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Assessment of spasticity by a pendulum test in SCI patients who exercise FES cycling or receive only conventional therapy

Lana Popović-Maneski, Antonina Aleksić, Amine Metani, Vance Bergeron, Radoje Čobeljić, Dejan B. Popović, *Member, IEEE*[1]

***Abstract*— Increased muscle tone and exaggerated tendon reflexes characterize most of the individuals after a spinal cord injury (SCI). We estimated seven parameters from the pendulum test and used them to compare with the Ashworth modified scale of spasticity grades in three populations (retrospective study) to assess their spasticity. Three ASIA B SCI patients who exercised on a stationary FES bicycle formed group F, six ASIA B SCI patients who received only conventional therapy were in the group C, and six healthy individuals constituted the group H. The parameters from the pendulum test were used to form a single measure, termed the PT score, for each subject. The pendulum test parameters show differences between the F and C groups, but not between the F and H groups, however statistical significance was limited due to the small study size. Results show a small deviation from the mean for all parameters in the F group and substantial deviations from the mean for the parameters in the C group. PT scores show significant differences between the F and C groups and the C and H groups and no differences between the F and C groups. The correlation between the PT score and Ashworth score was 0.88.**

***Index Terms*— pendulum test, spinal cord injury, spasticity, exercise, FES cycling**

I. INTRODUCTION

SPINAL cord injuries or diseases can lead to disability because they diminish the flow of neural signals between the higher centers of the central nervous system and the peripheral sensory and motor systems. In short, a spinal cord injury results in the following consequences: paralyzed muscles dedicated for motor function are not used, range of movement of joints is decreased from lack of balance between synergistic muscles, muscles used for gravity compensation are atrophied, some muscles lose their contractile properties, and spinal reflexes are modified leading to increased rigidity and enhanced response to stretching.

Muscles that lose innervation undergo rapid deterioration [1], which for SCI is attributed to muscle inactivity after losing efferent nerve signals from the brain and spinal cord segments to motoneurons [2]. Indeed, neuromuscular activity is reduced after spinal cord lesions, but it varies depending on the level of spasticity [3, 4]. Furthermore, the amount of disuse atrophy varies widely in humans and animals after spinal cord lesions, but it does not correlate with the decline in neuromuscular activity [4 - 9]. Studies to date suggest that much of the disuse atrophy of the paralyzed muscles should be attributed to concurrent changes in muscle length or loading conditions, rather than a decline in neuromuscular activity [3, 10]. Preventing denervation atrophy of muscles depends on the capacity of surviving motoneurons to sprout and reinnervate muscle fibers. Consequently, muscle fibers may survive and contract in response to artificially elicited activation, i.e., electrical stimulation of neuro-muscular structures.

The atrophy is more pronounced in muscles that cross a single joint [10, 11]. These muscles are primarily responsible for maintaining posture and bearing weight [10]. For example, the soleus m. which is used for control of position undergoes significant atrophy, while the tibialis anterior m, which does not contract against resistance, shows very little atrophy [3, 9]. The medial gastrocnemius m, which crosses the knee and the ankle joint, undergoes less atrophy than the soleus m. Non-weight-bearing paralyzed muscles demonstrate little atrophy [11]. In contrast, the quadriceps femoris m. which holds the body while standing shows significant atrophy after spinal cord injuries [12]. A similar pattern of atrophy of limb muscles was found [13] under nonstandard conditions (space flight, joint immobilization, shortening contractions not resisted by the normal load). These findings also suggest that changes in loading or length of paralyzed muscles after spinal cord lesions are responsible for the atrophy. That said, the loss of motoneurons several segments below a spinal cord lesion can also cause muscle atrophy [14].

Current clinical findings suggest that in most subjects with spinal cord injury activity that involves paralyzed muscles (passive exercise, active exercise, electrical stimulation, vibration, assisted standing and walking by a robotic system) contributes to the recovery of function, minimization of muscle loss and prevention of contractures [15 - 19]. A particular exercise becoming very popular is pedaling with electrical stimulation on a stationary exercise bicycle or an adapted recumbent tricycle for commuting [18].

