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The Assessment of Spasticity: Pendulum Test Based Smart Phone Movie of Passive Markers

Antonina Aleksić[1], Stevica Graovac[2],
Lana Popović Maneski[3], Dejan B. Popović[3,4]

Abstract: The pendulum test is the method for quantification of the level of spasticity in persons with spinal cord and brain injuries/diseases. The data for the assessment comes from the analysis of lower leg rotation in the sagittal plane while sitting caused by gravity. We built a simple instrument that uses the smart phone and passive markers for studying the pendulum movement of the leg. We compared the results of the new device with the results acquired with the conventional apparatus which uses a knee joint angle encoder and inertial sensors mounted on the upper and lower leg. The differences of parameters estimated from the test between the two systems are in the range of 5%, which is in the same range as the precision of the positioning of the pendulum apparatus on the leg. The new system is simple for the application (donning, doffing, setup time, accuracy, repeatability) and allows a straightforward interpretation to a clinician.

Keywords: Spasticity assessment, Pendulum test, Image processing, Smartphone.

1 Introduction

A frequent impairment in persons with central nervous system injury/lesion is the poor muscle performance expressed as a combination of paralysis/paresis, increased tendon reflex response to stretch and hypertonia. The modified stretch reaction and hypertonia are called spasticity [1]. A clinician assesses spasticity using the Ashworth scale or the modified Ashworth scale by manually estimating the increased resistance of a particular muscle group [2]. The pendulum test was introduced to eliminate the subjective component of the assessment [3, 4]. The knee joint angle *vs.* time data, collected during the pendulum motion is used to calculate a set of parameters that reflect the intensity and type of spasticity. Recently, we modified the instrumentation for

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[1] School of Electrical Engineering (Ph.D. student), University of Belgrade, Bulevar kralja Aleksandra 73, 11020 Belgrade, Serbia; E-mail: aleksicantonina@gmail.com
[2] School of Electrical Engineering, University of Belgrade, Bulevar kralja Aleksandra 73, Belgrade, Serbia; E-mail: graovac@etf.rs
[3] Institute of Technical Sciences of the Serbian Academy of Sciences and Arts, Knez Mihailova 35, Belgrade, Serbia; E-mail: lanapm13@gmail.com
[4] Aalborg University, Department of Health Science and Technology, Aalborg, Denmark; E-mail: dbp@etf.rs

the pendulum test and introduced new parameters for more appropriate classification of spasticity [5, 6].

Standard methods to measure joint angles are camera-based systems in motion laboratories with passive/active markers [7, 8]. These systems are complicated and expensive and require substantial effort for setting them up. The smartphones and the gaming interfaces (i.e., Microsoft Kinect) are becoming popular as a simplified substitution of laboratory instrumentation for clinical settings and part of evidence-based medicine [9, 10].

We present a new system consisting of four passive markers mounted on the lateral side of the thigh and shank (two per segment) and the smart phone camera for estimating the parameters of spasticity. The processed data acquired as a movie by the smart phone allow a clinician to follow on the computer screen the knee joint angle vs. time curve along the pendulum movement of the shank. The program outputs the parameters that reflect the level of spasticity. The application of the system was tested for the assessment of spasticity using the measures introduced by Bajd and Vodovnik [3], and further expanded to a pendulum score (PT) as described in Popović Maneski *et al.* [6].

2 Method

2.1 Subjects

Two subjects participated in this study: a healthy female, 25 years old, and a male, spinal cord injury, ASIA B, Th7 lesion, 58 years old.

Both subjects signed the informed consent approved by the local ethics board obtained from the Clinic for Rehabilitation “Dr. Miroslav Zotović,” Belgrade.

