ORIGINAL ARTICLE

Development of a New Method for Objective Assessment of Spasticity Using Full Range Passive Movements

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ABSTRACT. van der Salm A, Veltink PH, Hermens HJ, IJzerman MJ, Nene AV. Development of a new method for objective assessment of spasticity using full range passive movements. Arch Phys Med Rehabil 2005;86:1991-7.

Objective: To develop a method for assessment of spasticity, in which the whole range of motion (ROM) at a wide variation of speeds is applied.

Design: Cross-sectional design to study construct validity.

Setting: Research department affiliated with a rehabilitation hospital in the Netherlands.

Participants: Nine patients with complete spinal cord injury recruited from the rehabilitation hospital.

Interventions: Not applicable.

Main Outcome Measures: Thirty to 45 stretches over the whole ROM were applied to the triceps surae muscle at varying velocities measuring from 30° to 150°/s. Electromyographic responses were measured in order to assess reflex excitability. The torque over the ankle joint was measured during the whole stretch. The angle and velocity at which the reflex was initiated was also determined.

Results: The electromyographic responses increased significantly at increasing stretch velocities ($P<.001$). The applied maximum angles are reproducible (intraclass correlation coefficient, .81) and provide representative torque responses.

Conclusions: The assessment method of spasticity using full range passive movements provides objective outcomes. The angular velocity is responsible for an exponential increase in amplitude of the electromyographic response.

Key Words: Electromyography; Muscle spasticity; Reflex, stretch; Rehabilitation; Spinal cord injuries.

SPASTICITY MAY BE VERY IMPAIRING in patients with upper motoneuron lesions. Several authors state that spasticity can cause gait impairments.[1-3] An important aspect of this impairment is increased plantarflexion during swing. Affected patients have to compensate for this by circumduction of the leg or hiking of the pelvis. Thus, a relatively small impairment such as the increased plantarflexion can have a large impact on the general movement pattern. Increased plantarflexion during stance, ankle vaulting, is also frequently observed.[4] These gait impairments may be due to cocontractions[5] or hyperreflexive movements in response to muscle stretch.[6-10]

Spasticity is defined as a "velocity dependent increase in the tonic stretch reflex (muscle tone) with exaggerated tendon jerks, resulting from the hyper excitability of the stretch reflex, as one component of the upper motor neurone syndrome."[11(p606)] It should be noted that spasticity is only 1 part of muscle stiffness; another part is passive muscle stiffness.[12] Passive muscle stiffness depends on soft tissue changes. These changes provide a biomechanic, nonreflexive, component of muscle stiffness.[13] It is important to distinguish between these components of muscle stiffness, because it may have consequences for treatment. Therefore, an assessment for spasticity should objectively measure both the reflexive and nonreflexive components of muscle stiffness.

Frequently used clinical tests of spasticity are: the Ashworth Scale,[14] the Modified Ashworth Scale (MAS),[15] and the Tardieu scale.[16] The Ashworth Scale is a 5-point scale graded from 0 (normal muscle tone) to 4 (limb rigid in flexion or extension). The MAS is extended with an extra grade between 1 and 2 (ie, 1+). The scores are determined by moving the joint over its entire range of motion (ROM). Commonly used velocities are approximately 50°/s.[17,18] A disadvantage of the Ashworth Scale and MAS is the poor intertester reliability.[19,20] The outcome of the Tardieu test is the angle at which a catch can be felt. The catch is defined as a sudden increase in muscle stiffness in response to a brisk muscle stretch. The inter- and intratester reliability correlation coefficient of the Tardieu test was found to vary from .38 to .90.[21] Thus, this reliability is poor in several cases.

Other measurements of spasticity have been reported that do not require subjective assessment and therefore may be more reliable, for example, the H-reflex and tendon tap.[22] However, these measurement methods do not assess spasticity in the functional range. It can be concluded that no objective assessment for spasticity in the functional range is clinically available. The goal of this study is to propose such an assessment method. It uses the same movement range as the MAS, but assesses both the reflexive and nonreflexive components of muscle stiffness, using physical measures.

