Validation of the new wearable instrument for the pendulum test based on inertial sensors

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Abstract— **The important indicator of the impairment and the course of the recovery in humans with the central nervous system is the assessment of spasticity. The pendulum test was accepted as the quantification method of knee muscles' spasticity. We present a new, inexpensive, easy to use wireless pendulum test device for estimation of spasticity of knee muscles (quadriceps and hamstrings). The new system uses inertial, and electromyography (EMG) sensors positioned at the upper and lower leg segments. The measurement device was applied for the pendulum test on a population of thirteen healthy volunteers. We estimated seven parameters from the pendulum test, which form a single measure of spasticity in patients, termed the pendulum test (PT) score. Results show a small deviation for all parameters between subjects, and mean values of PT score are below 1, which is in the range for healthy persons from the literature. Hence, the mean values of these seven parameters can be used as a reference for the PT score estimation in patients.**

Index Terms—spasticity assessment, wireless pendulum test device, PT score.

I. Introduction

The quantification of the level of impairment is essential for clinicians to select the most appropriate treatment for patients after spinal cord injury (SCI), stroke, multiple sclerosis (MS) or cerebral palsy (CP). Spasticity is one of the main impairments resulting in an automatic increase of the tonus of affected muscles and increased sensitivity to the stretch in SCI patients [1]. More precisely, spasticity is defined as "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 [2]. The conventional method for assessing spasticity by a clinician is using the modified Ashworth scale [3]. The pendulum test was introduced to meet the need for a more accurate quantification method for assessing spasticity and reducing the subjective component of the evaluation of spasticity[4] [5]. The type and intensity of knee muscles spasticity are determined from a set of parameters calculated from the knee joint angle vs. time data curve acquired from the pendulum test [1, 4].

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During the pendulum test, while the subject is sitting on the side of bed or similar, the examiner releases the subject's lower leg from a position where the knee joint is fully extended and observes deviations of the knee angle from the dumped oscillation pattern. Standard methods to measure knee joint angle include Hall-effect joint angle encoder of the knee joint [1], potentiometer measuring the knee joint [4], smartphone camera-based system with passive markers at the lateral side of the knee joint [6] or angle camera-based systems in motion laboratories with passive/active markers [7, 8].

We presented a new pendulum test device for the estimation of knee joint muscles spasticity. The instrumentation comprises inertial sensors (gyroscope and accelerometer) mounted on the anterior side of thigh and shank (one 3D gyroscope and one 3D accelerometer per segment) and EMG amplifier that measures muscle activities of two muscles *via* surface electrodes. All signals are wirelessly sent to the host computer with the user-friendly acquisition program. The acquisition program allows the examiner to follow EMG signals from quadriceps and hamstring muscles and angular velocities and acceleration of the thigh and shank vs. time during the pendulum test on the computer screen. The data recorded are used to estimate the Pendulum test (PT) score, as defined by Popović-Maneski et al. [1].

In this paper, we show the data recorded in a group of 13 healthy volunteers, and we show the estimated mean values necessary for the calculation of the PT score in patients.

II. The Method

A. Subjects

The study includes 13 healthy volunteers with demographic data given in Table 1.

TABLE I
BASIC DATA FOR HEALTHY SUBJECTS PARTICIPATING IN THE STUDY

N°	Sex	Age	Height [cm]	Mass [kg]
1H	F	33	178	65
2H	F	61	166	80
3H	F	35	178	90
4H	F	36	162	55
5H	F	52	162	50
6H	M	30	175	87
7H	M	34	170	82
8H	M	68	178	92
9H	M	35	182	76
10H	M	68	179	115
11H	F	35	162	55
12H	M	24	177	81
13H	F	25	168	60

The inclusion criteria for healthy volunteers were the following: no known sensory-motor impairment, controlled blood pressure and pulse, and able to follow the protocol of the pendulum test.

