a left or right side is described. This system is composed of Weight Balance Analyzer (two force plates and bio-feed-back display unit), data recorder and minicomputer. Preliminary experiments have so far been carried out on 25 normal subjects and 47 hemiplegic patients, using this system. The performance of a patient was diagrammatized as hepta-gram and was quantified as total score in order to recognize and evaluate results more easily.

Data analysis, experimental results and applicability of the system to clinical evaluation are described. There was a general relation that the better Bunnstrom's stages (one of evaluations of hemiplegic function in clinics), the better the dynamic controllability and the less the difference from a normal.

An Evaluation System of Dynamic Postural Controllability of Hemiplegic Patients

1. Introduction

In a process of rehabilitation for patients who lost walking ability temporally because of accidents or disease, a training to obtain an sufficient ability of maintaining an erect standing posture is necessary not to walk with an abnormal pattern before starting gait training. Walking and other human motions are based on the ability to maintain an erect standing posture. This ability largely depends not only on muscle powers but also on neuro-muscle coordination.

There are many studies about a measurement and an evaluation of the standing postural controllability in the field of clinic and physical education. But most of studies are reports concerning to the static standing postural controllability 1) by analyzing the movement of center of gravity (c.g.) in an erect standing and there are very few reports 2) which study dynamically postural controllability in due consideration of time factor (velocity and accelation etc).

Considering an actual motion or gait in a daily life, it is very important especially in clinics to evaluate dynamic controllability to stabilize posture not to fall down against various external disturbances (terrain road and vibrations in a tram etc.). To measure the stability of postural equilibrium, the method of adding external disturbances to a subject is often adapted in the engineering field. But it is not always optimum to vibrate right or left (fore and after) the plate on which a subject stands, because, in rehabilitation process, it is very important that a patient demonstrates his controllability by himself and there are some difficulties (dangers etc.) in the method.

So in order to measure and evaluate the dynamic standing postural controllability by the performance of c.g. tracking motion to a left or right side according to target signal using visual feedback in standing with both legs, we developed a evaluation system of dynamic postural controllability and tried to express the performance of the tracking motion in the form of hepta-gram and total score so as to help a doctor and a physical therapist recognize the results intuitively and quantitatively.

Using this system, the preliminary experiments were carried out on normal subjects and hemiplegic patients in order to check the applicability of the system in clinical fields.

In this paper, 1) the constitution of the evaluation system, 2) the experimental method, 3) the method of data analysis, 4) the experimental results about normal subjects and hemiplegic patients and 5) the relation between clinical evaluation (Brunnstrom's stages) and the experimental results of hemiplegic patients are described.

2. Evaluation System

The evaluation system of controllability of c.g. tracking motion is composed of Weight Balance Analyzer, data recorder and minicomputer.(Fig.1) Weight Balance Analyser, which was developed by our laboratory and was made by Yaesu Rehabili. Co., Ltd., is composed of two force plates (a left force plate and a right one) and the bio-feedback display unit. The force plate is consisted of three differential transformers and calculates the total vertical force acting onto the plate, adding three electric signals detected by each of three differential transformers. The difference ($F_R - F_L$) of two vertical forces (F_R, F_L) which act respectively onto each of two force plates are shown as output of the system in the form of L.E.D. matrix on the face of the bio-feedback display unit and the target signal (input), which is random step sequence, is indicated with lighting of either of two L.E.D. lamps located in a right and left side of the face of the bio-feedback display unit, too. Input and output signals are recorded into a magnetic tape by data recorder. Then the signals are sampled at 20 Hz by A-D converter and are processed to the data available in clinics by minicomputer (PDP-12).

3. Experiment

3.1 Experimental Method

A subject is asked to stand with both legs on one of the two force plates and the body weight of a subject is measured in order to represent an amplitude of input by a percentage to the weight.

