A new biomechanical method for objective measurement of spasticity: A preliminary study

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The assessment of the various impairments in brain damage including spasticity is important. The purpose of this study was to develop a new biomechanical method based on quantification of velocity reduction (VR) suitable for clinical use.

A highly reliable system was developed to apply a constant torque perturbation at the elbow. This system was used to measure the VR in 30 healthy adults and 10 hemiplegic patients. In healthy subjects, the mean VR was 3.02% (SE (standard error) = 0.29). In hemiplegic patients, the mean VR in the impaired arm (81.47%, SE= 2.87) was significantly higher than the VR (%) either in the non-impaired arm (9.86%, SE= 0.92) (WSRT (Wilcoxon Signed Ranks Test) : Z = -12.74; p<0.001), or the normal (3.02%) p<0.001. The interaction between the associated reaction (AR) and the asymmetrical tonic neck reflex (ATNR) with head away from the impaired arm made a significant higher VR (90.41%, SE=3.43) (p<0.001). The correlation between the VR (%) and the Modified Ashworth Scale scores was significant (Spearman’s rho = 0.77, p<0.001).

It is concluded that the quantification of velocity reduction may be used as an objective method of measuring spasticity in neurological conditions.

Key words: Spasticity, measurement, velocity reduction, hemiplegia


Spasticity has been defined as a motor disorder characterized by a velocity-dependent increase in tonic stretch reflexes resulting from hyperexcitability of the stretch reflex (Lance, 1980). Excessive and untreated spasticity may delay a patient’s recovery and can be a factor preventing functional improvement (Francis et al, 2004). Thus, many therapeutic approaches aim to improve function by reducing spasticity (Bobath, 1990; Barnes, 2003).

Although such approaches can benefit patients, their effect on spasticity is unclear as there is a lack of objective measures that can be used in routine clinical practice (Francis et al, 2004). Thus, many therapeutic approaches aim to improve function by reducing spasticity (Bobath, 1990; Barnes, 2003).

When using the Ashworth scale, a fast passive movement of a joint in a relaxed limb encounters a rapid increase of resistance (spasticity) that opposes the movement and reduces the velocity (Johnson, 2001; Sheean, 2001). The authors assumed that it would be possible to record the amount of velocity reduction (VR) as an index of severity of spasticity.

In previous studies, constant velocity is used but the velocity applied for displacement is not stand-
ardized, and at different investigations, different velocities are used (Hufschmidt and Mauritz, 1985; Allison and Abraham, 2001). When using a qualitative clinical scale such as the Ashworth scale, the examiner stretches the muscle over a duration of about 1 second. (Bohannon and Smith, 1987).

This study aimed to develop a standard, objective method to quantify spasticity which could be used in the clinic. In order to standardize the method, the authors applied a constant torque to stretch the muscle passively over a duration of about 1 second and measured the percentage velocity reduction as the dependent variable. The authors hypothesized that in normal subjects there is no significant VR, and in spastic patients, the VR in the impaired arm is significantly higher than in the non-impaired arm, or normal arm. There is also a significant correlation between the VR and the modified Ashworth scale scores.

During recovery after stroke, abnormal movement in the paretic arm may be observed following effortful movement of other parts of the body (Bobath, 1990). These limb movements, termed associated reactions (AR) may become a long-term feature, particularly if there is poor recovery (Bhakta et al, 2001). Based on observations made during recovery, AR are considered to hinder development of normal movement (Bobath, 1990). AR are reported to be more prominent in the paralyzed spastic limb compared with the flaccid limb (Bobath, 1990; Brunnstrom, 1956). Bobath (1990) has described that AR are in interaction with asymmetrical tonic neck reflex (ATNR) so that spasticity is higher with the head away from the impaired arm. To test this hypothesis the magnitude of AR produced by interaction with ATNR was also measured as percentage VR.

The elbow flexors were selected for this study, as they are a common site of spasticity.

