PENDULUM TESTING OF SPASTICITY

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ABSTRACT
Simple and inexpensive instrumentation required for pendulum testing of spasticity is described. It is based on the use of an electrogoniometer and tachometer. Eight parameters are extracted from the goniogram and the tachogram to evaluate the degree of spasticity. The correlation coefficients are calculated to determine the parameters relevant for the estimation of spasticity. Spasticity was assessed in the knee extensors of ten spinal cord injury patients and in five hemiplegics. The described instrumentation and evaluation of the pendulum test provide an effective spasticity testing in the clinical environment.

Keywords: Locomotor system, spasticity, electrogoniometer, tachmeter

INTRODUCTION

The term spasticity is used to denote the presence of different phenomena which are characteristic for the upper motor neuron syndrome: decreased dexterity, loss of strength, increased tendon jerk, hyperactive flexion reflexes, and increased resistance to passive muscle stretch[1]. Spasticity of muscles of the upper and lower extremities is usually assessed by physical therapists as increased resistance of a particular muscle group to manually induced passive movement. In the present study the possibilities of measuring and evaluating spasticity by provoking the stretch reflexes during the passive swing manoevres of a limb were investigated. Such an approach is called a pendulum test.

The pendulousness of the lower extremities was for diagnostic purposes first examined by Wartenberg[2]. During his testing, the patient was sitting on the edge of a table with the legs hanging freely. The examiner had to lift the patient's legs simultaneously to the same horizontal level, then release them, permitting them to swing freely. The presence of abnormalities was observed from the swinging time or the number of swings, from the forward-swing which is more jerky and of greater range, and from the backward movement which is diminished. He noticed also irregular zigzag movements out of the anteroposterior (sagittal) plane, and compared the swinging time of the right and left leg. The test was only evaluated qualitatively. The pendulum test was quantified by fastening an electric light to the big toe and recording the swinging movements on a film of a slowly moving camera[3].

Much simpler approach to the measurement of knee extensor spasticity was introduced by assessing the joint movement with an electrogoniometer[4]. The start of the measurement was determined by a switch on the patient's ankle held by the examiner. Surface EMG of the quadriceps was measured in order to determine the beginning and duration of knee extensor activity. Knee joint goniogram, switch output and EMG potential were recorded by use of a visicorder light oscillograph.

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The pendulum testing of spasticity was found to be especially convenient to evaluate different approaches to reduce spasticity. The treatment with antispastic drug was evaluated by Boczko[3], while Bowman *et al.*[5] and Vodovnik *et al.*[6] studied the influence of electrical stimulation on spasticity.

The aim of the present study was to develop simple and inexpensive instrumentation required for the pendulum test around the knee joint and to extract those properties of the pendulum test which are relevant for the quantification of spasticity in spinal cord injury and hemiplegic patients.

INSTRUMENTATION

Spasticity of the knee extensor muscles was tested by placing the patient on a tilt table in supine position with both legs bent over the edge hanging free at the knee. The patient was asked to relax as much as possible. The examiner grasped the foot and brought one leg to a horizontal position. The limb was allowed to fall freely while recording knee angle with an electrogoniometer or knee joint velocity with a tachometer (*Figure 1*).

The most simple approach to assessing movement of a swinging limb is the analogue measurement of joint angle by potentiometer. Advantages of this