Then a subject stands upright on two force plates, placing his right foot on the right force plate and left foot on the left one, and looks at the face of the bio-feedback display unit. If he supports equally his weight with each of two legs, output indicates zero. If he shifts horizontally his body to a right side, the indicator of output shifts to the right by the amount linear to movement of c.g.. Thus the change of output reflects the movement of c.g. in medio-lateral plane, because the movement of acting point of floor reaction force within both plantars is small enough to be neglected. A subject shifts his c.g. left or right according to the movement of input signal as fast and accurately as possible to make the tracking error (i.e. difference between input and output signal) into zero through his visual feedback. In this motion, a subject is asked to move horizontally his pelvis keeping his trunk vertical to the ground.

The input signal adapted in the experiment is random sequence of step signal which has two values and it's amplitude depends on the value of rate of load supported with one leg to his weight (supporting rate). (Fig.2) In this experiment, supporting rate (S.R.) was changed from 60% to 95% (5% interval) and at each supporting rate, the trial for about 3 minutes was recorded after enough training for a subject to become accustomed to the experiment.

3.2 Subjects

The experiments were done about 25 normal subjects (male 22, female 3) and 47 hemiplegic patients (L-hemi. 25 (m 14, f 11), R-hemi. 22 (m 17, f 5). As some hemiplegic patients were examined several times every about two weeks to follow their process of recovery, the number of the experiment in hemiplegic patients was 80. An experiment on a patient who needed a brace (i.e. foot-up, S.L.B. or L.L.B.) was done without removing a brace.

4. Data Analysis

4.1 Quantification of Step Response

In order to quantify a speed and a stability of c.g. tracking from the step response curve in this experiment, the factors shown in Fig.2 were defined as follows.

* Time Lag (T.L.) : A time needed for a subject to start reaction after the change of input. (sec.)
* Reach Time (R.T.) : A time needed for a subject to reach to 90% line of input after reaction. (sec.)
* Inverse Value (INV.) : There is an inverse phenomeon in a response. A rate of this peak value to a subject's weight.(%)
* Notch Count (N.C.) : A number of notch which appears from an inverse peak to reaching to 90% line of input. This notch was

observed especially in a patient's response.

- * ERROR I, II : A rate of average of absolute tracking error every two seconds after reaching to 90% line of input to a subject's weight.(%) The rate in the first two seconds is ERROR I and the next is ERROR II.
- * Improvement Rate (IMP.) : ERROR I/ERROR II This factor shows convergency of tracking error.

As there were more than five step responses of c.g. tracking to each of sides (right and left) in a trial for three minutes at each supporting rate, average value of five measurements in step responses was calculated for each of the factors mentioned above.

4.2 Evaluating Factors of Dynamic Controllability

It was so complicated to evaluate the differences of the controllability of c.g. tracking among subjects by the values of the factors at each supporting rate (of 60 to 95%) and most of hemiplegic patients, not to speak of normal subjects, could track input signal when supporting rate was 70,75 and 80%.

Therefore the 7 evaluating factors were selected as follows.

1) Maximum Supporting Rate (M.S.R.) : Maximum value of supporting rate in which a subject can track input.

2)∽6) Average values of three values at 70, 75 and 80% of the following factors,
   2) R.T. 3) INV. 4) N.C. 5) ERROR II 6) IMP.

7) Reappearance Rate (REAP.) : The standard deviation of values of R.T. at 70, 75 and 80%. This factor shows degree of reappearancy of step responses.

The factor T.L. was not discussed in this paper because there were no clear differences between normals and patients (.2 to .4 sec. in normals and .2 to .7 sec. in patients).

5. Results and Consideration

As shown in Fig.3, there were clear and evident differences of factors' value at each supporting rate between a normal and a patient. Especially, as supporting rate increased, the R.T. value of patient increased, though the R.T. value of normal was almost same at any supporting rate.