**METHODS**

**Participants**

Thirty neurologically healthy volunteers were included for comparison provided that they were 18 years of age or older, had no history of injury to the CNS and had no previous history of orthopaedic problems that might cause changes in elbow range of motion (ROM) and resistance to passive movement (RTPM).

Ten hemiplegic patients with muscle spasticity were recruited. Inclusion criteria were: no previous history of orthopaedic problems, to be able to provide informed consent directly or via a care giver and to understand the instructions. The experimental procedures were approved by the research council of Tarbiat Modarres University and the local ethics committee. Written informed consent was obtained from all patients.

**Apparatus**

The testing apparatus (Figure 1) consisted of two mechanical and driving sections. The mechanical section consisted of a rotating axis, a rotating limb for extending the forearm and a stabilizing limb for stabilizing the arm. The rotating limb was attached to a rotating axis with the axis of rotation aligned with the lateral epicondyle of the elbow (The approximate centre of rotation of the elbow).

At the other end of the rotating limb, there was a balancing weight to counterbalance the forearm – hand weight and gravitational pull. The driving section consisted of a pulley acting also as a conventional goniometer, a brake system and the weights. The weights were suspended from a rope passing around the pulley of 6.5cm radius. The other end of the rope was attached to the braking system to adjust the starting position in flexion. The weights suspended vertically from the end of the rope created a torque that rotated the rotating limb and elbow into extension. This ensured that a constant torque was applied, regardless of elbow angle.

The elbow movement was recorded with a potentiometer based goniometer. Four strain gauges attached on the central shaft were used to record the applied torque. The strain-gauge and potentiometer were connected via an amplifier to a 16-bit A/D...
converter in an IBM compatible PC. A computer program was used to collect data using Labview software. Data were displayed during the assessment online, then were stored in a coded file for analysis at a later stage. Instantaneous angular velocity was calculated from displacement data using numerical differentiation. Here, the angular velocity has been considered as the rate of change of angular displacement with respect to time (\( w = \frac{Dq}{Dt} \)).

The validity of the torque was determined by application of known loads and the validity of the measured angle correlated with angles on the goniometer (\( p < 0.001 \)). The accuracy of the angle was \( \pm 1^\circ \).

For reliability study, three measurements were recorded and the intraclass correlation coefficient (ICC) for torque and angle measurements was 0.99 and 0.97 respectively. For test–retest reliability, the ICC for the measurements taken one week apart was 0.99. Repeated measures ANOVA did not show a significant difference between measurements taken in a session and between days. Therefore, the device used was highly reliable.

**Procedure**

Subjects were interviewed to determine basic demographic details comprising age and gender. Data pertaining to the brain injury, comprising side of hemiplegia and time from onset of injury to assessment were also collected for the patients.

Weight and height of the subjects were measured. The weight of the forearm and hand was calculated as suggested by Winter (1990) (segment weight/total body weight = 0.022). The length of the forearm was measured in standing position with the shoulders abducted 90°, elbow fully extended. The distance between lateral epicondyle of the elbow and ulnar styloid was measured. The range of motion was measured for elbow with goniometer. The weight applied to extend the elbow was calculated using this equation: 0.065 \( w = \frac{fl}{3} \times fhw \) in which \( w = \) weight (Kg); \( fl = \) forearm length (m); \( fhw = \) forearm and hand weight (Kg); 0.065 = constant (radius of the pulley) (m).

**The modified Ashworth scale**

Spasticity of the elbow flexors was assessed clinically with the modified Ashworth scale (MAS). The MAS was undertaken before instrumented evaluation of velocity to grade the severity of the resistance encountered during rapid passive lengthening of the elbow flexors. In order to eliminate interrater variability, the tests were carried out by one physiotherapist experienced at using the MAS. The assessor was blinded to all instrumented measurements. The resistance to passive stretch was measured at the elbow joint of the hemiplegic upper limb with the patient in the supine position and the arms alongside the trunk as described by Bohannon and Smith (1987).