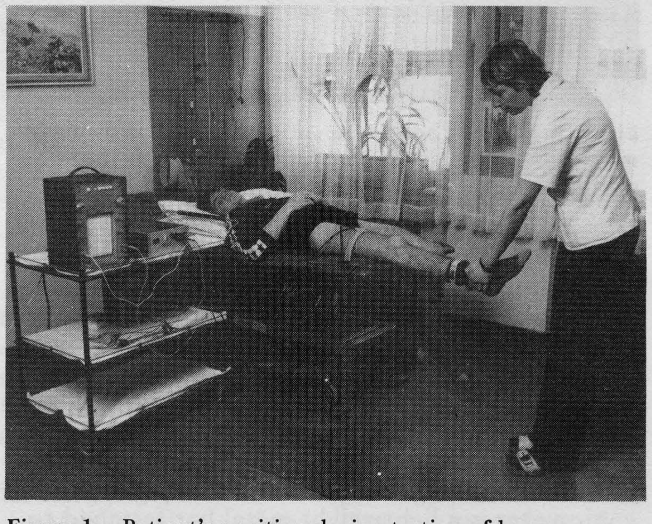

Figure 1 Patient's position during testing of knee extensors spasticity

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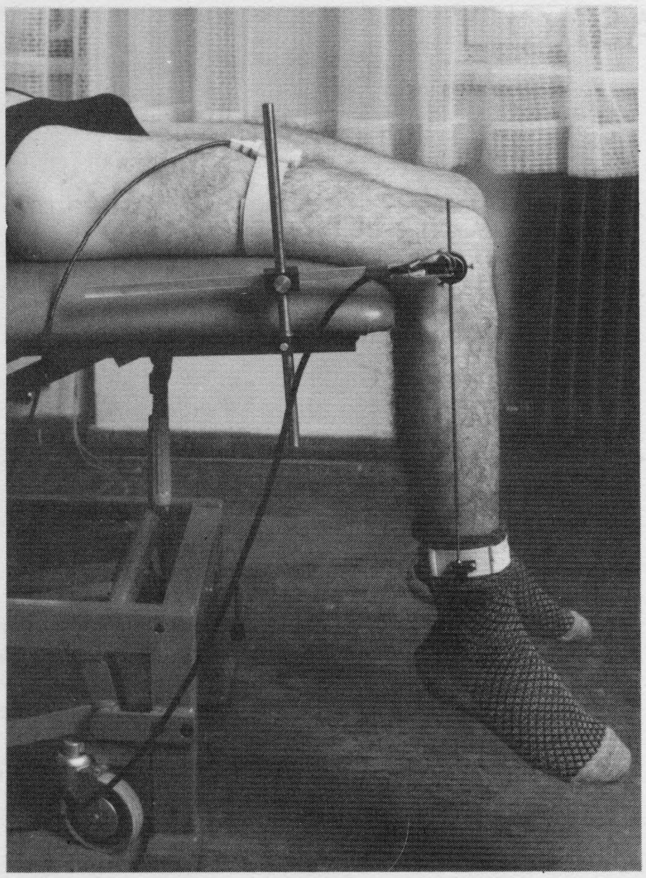

Figure 2 Attachment of the goniometer to the tilt table and patient's ankle

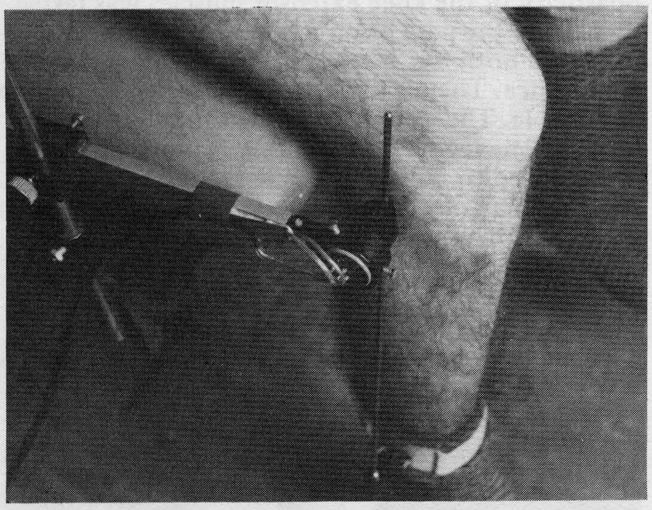

Figure 3 Oblong hole in potentiometer axis, allowing free movement of the joining bar, perpendicularly to the sagittal plane and in proximal–distal direction

method are simplicity, low cost and suitability for on-line computer analysis. The desired reliability was achieved by attaching one leg of the goniometer to the tilt table on which the test was performed. The potentiometer is fixed to that goniometer leg and can be shifted both in the horizontal and vertical direction in order to place the axis of the potentiometer in the approximate centre of the joint rotation (*Figure 2*). The second leg of the goniometer is a lightweight metal bar fastened to the calf of a subject. On the side of attachment to the lower limb there is a ball joint allowing free displacements out of the sagittal plane. At the other end the bar slips through a hole in the potentiometer axis. The hole is oblong and runs along the potentiometer axis[7] (*Figure 3*). Such design of the goniometer prevents bending stresses on the bars arising, because during the swinging the centre of joint rotation is not fixed with regard to the segments of the extremities. In this way sufficiently accurate and repeatable assessment of joint angle in the sagittal plane was achieved. The electronics consist of the circuit for automatic zero adjustment, amplifier, digital voltmeter and LCD display. The output for recorder or A/D converter is also provided.

In addition to the electrogoniometer, the tachometer was used to measure the velocity of the joint movement. It was placed at the joint in an identical way to the potentiometer and directly connected to a Gould Brush 220 recorder. Surface EMG measurement was added to obtain a qualitative estimate of knee extensor activity during the pendulum test.

PATTERN OF THE GONIOGRAM AS A MEASURE OF SPASTICITY

Schwab[8] was the first to attempt to quantify the swing test by assigning numbers to the deficits in swing, starting from 0 (normal, absence of any deficit in swing) to 4 (maximum rigidity, total absence of swing).

Boczko[3] confirmed Wartenberg's findings of 6 to 7 cycles in normal subjects and a reduced number of oscillations in spastic patients. In addition to measuring the swinging time, T, he defined an 'amplitude ratio' for spasticity. *Figure 4* shows a typical oscillation of a normal subject. The swinging time, T, as well as the amplitude ratio, R_1 is defined in the figure. In normal subjects R_1 has been found to be greater than 5, whereas patients with spasticity have an R_1 of about 2.6.