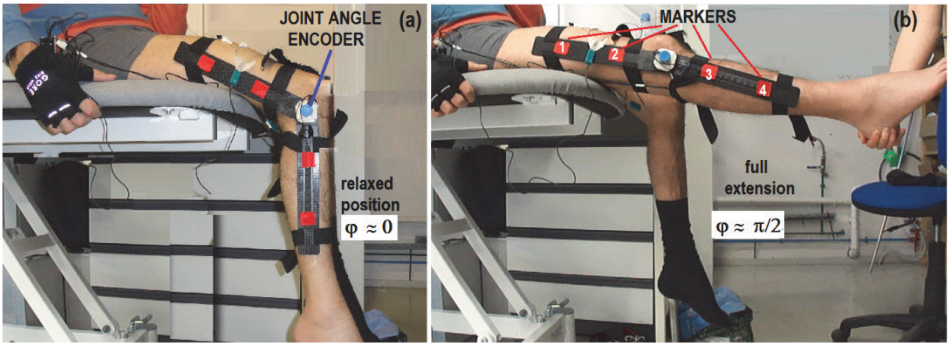
2.2 Instrumentation

Two systems were used in parallel for validation of the method: 1) a system with markers and 2) a system with the joint angle encoder and inertial measurement units.

<u>A system with markers</u>. Set of four red markers were used for angle detection. Markers were attached to the graphite bars at the inter-distance of 14 cm (Fig. 1b). Graphite bars are connected to the thigh and shank having the direction along the bodily segments. The size of the shiny, red, reflexive markers is 4×5 cm. A Samsung Galaxy S6 Edge Plus smart phone with a 16-megapixel camera, set at the sampling frequency of 30 frames per second (fps) was used for the recording of a movie.

<u>A system with the joint angle encoder and inertial measurement units</u>. A two-thin bar graphite mechanism was fixed to the thigh and shank cuffs by the Velcro bands [5]. A low friction hinge joint, positioned to be coaxial to the knee

joint axis is connecting the bars [1]. A joint angle encoder was mounted at the hinge joint to measure the rotation angle. The NI 6009 USB A/D card, 16-bit resolution connected via cable to the laptop digitized data from the encoder. The sampling rate was set at 1 kH.



(a) (b)

Fig. 1 – *(a) The neutral position of the leg showing the joint angle encoder as described in Popović Maneski et al. [5]. (b) The fully extended leg with passive markers. Four red squared markers along the thigh (1 and 2) and shank (3 and 4) determine the directions of the upper and lower leg.*

2.3 Data processing

MATLAB (Mathworks, Natick, USA) software was used for analysis. Frames were extracted from the recorded movie and converted to series of images. The images were converted from the RGB format to a grayscale intensity image. Only red components of the image were processed. The threshold for processing was obtained from an image histogram, threshold = 30. Different morphology operations were tested. The first procedure was applied to fill all black pixels with white color if all the neighbors of the pixel were black. Secondly, all the pixels which had at least five white neighbors were set to white if they were previously black. Finally, erosion and dilatation were applied. Dilatation was made with a segment of 15×22 pixels and erosion was implemented using a 17×17 pixel segment. After morphological processing, centroids of the detected markers were calculated. Then, the centroids were sorted on y scale, for line detection.

The direction of the first segment was defined with the line that contains the first two centroids (1 and 2) and recognized by their lower y values. The second two centroids (higher values on the y scale) determined the direction of the second segment line.

The angle at the knee joint φ was calculated by using the line slopes k_1 and k_2 *vs.* the horizontal axis (x). The slopes are defined by (1) and (2) respectively:

$$k_1 = \tan\varphi_1 = \frac{y_2 - y_1}{x_2 - x_1}, \tag{1}$$

$$k_2 = \tan\varphi_2 = \frac{y_4 - y_3}{x_4 - x_3}, \tag{2}$$

$$\phi = \arctan\left(\frac{k_2 - k_1}{1 + k_2 k_1}\right). \tag{3}$$

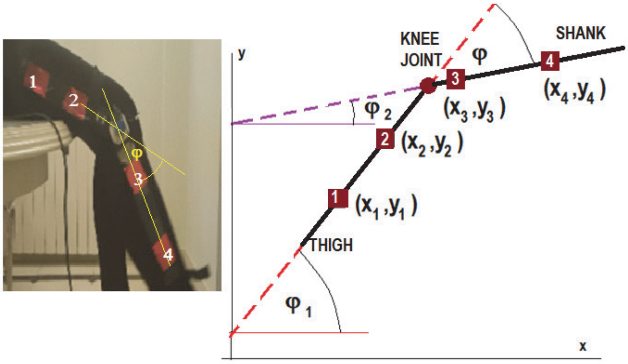


Fig. 2 – *Sketch of the markers (1, 2, 3, and 4) and angles used for the calculation of the knee joint angle* φ. *Coordinates* (x_1, y_1) *and* (x_2, y_2) *define the thigh direction* φ_1 *vs. the horizontal line. Coordinates* (x_3, y_3) *and* (x_4, y_4) *define the direction of the shank* φ_2 *vs. the horizontal line.*