METHODS

Participants

We recruited subjects with spinal cord injury (SCI) from a database of a rehabilitation center in the Netherlands (Het Roessingh, Enschede).

Inclusion criteria were: presence of spasticity (Ashworth grade 1 or higher), absence of voluntary movements in the triceps surae, time since injury at least 6 months, triceps surae muscles and tibialis anterior muscle must be able to contract

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using electric stimulation, and age above 18. Patients were allowed to take antispasticity medication, but they agreed not to change the dose for 2 weeks before and during the experiment. Patients with hypersensitive skin of the legs, absence of the dorsiflexion beyond anatomic position, or diseases that could temporally increase tonus (specifically bladder infection) were excluded. All subjects gave informed consent to participate and the experiment was approved by the local ethics committee.

Patients were measured 3 to 4 times with 3 to 14 days in between. All measurement session started at the same time of day.

Stretch Reflex Over the Whole ROM

The patients were seated upright and the knee was flexed 75°, 0° being defined as knee extension (fig 1). The foot was fixed to a footplate, which could be rotated around 1 axis, thus providing dorsi- and plantarflexion at the ankle joint. The foot was strapped to the plate using a soft, flexible brace and Velcro in such a manner that the heel could not lift from the plate, yet the ankle joint could freely be moved. The rotation axis of the ankle joint, defined as the line through the malleoli, was aligned with the rotation axis of the device. Before the measurement started the ROM of the ankle joint was determined manually. Stops were inserted at the maximal plantarflexion and dorsiflexion, to prevent movement in excess of the ROM. Dorsiflexion and then plantarflexion movements were applied manually using a handle. The movement of interest was the dorsiflexion movement to assess soleus muscle spasticity, which is clinically most relevant. Thus, a movement from maximal plantarflexion to maximal dorsiflexion was applied. Between 2 successive movements, at least 5 seconds rest in plantarflexion was prescribed, whereas the duration of the stretch was less than 2.3 seconds. For safety reasons, the first 4 stretches were slow. As the test progressed, both slow and fast movements were carried out. The latter stretch velocities were applied in random order. The angles and angular velocities were measured simultaneously. The applied stretch velocity was presented after each movement; therefore, it was possible to equally spread the applied velocities over the whole range. In 1 session about 30 to 45 stretches were applied, ranging from 30° to 150°/s. The duration of 1 session was approximately 5 minutes.

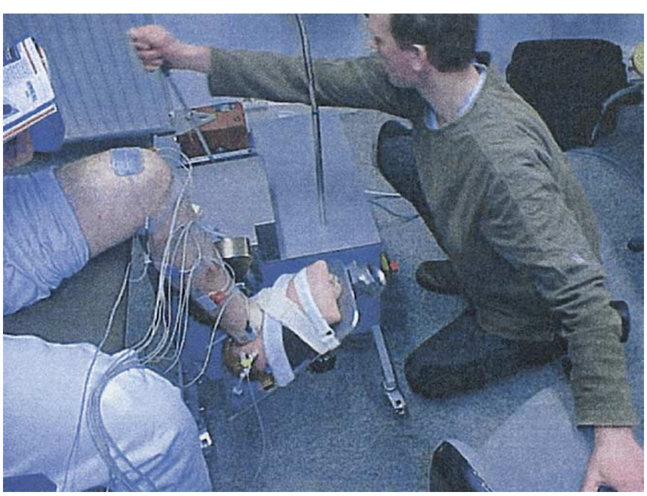

Fig 1. Setup for testing stretch reflexes. The foot is fixed on a plate and can be moved over the whole ROM of the ankle by a handle. The handle contains a strain gauge for torque measurement. The ankle angle is measured using a potentiometer at the axis of rotation and the angular velocity is determined with a gyroscope fixed on the footplate. Electromyographic activity of the soleus is measured simultaneously with the physical measurements.