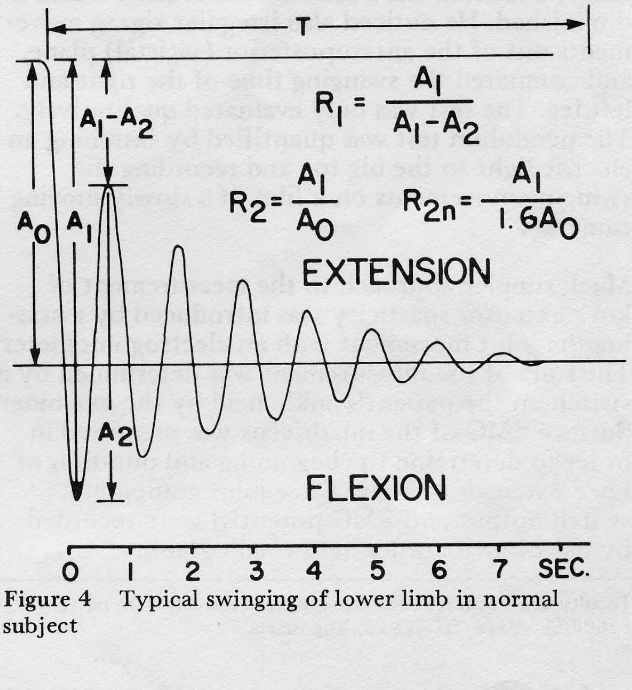

Figure 4 Typical swinging of lower limb in normal subject

From the records obtained on ten spinal cord injured (SCI) patients, Bowman and Bajd[5] suggested that the initial drop of the leg was most characteristic of the level of spasticity. They therefore defined a relaxation index R_2 as the ratio between the magnitude of the first drop A_1, and the magnitude of the initial angle A_0 (*Figure 4*). In normal subjects, R_2 was found to be 1.6 or more, therefore a normalized index R_{2n} was proposed as $R_2/1.6$. Thus $R_{2n} > 1$ would signify a non-spastic limb whereas $R_{2n} < 1$ would quantify various degrees of spasticity.

These numerical methods of describing the goniogram take into account only the first cycle of motion. There is a question, however, as to whether these methods of evaluating the goniogram are sufficiently adequate to describe a representative level of spasticity. The clinical value of the relaxation index may be quite useful when comparing patients with consistent patterns of spasticity. However, more often than not, a patient's levels of spasticity are inconsistent. The patterns of spasms may change dramatically from one test to another and consequently numerical values obtained at the start of the test become meaningless. To illustrate the point, two tests of spasticity obtained from a paraplegic patient on two consecutive days are shown in *Figure 5*. The amplitude ratio R_1 is 1.8 in *Figure 5a* and 2.0 in *Figure 5b*, the ratio R_{2n} is 0.60 in *Figure 5a* and 0.69 in *Figure 7b*. Both ratios changed by only about 10%