B. *Instrumentation*

The pendulum test device (Fig. 1) consists of two separate housings interconnected with a spiral wire. The housings are fixed with stretchable velcro straps on the anterior side of the thigh and shank. The distances of the thigh and the shank housing from the knee joint are about 15cm and 20cm. The distance between housings does not influence the measurements, but it is essential to position them perpendicularly to the sagittal plane. Thigh housing has leads connected with the electrodes for the recordings of two EMG signals with reusable surface electrodes (four leads for the measurements and one lead for the grounding). We used, for the test purposes, one EMG channel for e recording the muscle activity of the quadriceps. EMG signal recording was accomplished with pre-gelled Ag/AgCl electrodes (NM 3351 OFI, Top Trace, CERACARTA S.p.A., Forli, Italy) placed over the bulk of the quadriceps muscle with the inter-electrode distance of 2cm. The ground electrode was placed over the bony part of the knee joint. We do not show in this paper the EMG recordings.

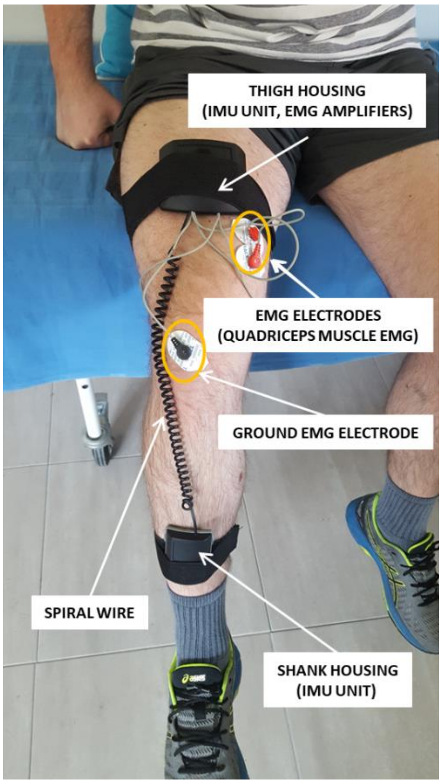

Fig. 1. The wireless instrument for the pendulum test. The thigh and shank housings have inertial measurement units: 3D accelerometers and 3D gyroscopes. Thigh housing also has the EMG amplifiers for bipolar measuring of the muscle activity.

Both thigh and shank housings have an inertial measurement unit (IMU), consisting of one gyroscope and one accelerometer sensor. IMU unit is based on the MPU6050 unit (InvenSense, San Jose, California, USA). This particular IMU unit has a 16bit AD converter, 100Hz sample rate, +/- 500deg/s gyroscope sensor range, and +/-4g accelerometer sensor range. EMG amplifiers in thigh housing are based on one ADS1294 ECG chip (Texas Instruments, Dallas, USA). ECG unit has a 24bit AD converter, 500Hz sampling rate, DC coupling, and inputs for 2 EMG leads.

The pendulum test device has a battery power supply in thigh housing. There is also an “on/off” button for Bluetooth wireless connection with laptop computer and pendulum test acquisition program. All measurement signals from inertial sensors and EMG amplifiers are time-synchronized and subsequently digitized. Signals from inertial sensors are resampled to 500 samples per second.

A subject was sitting on a stable wheel-fixed clinical bed with the back support with a firm pillow (hip joints flexed at approximately 135°). The knee joint was positioned about 5 cm in front of the edge of the bad to ensure that the lower leg swings freely.

C. *Measurements*

The test was performed on thirteen healthy subjects. Subjects were asked to relax the leg muscles and try not to activate them during the trial. The examiner released the subject’s lower leg from a position where the knee joint was fully extended and allowed shank to oscillate like the physical pendulum about the knee joint until the foot stopped the swinging (Fig. 2). The angular velocity and the angular acceleration of shank and thigh and EMG signal from the quadriceps m. were simultaneously recorded during the pendulum movements. The pendulum test was repeated with a pause of 15 seconds between the trials until three successful pendulum test measurements were obtained. The successful trial is described as a pendulum test movement with no EMG or minimal EMG activity. EMG recordings from the quadriceps were used for online inspection of the leg muscle activity.