Data Recording

We measured the electromyographic activity of the soleus muscle with surface electrodes[a] (Ag-AgCl gel electrodes; diameter, 12mm; interelectrode space, 20mm) using a bipolar arrangement. A ground electrode was applied on the lateral malleolus. The electrodes were applied on one third of the line through the medial malleolus and the medial epicondyle of the femur[23] (see fig 1). Before application, the skin was shaved, abraded and cleaned with alcohol. For the electromyographic recording, we used TMSI hardware and software.[b] The sample frequency of the electromyographic activity was 2048Hz. The electromyographic data were band-pass filtered applying cutoff frequencies of 20 to 200Hz. We used a 22-bit analog-to-digital (A/D) converter, which had an effective resolution of 71.9nV. The angles, angular velocities. and torques were measured with a sample frequency of 1000Hz.

We measured angles with a calibrated potentiometer fixed over the axis of ankle rotation. For the movement of the foot the anatomic position was defined as 0° and plantarflexion was defined as being negative. The angular velocity was measured with a calibrated angular velocity sensor (gyroscope) on the footplate. Torque was measured with a calibrated strain gauge in the handle. The angle, angular velocity, and torque data were recorded on a laptop computer using an A/D converter and LabView software.[c] The analysis of the data was performed in Matlab.[d]

Data Analysis

The stretch movements were applied manually, comparable to the stretches of MAS movements and stretches in daily life. The average velocity during the dorsiflexion over the whole range was defined as the stretch velocity. The start of the electromyographic burst in the filtered electromyographic data was detected with a threshold. This threshold was 3 times the standard deviation (SD) of the noise level, determined before the stretch started.

We detected the start of the electromyographic burst during the stretch. This detection time was corrected for the delay of the reflex loop, which was estimated as 45ms.[24,25] When a burst was detected the root-mean-square (RMS) value of the electromyography signals over a 100-ms window was calculated. This window length matched the largest burst times. The window started at the beginning of the burst.

The RMS values of the electromyographic response to the stretch were plotted against average stretch velocities. The increase of electromyographic responses at increasing speed was described with an exponential fit over the 30 to 45 responses in 1 session. The electromyographic responses at 50°/s (EMG_{50}), 75°/s (EMG_{75}), and 100°/s (EMG_{100}) were calculated from the fitted curve.

We determined the state (angle, angular velocity) in which the stretch reflex was initiated. In detail, 45ms before the beginning of the electromyographic burst the angular velocity and the angle of the stretch movement were determined. The results were plotted in an angular velocity/angle graph.

The average and the SD of the slope values of the linear-regression lines in the angular velocity/angle graphs were calculated.

The angle that triggered the burst start (reflex-initiating angle) was defined at the velocity of 100°/s. This velocity is commonly used for the Tardieu scale.[16,21]

Table 1: Demographic Data of Patients

Patient No.	Sex	Age (y)	Injury level	Time Since Injury (mo)	MAS Score	Clonus
1	M	36	T4	71	1+	Yes
2	M	30	T5	33	1	Yes
3	M	42	C6	211	1+	Yes
4	M	30	C6-7	28	3	Yes
5	F	41	T8	208	1+	No
6	M	34	C6	105	3	No
7	M	37	T11	217	1	Yes
8	F	21	C5	97	1	Yes
9	M	41	T4-5	275	1	No

Abbreviations: F, female; M, male.

We used 2 devices in this study. The device that was used for the first 5 measurements, had a relatively large inertia to ensure smooth movements for low velocities, but the ankle torque could not be measured due to this large moment of inertia. To allow measurement of ankle torque at varying velocities, we used a second device, with a low moment of inertia (.065kg·m^2), in the last 4 experiments. The torques measured at velocities smaller than 70°/s were averaged. At velocities higher than 70°/s the influence of inertia on the torque may interfere with the torque from the muscle. The average values of the first, second, and third one third of the movement were determined and analyzed (ie, early, mid, and late movement torque).

Statistical Analysis

Electromyographic responses were statistically analyzed. The RMS values at the 3 speeds, 50°, 75°, and 100°/s did not have a normal distribution. Therefore, we used a nonparametric test to determine the velocity effect: the Friedman test for comparison of more than 2 related groups. For post hoc tests we used the Wilcoxon signed-rank test.

To evaluate reproducibility of movement ranges, we determined the intraclass correlation coefficient (ICC), using a 2-way random model with absolute agreement. The 95% confidence interval (CI) was determined as well.

