Portable measurement system of the spasticity based on the K-means clustering algorithm of the tonic stretch reflex threshold

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Abstract - *Conventional clinical scales used for the evaluation of the spasticity have some limitations, and their reliability remains controversial. The aim of this study is to develop a portable spasticity measurement system for quantifying the grade of spasticity based on the K-means clustering algorithm of the tonic stretch reflex threshold (TSRT). Fifteen stroke patients (age: 63.5±15.6) participated in the study. As a result, there was a strong negative correlation ($r=-0.95$, $r^2=0.90$, $p<0.05$) between the spasticity level and TSRTs. This result showed that our system could be made clinically available for the more reliable discrimination of the spasticity level, compared to conventional scales..*

Keywords: spasticity, tonic stretch reflex threshold

1 Introduction

Spasticity is a major source of disability caused by central nerve injuries such as stroke. It is most commonly defined as a motor disorder characterized by a velocity-dependent increase in the muscle tone with exaggerated tendon jerks, resulting from hyper-excitability of the stretch reflex (SR), as one component of the upper motor neuron syndrome [1,2]. Spasticity is the manifestation of a lesion of the supraspinal motor pathways and is caused by adaptive changes in transmission in the spinal networks distal to a lesion of the descending motor pathways. Clinically, this implies increased muscle tone, enhanced tendon reflexes, involuntary reflex zones and clonus. The measurement of the spasticity is a difficult and unresolved problem, partly due to its complex and multi-factional nature. The previous methods of quantifying or qualifying the spasticity are based on clinical scales or the biomechanical and neurophysiological analysis of the limb resistance to passive or voluntary movements.

The clinical scales employed are the Ashworth scale (AS), modified Ashworth scale (MAS), Tardieu scale, composite spasticity index (CSI) and spasm frequency scale [3-7]. Among these scales, the MAS has been widely used in the clinical field since they are simple, easy to use and require no instrumentation. It rates the subjective impression of the evaluator of the amount of resistance felt during stretch of the relaxed muscle. However, the amount of resistance felt results from the net EMG activity in the muscle without consideration of the velocity-dependence of the response, thus, the MAS measurement is a disagreement with Lance's definition [1]. Therefore, their inter- and intra-rater reliability remains controversial, because the scores are obtained based on the subjective feeling of the rater, such as the observation of the catch and spasm of the muscle, and largely rely on the experience of the examiner. Several researchers had reported the poor inter-rater reliability of AS [8,9], MAS [10,11] and Penn spasm frequency scale [8].

Neurophysiologic analysis is the measurement of the electrical activity, such as EMG signals in order to evaluate the spasticity. Several studies have accordingly used EMG to measure the responses evoked by either the stretching of the muscle (M-reflex), tendon tap (T-reflex) or electrical stimulation of the peripheral nerve supplying the muscle (H-reflex), in order to evaluate whether these responses are exaggerated in spastic individuals and related to the degree of spasticity [12]. However, several researchers reported that the ratio of the H-reflex to SR of the muscle (H/M ratio) was not correlated with the MAS, although it was increased in patients with spinal cord injury (SCI) [13,14] or stroke [15,16] compared to that in healthy subjects. The pendulum test, introduced by Wartenberg in 1951 [17], is a biomechanical method of evaluating muscle tone by using gravity to provoke muscle SRs during the passive swinging of the lower limb. Some researchers have reported that the ratio of the amplitude of the first swing to that of the final position is significantly correlated with clinical scales such as the AS and MAS scores in spastic patients [18-20]. However, this correlation depends decisively on the sitting posture and the ability of the person to fully relax. Also, it could only be applied to evaluate the spasticity in the knee flexor and extensor muscles and is limited to separate the increased resistance of the spastic muscles, due to the changes of the viscoelastic resistance from the velocity-dependent resistance [12].

The isokinetic dynamometer has been widely used for the quantitative assessment and evaluation of the spasticity. It allows the velocity and amplitude applied to evoke muscle stretches to be standardized; consequently it is able to quantify the velocity-dependent resistance according to the passive movement of the muscle. Firoozbakhsh et al. [21]

found a significantly greater sum torque and slope of the torque-velocity regression lines in the spastic group compared to the normal group. Pisano et al. [22] demonstrated that the total stiffness indices (TSI), stretch reflex threshold speed (SRTS) and SR area were highly correlated with the AS. Pandyan et al. [23,24] showed that there was a high correlation coefficient between the MAS and resistance to passive movement (RTPM) and that the RTPM in the impaired arm was relatively larger than that in the non-impaired arm. Chen at al. [25] and Lee et al. [26] showed that there was a decrease of the biomechanical viscosity and reflexive EMG threshold (RET) of the biceps brachii after the injection of Botulinum toxin type-A.