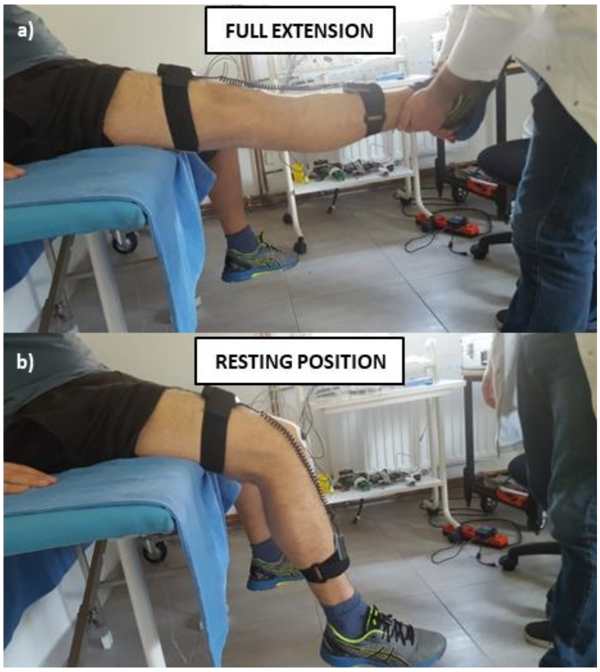

Fig. 2. The fully extended leg reached by the examiner (a) and resting position of the leg (b)

D. *Data processing*

The EMG signals from quadriceps were high-pass filtered above 30 Hz, normalized to the maximal value for each swing, and filtered with a notch filter at 50 Hz with a 3rd order Butterworth filter. The sagittal angular velocity signals from the gyroscopes and sagittal angular acceleration signals from accelerometers were filtered with the moving average filter that included 50 samples. The mean value of the last second of the signal (resting position) was subtracted from all angular velocity and angular acceleration signals due to different resting angles for each subject. Corrected sagittal angular velocity of the shank was calculated as the difference of angular velocity of the shank, measured by shank gyroscope, and angular velocity of the thigh, measured by thigh gyroscope, to compensate the thigh movement during pendulum test. The sagittal angle signal was calculated as the first integral of the corrected angular velocity signal. We developed a program for data acquisition in a C# environment and automatic data processing in Matlab.

The parameters from the test for the estimation of spasticity, as defined in [1], are: R_{2n} – the normalized relaxation index, N – the number of swings, ϕ_{max} – the first maximum of the angle signal after releasing the leg, and ω_{max} and ω_{min} - the maximum and minimum angular velocity of the shank, f- the frequency of dump oscillations of pendulum test and $|P_+ - P_-|/P_{total}$ [%] - the absolute difference between the positive and negative areas between the angle signal and neutral line starting from the first minimum and divided with the total area. The normalized relaxation index was calculated from the knee joint angle signal (angle between shank and thigh). The index was calculated as $R_{2n} = A_1/1.6A_0$ where A_0 is the knee joint angle between the full extension (starting position) and the neutral knee joint angle (resting position), and A_1 is the difference between the starting angle and the maximum flexion (the first minimum in the angle signal) as defined by Bajd et al. [4]. N was estimated by counting the number of maxima of the knee joint angle more significant than 1° during the recording session.

The above-listed parameters are used to calculate the PT score with the following equation:

$$PT_i = \left(\left|\frac{(R_{2n_i} - \hat{R}_{2n_H})}{7 * \hat{R}_{2n_H}}\right| + \left|\frac{(N_i - \hat{N}_H)}{7 * \hat{N}_H}\right| + \left|\frac{(\varphi_i - \hat{\varphi}_H)}{7 * \hat{\varphi}_H}\right| + \left|\frac{(\omega_{max_i} - \hat{\omega}_{max_H})}{7 * \hat{\omega}_{max_H}}\right| + \left|\frac{(\omega_{min_i} - \hat{\omega}_{min_H})}{7 * \hat{\omega}_{min_H}}\right| + \left|\frac{(f_i - \hat{f}_H)}{7 * \hat{f}_H}\right| + \left|\frac{\left(\left|\frac{P^+ - P^-}{P_{total}}\right|_i - \left|\frac{\widehat{P^+ - P^-}}{P_{total}}\right|_H\right)}{7 * 100}\right|\right) * 10 \quad (1)$$

Where i denotes a subject, H is used for the values of healthy subjects and ^ represents the mean value for all subjects. Each member of the equation is divided with 7 (total number of parameters) for normalizing the PT score.

In this study, we estimated the values in Equ. 1 denoted with the nominator H (acronym for healthy).