Slopes of fitted lines in reflex-initiating angle–angular velocities plots were determined. The average slope value was calculated with the 95% CI. Alpha was .05 in all cases.

RESULTS

Participants

Thirty-three patients were found to be suitable, according to the files. These patients were contacted. Sixteen patients were not willing to participate, because of other commitments or lack of interest. Seventeen patients were seen for intake. Seven of them were excluded because of lack of spasticity in the triceps surae muscles. One of the patients could not sit in the experimental setup due to trunk instability and it was not possible to measure this patient in his wheelchair. Finally, we selected 9 patients with SCI who participated in the study. The demographic data of these patients are presented in table 1.

For the results of the electromyographic response the power was calculated. This power was found to be .79 (average SD, 3.35; average difference, 3.2; α=.05; n=8).[26]

Data

Figure 2 shows electromyographic responses, angles, and angular velocities in 1 subject for stretches at 3 speeds (67°, 84°, 102°/s). In this session the ROM was from 29° of plantarflexion to 14° of dorsiflexion. At increasing speed the electromyographic response increased. This relation between mean speed of the movement and RMS of the electromyographic burst is presented in figure 3 for 45 stretches applied during 1 measurement for the same subject. The response was found to be exponential, which agrees with the sigmoid shape found in the literature.[27,28] This study only evaluated the threshold of the sigmoid shape. The RMS values of the electromyographic response at 50°, 75°, and 100°/s were determined.

Subjects demonstrated the same increase of average values of the $EMG_{50/75/100}$ data with speed (fig 4). Electromyographic activity could not be measured in patient 8. The increase over the mean speed was less pronounced in the data of subjects 4, 5, 7, and 9. The within-subject effects of the RMS values of the electromyographic activity over the velocities were significant (Friedman nonparametric test, $P<.001$). Specifically, the EMG_{75} values were significantly larger than the EMG_{50} values (Wilcoxon signed-rank test, $P<.001$) and the EMG_{100} values were significantly larger than the EMG_{75} values (Wilcoxon signed-rank test, $P<.001$).

The torque curves at velocities up to 70°/s show the characteristic shape of tissue stretch. Three ranges were distinguished: early, middle, and late movement torque. Variability of the maximum angle may influence the outcome of the torque, because at the end of the range of dorsiflexion the

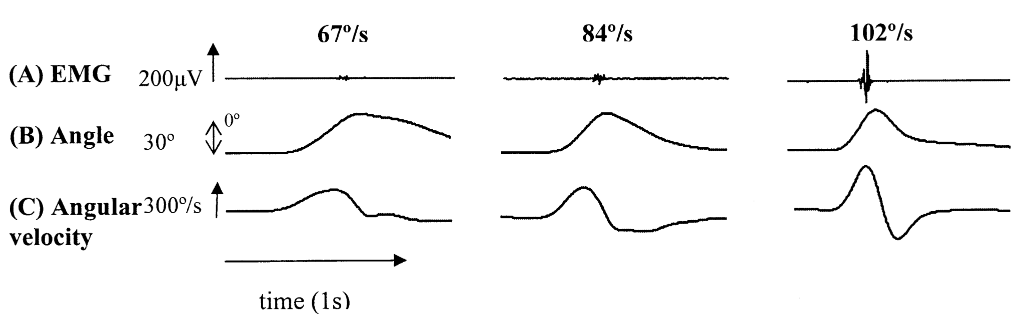

Fig 2. Examples of electromyographic responses of the soleus muscle to stretches at 67°, 84°, and 102°/s over the whole ROM in 1 patient. The start of the graph is the start of the stretch; the end of the graph is kept equal for each graph. (A) The electromyographic burst resulting from the stretch. The electromyographic responses (EMG) increase at higher speeds. (B) The angles during the stretch movement, measured with a potentiometer over the ankle rotation axis. (C) The angular velocity during the stretch movement, measured with a gyroscope fixed on the footplate.