**Instrumented measurement**

The subjects were positioned in supine position on a bed, head in midline and the arms at the side of the body. Testing commenced 5 minutes after the subjects had been positioned. The subjects were asked to remain relaxed during the procedure. The device was set at bedside. Before attaching the device the calibration was performed based on a computer program. The stabilizing limb stabilized the arm proximal to the elbow and the rotating limb was attached to the forearm proximal to the wrist. The forearm was in supination. Balancing weight of the device was set at the extended elbow position to ensure that forearm-hand and balancing weight were in a balanced state. The elbow was then positioned in maximal possible flexion.

The amount of weight to apply torque for each subject was normalized according to the weight and length of the forearm to extend the elbow over a duration of about 1 second. Three repeated measures, separated by an interval of approximately 20–30 seconds, were taken on each arm. Measurements were taken randomly on right or left side (impaired or non-impaired in patients). The outputs were displayed online on a computer and then stored for off line analysis. RTPM was quantified by calculating percent reduction in velocity from the point the velocity declined \([VR\% = \frac{(VCP - VRP)}{VCP} \times 100]\) in which \( VR\% = \) percent angular velocity reduction; \( VCP = \) angular velocity at the catch point; \( VRP = \) angular velocity at the release point. For this study, 180 degree denotes full extension.

The measurements were repeated in the impaired arm after 5 minutes. The patients were then tested with head rotated either to the impaired arm or non-impaired arm while the individuals squeezed a bulb dynamometer (Sammons Preston, USA) with sound hand with a force of at least 10 pounds per square inch. The hand was held in a holder with the forearm in a neutral position and the wrist in extension (Kraft and detels, 1972). Again, three successive movements were taken.

Before data collection, reliability of the measurements using the procedure described, was evaluated in 20 healthy subjects, with a median age of 28 years (range 19–43 years), who were not participating in the study, agreed to participate in the assessment of reliability. Three successive measurements were recorded. The mean time taken to complete the ROM was 0.98 second (SE= 0.01), suggesting that the procedure stretched the muscle over a duration of about 1 second, ensuring the stretch reflex could be elicited. The ICC, for torque, angle and veloc-
velocity recorded was 0.88 (95% CI: 0.86–0.90), 0.95 (95% CI: 0.94–0.96) and 0.90 (95% CI: 0.89–0.92), respectively. Repeated measures ANOVA showed no significant difference between torque measurements (F= 1.84; df = 1.88; p = 0.16).

This suggests that the torque applied was constant. The Bonferroni test showed no significant difference between measurements for angle and velocity (p>0.05). The results were deemed to be appropriate for proceeding with this study.

Statistical analysis
ICC, (a one-way random effects model) was used to determine the reliability of the measurements. ICC allows comparison of two or more repeated measures. Analysis of variance, repeated measures ANOVA and Bonferroni were used to determine whether significant differences between the three repeated measures existed. Greenhouse – Geisser correction was used for sphericity. The paired t-test and the ‘Wilcoxon signed ranks test’ (WSRT) were used to determine whether significant differences existed between the arms. The interaction of ATNR and AR with head rotation away or towards impaired arm was tested with WSRT. The Mann Whitney U test was used to determine whether significant differences existed in VR between the impaired and non-impaired arms with normal.

Spearman’s rho was used to test the relation between the VR and the MAS score in patients. All procedures were carried out using SPSS for windows V 11.5.

RESULTS

Healthy subjects
Thirty healthy men with a median age of 28 years (range 18–79 years) participated in the study. The time taken to move the limb through range was about 1 second (1.04, SE=0.008). The mean value of the applied torque was 1.89Nm (SE: 0.01; range: 1.40–2.77). There was no significant difference between torque measurements during test run [Mean (SE):1.25 (0.02)] (ANOVA: p>0.05), suggesting that the torque applied was constant. The velocity showed a significant difference between the arms (t = -2.32, p = 0.02). The mean VR (%) in the right arm [3.02 (SE: 0.29)] was significantly higher than the left arm [0.92 (SE: 0.13)] (t = 6.48, p<0.001). The difference in passive range of motion (PROM) between arms was not significant (t = 0.24, p = 0.81) (Table 1). In healthy subjects the analysis was performed on the first measure.

