A Measure of Spasticity Based on the Exponential Fit of the Knee Joint Torque Estimated from the Goniogram During the Pendulum Test

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***Abstract*— Pendulum test is a method to quantify the spasticity. We used the goniogram recorded during the pendulum test to estimate the knee joint torque based on the model which considers spastic reflex activity. We fitted the exponential curve $T_h = ae^{-bt}$ to the estimated knee joint torque to calculate the parameters a and b. We compared the scaled value log a/b with the modified Ashworth score. We used 8 sets of data collected in a clinical study with six complete paraplegic subjects. The comparison shows that the ratio a/b correlates with the MAS scores; thereby, can be used as a measure of spasticity. The advantage of using the ratio a/b is that this score is not rater dependent and that the scores are real numbers compared the MAS scores; thereby, providing better resolution of the level of spasticity.**

***Index Terms*—spinal cord injury; pendulum test; spasticity; modelling**

I. Introduction

Spasticity often follows nervous system lesions at the cortical and spinal levels (e.g., spinal cord injury, multiple sclerosis, cerebral palsy). The spasticity is defined as a motor disorder characterized by a velocity-dependent increase in tonic stretch reflexes ("muscle tone") with exaggerated tendon jerk, resulting from hyperexcitability of the stretch reflex, as one of the components of the upper motor neuron syndrome [1]. For clinicians, the quantification of the spasticity is of interest to select the most appropriate therapy for the patient. The modified Ashworth Scale (MAS) is the most often method to score the spasticity [2]. The MAS based assessment is characterized by interrater and intrarater reliability [3-5]. Therefore, Wartenberg introduced the pendulum test to eliminate the subjective component when assessing spasticity [6]. The model was expanded by Bajd and Vodovnik [7], Bajd and Bowman [8], and mc later Le Cavorzin et al. [9-11].

Our group recently introduced a score termed Pendulum Test (PT) score [12]. The clinical study proved that the PT score is correlated with MAS [12]. In addition, we used the complex biomechanical model of the pendulum type lower leg movements, and introduced the new measure termed SPASticity Scale (SPAS) [14]. Here we present the correlation of SPAS and MAS on data from 48 pendulum tests and show that the SPAS is more sensitive compared with MAS and show the type of spasticity; thereby, that is useful for clinicians.

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II. The Method

A. Subjects

The data were recorded within the clinical study reported in [14]. Six subjects signed the consent approved by the Clinic for rehabilitation "Dr Miroslav Zotović", Belgrade, Serbia. The inclusion criteria were: 1) a complete lesion above the Th12; 2) a stable neurological and medical status; 3) no autonomic dysreflexia; 4) no cognitive disorders; and 5) no medical history of hearing or balance disorders. The recordings were done four times during two sessions. This provided 48 data sets for the analysis.

B. Instrumentation

The pendulum test was recorded using a device that consists two units: one unit mounted at the thigh comprising an amplifier for two electromyography (EMG) signals and an inertial measurement unit - IMU (3D accelerometer and 3D gyroscope), and the second IMU mounted at the shank (Fig. 1, left panel). The sampling frequency of the EMG signal was 1kHz. Both units sent a signal to the host computer wirelessly at 1000 samples per second. More about the device can be found in [15].

C. Data processing

All the data processing was done using MATLAB (Mathworks, Natick, USA). The motion can be modeled with the nonlinear model which includes the passive resistance and the active resistance due to involuntary activity of the stretched paralyzed muscles during the pendulum like movements of the lower leg about the immobile knee. The equation of the motion is the following:

$$J\ddot{\varphi} = -B\dot{\varphi} - K\varphi - \frac{1}{2}mgl\sin\varphi + T_h \quad (1)$$

φ is the knee joint angle measured to the gravity line, J is the moment of inertia for the lower leg, B and K are the damping and stiffness coefficients of the linear model of passive resistance at the knee joint, m is the mass of the shank/foot complex, l the length from the knee to sole. The torque *Th* represents involuntary activities of the paralyzed knee extensors and flexors

$$T_h = T_E(\varphi, \dot{\varphi}) - T_F(\varphi, \dot{\varphi}) \qquad (2)$$

We fitted the recorded goniogram φ *(t)* with the minimum quadratic error method with the model (1) and (2) and calculated the knee joint torque *Th*. The next step was the fit the exponential curve to the calculated torque.

$$T_h = ae^{-bt} \qquad (3)$$

The output from the fitting were the numbers *a* and *b*. We than defined the measure SPAS to limit that output to the range of the scorers of the MAS.

$$\text{SPAS}=4 * \log|a/b| \qquad (4)$$

More detail can be found in Aleksić [14].