The signals from the joint angle encoder were filtered with the moving average filter of 20 samples as described in [5]. The results measured by the joint angle encoder and signals estimated from the series of images were compared. First, the data from the joint angle encoder were resampled from 1 kHz to 30 Hz to allow the comparison of two-time series. The two sets of data were synchronized. The processed data from the joint angle encoder and angles estimated from the movie (series of images) were differentiated to calculate the angular velocities.

2.4 Parameters for the assessment of spasticity

Bajd and Vodovnik [3] introduced the parameters A_0, A_1, A_2, and A_{2n} (Fig. 3, top panel). The normalized relaxation index $R_{2n} = A_1/1.6A_0$ was calculated, where A_0 is the knee angle between the full extension and the neutral knee joint angle and A_1 is the difference between the starting angle and the maximum flexion in the first swing, and A_2 the angular change between the first minimum and second maximum. Bajd and Vodovnik also analyzed maximum (ω_{max}) and minimum (ω_{min}) angular velocities of the lower leg (Fig. 3, bottom panel). They used the tachogram to measure the angular velocity. We calculated the angular velocities from the recorded data by differentiation.

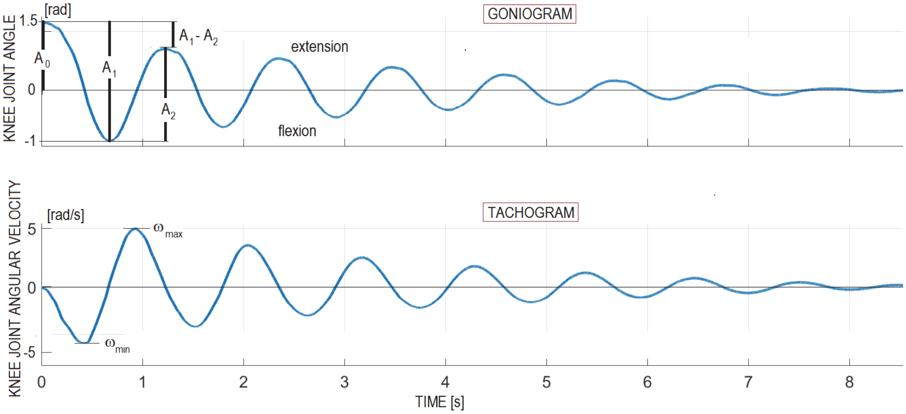


Fig. 3 – *The knee joint angle goniogram and tachogram in a healthy subject during the pendulum test. The goniogram shows the lower leg oscillating from the full extension (horizontal position of the lower leg) until stop (vertical position of the lower leg).*

In our recent work [6] we expanded the set of parameters and introduced: the frequency of oscillations (f) and the relative difference $|P^+ - P^-|/P_{total}$ between the positive and negative areas and the total area between the goniogram and the neutral line starting from the first minimum. P_{total} is the area between the goniogram and the time axis. We also introduced the pendulum test score (PT) as a global measure of the spasticity [6]. The PT score is given by (4):

$$PT_i = \left|\frac{\left(R_{2n_i} - \hat{R}_{2n_H}\right)}{7\hat{R}_{2n_H}}\right| + \left|\frac{\left(N - \hat{N}_H\right)}{7\hat{N}_H}\right| + \left|\frac{\left(\varphi_i - \hat{\varphi}_H\right)}{7\hat{\varphi}_H}\right| + \left|\frac{\left(\omega_{\max_i} - \hat{\omega}_{\max_H}\right)}{7\hat{\omega}_{\max_H}}\right| + \left|\frac{\left(\omega_{\min_i} - \hat{\omega}_{\min_H}\right)}{7\hat{\omega}_{\min_H}}\right| + \left|\frac{\left(f_i - \hat{f}_H\right)}{7\hat{f}_H}\right| + \left|\frac{\left(\left|\frac{P^+ - P^-}{P_{total}}\right|_i - \widehat{\left|\frac{P^+ - P^-}{P_{total}}\right|}_H\right)}{7\cdot 100}\right|, \quad (4)$$

i denotes a subject, H index is used for the values of a healthy subject ($i = 1$), and the sign ^ indicates the mean value. To normalize PT, each member in the equation is divided by the total number of parameters used to calculate PT [6].