One of the pathologic responses after SCI is an automatic

Lana Popović-Maneski is with Institute of Technical Sciences of the Serbian Academy of Sciences and Arts, Knez Mihailova 35/IV, Belgrade, Serbia (e-mail: lanapm13@gmail.com) .

Antonina Aleksić is with School of Electrical Engineering, University of Belgrade, Belgrade, Serbia.

Amine Metani and Vance Bergeron are with University Lyon, ENS de Lyon, University Claude Bernard, CNRS, Laboratoire de Physique, F-69342 Lyon, France.

Radoje Čobeljić is with Clinic for Rehabilitation „Dr. Miroslav Zotović", Belgrade, Serbia.

Dejan B. Popović is with Institute of Technical Sciences of the Serbian Academy of Sciences and Arts, Knez Mihailova 35/IV, Belgrade, Serbia and Aalborg University, Aalborg, Denmark.

increase of the tonus of affected muscles and increased sensitivity to the stretch. The effect is an absence of inhibitory inputs and pathologic output to the motor systems, which leads to a condition referred to as spasticity. In 1981 Landau [20] introduced the following definition of the spasticity: 1) decreased dexterity, 2) loss of strength, 3) increased tendon jerks, 4) increased resistance to slower passive muscle stretch, and 5) hyperactive flexion reflexes (flexor spasms). The associated pathologic motor behavior (resistance) includes an increase in the passive stiffness of tendons and muscles, along with an increase in the stiffness of the contracting muscle and an increase in the stiffness due to a stretch reflex. To study the importance of the different components, a brief passive stretch can be applied to the muscle of interest during different activities. The measured forces, kinematics, and changes in electrical activity of the muscle provide information that is of interest for rehabilitation therapy [21].

We report on differences in the status of leg spasticity between SCI individuals who practice functional electrical stimulation (FES) cycling and SCI individuals who receive only conventional therapy. Our retrospective study included three small populations: FES group (F) - three SCI patients who regularly exercise on a stationary FES bicycle, control group (C) – six SCI patients who received conventional therapy only, and a healthy group (H) – six healthy individuals. We used the Ashworth scale and the pendulum test for assessing the spasticity in the knee joint of the SCI patients. The "pendulum test" allows for detailed motion analysis of the lower leg swinging under the influence of gravity. We compared results between the pendulum and Ashworth test, and examined the hypothesis that the spasticity is more pronounced in group C compared with group F.

II. Methods and Materials

A. *Subjects*

The study included nine patients with SCI and six healthy volunteers (Table 1). A patient consent form which follows the Helsinki declaration was approved by the Ethics Committee of the Clinic "Dr. Miroslav Zotović," Belgrade, Serbia, and was signed by all participants before the beginning of the measurements.

The inclusion criteria for the patients were the following: Asia score B, spinal cord injury above Th12, no other neurological diseases, controlled blood pressure and pulse, and able to follow the protocol of the test. The demography of the study population is provided in Table 1. The F group exercised on a RT300 FES cycling system (Restorative Therapies Inc., USA) during six months three times weekly for 1 hour periods while preparing for the Cybathlon FES cycling race in 2016 [22]. The rotation of pedals was generated by stimulation of the quadriceps, hamstrings, and gluteus muscles on both legs. The C group regularly received lower-limb mobilization therapy provided in the Clinic or at home by a physical therapist.

All SCI subjects who use medications for control of spasticity on a regular basis skipped their daily dose for a period at least 2 hours before the measurements, except the patient who uses an implanted baclofen pump.