III. Results

A typical example of the signals recorded in one out of thirteen volunteers is in Fig. 3 and represents subject 6H. The normalized EMG recordings from the quadriceps muscle, and estimated knee joint angle and the angular velocity are plotted together for six consecutive repetitions of the test in Fig. 3a. Three trials were selected where the EMG was minimal for the calculation of the pendulum test parameters. The time beginnings of the selected three trials are marked with vertical green lines in Fig. 3a. The knee joint angle, angular velocities, and EMG signal for the selected three trials are in Fig. 3b. Fig. 3c. presents the knee joint angles for the selected 3 trials. There are also marked angles A_0 and A1 (red lines), used for calculation of normalized relaxation index R_{2n}, maximal angle of swings (green dots), which total number represent a number of swings N.

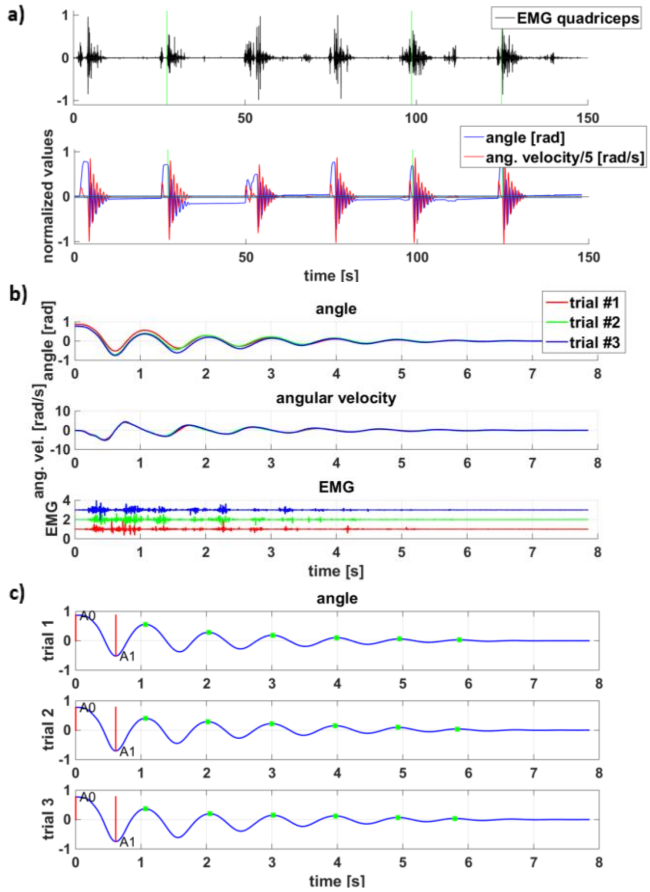

Fig. 3. The recordings of processed signals for subject 6H: EMG signal of quadriceps (normalized), the knee joint angle, and angular velocity of the lower leg for one healthy subject (a). The processed knee joint angle, angular velocity, and normalized EMG activities of quadriceps for the selected 3 trials (minimal EMG activity), started at the vertical green line (b). The knee joint angles for the selected 3 trials with marked positions of the local maxima (green dots), A0 and A1 angles (red lines)(c).

PT values for the selected 3 trails for all subjects are shown in Fig.4. To calculate the PT score, we used the mean values of the parameters with the H index in Eq.1 from all subjects (three trials each). High variability of the scores comes directly from the subjects' inability to relax the muscles completely. The example of the signal in Fig.3. supports this claim because it is visible that the stronger EMG activity in trial 3 changed the regular oscillatory pattern of the angle signal. In further analysis, we used only the minimal PT score value for each subject. In Fig.5, we show the mean values and standard deviations of the seven parameters for the whole set using the trial with minimum PT score in each of 13 subjects. The value for the normalized relaxation index R_{2n} (1.06±0.06), number of swings N (7.08±1.04), the first maximum of the angle signal

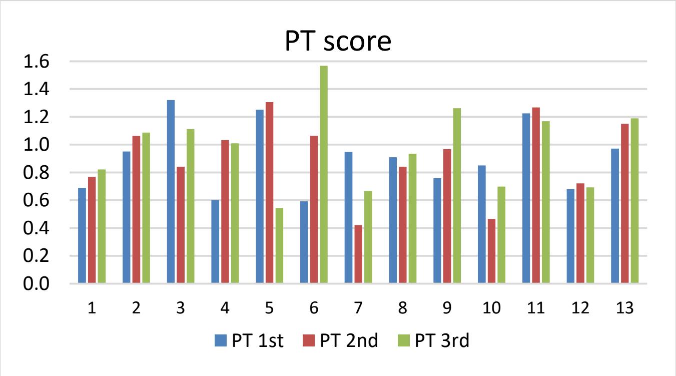

Fig. 4. PT scores for the three selected trials in 13 healthy subjects.