Patients
Ten patients, seven male and three female with a median age of 45 years (range 25–69 years) recruited. Eight patients had right hemiplegia and two had left hemiplegia. Patients had stroke (n=8) and other diagnoses (n=2). The median time since injury was 18 months (range 1–36 months). Six subjects had MAS score of 2 and 3 (n=3 each). Two subjects had a MAS score of 1+, and two subjects had 0 and 1 MAS scores. The measurements taken in the arms of patients were reliable. In the impaired arm, the ICC For torque, angle and velocity was 0.83 (95% CI: 0.790.86), 0.98 (95% CI: 0.97–0.98), 0.95 (95% CI: 0.94–0.96), respectively. In the non-impaired arm, the ICC For torque, angle and velocity was 0.86 (95% CI: 0.82–0.89), 0.99 (95% CI: 0.98–0.99), 0.97 (95% CI: 0.96–0.98), respectively.

The mean applied torque was 1.81Nm (Newton meter) (SE: 0.02; range: 1.34–2.08). In patients with a MAS score of 2 and higher, it took more than 1 second to extend the elbow. However, the resistance occurred within 1 second. In order to analyse the data in patients, the first measure was used because the evaluation’s validity decreases as the number of times the test is performed increases (Ansari et al, 2006).

The velocity in the impaired arm was significantly variable in three successive measurements (F = 57.4, df = 1.75, p<0.001) (Table 2). The velocity in the impaired arm was significantly lower than the non-impaired arm (WSRT: Z = - 6.47, p<0.001). The VR (%) in the impaired arm was significantly variable and the VR (%) in the first measure was higher than the second and third measures (p<0.001). The VR (%) in the non-impaired arm was significantly higher than the VR (%) either in the non-impaired arm (WSRT: Z = -12.74, p<0.001), or the normal (p<0.001). The VR (%) in the non-impaired arm was significantly higher than the normal (p<0.001). The VR (%) taken on the impaired arm after 5 minutes was significantly variable (F = 93.35, df = 1.53, p<0.001). The VR (%) in the impaired arm was significantly higher than the VR (%) in the same arm taken after 5 minutes (WSRT: Z= - 6.54, p<0.001). However, the velocity in the impaired arm had no significant difference with velocity taken after 5 minutes (WSRT: Z= - 0.82, p = 0.42).

<p>| TABLE 1. The summary of the results mean (SE) in healthy subjects. |
|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|</p>
<table>
<thead>
<tr>
<th>variables</th>
<th>right arm</th>
<th>left arm</th>
<th>Paired t-test (t value)</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PROM (deg)</td>
<td>86.79 (1.56)</td>
<td>86.61 (1.65)</td>
<td>0.24</td>
<td>0.81</td>
</tr>
<tr>
<td>Angular velocity (deg/s)</td>
<td>130.49 (2.75)</td>
<td>135.52 (3.24)</td>
<td>-2.32</td>
<td>0.02</td>
</tr>
<tr>
<td>Velocity Reduction (%)</td>
<td>3.02 (0.29)</td>
<td>0.92 (0.13)</td>
<td>6.48</td>
<td>P &lt; 0.001</td>
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<td>*PROM,=passive range of motion</td>
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</table>
The interaction of AR and ATNR with the head rotated towards the impaired arm significantly increased the velocity than the head away from the impaired arm (WSRT: Z= -5.86, p <0.001). The VR (%) with head rotated away from the impaired arm was significantly higher (p<0.001). The VR (%) in the impaired arm had a significant relationship with the MAS scores (Spearman’s rho = 0.77, p<0.001).

**Discussion**

In this study, a new insight into objective measurement of spasticity presented itself, that is, a constant torque was applied and VR was recorded as an index of spasticity. The amount of torque was set so that it could move the forearm over a duration of about 1 second. This was performed to standardize the method.