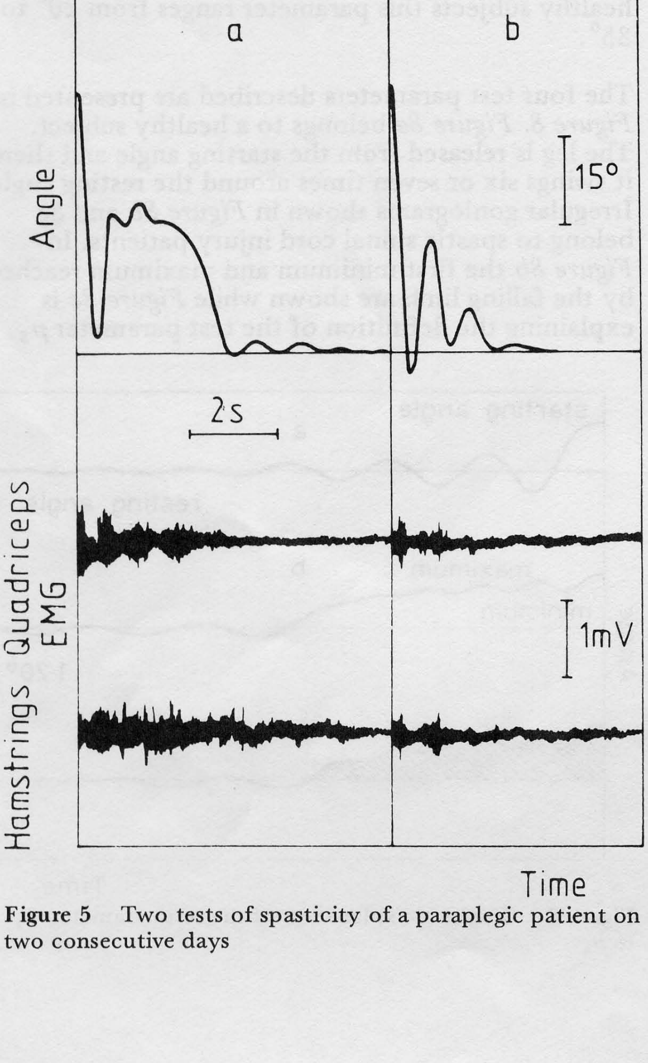

Figure 5 Two tests of spasticity of a paraplegic patient on two consecutive days

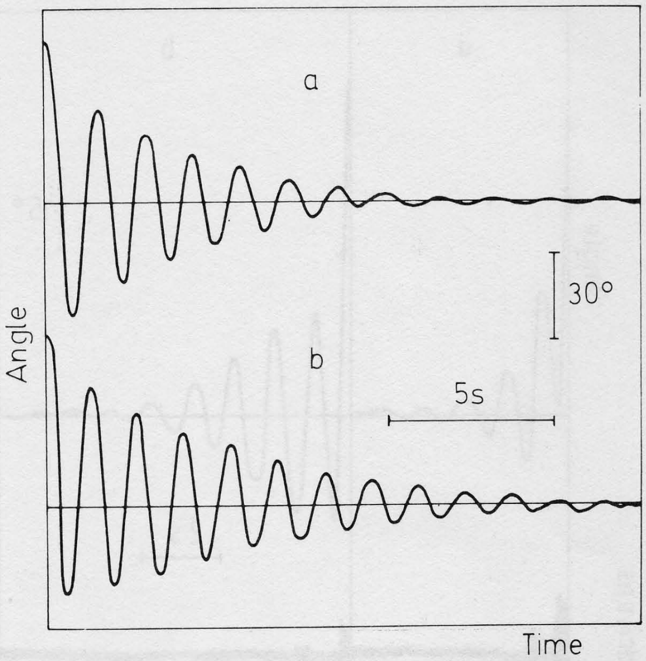

Figure 6 Goniogram of normal subject (a) and hypotonic paraplegic patient (b)

which might easily be accounted for by measurement errors and variability of spasticity. Still it is obvious from the EMGs, as well as by inspecting the pattern of the angle ϕ, that the patient was less spastic on the second day.

In cases of strong spasticity the area under the goniogram could be a rather sensitive measure for assessing spasticity. In fact, measurements of the surface (with a planimeter) from 0–4 s gave 33 arbitrary surface units for *Figure 5a* and 13 units for *Figure 5b*. The numerical change in spasticity is thus 250% compared with a 10% change shown by the other criteria.

It was found on several occasions that changes in spasticity could be more readily observed in the shape of the goniogram than in the amount of myoelectric activity. Thus, for example, no EMG could be detected in a relaxed, normal subject and similarly no EMG could be found in a hypotonic patient with complete paraplegia. Yet as many as 12 swings were observed in a hypotonic patient, whereas no more than 7 swings were observed in a normal subject (*Figure 6*). It should be noted that no attempt was made to compare sensitivity of EMG using percutaneous needles or wires to the goniogram. Such methods may provide a more sensitive measure of EMG but are not as easy to apply and are not generally as clinically acceptable.

Another example of the value of the goniogram to evaluate spasticity is shown in *Figure 7*. The EMG of the knee muscles and the goniogram were recorded before and after one hour of electrical stimulation treatment of the quadriceps and the hamstrings of a stroke patient[6]. While there is an obvious reduction in EMG, the changes in the goniogram are by far the more pronounced and easily observed. In a simple clinical test of spasticity, the recording of only the goniogram might therefore be quite adequate.

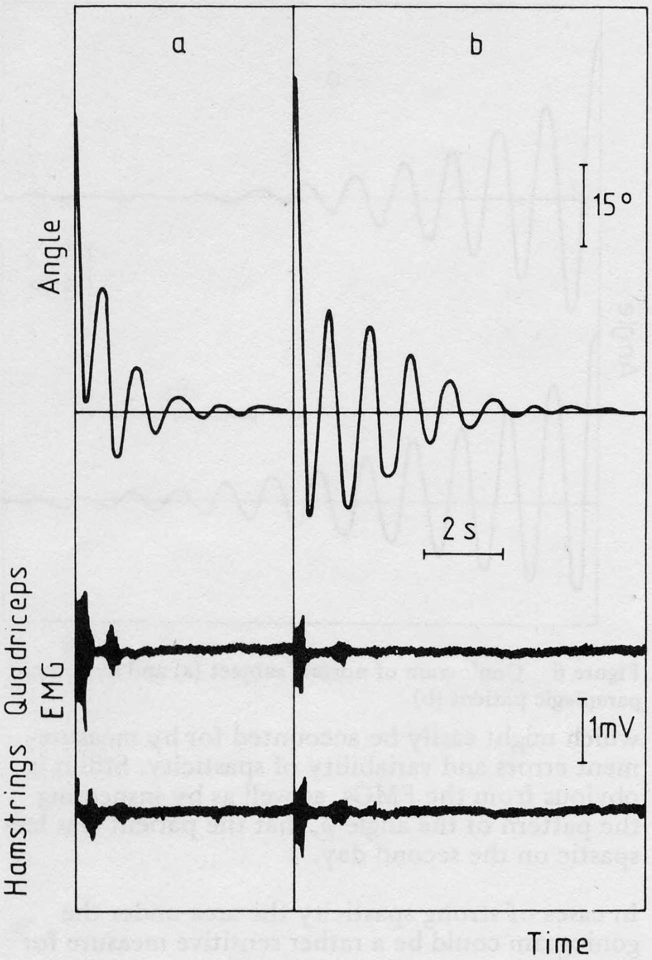

Figure 7 EMG and goniogram of stroke patient before (a), and after (b), one hour of electrical stimulation