The theoretical concept for tonic stretch reflex threshold (TSRT) measurement, based on motor control theory, was first published by Levin and Feldman [27]. The TSRT is based on the evaluation of the excitability of the motor neurons caused by both descending and segmental effects, and the measurement of these effects is the SR threshold, the integral part of the λ model of motor control. The SR threshold depends on the stretch velocity. In the λ model, the dynamic stretch reflex threshold (DSRT) is expressed in velocity and angular coordinates, i.e. the velocity and joint angle at which the muscle activity first appears. When calculated in such coordinates, the DSRTs and TSRT are expressed in relation to the actual configuration of the joint within the body frame of reference. In particular, when the threshold lies within the biomechanical range of the joint and the patient has no ability to shift this threshold angle, it separates the joint configurations in which the muscles are spastic from those in which they are not, thus quantifying an important, spatial aspect of the motor control [28]. Some researchers have reported the validation of the TSRT. Levin et al. [27,29] showed a negative correlation between the CSI and TSRT and positive correlation with the Fugl-Meyer scale in elbow flexors and extensors of the spastic patients with stroke. Jobin et al. [30] showed the good test-retesr reliability of TSRT measurement for the children with cerebral palsy. Recently, Calota et al. [31,32] described a portable device for TSRT measurement and demonstrated the moderately high reliability of TSRT measurement for patients with moderate to high spasticity. These results indicate the TSRT could be a more representative measure since it satisfies Lance's criteria for the velocity-dependent increase of the spasticity.

The objectives of this study are to develop a hand-driven portable system for quantifying the grade of spasticity, which can calculate the bio-mechanical as well as neurophysiologic parameters, and to determine the relationship between the TSRT measured by the developed device and the level of the spasticity. The TSRT of each spastic patient was measured during both the extension and flexion of the forearm in order to take into account threshold of both agonist and antagonist muscles, and TSRTs obtained from all of the patients were grouped by means of K-means clustering method for the objective discrimination of the severity of the spasticity. We hypothesized that there would be a negative correlation between them (i.e., the larger the severity of the spasticity, the smaller the TSRT) through the literature reviews of the previous papers [29-32]. We implemented this approach in a portable device and applied it to the evaluation of the spasticity

2 Portable spasticity measurement system

The developed spasticity measurement system is designed to measure the angle by means of a twin-axis flexible electro-goniometer (SG150, Biometrics Ltd., U.K.) and EMG signals by means of surface electrodes (Meditrace 200, Kendall, U.S.). Also, the angular velocity is calculated by the differentiation of the angle signals. This device is composed of a sensor module for signal conditioning and control module to monitor the measured data and the physiological parameters. All signals are pre-processed by the signal conditioning circuit in the sensor module. Fig. 1 shows a block diagram of the developed system.

In order to store and analyze the data obtained during the study, data acquisition and analysis software were developed using the LabVIEW language (ver. 8.6, National Instruments™, U.S.). It can show the trace of the angle, angular velocity and two EMG signals continuously on a monitor using figures and numbers and simultaneously store the data on a hard-disk drive. Also, the system is equipped with a beep sound generator like a metronome, in order to announce the velocity of the flexion and extension of the upper limbs (stretch velocity) in a simple manner to both the subject and rater during the movements. The period between beep sounds can be selected manually in the range of 30 and