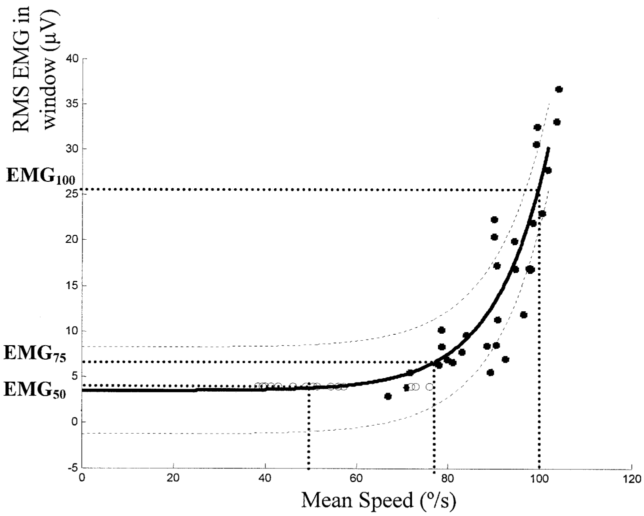

Fig 3. Plot of 1 session in 1 subject (same subject and measurement as fig 2). The RMS values of the electromyographic signal over about a 100-ms window at the time of burst, are shown. These are responses to stretches ranging from 38° to 102°/s. The fitted (solid) curve (±1 SD, dotted curves) shows clearly the increase in the electromyographic response amplitudes at increasing velocities. The fitted curve is used to determine the RMS values at 50°, 75°, and 100°/s, respectively EMG_{50}, EMG_{75}, EMG_{100}. Legend: ●, the RMS values of the electromyographic signal as a result from the reflexes; ○, the electromyographic responses below the threshold value, defined as 3 times the noise level.

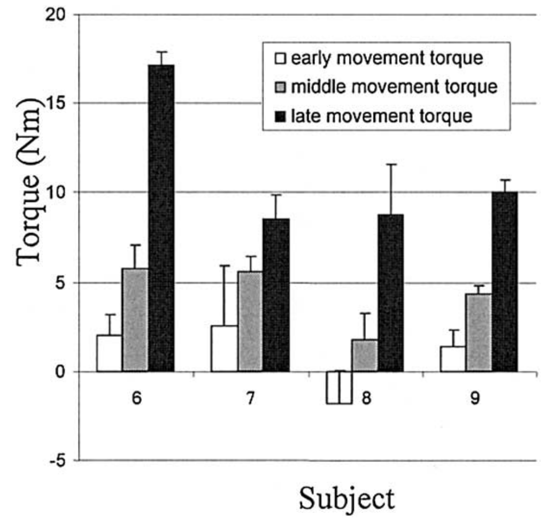

Fig 5. Average values (+1 SD) for the torques over the ankle joint during dorsiflexion in subjects 6, 7, 8, and 9. Torques are determined at stretches smaller than 70°/s. The average torques are calculated over the first, second, and third one third of the total ankle range (ie, early, middle, and late movement torques).

torque increases rapidly. Therefore we checked the reproducibility of the maximum angles. The reproducibility of these angles was good (ICC=.81; 95% CI, .53–.96). In addition, no relevant change in the shapes of the curves was present.

The average torque responses (+1 SD) for subjects 6, 7, 8, and 9 are presented in figure 5. These results were not statistically evaluated because the torque was only measured in 4 subjects. As expected, the torque increases when the muscle is progressively stretched. Especially in subject 6 the increase in the late movement torque was remarkable. This subject showed also large electromyographic responses (see fig 4).

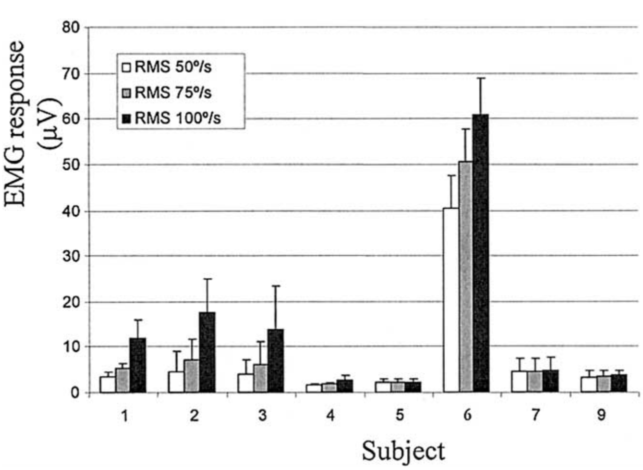

Fig 4. Average values (+1 SD) for the RMS values of the electromyographic responses, except subject 8. The presented RMS values represent the responses at stretches at 50°, 75°, and 100°/s, respectively, EMG_{50}, EMG_{75}, and EMG_{100}.