Thus it seems important to inquire the relation between factors' value and supporting rate in patients' data. But in this paper the results on 7 evaluating factors (M.S.R., R.T., REAP., INV., N.C., ERROR II and IMP.) are discussed.

5.1 Normal Subjects

Fig.4 (a) shows five step responses of a normal subject at the the supporting rate of 80%. There was no significant difference (level of significance 1%) between step responces to both left and right side as a result of testing statistically the difference between the average values of R.T. to both sides for each of normal subjects. The coefficient of correlation between subject's age and each of factors and the linear regression curve of each factor to age were calculated. (Tab.1)

As shown in Tab.1, there were positive correlations between age and each of R.T. and REAP. and there was negative correlation between age and INV.. And also the inclinations of linear regression curves (of R.T., REAP. or INV. to age) were not small enough to be neglected. Though the performance of this motion depended on subject's age as mentioned above, the average values and standard deviations of all normal subjects' data were calculated to compare hemiplegic data with normals' average data, because the number of normal data was too small to calculate for each generation.(Tab.2)

5.2 Hemiplegic Patients

The difference of performance between normal group and hemiplegic group can be found from Tab.2. In hemiplegic patients, the step response pattern to affected side was worse than the one to non-affected side and the deviation of patients' pattern from normal subjects' one increased as the degree of hemiplegia became worse. (Fig.4)

5.2.1 Relation with Brunnstrom's Stages

Brunnstrom's stages (B.stages) is used in clinics as one of evaluating methods of hemiplegic function. Tab.3 shows the co-efficient of correlation between Brunnstrom's stages and each evaluating factor in step responses to affected side. There were significant correlations between B.stages and evaluating factors except ERROR II as shown in Tab.3. As B. stages became to be better, the value of M.S.R. increased (Tab.4) and the value of R.T. became to be less (Fig.5).

5.2.2 Hepta-gram and Total Score

The performance of this experiment was diagrammatized in the form of hepta-gram and was quantified by total score. (Fig.6(a))

Hepta-gram has seven factor axes and each of evaluating factors is plotted on each of axes. Average values of normal group are located on the highest points of heptagon and values of hemiplegia are plotted on axes at distance d_{ij} from the points of normal subjects. The d_{ij} is described as follows.

$$d_{ij} = k \cdot \frac{X_{Pij} - X_{Ni}}{S_i} \qquad i = 1 \text{ to } 7, \quad j = 1 \text{ to } 80$$

X_{Pij} : value of i th factor of j th hemiplegic patient's data

X_{Ni} : average of i th factor of 50 normals data

S_i : standard deviation of i th factor of 80 hemiplegia's data

K : K = 1 for i = 1, 4 and 7 and K = -1 for i = 2,3,5 and 6

The subscript i denotes the factors and the subscript j denotes the measured hemiplegic paient's data.

The points of a hemiplegic patient are connected with a wide line and the average values of evaluating factors in the B. stage in which a subject belongs are connected with a broken line. As shown Fig. 6 (b), it is easily found that the performance was not better because of various impediments (balance impediment, recognition impediment, high age and lowering of kinethesis), though the degree of B. stages was better.

Thus it is found intuitively by hepta-gram that how much the performance of a hemiplegia is deviated from normal group and which factor is better or worse than the average of the patient's B. stage.

As there were correlations among 7 evaluating factors, two principal component variables (Z_1, Z_2) were calculated from hemiplegic data using Principal Component Analysis[3] (P.C.A.). The principal component variable is a linear weighted combination of seven factors and there is no correlation between two component variables. Seeing coefficients of correlation between each of two principal component variables and each seven evaluating factors as shown in Tab.5, it was found that the first component (Z_1) quantified the degree of amplitude and speed of c.g. tracking in transient state of step response and the second one (Z_2) showed a degree of stability in constant-value control after reaching to 90% line of input. So it is possible to say that the larger the first component and the smaller the second one, the better the performance. The values of two principal components for both normal and hemiplegia are plotted in Fig.7.