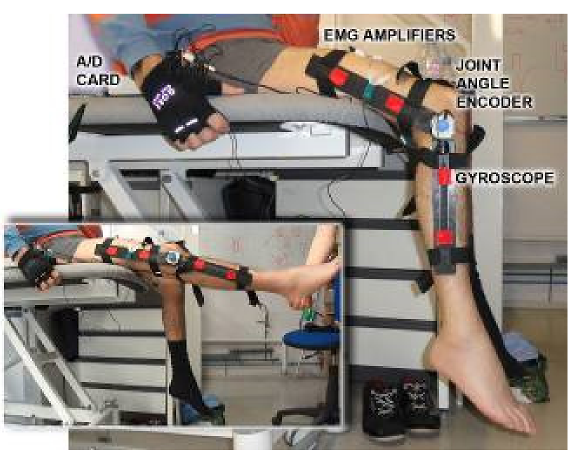

Fig. 1. The sketch of the setup for the pendulum test of spasticity

TABLE 1: BASIC DATA FOR SUBJECTS PARTICIPATING IN THE STUDY

N°	Sex	Age	Height (cm)	Mass (kg)	Level of lesion	Ashworth (knee extension)	Month after lesion	Cause of lesion	Antispasticity medication	PT score
FES active SCI subjects										
1F	M	54	182	75	C4	0	48	traffic	no	0.58
2F	M	52	181	72	C6	0	37	traffic	pump	0.89
3F	M	37	184	73	C7	0	56	traffic	no	0.58
Non-active SCI subjects										
1C	M	58	180	80	Th7	3	14	fall	oral	4.57
2C	M	36	186	85	C5	2	29	jump	oral	0.84
3C	M	60	176	86	Th7	3	24	fall	oral	4.59
4C	M	62	185	85	C5	3	120	fall	oral	4.09
5C	M	28	188	70	C6	2	28	traffic	oral	1.95
6C	M	40	180	78	Th5	2	267	ski	oral	2.83
Healthy subjects										
1H	M	56	170	89	/	/	/	/	/	0.81
2H	M	34	174	83	/	/	/	/	/	0.74
3H	F	24	173	71	/	/	/	/	/	0.87
4H	F	32	161	65	/	/	/	/	/	0.47
5H	F	46	172	67	/	/	/	/	/	0.38
6H	M	51	168	73	/	/	/	/	/	0.93

B. *Instrumentation*

The pendulum test apparatus consists of two bars connected by a low friction hinge joint that houses an absolute joint angle encoder and an analog gyroscope mounted on the segment aligned with the shank of the subject (Fig. 1).

We used a gyroscope to avoid numerical derivation problems ensuing form the encoder data. We also recorded the muscle activity of the quadriceps m. and hamstrings m. This was accomplished with 10 mm flat pregelled Ag/AgCl electrodes (GS26, Bio-Medical Inc., Warren, USA) and EMG amplifiers (Biovision Inc, Wehrheim, Germany) for bipolar recordings. The ground electrode was placed over the bony