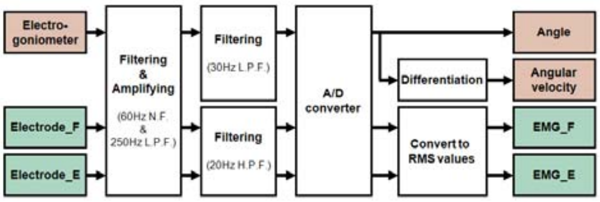


Fig. 1. Block diagram of the sensor module

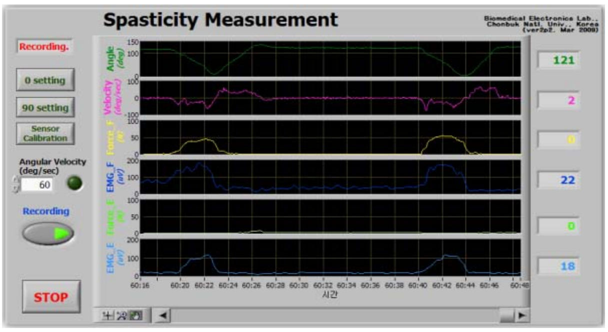


Fig. 2. Graphic user interface for data acquisition and parameter analysis

360 °/sec by the rater. Fig. 2 shows the graphic user interface for data acquisition and parameter analysis.

3 Materials and methods

3.1 Participants

Fifteen patients (7 males and 8 females) with stroke participated in the study (mean age 63.5 ± 15.6, range 38-84 years) after giving their informed consent. Eleven patients had a cerebral infarction and four had a cerebral hemorrhage. The affected sides were 9 in the right arm and 6 in the left. The mean period since stroke was 6.7 months (range 1-36 months). The clinical grading by MAS was '1' in 6 patients, '1+' in 5 and '2' in 4. The MAS scores were considered as an auxiliary tool for the assessment of the trend of the TSRTs according to the level of the spasticity. All tests were performed on the more affected upper limb. Subjects were included if they had (a) sustained a stroke; (b) spasticity in the elbow flexors or extensors and (c) at least a 120° passive range of motion in the elbow joint. To calculate the clinical parameters, the presence or absence of spasticity in the elbow flexors and extensors was confirmed by manually stretching the elbow from full flexion to full extension at an arbitrary stretch velocity. Subjects were excluded if they (a) could not understand simple commands due to the decrease of their cognitive functions; (b) had subluxation or sprain of the shoulder or (c) elbow contracture.

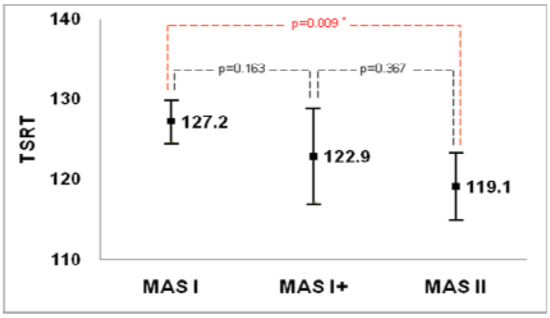
3.2 Experimental protocol

Number Two clinicians (two males) evaluated each subject. The raters had different amounts of clinical experience (3.5 and 5.5 years). To ensure a standardized level of training, both evaluators received written documentation and participated in two one-hour training sessions with the developed device.

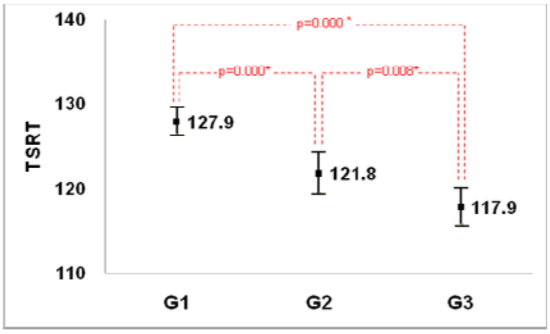
For the measurement of the angular displacement of the upper limb, a flexible electro-goniometer was placed on the lateral aspect of the elbow with the axis of rotation at the joint line and its two wings were fixed on the forearm and upper arm, respectively, by an elastic band. To monitor the activity of the elbow flexors and extensors, five surface electrodes (Meditrace 200, Kendall, U.S.) with a diameter of 10 mm were attached to the upper arm. The electrode sites were lightly shaved and cleaned with a 95 % ethanol mixture to reduce the skin impedance. For the elbow flexors, the active and reference electrodes were located on the biceps, while those used for the extensors were located on the triceps. A ground electrode was placed on the medial side of the elbow.

A motion from full flexion to full extension is defined as 'elbow extension', whereas 'elbow flexion' is defined as a motion from full extension to full flexion. 'Full extension' means an angle of 0° between the forearm and upper arm, while 'full flexion' means an angle of about 120°. One cycle consisted of one elbow extension and one flexion over an approximate angle range of 120°→0°→120° in an approximate period of one cycle. The velocity of the extensors was determined as its total angular displacement per a period of one extension, while the velocity of the flexors was as the total displacement per a period of one flexion. If the periods of one extension and one flexion were 1 and 2 seconds, the stretch velocity were 120 °/sec in the extensors and 60 °/sec in the flexors, respectively.