The total score of the performance was described as the linear weighted combination of two components obtained by P.C.A. as follow.

$$\text{Score} = W_1 \cdot Z_1 + W_2 \cdot Z_2$$

W_1, W_2 : weighting coefficient

Z_1, Z_2 : principal component

In this paper total score was calculated from only the first principal component (i.e. $W_2 = 0$) so that the score of normal group became to be about 100. A total score for a patient was described with a number of two figures below hepta-gram. There was correlation of .8 between B. stages and total score in hemiplegic data. But the total score of a patient who had some impediment was worse considering his B. stage. (Fig.6 (b)).

As mentioned above, the dynamic controllability of c.g. tracking of hemiplegic patient is able to be evaluated in detail with heptagram and to be recognized overall with total score. Therefore, it will become much easier to compare the difference among subjects and to check training effect of a same subject.

5.2.3 Comparison between Affected Side and Non-affected Side

As a result of testing statistically the difference of R.T. value between affected side and non-affected side (see 5.1), there was significant difference in 35 samples of 80 but no significant difference in 45 samples. There was correlation of .7 between score of affected side and score of non-affected side and score of non-affected side was better than the one of affected side. (Fig.8)

It is found from Fig. 8 that as the patient's B. stage decreases, the score of both affected side and non-affected one decrease.

5.2.4 The Change of Dynamic Controllability by Training

Tab.6 shows changes of the score of this experiment in 5 hemiplegic patients on whom several experiments were carried out every about 2 weeks. It was found that there was remarkable advance for some patients but there was none for others.

Thus the change of dynamic controllability by training in rehabilitation process is able to be evaluated quntitatively by total score.

6. Conclusion

We developed the evaluation system of dynamic postural controllability, in which the performance was expressed in the form of hepta-gram and total score so as for a doctor, a physical therapist and a patient to recognize the experimental results easily.

From the experimental results, it was found that as B. stages decreased, the dynamic controllability of c.g. tracking became to be much worse than the one of normal subjects and the dynamic postural controllability lowered because of various impediments which were not evaluated by B. stages. Comparing the patients' performance with braces used by patients, it seems that transient period from training of standing to gait training with a help of brace and came is maximum supporting rate of 75% and a subject whoes maximum supporting rate is 85% can walk without a help of brace.

Thus the system semms to be available in clinics for an evaluation of dynamic postural controllability of hemiplegia and a determination of a brace required for a patient to walk steadily.

It is expected that the system is optimum self-training machine for patients, because the training effects (or results) are fed back to a subject himself as hepta-gram and total score and it results to increase his attitude toward training.

It is future subject to study dynamic controllability of c.g. tracking in anterior-posterior plane (A-P plane).

Now, we are improving this system which can directly show the results of the experiment on a graphical display processing data online by microcomputer. It will much enhance applicability of the system in rehabilitation training.

Refferences

1) Proceedings of Second Symposium on Posture, Tokyo, Japan, 1971, Human and Technology Co., Ltd., 1972, p.41～p.69 and p.219～p.276.
2) K. Murase et al. "Sense of Sight and Postural Control", Proceedings of Fifth Biomechanism Symposium, Japan, 1977, p.333～p.342.
3) T. Okuno et al., The Method of Multivariate Analysis, Nikka-giren Press, 1977, p.159～p.257.