Burst Start and Amplitude

Figure 6 presents the angular velocity and angle at the time of the reflex start in 1 subject during 1 measurement. If velocity were the initiator of the burst start, it could be expected that all triggering states occur at the same velocities. Then the range of the reflex-initiating velocities would be very small, compared with the total range of applied velocities. In that case, the slope of the angular velocity/angle graph would be ∞. On the other hand, if the angle were the initiator of the burst start, the triggering states would occur at the same angle every time. In this case, a small range of reflex-initiating angles would be found compared with the total range of motion. The slope of the graph would be 0.

We tested the slopes of the regression lines through the curves (fig 6). The mean calculated slope of the subjects was .018±.035°/s. The distribution of the values was assumed to be normal, because the kurtosis and curve skewness (respectively, −.08 and −.70) were almost zero. The 95% CI of the slope was −.011 to .048. Thus, the slope did not differ significantly from 0. This indicates strongly that the angle was the initiator for the start of the electromyographic burst.

Figure 7 shows the range of the reflex-initiating angles at 100°/s for 3 or 4 measurements of each subject. The ROM of the ankle joint is also presented. All responses were initiated in the mid range of the movement and were relatively small compared with the total ROM. Only in subjects 3 and 5 was the range of the reflex-initiating angle larger than 30% of the total ROM. Note that plantarflexion was negative and the anatomic position of the ankle joint was zero.

DISCUSSION

Reflex excitability is commonly assessed by grading the reflex response to an impulse delivered to the tendon of a muscle. This is a much simpler response than the complex patterns of activity which may be seen following muscle stretch caused by active or passive movement.[29] The use of the stretch reflex over the whole ROM, with velocities from 30°/s to 150°/s, is a better approach to movements of daily life. In normal gait the average angular velocities of the ankle dorsi-

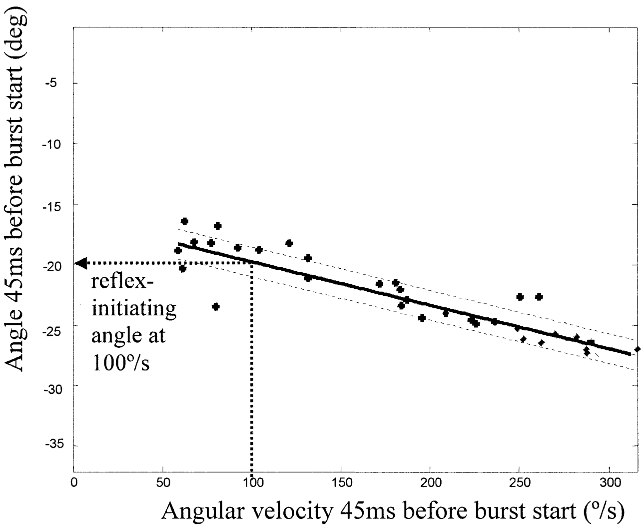

Fig 6. Graph of angular velocities and angles 45ms before the start of the electromyographic response. The graph is derived from 1 subject during 1 measurement involving 34 stretches. The linear regression line is fitted through the scatterplot. In the graph the reflex-initiating angle is indicated at 100°/s.

flexion ranges from about 20° to 75°/s in stance.[30] This is slightly higher in swing, 25° to 90°/s (estimated from normal data described by Perry[30]). Other stretch velocities during daily life in spastic patients may be even higher, for example, the shocks while wheelchair riding and sudden foot-ground contact during transfers. The described stretch reflex over the whole ROM also is comparable to the clinically used MAS. In literature stretch velocities of 30° to 70°/s are reported for the MAS.[17,18] But, very brisk movements are also applied in clinical settings to determine spasticity. For the comparability to the MAS we looked at the electromyographic response of the muscle at a mean velocity of 50°/s (EMG_{50}). For comparability to stretches in daily life, mean stretch velocities of 75°/s (EMG_{75}) and 100°/s (EMG_{100}) were also determined (see fig 3).