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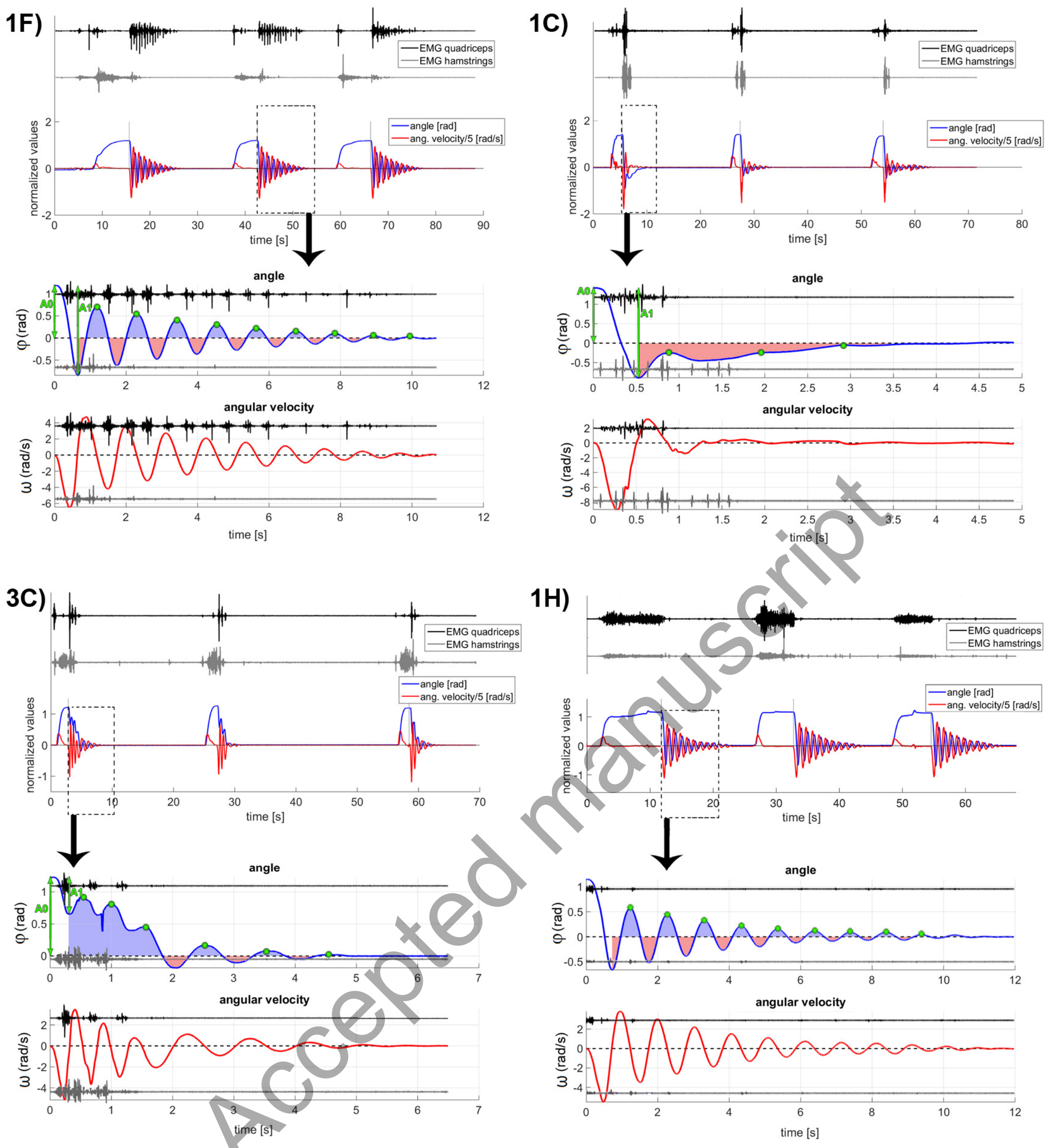

Fig. 2: The recordings of the EMG signals, knee joint angle and angular velocity of the lower leg for four particular subjects (1A, 1C, 3C, and 2H) representing the active and the non-active population of patients and a healthy subject. The lower panel shows the processed knee joint angle, angular velocity and normalized EMG activities for the trials marked by a dashed rectangle in the top panels. Positive areas between the first minimum of angle and zero line are colored in light blue, and negative areas are colored in light red. Green markers denote positions of the local maximums. A_0 and A_1 are the parameters defined in [24].

part of the knee joint. One pair of electrodes was placed on the rectus femoris on 50% of the line from the anterior spina iliaca superior to the superior part of the patella. The other pair targeted the biceps femoris on the line between the ischial tuberosity and the lateral epicondyle of the tibia, 15cm from the popliteal fossa. Inter electrode distance was 2cm.

Signals from the sensors and EMG amplifiers were subsequently digitized (NI 6009 USB A/D card, 14-bit resolution, 1 kHz sampling rate). The data processing and further details concerning the device can be found in Popović-Maneski et al. [23].

The pendulum apparatus was fixed to the subject’s thigh and shank with soft Velcro straps, and a firm mattress supported the back of the subject (hip joints flexed at approximately 135°). A custom designed support for the thigh had an aperture to allow for mounting of the recording electrodes on the hamstrings m. The knee joint was positioned approximately 5 cm in front of the edge of the thigh support to ensure that the lower leg swings freely.