		M.S.R.	R.T.	REAP.	INV.	N.C.	ERROR II	IMP.
AGE		0	.65	.56	−.58	0	.2	−.41
Y = AX+B X : AGE	A	0	.019	.007	−.344	0	.02	−.02
	B	95	.262	−.082	37.67	0	3.02	3.43

Tab. 1

		M.S.R.	R.T.	REAP.	INV.	N.C.	ERROR II	IMP.	AGE
NORMAL	AVE.	95.	1.03	.21	23.7	0	3.8	2.6	40.7
	S.D.	0	.045	.2	9.	0	1.5	.7	15.3
HEMI	AVE.	83.1	3.38	1.01	10.74	1.75	6.2	1.7	59.1
	S.D.	7.35	1.84	.65	4.93	2.04	2.7	.52	14.5

Tab. 2

		M.S.R.	R.T.	REAP.	INV.	N.C.	ERROR II	IMP.
BRUNNSTROM'S STAGES		.78	−.66	−.62	.62	−.57	−.35	.58
$Y = A \cdot X + B$ X : B.S.	A	2.29	−.46	−.17	1.18	−.39	−.38	.13
	B	70.76	5.74	1.94	4.5	3.68	8.35	.997

Tab. 3

		BRUNNSTROM'S STAGES										
		2	3-1	3-2	3-3	3-4	4-1	4-2	5-1	5-2	6	TOTAL
MAXIMUM SUPPORTING RATE	65 %	1										1
	70 %	1	2	1	1							5
	75 %		6	5	2	1	2					16
	80 %			1	5	4	1					11
	85 %			4	5	6	2	3	2			22
	90 %				3	2	1	2	1	6	3	18
	95 %								1	2	4	7
	TOTAL	2	8	11	16	13	6	5	4	8	7	80

NS = 80   COEFFICIENT OF CORRELATION = 0.78

	M.S.R.	R.T.	REAP.	INV.	N.C.	ERROR	IMP.
Z_1	.85	-.88	-.84	.74	-.83	-.42	.57
Z_2	.02	-.40	-.03	.03	-.40	.80	-.71

Tab.5

	A.K. L-Hemi	H.S. R-Hemi	B.A. L-Hemi	T.I. R-Hemi	I.A. R-Hemi
1 st Exper.	45 (3-1, L.L.B.)	15 (3-1, F.U.)	23 (2, L.L.B.)	45 (3-3, F.U.)	72 (5-2, None)
2 nd	54 (3-2, L.L.B.)	39 (3-2, F.U.)	19 (2, L.L.B.)	53 (3-3, F.U.)	77 (5-2, None)
3 rd	59 (3-3, S.L.B.)	54 (3-3, F.U.)	26 (3-1, L.L.B)	47 (3-3, F.U.)	75 (5-2, None)
4 th	59 (3-4, S.L.B.)	43 (3-4, F.U.)	25 (3-1, L.L.B.)	54 (3-4, F.U.)	—
5 th	68 (4-1, None)	45 (3-4, F.U.)	36 (3-1, L.L.B.)	—	—

(Brunnstrom's stages , Brace)

Tab.6

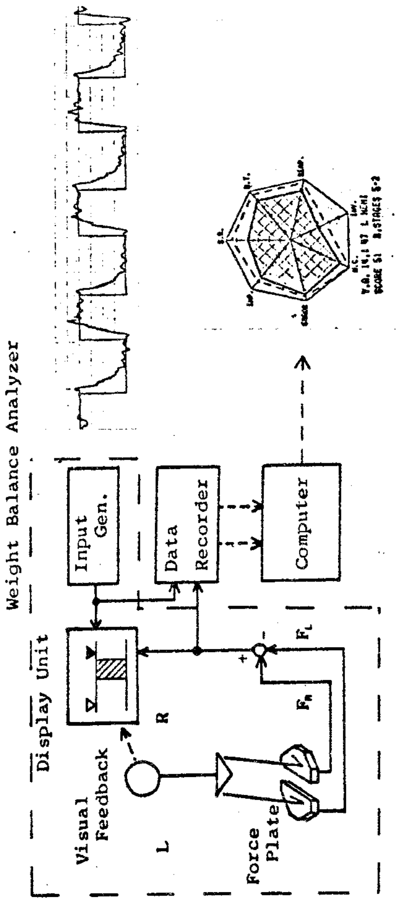
Weight Balance Analyzer
Display Unit
Visual Feedback
L
R
Force Plate
Input Gen.
Data Recorder
Computer
F_R
F_L
+
-