Table 1 Parameters measured

Parameter	Description
p_1	Relaxation index
p_2	Number of swings
p_3	Area between goniogram and resting angle (cm^2)
p_4	First maximum of the goniogram (degrees)
p_5	Relaxation index at the half-swing
p_6	Average relaxation index of ten successive swings
p_7	First maximum of the tachogram (rad s^{-1})
p_8	First minimum of the tachogram (rad s^{-1})

EXTRACTION OF SIGNIFICANT PARAMETERS FROM GONIOGRAM PATTERN

To estimate the degree of spasticity, eight characteristic parameters were extracted from the goniogram and tachogram recordings. They are listed in the *Table 1*.

The first parameter (p_1) was the relaxation index R_{2n} (*Figure 4*). This corresponds to the angle at which the spasticity stops the natural backward swing. To eliminate the influence of different resting angles belonging to different patients, or to the same patient at different testing days, the amplitude of the first backward swing was normalized by the difference in angles between the resting and starting position (A_0). In normal subjects this ratio displayed a value around 1.6. The parameter p_1 was further normalized by this value. A relaxation index of zero signifies no motion of the knee from extended positon and therefore extreme spasticity. A relaxation index of one signifies a normal limb swing and therefore no spasticity. Special importance was assigned to this parameter as it belongs to the first 'burst' of spastic activity which is the most cumbersome to paraplegic patients while performing daily activities such as dressing, transfers from the wheel-chair etc.

The second parameter was determined by counting the maxima of the sinusoidal goniogram after the release of the lower limb. The parameter p_3 was represented by the area above the resting angle and below the goniogram prior to the first crossing over the resting angle. It is expressed in cm^2 when performing the measurements at a sensitivity of $5°$ mm^{-1} and a chart speed of 25 mm s^{-1}. The parameter p_2 was measured only when the limb swung over the resting angle already at the first backward swing. In this case p_3 was not evaluated. When the leg was slowly approaching the resting angle, the area p_3 was taken into account while the number of swings was disregarded. The value of p_2 in a healthy subject is 6 to 7.

The fourth parameter is defined by the first maximum of the goniogram of the swinging lower leg (the difference $A_0 - (A_1 - A_2)$ in *Figure 4*). It provides evidence of how strongly the spasticity pushes back the limb towards the starting angle. In healthy subjects this parameter ranges from 20° to 35°.

The four test parameters described are presented in *Figure 8*. *Figure 8a* belongs to a healthy subject. The leg is released from the starting angle and then it swings six or seven times around the resting angle. Irregular goniograms shown in *Figure 8b* and *8c* belong to spastic spinal cord injury patients. In *Figure 8b* the first minimum and maximum reached by the falling limb are shown while *Figure 8c* is explaining the definition of the test parameter p_3.

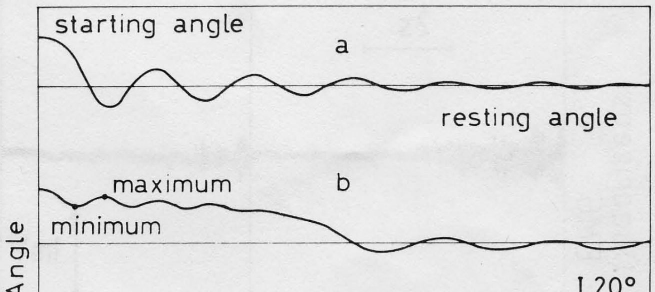

Figure 8 Graphical explanation of the test parameters p_1 to p_4

It has been shown by Burke *et al.*[9] that the stretch reflex is diminished when passive movement is commenced from a more flexed position or when the velocity of induced passive movement is lessened. The influence of the starting angle on the assessment of spasticity has been found also during the pendulum test[10]. In cases of slight spasticity, an irregular goniogram was obtained only when the leg was released from the largest starting angle. In patients with severe spasticity, the stretch reflex was provoked also at lower starting angles. This property of the pendulum test was therefore taken into account as a measure of the degree of spasticity. The parameter p_5 was defined as a relaxation index when the lower limb was dropped from the angle in between the starting angle (full extension) and resting angle (relaxed extremity).