C. Procedure

At the beginning of the session, an experienced physiatrist assessed the spasticity of the right leg using the modified Ashworth scale. This assessment was followed by the pendulum test. During the pendulum test, the examiner released the subject's lower leg from a position where the knee joint was fully extended. The knee joint angle, shank angular velocity, and EMG signals were simultaneously recorded during the pendulum movements until the foot stops swinging. The pendulum tests were repeated three times at approximately 15-second intervals. The EMG activity was used for qualitative analysis of the behavior and estimation of the onset of the spastic reflex activity.

H group subjects were asked to relax the leg muscles and try not to activate them during the pendulum test. As the EMG recordings were available for online inspection, the trials were repeated until acquiring three sessions with no EMG or minimal EMG activity, while the others were neglected.

D. Data analysis

The EMG signals were band-pass filtered between 30 and 300 Hz, normalized to the maximal value for each channel and each swing, and filtered with a notch filter at 50 Hz with a 3rd order Butterworth filter. The signals from the absolute joint angle encoder and the gyroscope were filtered with the moving average that included 20 samples. Having in mind that resting angles in different subjects are not the same, we subtracted the mean values of the angle and velocity from the corresponding data sets. We developed a program for data acquisition in a LabVIEW environment, and automatic data processing with Matlab.

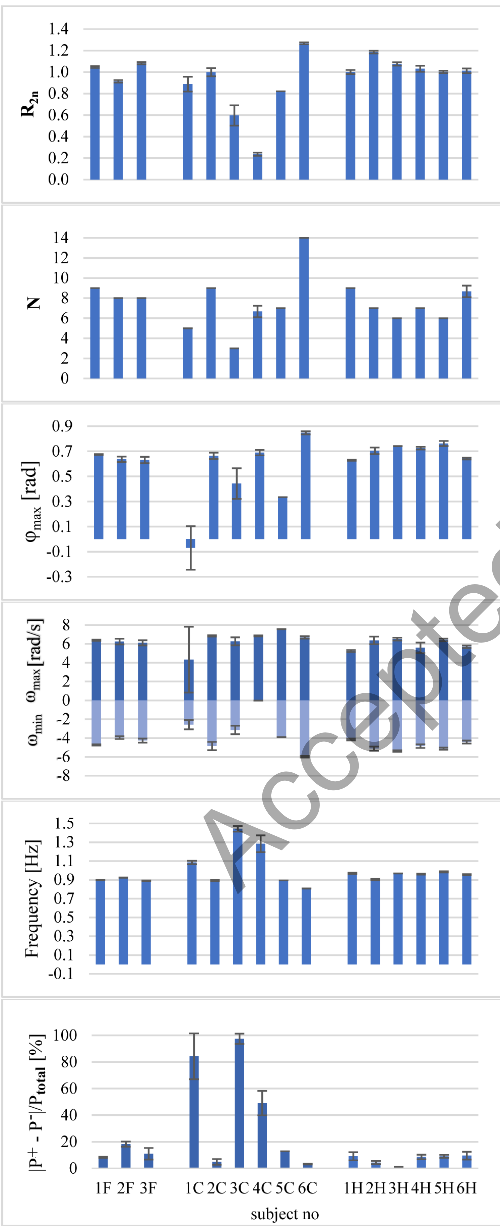

Fig. 3: Mean values and standard deviation (error bars) for the three trials for all subjects in the study. The bars are separated into three groups (F, C, and H). Panels show the relaxation index R_{2n}, a number of oscillations N, first maximum of the goniogram φ_{max}, positive and negative maximal angular velocities ω_{max} and ω_{min}, the frequency (f) of oscillations, and the absolute difference (in percentage) of the net positive area P+ and net negative area P- with respect the neutral joint angle calculated from the first minimum in goniogram.