The subjects lay on a bed in a relaxed position. The starting position involved the slight abduction of the shoulder, neutral position of the wrist and full extension of the elbow. In order to reduce the muscle tension, the subjects maintained this position for at least 2 minutes. The tests were performed after the rater checked whether all flexors and extensors were stabilized by monitoring their EMG signals. The subject's forearm was passively flexed and extended by the rater at a randomly selected stretch velocity among 60, 90, 120, 150 and 180°/sec, in order to avoid adaptation of the stretch response [33]. Measurements were performed repeatedly ten times at the selected stretch velocity with at least 10 seconds rest between sessions, because the motor unit recruitment threshold was 6 seconds during repeated contractions [34]. The total number of measurement sessions per subject was about 50. None of the sensors, including the electro-goniometer and surface electrodes, were displaced or



(a) MAS groups



(b) TSRT groups

Fig. 3. Comparison of the TSRTs among the groups (a) classified by the MAS and (b) by the K-mean clustering of the TSRT (*: p<0.05)

reattached during the test.

The DSRTs is defined as the joint angle and angular velocity value corresponding to the point at which the EMG signal increased by 2 times of standard deviations above the mean baseline EMG [31]. The baseline EMG was the EMG activity while the subject was at rest before beginning the evaluation session. At the end of each evaluation, the joint angle and angular velocity values at the time, when the first incident of the EMG activity of either the extensor or flexor was detected, were automatically obtained in the analysis software. Next, using these values the DSRT was calculated. Finally, the TSRT was computed by drawing the linear regression line through the DSRTs to zero velocity. The TSRT value was taken as the intercept of the regression line with the angle axis (dependent variable: angle, independent variable: angular velocity).

4 Results

Fig. 3 shows the comparison of the TSRTs among the groups classified by the MAS and K-mean clustering of the TSRTs. through the K-means clustering algorithm, the patients were classified into three groups (G1, G2 and G3) according to the criteria of the TSRTs. The centroids of each group were 127.9 in group G1, 121.8 in group G2 and 117.9 in group G3 and the Euclidean distances were 6.099 between groups G1 and G2, 10.052 between groups G1 and G3 and 3.952 between groups G2 and G3.

When grouping the patients according to the level of the MAS, the mean and standard deviation (S.D.) values of the TSRTs were 127.2±2.5 in the MAS1, 122.9±4.7 in the MAS1+ and 119.1±2.6 in the MAS2 groups, respectively. In order to compare the differences of the TSRTs between the MAS groups, the one-way ANOVA test was performed. Consequently, the average TSRT in the MAS1 group were the largest, while that in the MAS2 group were the smallest ($p<0.05$). Also, there was a negative correlation ($r=-0.74$, $r2=0.54$, $p<0.05$) between the TSRT and MAS. However, through the post hoc analysis, the differences between the average TSRT of the MAS1 group and that of the MAS1+ group ($p=0.16$) and between the average TSRT of the MAS1+ group and that of the MAS2 group ($p=0.37$) were not significant, as shown in Fig. 3(a).

On the other hand, when grouping by means of the K-means clustering of the TSRTs, the mean and S.D. values of the TSRTs of groups G1, G2 and G3 were 127.9±1.6, 121.8±1.5 and 117.9±1.3, respectively. There was a strong negative correlation between the TSRTs and groups ($r=-0.95$, $r2=0.90$, $p<0.05$). Also, there were significant differences between the TSRTs of each group ($p<0.05$), as shown in Fig. 3(b).

5 Conclusions

We developed a portable spasticity measurement system and classification algorithm for the objective and reliable discrimination of the level of spasticity based on the K-means clustering of the TSRTs. Our results showed the existence of a strong negative relationship between the TSRTs and classified groups ($r=-0.95$, $r^2=0.90$, $p<0.05$). This demonstrates that our method could be made clinically available for the more objective and reliable discrimination of the spasticity, instead of the conventional MAS grade. In a future work, we will apply our system to a larger number of spastic patients with various upper motor-neuron disorders and verify its feasibility.

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