As coughing, sneezing, movements of the head, and movements of the contralateral limb result in sudden increase or decrease of spasticity, the repetition of the pendulum test was introduced in order to improve the reliability of the proposed measurement. The knee extensor's spasticity was therefore

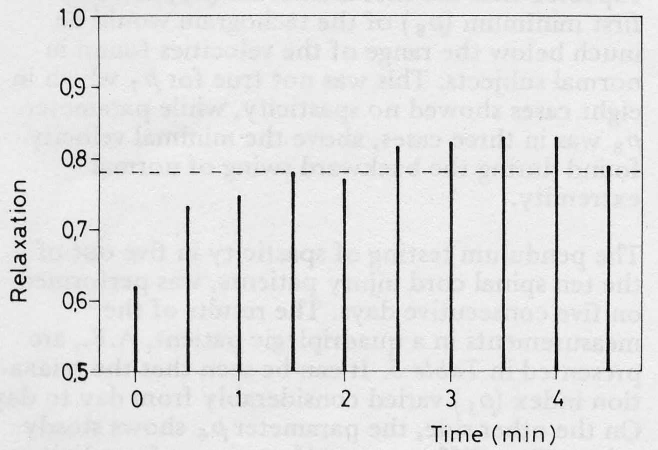

Figure 9 Fluctuations of relaxation index due to fast repetitions of the pendulum test

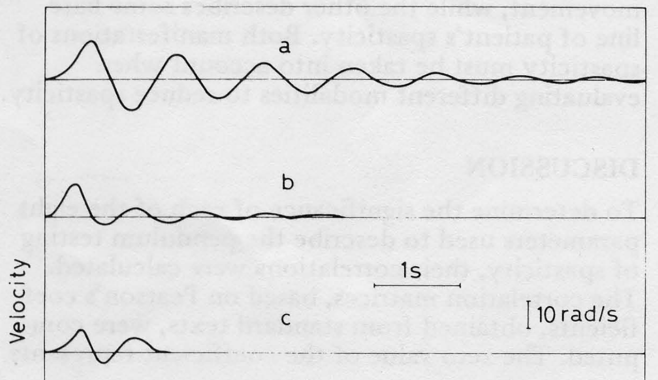

Figure 10 Tachograms belonging to different degrees of spasticity: (a) absent, (b) slight, (c) moderate, (d) severe

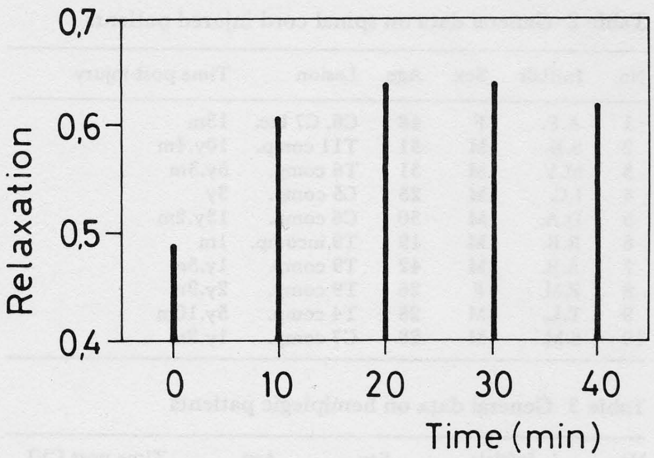

Figure 11 Changes in relaxation index when repeating the spasticity test each 10 min

tested ten times every 30 s. At fast repetitions of the measurements the test itself influences the next tests and the degree of spasticity is lessened. In *Figure 9,* fluctuations of the relaxation index due to repetitive testings are shown. A plateau of the relaxation index is usually attained after two or three pendulum tests. First, the average value and the standard deviation of ten successive relaxation indices were calculated. Then all the relaxation indices, outside the range determined by two standard deviations, were eliminated. The average value of the remaining relaxation indices was calculated and denoted as p_6.

Taking into account the velocity dependence of the stretch reflex, the maximal velocity of the first backward swing and the first forward swing were also considered as a measure of a degree of spasticity. The first maximum and the first minimum of the tachogram were denoted by p_7 and p_8, respectively. The parameter p_7 ranges from 11 to 17 rad s^{-1} in healthy subjects and p_8, from 9 to 12 rad s^{-1}. *Figure 10* shows how different degrees of spasticity influence the tachogram. *Figure 10a* represents a record from a healthy subject. The patterns shown in *Figures 10a, 10b,* and *10d* are of slight, moderate and severe spasticity, respectively. Differences among particular recordings are mainly in the maximal and minimal values of the velocity of the swinging lower leg. There is a difference also in the overall swinging time, oscillation frequency, and damping.