The primary parameters from the pendulum test used in our analysis are: R_{2n} – the normalized relaxation index, N – the number of swings, φ_{max} – the first maximum of the goniogram after releasing the leg, and ω_{max} and ω_{min} - the maximum and minimum angular velocity of the shank as defined in [24]. The normalized relaxation index is given by, $R_{2n}=A_1/1.6A_0$ and was calculated from the goniogram where A_0 is the knee angle between the full extension (starting position) and the neutral knee joint angle (end position), and A_1 is the difference between the starting angle and the maximum flexion (the first minimum in the goniogram). R_{2n} indicates the strength of the spasticity. In healthy subjects, the parameter $R_{2n} > 1$ [24]. N was obtained by counting the maxima of the knee joint angle larger than 1° during the test. According to [24], values of N for healthy subjects range from 6 to 7. The parameter φ_{max} provides evidence of how strongly the spasticity retains the limb towards the starting angle. The value of φ_{max} for healthy subjects is from 0.34 to 0.61 rad [24]. The maximum angular velocities of flexion ω_{max} and extension ω_{min}, provide supplementary information about the amount of tonic and phasic components of spasticity. The values of ω_{max} for healthy subjects [24] are between 11 to 17 rad/s and the values of ω_{min} are between -12 to -9 rad/s [24].

We introduced two additional parameters in this study: the frequency of oscillations (*f*) and the absolute difference between the positive and negative areas between the goniogram and neutral line, $|P^+ - P^-|$, starting from the first minimum. The absolute value of the difference between the two areas divided with total area relates to the strength of the spasticity.

A single score representing a global measure of the spasticity from the pendulum test was calculated using all the measured parameters as following:

$$PT_i = \left|\frac{\left(\bar{R}_{2n_i} - \hat{R}_{2n_H}\right)}{7*\hat{R}_{2n_H}}\right| + \left|\frac{(\bar{N}_i - \hat{N}_H)}{7*\hat{N}_H}\right| + \left|\frac{(\bar{\varphi}_i - \hat{\varphi}_H)}{7*\hat{\varphi}_H}\right| + \left|\frac{\left(\bar{\omega}max_i - \hat{\omega}max_H\right)}{7*\hat{\omega}max_H}\right| + \left|\frac{\left(\bar{\omega}min_i - \hat{\omega}min_H\right)}{7*\hat{\omega}min_H}\right| + \left|\frac{(\bar{f}_i - \hat{f}_H)}{7*\hat{f}_H}\right| + \left|\frac{\left(\left|\overline{\frac{P^+ - P^-}{P_{total}}}\right|_i - \left|\widehat{\overline{\frac{P^+ - P^-}{P_{total}}}}\right|_H\right)}{7*100}\right| \quad (1)$$

Where *i* denotes a subject, *H* is used for the values of healthy subjects, ¯ represents a mean value of three trials in the same subject, and ^ represents the mean value for the whole population (i.e., H group population). To normalize PT, each member in the equation is divided by the total number of parameters used to calculate PT (i.e., seven parameters).

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E Statistics

Statistical analysis was done in an Excel Xlstat program. Data in groups C and H were tested for normality with the Shapiro-Wilk normality test. However, due to a relatively small sample of subjects we used non-parametric tests. The significance of the results was tested by the Kruskal-Wallis test for independent samples with the significance level p=0.05.

III. RESULTS

Fig. 2 presents four original sets of signals from the recordings from four different subjects, one from the very active group (1A), two from the inactive group (1C & 3C) that includes sub-acute and chronic patients, and one from a healthy group (2H). For each set of signals, EMG recordings for the quadriceps and the hamstrings, together with the knee joint angle and its velocity are plotted for three consecutive pendulum tests. Below these plots, one of the knee joint angle and angular velocity plots have been chosen and re-plotted on an expanded timescale to reveal details. From the plots, it can be seen that the knee joint angle oscillates around the 0 rad position which corresponds to the relaxed state of having the leg dangling motionless.