D. Procedure

The subject was sitting on a stable desk with the stable back support, with the hip angle $\varphi \approx 135°$. The thigh was resting on a flat surface while the knee was in front of the edge of the table to allow free rotation of the lower leg about the joint. The pendulum test was performed on each subject 4 times in 2 recording sessions. The examiner extended the knee joint to the full extension ($\varphi \approx \pi/2$), released it, and the lower leg started damped oscillations which stopped in vertical position ($\varphi \approx 0$).

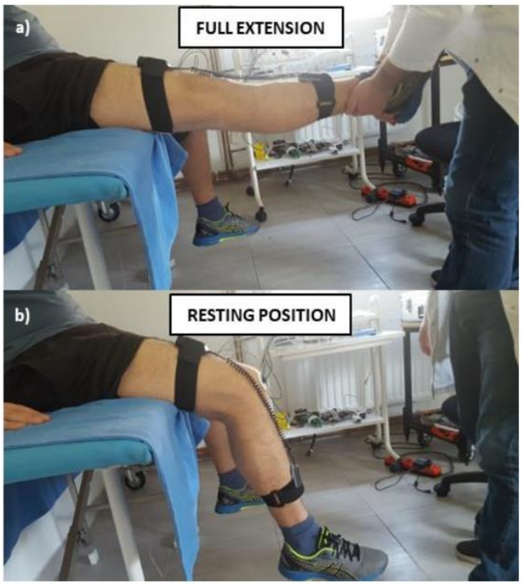

Fig. 1. The setup showing the initial and terminal position of the lower leg during the pendulum test (modified from [15]).

III. Main Results

Figure 1 shows the scaled goniogram of the knee joint by the dashed black line, the calculated moment *Th* shown in red, and the exponential fit in blue. The top two traces show spastic EMG signals that are directly related to the spasticity and the reason of disrupting the normal pendulum like movement in the field of gravity.

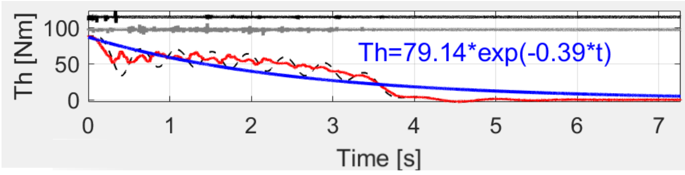

Fig. 2. An example of the estimated torque and the exponential fit for one of the subjects. Red line shows the estimated torque *Th*, the blue line and the equation represent the best exponential fit to the torque *Th*. The dashed black line shows the scaled goniogram of the knee joint $\varphi(t)$ that starts from $\pi/2$ and ends at 0. The black and grey traces at the top are the measured EMG signal (< ±0,5mV) of the knee joint flexors and extensors, respectively.

The MAS and the SPAS values for all the subjects that participated in the study are in Table I.

TABLE I
MAS and SPAS scores for the six subjects estimated four times in each of the two recordings sessions (F - first recording session, S - second recording session)

No	1st MAS	1st SPAS	2nd MAS	2nd SPAS	3rd MAS	3rd SPAS	4th MAS	4th SPAS
1f	3	2.43	3	2.24	3	3.24	3	1.30
1s	3	2.97	3	1.52	3	2.89	3	2.31
2f	2	2.62	1	0.67	1	2.02	2	1.63
2s	2	1.83	1	1.90	1	2.01	1	1.55
3f	1	1.19	1	0.78	1	1.22	1	1.50
3s	2	4.80	4	4.85	2	5.13	2	3.66
4f	2	1.75	2	0.78	2	0.74	2	0.98
4s	2	1.16	2	0.08	2	0.41	1	0.32
5f	3	5.68	3	5.52	3	4.76	3	4.88
5s	3	3.78	2	2.21	2	2.94	2	2.35
6f	2	0.63	2	1.00	2	0.34	1	0.08
6s	2	0.31	1	0.17	1	0.17	1	0.17

Data from Table I is presented in Fig. 3. We applied the linear regression and obtained that SPAS = 1.06 MAS -0.12, R^2=0.31 when plotting SPAS vs. MAS.