The first four parameters were extracted from the same goniogram recorded during the first pendulum test. After a 5 min rest, introduced to exclude the influence of repetitive testings, the half swing was performed. After a five minute pause, ten spasticity tests were carried out every 30 s. Finally, the goniometer was replaced by the tachometer and the last swing was performed after a 5 min rest. The patients were lying for about 20 min, relaxed, on a tilt table, with both legs bent over the edge and therefore the degree of spasticity would be expected to be decreased. In *Figure 11* the fluctuations of the relaxation index are shown when the spasticity tests were performed every 10 min. Here the

Table 2 General data on spinal cord injured patients

No.	Initials	Sex	Age	Lesion	Time post-injury
1	A.F.	F	48	C6, C7 inc.	13m
2	S.K.	M	31	T11 comp.	10y.4m
3	M.V.	M	31	T6 comp.	5y.3m
4	I.C.	M	23	C5 comp.	3y
5	D.A.	M	30	C6 comp.	13y.2m
6	R.B.	M	19	T9 incomp.	1m
7	A.B.	M	42	T9 comp.	1y.5m
8	Z.M.	F	26	T9 comp.	2y.9m
9	T.L.	M	28	T4 comp.	5y.10m
10	S.M.	M	28	C7 comp.	1y.2m

Table 3 General data on hemiplegic patients

No.	Initials	Sex	Age	Time post CVI
1	F.M.	M	64	3y.10m
2	J.S.	M	58	1y.1m
3	P.M.	F	66	6m
4	Š.M.	M	63	3m
5	S.M.	M	60	1y

Table 4 Results of the measurements in spinal cord injured and hemiplegic patients

No.	Initials	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8
1	A.F.	0.29	–	9.4	76	0.87	0.79	12.5	8.5
2	S.K.	0.08	–	8.3	80	0.69	0.67	9.5	3.0
3	M.V.	0.02	–	7.8	66	0.97	0.35	8.0	7.0
4	I.C.	0.13	–	8.4	60	1.00	0.96	14.0	11.5
5	D.A.	0.13	–	16.0	60	0.56	0.43	8.5	2.0
6	R.B.	0.60	–	1.5	6	0.60	0.64	12.0	2.2
7	A.B.	0.60	–	1.4	9	0.86	0.74	12.5	8.0
8	Z.M.	0.50	–	1.2	12	0.95	0.41	5.0	4.0
9	T.L.	0.71	4	–	10	0.99	0.75	10.5	6.0
10	S.M.	0.70	6	–	12	0.91	0.79	14.0	9.5
11	F.M.	0.38	–	1.3	24	0.42	0.44	4.0	4.0
12	J.S.	0.50	–	7.0	44	0.55	0.57	11.0	8.0
13	P.M.	0.54	–	1.7	35	0.70	0.66	15.5	11.0
14	Š.M.	0.56	–	3.6	32	0.54	0.55	8.0	6.0
15	S.M.	0.69	5	–	26	0.80	0.62	12.0	7.5

plateau was usually attained after ~ 20 min. As the order of the testings was always kept the same, the influence of relaxation was not crucial for the analysis of the data measured.

RESULTS

The general data on ten complete and incomplete paraplegic and quadriplegic patients are listed in *Table 2.* The causes of the accidents were in most cases motor vehicles and diving. The patients showing at least moderate spasticity on manual testing were chosen for the study. In *Table 3* the general data on five hemiplegic patients are collected.

Table 4 contains the results of the described measurements, first in ten spinal cord injured patients and next in five hemiplegics. The relaxation index (p_1) shows that the degree of spasticity in spinal cord injury patients ranged from severe ($p_1 = 0.02$) to mild ($p_1 = 0.71$). Moderate spasticity was found in the relaxation indices of the five hemiplegics. Only in three patients, having the largest relaxation index, was the number of swings (p_2) counted. In the rest of the patients the area (p_3) between the goniogram and the resting angle was determined. The first maximum of the goniogram (p_4) can display lower or higher values than those encountered in healthy subjects. In cases of severe spasticity, p_4 is above the value found in normals. This parameter can be in the normal range even when noticeable spasticity is present. The first maximum alone cannot therefore be considered as a reliable measure of spasticity. The relaxation index at the half swing (p_5) shows in almost all cases, a smaller degree of spasticity than the relaxation index measured when the lower limb was released from the full extension. In a few cases (patients M.V., I.C., Z.M., T.L., and S.M.) the goniogram was close to normal. The same is true for the average relaxation index found from ten successive swings (p_6). In patients with moderate or severe spasticity, parameter p_6 is significantly higher than parameter p_1 (except in patient Z.M.). In spinal cord injury patients displaying mild spasticity, and in all hemiplegic patients, the difference between p_1 and p_6 is smaller. It was expected that the first maximum (p_7) and the first minimum (p_8) of the tachogram would be much below the range of the velocities found in normal subjects. This was not true for p_7 which in eight cases showed no spasticity, while parameter p_8 was in three cases, above the minimal velocity found during the backward swing of normal extremity.

The pendulum testing of spasticity in five out of the ten spinal cord injury patients, was performed on five consecutive days. The results of the measurements in a quadriplegic patient, A.F., are presented in *Table 5.* It can be seen that the relaxation index (p_1) varied considerably from day to day. On the other side, the parameter p_6 shows steady values. Two different manifestations of spasticity were observed. One belongs to the first 'burst' of spasticity provoked by sudden passively induced movement, while the other describes some base line of patient's spasticity. Both manifestations of spasticity must be taken into account when evaluating different modalities to reduce spasticity.