Positive and negative angle deviations are shaded in blue and red respectively. For the healthy and active groups, the areas of positive and negative deviations are almost symmetrical. To the contrary, the plots for the inactive patients show ether dominantly positive or negative deviations. For the inactive group, the signal set 1C in Fig. 2, shows that after the leg is released, it swings below the resting angle and continues to oscillate while maintaining negative knee joint angles. This is an indication of flexion spasticity. Conversely, we witness extension spasticity in the signal set 3C in the inactive group.

TABLE 2: ESTIMATED PARAMETERS FOR ALL SUBJECTS

group		R_{2n}	N	φ_{max} [rad]	ω_{max} / ω_{min} [rad/s]	f [Hz]	$\lvert P^+ - P^-\rvert / P_{total}$ [%]
F	Mean	1.01	8.33	0.65	6.24/-4.32	0.90	12.54
	Std	0.09	0.58	0.02	0.13/0.39	0.02	5.15
C	Mean	0.80	7.44	0.48	6.42/-3.40	1.07	41.97
	Std	0.35	3.79	0.33	1.11/2.06	0.25	41.53
H	Mean	1.05	7.28	0.70	5.96/-4.84	0.96	6.94
	Std	0.07	1.29	0.05	0.53/0.47	0.03	3.55

Fig. 3 contains bar graphs that display values of the different experimental parameters obtained for the whole population involved in the study.

We found that the number of oscillations in healthy individuals varies between 6 and 8 which is slightly higher than reported by Bajd and Vodovnik [24], but this may be due to the less strict limit condition of 1° for the knee joint angle used in this study compared to [24]. More striking differences were found for the maximal angular velocities in healthy individuals (5 - 6 rad/s), which are much lower compared with those presented in the literature.

Results (number of oscillations, maximal angle and angular velocity) reveal significant deviations from the mean

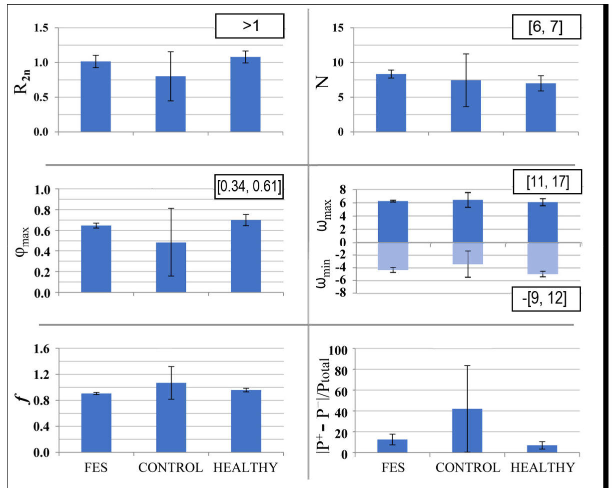

Fig. 4: Bar graphs for the whole population in Fig. 3. Values inside the black rectangles represent ranges for healthy subjects according to [24].

in the group C, while data for the groups F and H show little deviations from the mean. The deviations are the consequence of the particular conditions of the muscles and type of spasticity (flexion or extension) in each of the patients. Averaging of such data over each study group leads to a misleading conclusion (the mean values for group C are within the healthy range); however, the values of standard deviations are several times larger than in the groups F and H. Table 2 tabulates the mean and standard deviation for the parameters measured by the pendulum apparatus for each group studied and bar graphs which demonstrate these findings are displayed in Fig. 4. All the data from group C and data from group H except for R_{2n}, f and $|P^+$ vs. $P^-|$, follow the Normal distribution, while data in group F could not be tested due to the small sample size.

Total pendulum test scores, *PT*, for each subject is shown in Table 1. Characteristic values for healthy subjects are <1. Group statistics are shown in Figure 5. *PT*-score shows relative deviations of all pendulum test parameters from the mean values in the group H. Statistical analysis revealed significant differences between groups C and H as well as between groups C and F, and no difference between groups F and H.