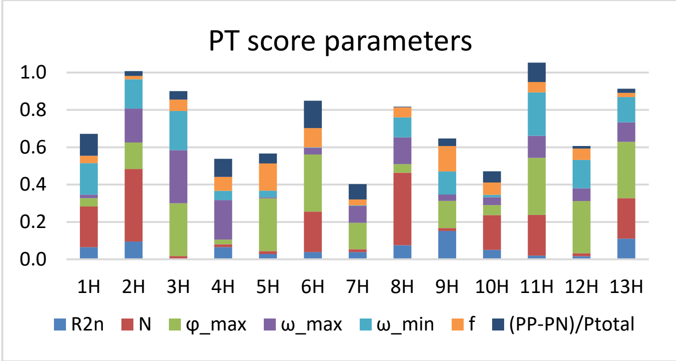

Fig. 6. The value of the PT score (equal to the total height of the stacked bar) with the contribution of seven parameters from equation (1) used in the calculation for each subject.

ϕ_{max} (0.62±0.09 rad), the frequency of oscillations f (1±0.05 Hz), the absolute difference between the positive and negative areas between the angle signal and neutral line $|P^+ - P^-|/P_{total}$ (7±5 %), have values in range for healthy individuals according to the literature [1][4].

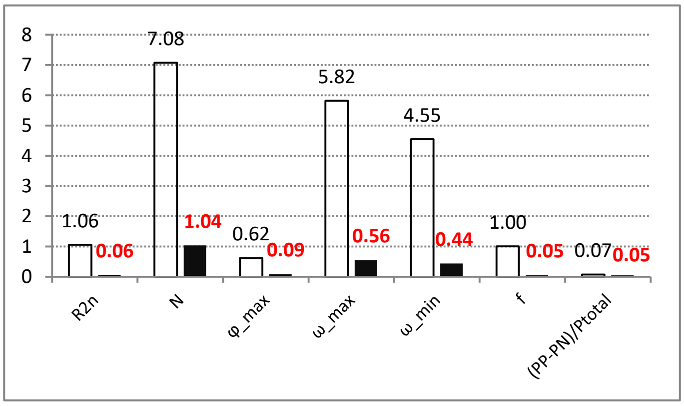

Fig. 5. Mean absolute values of seven parameters (empty bars) and standard deviations (black bars) from 13 healthy subjects.

The standard deviation for parameters R_{2n}, N, and f is low, for parameter ϕ_{max} relative small and for parameter $|P^+ - P^-|/P_{total}$ relatively high; however, the absolute values of this parameter are close to zero. The value for maximum and minimum angular velocity, ω_{max} (5.82±0.56 rad/s) and ω_{min} (-4.55±0.44 rad/s) are much lower than values for healthy range given by [4], but they are in the healthy range given by [1], which could be explained by the fact that we used calculation method for these parameters that are exact and more strict than in [4]. Standard deviations for ω_{max} and ω_{min} are relatively low. Values for pendulum test score PT (0.73±0.22) are below 1, and they are in healthy individual range according to [1].

Fig. 6. shows the values of calculated PT score with the contribution of every parameter included in its calculation according to (1), for each of thirteen healthy subjects. Contribution of parameter $|P^+ - P^-|/P_{total}$, which is relatively unreliable because of high standard deviation, in the calculation of PT score, is low for all subjects.

IV. Conclusion

Previous studies with PT score included a small number of healthy subjects; hence, the reference "healthy" values previously used for calculation of PT score in patients were unreliable. We calculated PT score components from 13 healthy subjects of different age and sex to determine a set reference values that can be used in future clinical studies in persons with disabilities. Six out of seven parameters of the PT score determined for the tested group had the standard deviation below 15%. The standard deviation for the seventh parameter ($|P^+ - P^-|)/P_{total)}$ is in range of 75%. However, the magnitude of this parameter in healthy is close to zero, so the contribution to the PT score is negligible. The magnitude of this parameter is large for the patients and it shows if the extension or flexion components of spasticity is dominant [1]. The mean values determined in this study will be used in future clinical studies with SCI, stroke, MS, and CP patients to assess their knee spasticity.

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