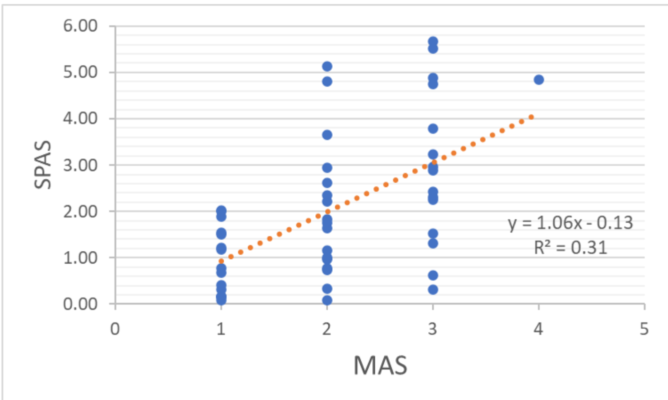

Fig. 3. The SPAS vs. MAS scores and the linear regression for all 48 recording sessions

Figure 4 shows the linear regression of the SPAS vs. MAS without the outliers. The outliers were chosen as the two greatest and lowest SPAS measures for MAS scores 1, 2 and 3. This outlier elimination left for the analysis 36 recordings. The linear regression was SPAS = 0.94 MAS – 0.15, R^2=0.55.

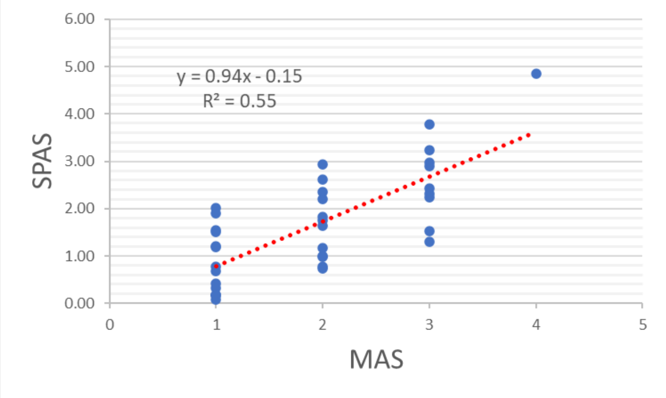

Fig. 4: The linear regression of SPAS vs. MAS of data from 36 recordings.

Figure 5 shows the SPAS and MAS scores from eight recordings for Subject 1 (1f and 1s).

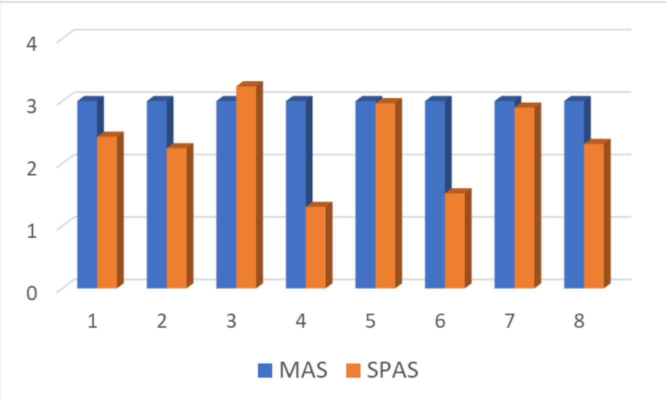

Fig. 5: Bar graph showing the MAS and SPAS scores for Subject 1 (1f and 1s) in eight recordings.

IV. Discussion

Table 1, gives an insight into SPAS and MAS comparison. The graphical presentation of this data (Fig. 3) with the linear fit to has the slope of y=1.06, and R2=0.3. When we exclude 12 outliers, the linear fit equation is y= 0.94x - 0.15, yet with the increased value R^2=0.55. The slope is now smaller compared to the slope with all data, but also close to 1.

In Fig. 5 we show the comparison of the MAS and SPAS for Subject 1. Here, the MAS grade was constant and equal to 3. The SPAS grade varied, being smallest for the fourth recording SPAS=1.3, and highest for the fifth recordings, SPAS=2.97. This clearly suggests how much is the SPAS more sensitive compared with the MAS.

V. Conclusion

We show the relation between the MAS and SPAS scores. Due to the fact that MAS is an integer value and the SPAS is a real number, the sensitivity of the SPAS scale is better compared with the MAS. This increased sensitivity is important for the clinician when deciding which therapy works and following the progress of the recovery of the patient. The SPAS is a measure that automatically determined from the goniogram of the knee joint during the pendulum test.

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