In healthy subjects, no significant reduction in velocity was recorded and the range of motion completed over a duration of about 1 second. Small VR (%) could be the result of poor subject compliance, i.e., resisting the movement because of insufficient relaxation. The higher VR in the right arm may be the result of actively resisting the movement because 23 out of 30 participants were right handed (dominant arm). Some resistance to passive movement may occur normally in able-bodied people and any resistance detected may be from a voluntary contraction by the individual.

In the impaired arm of the patients with severe spasticity (MAS score of 2 and 3), the applied torque did not complete the elbow ROM over a duration of 1 second. However, the resistance occurred within 1 second. The authors analysed the data in a 1-second window. The calculated torques were sufficient to complete the ROM over a duration of about 1 second in patients with lower grades of spasticity. The greater torque may be unnecessary for patients with severe muscle spasticity, because the passive movement reduces muscle spasticity (Vattanasilp et al, 2000) and the resistance appears within 1 second. Nevertheless, a further study is needed to determine the range of torque to apply in patients with upper grades of spasticity.

The non-impaired arm, showed a significant higher VR (%) than the normal. This may result from pathological changes which occurred in the non-impaired arm (Thilmann et al, 1990).

In the impaired arm, the VR (%) was significantly higher than normal. Although the neural and biomechanical contributions to RTPM were not separated, but it is unlikely the mechanical factor such as contracture to participate in the velocity reduction, as the patients did not have a significant contracture (Burne et al, 2005).

The measurement of interaction of ATNR and AR aimed twofold: the sensitivity of the method to changes in spasticity resulting from supraspinal reflexes, and the contribution of neural element (spasticity) in the recorded VR. The higher VR occurred from ATNR and AR interaction indicating that the method has enough sensitivity to record the spasticity changes from supraspinal reflexes. This finding also validated the interaction between the two reflexes (Bobath, 1990). The resistance from mechanical factors is unlikely to change with the supraspinal reflexes, indicating the neural contribution in recorded VR.

Spasticity is a velocity dependent phenomenon (Lance, 1980). However, the relationship between the velocity and the VR as an index of resistance was not consistent with this neurophysiological definition (Table 2), that is, as the velocity increased the resistance to passive movement tended to decrease. This is an agreement with Pandyan et al (2001) who found no direct association between the velocity and resistance. The discrepancy between these findings and Lance’s definition (1980) may be the result of

<table>
<thead>
<tr>
<th>Table 2. A summary of the results (mean; standard error) (RMn = repeated measure n; n = 1, 2, or 3) in patients taken on both the impaired and non-impaired arm.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Impaired</strong></td>
</tr>
<tr>
<td><strong>PROM (deg)</strong></td>
</tr>
<tr>
<td>83; 1.97</td>
</tr>
<tr>
<td>77.63; 4.21</td>
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<tr>
<td>VR (%)</td>
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</table>

*PROM = passive range of motion; VR = velocity reduction.*

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the effect of repeated movements that caused the reflex to be modulated, or reduced (Schmit et al, 2000).

In the impaired arm, the VR taken after 5 minutes showed significant reduction. This suggests that repetitive passive stretches may have a lasting effect on spasticity reduction and stretch reflex adaptation. This is why the authors considered the first measure for the analysis. The phenomenon of stretch reflex adaptation needs to be taken into consideration when spasticity is quantified using repeated stretches.

The finding that spasticity is reduced in response to repeated passive stretches has therapeutic implications. That is, the repeated passive joint movements have a short-term effect on spasticity, and therapists may instruct patients to use it for reduction of spasticity when it impedes function.

Qualitative clinical scales such as the Ashworth scale offer qualitative information, however, lack reliability and validity (Pandyan et al, 2001, 2003; Bakhiet et al, 2003). Nevertheless, these clinical scales are in general use, and every study that evaluates the efficacy of spasticity treatment uses either Ashworth or the modified Ashworth scale (Ward, 2000; Elovie et al, 2004).