With our setup the torque was measured, including both the active and the passive responses to muscle stretch, making it possible to determine whether muscle stiffness is due to reflexive or nonreflexive components. It can be assumed that subjects with high electromyographic responses suffer from reflex hyperexcitability. Subjects with high grades of torque without high electromyographic responses will suffer from muscle stiffness due to passive components. The treatment of increased reflex excitability is very different from more passive increased muscle stiffness. In addition, the measurement provides objective results which might increase the intertester reliability. This intertester reliability is poor in the MAS.

The device that was used for the last 4 measurements allowed measurement of ankle torque, but did not impede the application of smooth movements. Therefore, we prefer to use the second device, which can be used in almost all spastic patients.

Manually performing the testing has several advantages over a motorized device. First, the setup is less complex and less expensive. Thus, this method of testing can be more easily applied in a clinical setting. Second, clinicians are able to feel the movement. Smooth movements can be applied by the operator, even with a low inertia of $.065 kg \cdot m^2$, using a relatively long handle of approximately 0.5m (see fig 1). This allows a clinical assessment of tissue stiffness.

The outcome of this study may be influenced by the relatively small number of patients, but the power was almost .80, which is acceptable. In addition, significant results were found. Only a few patients had high grades of spasticity. This reduces the contrast in the results. It is very likely that this makes it more difficult to detect statistical significant correlations or differences.

Other studies indicate that creep can be present when stretch is repeatedly applied to tissue.[31] The results show that no relevant creep was present during this representative session. Between each stretch movement there were 5-second rests, which may explain the absence of creep.

In some cases only single action potentials in the electromyographic signal could be distinguished. Single action potentials will not be detected by the MAS, because the muscle will only generate a very small force. In our setup these responses will not provide large outcomes in the $EMG_{50/75/100}$ because we used the RMS value over a 100-ms window. In addition, those small responses will generally not impair the patient.

The angle is most likely the initiator of the reflex response, because no significant difference is found from the horizontal slope in angular velocity/angle graph. The relation between angle and angular velocity at which the reflex was estimated to be generated (see fig 6) depends on the actual reflex delay. This delay was assumed to be 45ms, but it actually depends on leg length, because it is caused by the limited conduction velocity of the action potentials along the nerve fibers. This delay was not measured for each individual subject. Errors in the delay may influence the relation between reflex-initiating angle and velocity. In most subjects the reflex-initiating velocity was near the maximum, where the sensitivity for delay errors is minimal. However, it is advised to assess reflex delays for each individual, for example using a tendon tap. In some patients the muscle contraction due to the reflex caused a plantarflexion movement of the foot, lifting the heel of the footplate. This did

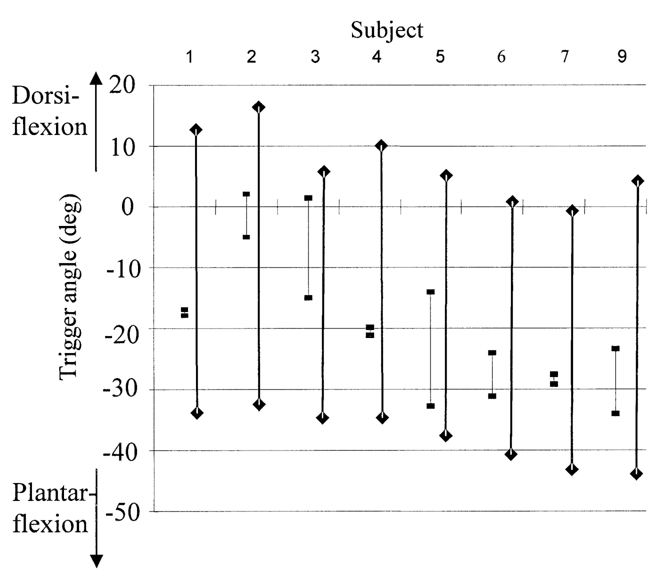

Fig 7. For each subject, the left line (▬) shows the range of the reflex-initiating angles at 100°/s stretch velocity in all subjects, except subject 8. The average ROM for each subject is presented (♦). The reflex-initiating angles are the ankle joint angles 45ms (used as reflex delay) before the electromyographic burst start. This velocity is comparable to the stretches of the Tardieu scale. Negative values stand for plantarflexion and 0° is defined as the anatomic position.