fig. 1

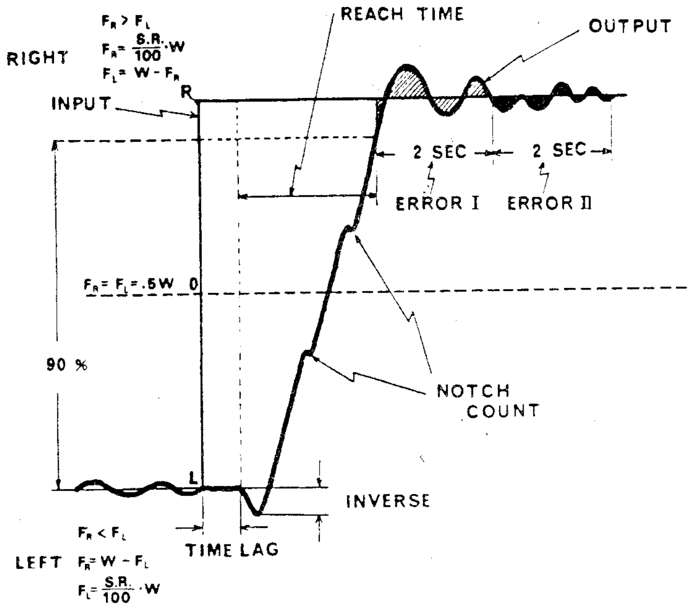
RIGHT
$F_R > F_L$
$F_R = \frac{S.R.}{100} \cdot W$
$F_L = W - F_R$
R
INPUT
REACH TIME
OUTPUT
2 SEC
2 SEC
ERROR I
ERROR II
$F_R = F_L = .5W$ 0
90 %
NOTCH COUNT
L
INVERSE
TIME LAG
LEFT
$F_R < F_L$
$F_R = W - F_L$
$F_L = \frac{S.R.}{100} \cdot W$

Fig. 2

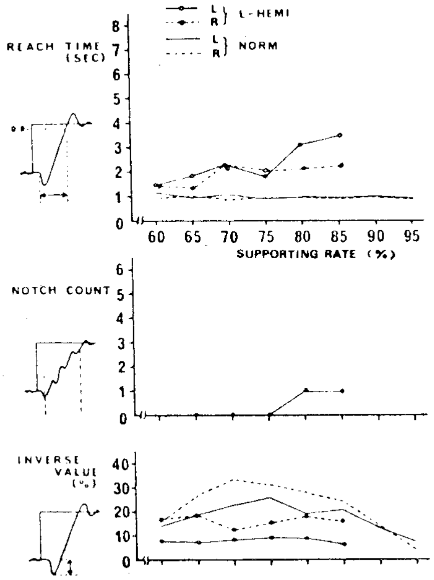
L
R
L-HEMI
L
R
NORM
REACH TIME (SEC)
8
7
6
5
4
3
2
1
0
0.8
60
65
70
75
80
85
90
95
SUPPORTING RATE (%)
NOTCH COUNT
6
5
4
3
2
1
0
INVERSE VALUE (%)
40
30
20
10
0

Fig.3

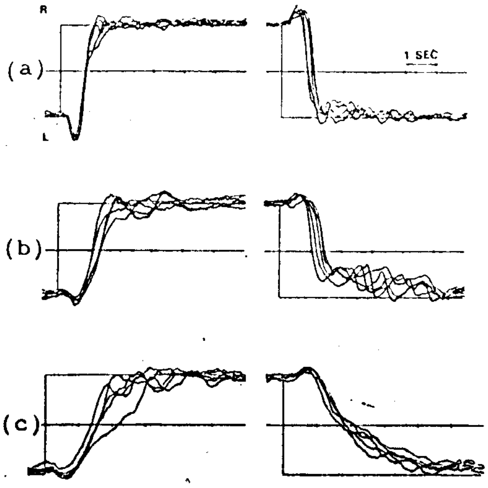
R
L
(a)
1 SEC
(b)
(c)