DISCUSSION

To determine the significance of each of the eight parameters used to describe the pendulum testing of spasticity, their correlations were calculated. The correlation matrices, based on Pearson's coefficients, obtained from standard texts, were computed. The zero value of the coefficient represents

Table 5 Results of the measurement in spinal cord injured patient A.F. on five consecutive days

Day	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8
1	0.29	–	9.4	76	0.87	0.79	12.5	8.5
2	0.79	5	–	16	0.87	0.74	12.0	3.2
3	0.17	–	5.9	66	0.77	0.76	13.0	4.8
4	0.65	5	–	14	0.91	0.76	14.0	8.3
5	0.80	5	–	24	0.89	0.82	14.0	7.0

Table 6 Correlation matrix for the parameters measured in ten spinal cord injury patients. Statistically significant correlations are underlined

	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8
p_1	1.000	−0.006	−0.604	−0.907	0.213	0.415	0.367	0.187
p_2	−0.006	1.000	0.000	0.015	−0.116	0.042	0.284	0.251
p_3	−0.604	0.000	1.000	0.700	−0.240	−0.072	0.003	−0.034
p_4	−0.907	0.015	0.700	1.000	−0.093	−0.054	−0.071	0.057
p_5	0.213	−0.116	−0.240	−0.093	1.000	0.304	0.104	0.774
p_6	0.415	0.042	−0.072	−0.054	0.304	1.000	0.872	0.649
p_7	0.367	0.284	0.003	−0.071	0.104	0.872	1.000	0.630
p_8	0.187	0.251	−0.034	0.057	0.774	0.649	0.630	1.000

Table 7 Correlation matrix for the parameters measured in five hemiplegic patients. Statistically significant correlations are underlined

	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8
p_1	1.000	0.000	0.183	−0.030	0.907	0.747	0.522	0.448
p_2	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000
p_3	0.183	0.000	1.000	0.766	0.012	0.144	0.165	0.124
p_4	−0.030	0.000	0.766	1.000	−0.013	0.381	0.467	0.543
p_5	0.907	0.000	0.012	−0.013	1.000	0.875	0.814	0.680
p_6	0.747	0.000	0.144	0.381	0.875	1.000	0.979	0.927
p_7	0.522	0.000	0.165	0.467	0.814	0.979	1.000	0.977
p_8	0.448	0.000	0.124	0.543	0.680	0.927	0.977	1.000

no correlation between two variables, while + 1 belongs to maximal positive and − 1 to maximal negative correlation. The correlation matrices for spinal cord injury and hemiplegic patients are shown in *Table 6* and *Table 7*, respectively. The significance matrix for Fisher *Z*-transformation was also calculated. In both tables the correlation coefficients tested at the 0.10 level of significance are underlined.

No significant correlation coefficients were found in parameter p_2, representing the number of swings, because of insufficient data. The number of swings can be higher in spastic patients (*Figure 8c*) than in normal subjects (*Figure 8a*). The pendulum test can provoke clonus, resulting in numerous oscillating movements of the lower limb. It is therefore suggested that this parameter be omitted when automatically evaluating the pattern of the swinging limb.

In spinal cord injury patients, parameters p_1 and p_4 are well correlated (zero significance coefficient). By measuring only one of them, the information contained in the other can be satisfactorily assessed. No correlation was found between the two parameters in hemiplegic patients. With hemiplegic patients, the parameters p_6, p_7, and p_8 are strongly related to each other. The coefficient of significance is 0.002 for the correlation between p_6 and p_7 and between p_7 and p_8, and 0.02 between p_6 and p_8. In spinal cord injury patients, the statistically significant correlation (0.01 coefficient of significance) occurred only between the parameters p_6 and p_7.

It is important to notice that the parameters describing the amplitudes of joint angles (i.e. p_1, p_4) are not associated with the parameters belonging to the velocity of the swinging lower leg (p_7, p_8). In some patients, the leg falls slowly towards the resting position while in other cases the leg starts to fall with the normal velocity and is briskly stopped by the activated stretch reflex before reaching the resting angle. The velocity does not need to be measured by means of a tachometer. It can be accurately obtained by analogue (electronic) or digital (microcomputer) derivation.

While the relaxation index (p_1), which accounts only for the first period of the test, might be useful in comparing patients with consistent patterns of spasticity, many patients exhibit rather erratic movements during the test. It is therefore suggested that the whole transient of the test be recorded and judgement about spasticity be made after estimation of significant parameters extracted from the goniogram pattern.

From a clinical viewpoint, the goniogram of the pendulum test has proven to be, in our experience, a quite practical and sensitive test. Simultaneous measurements of EMGs and goniograms have shown that gross surface EMG does not provide more information about spasticity than the goniograms. Thus it is believed that for fast routine tests, gross measurements of EMG are not necessary.

Taking into account the deficit of clinically applicable methods for the assessment of spasticity on the one hand and the simplicity of instrumentation and evaluation of the pendulum test on the other, it can be concluded that pendulum testing of spasticity has the potential to become an effective measuring method in rehabilitation.

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