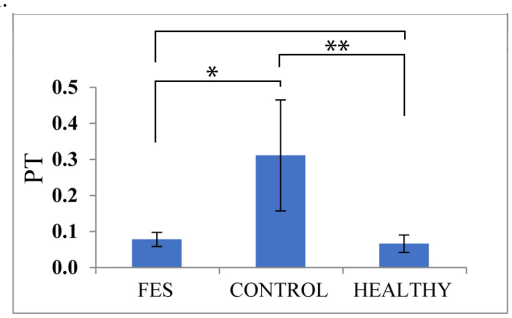

Fig. 5: The pendulum test spasticity score *PT* and statistical significances: *p<0.05, **p<0.01.

The correlation between the PT score and Ashworth score was 0.88. Fig.6 shows the composition of the PT score as well as visual comparison with the Ashworth score for each subject.

The patterns of EMG activities are different between the groups F and C. Group F patients had multiple packets of

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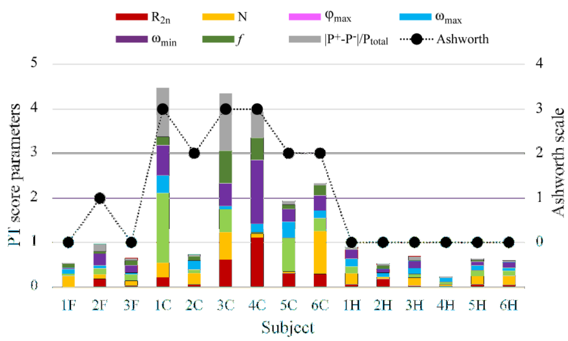

Fig. 6: The contribution of 7 parameters from equation 1 to the value of PT score for each subject (equal to the total height of the stacked bar) and values of measured Ashworth scale for each subject.

alternating EMG activities on both, quadriceps and hamstrings, throughout each trial (Fig. 2). The C group patients showed only a few reflex muscle activities after the start of the pendulum movements (single short bursts of EMG activities) on either flexor or extensor muscles, depending on their type of spasticity. The recordings show a short EMG burst being in the contra-phase of the stretch only at the initial two or three swings. As mentioned earlier, spasticity is defined as a velocity-dependent increase in tonic stretch reflexes ("muscle tone") with exaggerated tendon jerk, resulting from hyperexcitability of the stretch reflex [15]. In the group H we selected only trials with minimal EMG activity throughout the whole swinging motion (Fig. 3).

The acquisition of EMG was included in the test for the assessment if and when reflex muscle activities occurred. A detailed analysis of the EMG is not feasible with the setup that we used.

The pendulum test also shows that there is a general decrease in the frequency of damped oscillations during the test in spastic patients (Fig. 2, 3C).

IV. Conclusion

Pendulum test results showed notable differences in the relaxation index, maximal angle and angular velocity, frequency, number of oscillations and the ratio of positive and negative areas determined from the goniogram (e.g. knee joint angle deviations with respect to the resting knee joint angle) for the subjects in the group C compared to subjects in the groups F and H. Although there is no significant difference between mean values of the groups, the results show only slight deviations of all the parameters about the mean in the groups F and H, in contrast to substantial deviation seen among the C group members. Total pendulum scores (PT) showed significant differences between the groups C and H as well as between the groups C and F, and no difference between the groups F and H. Furthermore, there is a high correlation (0.88) between the calculated PT score and Ashworth scale rating, suggesting that the PT score can be used for automotive and quantitative assessment of spasticity.

Currently, the only feasible way for activation of the paralyzed muscles is the use of functional electrical stimulation [26]. We suggest that one of the best tools for integrating FES into a motivating exercise in high-level SCI population are stationary training bicycles or adapted recumbent tricycles [27 - 32]. This FES based exercise provides muscle activation and repetitive, controlled rotation of leg joints through a broad range of movement. The presented results suggest the importance of exercise in SCI patients to keep the spasticity at a low level.

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Conflict of interest: The authors declare that there is no conflict of interest regarding the publication of this paper.

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