Despite the limitations of the Ashworth scales (Pandyan et al, 1999), they continue to be used in the clinic and research (Johnson, 2001), and constitute the present standard against which the newer methods must be compared (Katz and Ryner, 1989). Therefore, it was important to know how this measure correlates with a modified Ashworth scale that has been shown to have high interrater reliability when testing elbow flexors (Bohannon and Smith, 1987). The VR obtained are significantly correlated with the MAS scores. The authors expected the correlation between the two to be even higher. Two patients with MAS scores of 1 and 1+ showed a higher VR because of shoulder pain elicited by passive movement and insufficient relaxation. Nevertheless, the significant correlation indicates the clinical relevance and the criterion validity of the method.

An important factor in the development of this measure was its clinical utility. Clinical utility includes the use of equipment that is easy to operate, short data collection and processing times, and results that would be simple but meaningful. The preliminary tests carried out have shown an easy use of the apparatus in the clinical setting and after about half an hour of training and practice with volunteers, the therapists would quite adequately operate the equipment. However, the authors used a custom-made piece of equipment, that is not currently available to hospitals and clinics, to quantify spasticity.

The amount of time required collecting and processing the data needs to be mentioned. The authors investigation required about 15 minutes to collect the data on the patients. Presently, the processing of the data takes about 10 minutes. However, it would be possible to reduce the processing time with the development of custom software. Nevertheless, this amount of time is not an inconvenience to the clinician or patients.

Finally, many of the objective measures used to quantify spasticity are not always easy to understand and are difficult to interpret (Gottlieb et al, 1978; Otis et al, 1983; Lehmann et al, 1989; Price, 1990). These measures are certainly valuable to the understanding and characterization of spasticity, however, the complexity associated with their development, understanding, and interpretation may make them difficult for clinicians to understand and interpret. The measure for spasticity used in the present investigation is a single number based on simple mathematical principles that are well known for the clinicians and therapists.

LIMITATION

There are some limitations to this study. First, only healthy men were included in the study, because the healthy women did not agree to participate. It was difficult to challenge and motivate women to agree to participate. Secondly, a small number of patients, resulting from slow recruitment, participated. Thirdly, in this study the subjects’ relaxation state was not checked by electromyography (EMG). Simultaneous EMG measurements were not taken from the elbow muscles (flexors and extensors) and thus it was not possible to study the role of neuronal activity.

The addition of EMG to the device used will increase the capability of the equipment and will give relevant data to analyse the neural and biomechanical factors. Fourthly, the actual resistive torque was also not calculated. Further work to associate the velocity reduction, with muscle resistive torque and neural activity in a large number of patients would be valuable.

CONCLUSIONS

A highly reliable device has been developed to produce objective measurements of velocity reduction at the elbow in patients with spasticity. The preliminary results suggest that, with further work and standardization, the method can provide a valuable contribution to evaluation of spasticity.

This study was supported by Tarbiat Modarres University. The authors would like to thank all subjects who participated in this trial. The authors would also like to thank faculty of rehabilitation, Tehran University of Medical Sciences.

Conflict of interest: none.
In the method based on velocity reduction, a constant torque perturbation is applied to stretch the muscle over a duration of about 1 second.

The velocity reduction (VR) in the impaired arm was significantly variable and the VR in the first measure was higher than the second and third measures.

The VR in the impaired arm was significantly higher than the VR either in the non-impaired arm, or the normal, and the VR in the non-impaired arm was significantly higher than the normal.

The relationship between the velocity and velocity reduction as an index of spasticity was not consistent with neurophysiological definition of spasticity, that is, as the velocity increases the resistance to passive movement tended to decrease.

The interaction between the associated reaction (AR) and the asymmetrical tonic neck reflex (ATNR) with head away from the impaired arm made a significant higher VR.

The resistance from mechanical factors is unlikely to change by activation of supraspinal reflexes, and higher velocity reduction due to AR and ATNR interaction indicates the neural contribution in velocity reduction.

There are a significant correlation between the values of VR and the modified Ashworth scale scores.