Fig.4

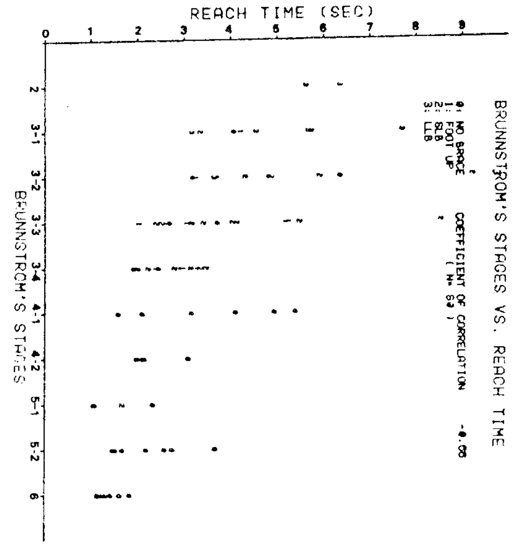
BRUNNSTROM'S STAGES VS. REACH TIME
0: NO BRACE
1: FOOT UP
2: SLB
3: LLB
COEFFICIENT OF CORRELATION -0.68
(N= 63)
REACH TIME (SEC)
0
1
2
3
4
5
6
7
8
9
BRUNNSTROM'S STAGES
2
3-1
3-2
3-3
3-4
4-1
4-2
5-1
5-2
6

Fig.5

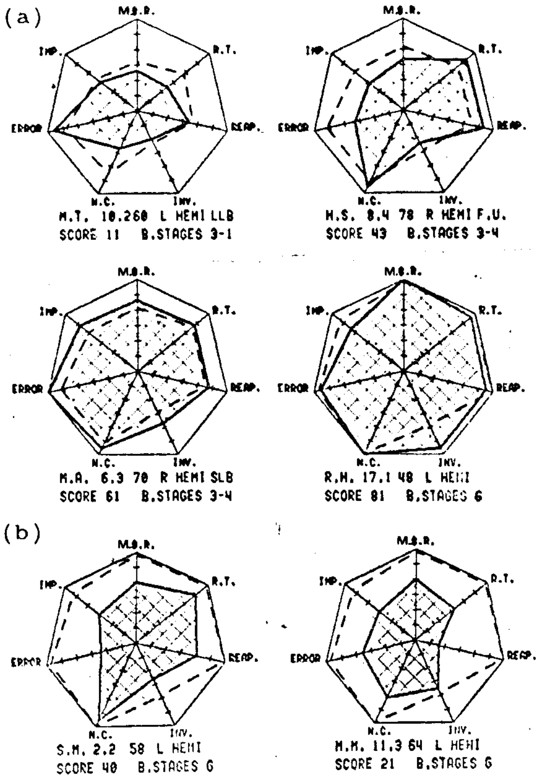
(a)
M.S.R.
R.T.
REAP.
INV.
N.C.
ERROR
IMP.
M.T. 10.260 L HEMI LLB
SCORE 11 B.STAGES 3-1
H.S. 8.4 78 R HEMI F.U.
SCORE 43 B.STAGES 3-4
M.A. 6.3 70 R HEMI SLB
SCORE 61 B.STAGES 3-4
R.H. 17.1 48 L HEMI
SCORE 81 B.STAGES 6
(b)
S.M. 2.2 58 L HEMI
SCORE 40 B.STAGES G
M.M. 11.3 64 L HEMI
SCORE 21 B.STAGES G