not influence the outcome of the reflex-initiating angle, because the value was determined as soon as the reflex started, thus, before the heel was lifted. The reflex-initiating angle outcome is comparable to the outcome of the Tardieu scale.

Reflexes are initiated by one or more of the sensing systems in the muscles, tendons, ligaments, or other stretched tissues.[32] In this study it is assumed that the reflex is initiated mainly by the muscle spindles. Other sensing systems may also provide a reflex, which appears later in time, because at varying velocities other sensing systems may be active. Nevertheless, the first and most important response will be from the muscle spindles.[24]

The finding that the angle is the trigger for initiation of the reflex response means that muscle spindles become active at the same point during the stretch. This may be caused by the slack of the stretched tissue. Passive structures like the muscle tendon have a certain slack. The muscle itself may also have a slack when it is shortened excessively. Then the muscle filaments cannot actively provide tension in the muscle.[33] Also, muscle spindles have a slack region.[34] In healthy muscles this slack in the muscle spindle is actively compensated with the intrinsic muscle fibers innervated by the gamma neurons.[35] In patients with upper motoneuron lesions, this active slack compensation is dysfunctional. Of course, changes in inhibition in the reflex loop, such as pre- or postsynaptic inhibition, may also result in a fixed angle at which the response is triggered. Further research to study the initiator of the reflex will be very informative to understand reflex responses.

Movement velocity influences the magnitude of the response as shown in figures 3 and 4. The exponential relation found in this study agrees with the sigmoidal input-output relation in monosynaptic reflex pathways.[27,28] This is a common input-output relation for several neurologic processes.[36] This assumption can also be explained from a neurophysiologic background. When the stretch velocity is increasing, more Ia-afferents from the muscle spindles will be recruited. When a certain threshold is reached, the alpha motoneurons in the spine start generating action potentials activating the muscles. When the velocity is continuously increased, the amount of participating monosynaptic reflexes increases simultaneously. In addition, not only monosynaptic reflexes but also bisynaptic and polysynaptic reflexes will be activated, initiated by multiple sensory systems. Sensors which will be involved are: muscle-spindles, tendon organs, skin, joint, and ligament receptors.[37,38] This recruitment takes place gradually.[38] At a certain stretch velocity, all reflexes will be recruited. Then the saturation level is reached. In our experiment the saturation level was never reached.

In subject 6 the electromyographic response was relatively high (see fig 4). This subject showed also a relatively low reflex-initiating angle (see fig 7). On the other hand, subject 5 showed a rather low reflex-initiating angle, which indicates a high reflex sensitivity, whereas the electromyographic response was low. All outcomes are reproducible. Thus, both outcomes represent other components of the reflex sensitivity. The high torque values in subject 6 (see fig 5) were likely due to the high reflexive responses to the stretches.

CONCLUSIONS

The method and device described can objectively assess muscle spasticity and distinguish between the reflexive and nonreflexive components of muscle stiffness. The stretches used in this measurement system are comparable to stretches occurring in daily life. The reflex activity is initiated at specific ankle angles, independent of the stretch velocity. The angular velocity is responsible for the amplitude of the electromyographic response, with an exponential increase noted at increasing velocity of stretch.

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Suppliers

a. Neuroline type 720 00-s; Medicotest A/S, Rugmarken 10, DK-3650 ∅lstykke, Denmark.
b. PortiLab EMG system; TMS International BV, Hendrik ter Kuilestr 181, 7547 SK Enschede, The Netherlands.
c. LabView 6.1; National Instruments Corp, 11500 N Mopac Expwy, Austin, TX 78759-3504.
d. Matlab 6.5, release 13; The MathWorks Inc, Apple Hill Dr, Natick, MA 01760-2098.