Fig. 6

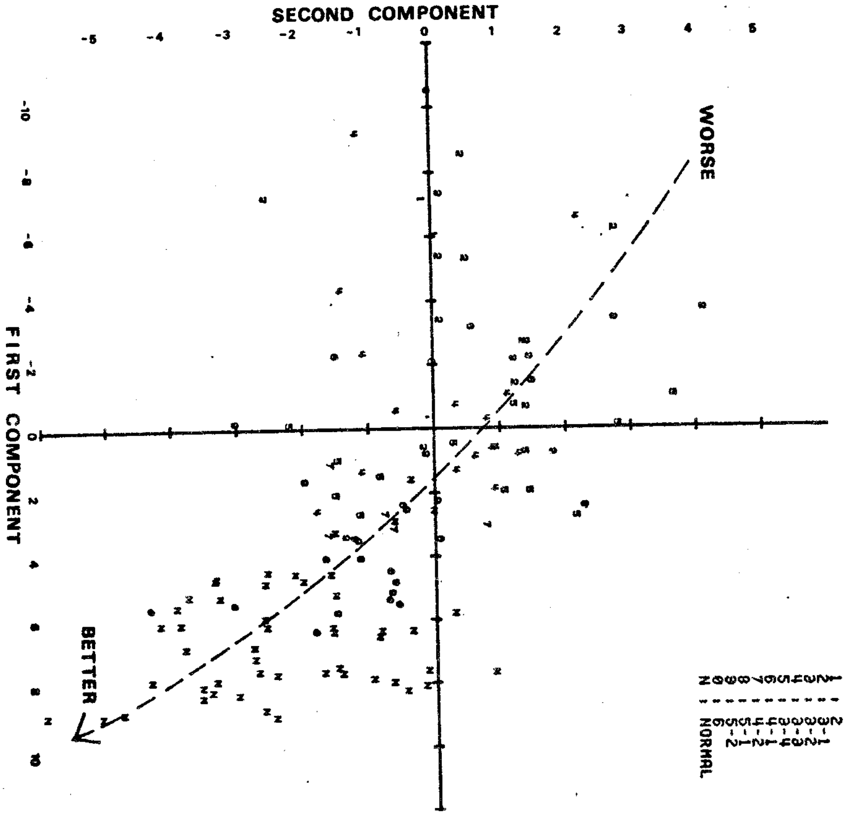
SECOND COMPONENT
-5
-4
-3
-2
-1
0
1
2
3
4
5
FIRST COMPONENT
-10
-8
-6
-4
-2
0
2
4
6
8
10
WORSE
BETTER
1 - 2
2 - 3-1
3 - 3-2
4 - 3-3
5 - 4-1
6 - 4-2
7 - 5-1
8 - 5-2
9 - 6
N - NORMAL

Fig. 7

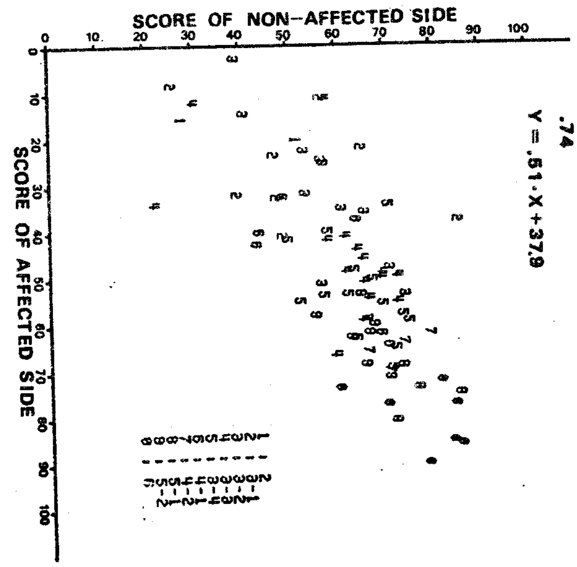
SCORE OF NON-AFFECTED SIDE
0
10
20
30
40
50
60
70
80
90
100
SCORE OF AFFECTED SIDE
.74
Y = ,51·X+37,9

Fig. 8