In this study, we analyzed the differences between the parameters and the PT score obtained from the two measurement systems. The averages of the differences and standard deviations have been used as the measures for validation of the new system.

2.5 Procedure

The subject was sitting on a stable desk with the back support (hip angle ≈ 135°). The thigh was resting on a flat surface. The knee was in front of the edge of the table to allow free rotation of the lower leg about the joint.

In Subject 1 (healthy) we performed two tests: 1) recordings of knee kinematics during the ten voluntary rotations of the lower leg. Each of the ten rotations included a cycle that started from the relaxed position of the lower leg ($\varphi \approx 0$) to the almost full extension $(\varphi \approx \pi/2)$ and the return to the starting position; and 2) The pendulum test where the examiner extended the lower leg to the angle $(\varphi \approx \pi/2)$, released it, and the lower leg started damped oscillations which eventually stopped $(\text{angle } \varphi \approx 0)$.

In Subject 2 (patient) we only performed the pendulum test since he was not able to voluntarily move the lower leg due to the spinal cord injury.

We filmed the motion in the sagittal plane with the camera (smartphone) and recorded data from the joint angle encoder.

3 Results

Fig. 4a shows images that were used for the estimation of the joint angle by the image processing. Fig. 4b shows the *R* component of the images shown in Fig. 4a.

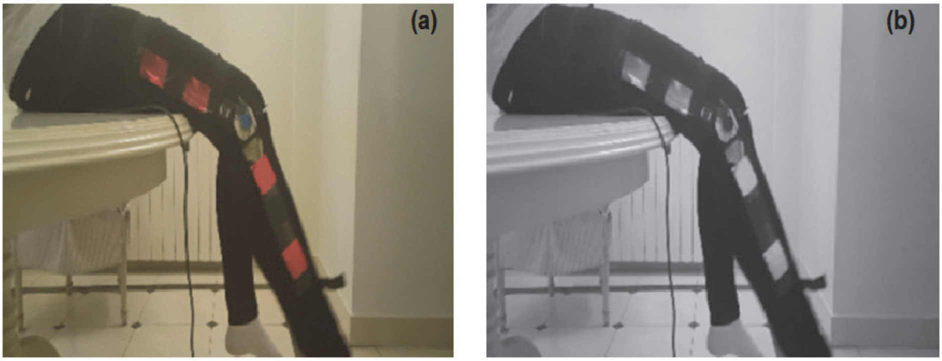


Fig. 4 – *(a) A selected frame for image processing. (b) R component of the image.*

Fig. 5 shows the histogram of the image shown in Fig. 3. The threshold was selected to be higher than 25 to allow efficient estimation of the position of the markers. We decided the value 30 (Fig. 5).

Fig. 7a shows the centroids detected and the line estimated from the centroids. Fig. 7b shows the data from Fig. 7a overlaid on the image of the leg.

Fig. 8a shows superimposed data estimated from the movie (red line) and the signals from the joint angle encoder (blue line) during ten consecutive extension/flexion movements of the lower leg.

Fig. 8b shows the image-based (red line) and encoder based (blue line) for the pendulum test in Subject 1 (healthy). The recordings mainly overlap, and the errors (differences in the values of the joint angles) are low (< 5%).

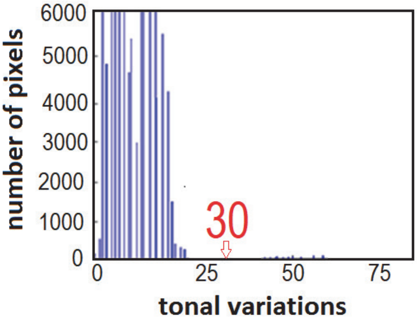


Fig. 5 – *A histogram of the image shown in Fig. 4 with the threshold values of 30.*

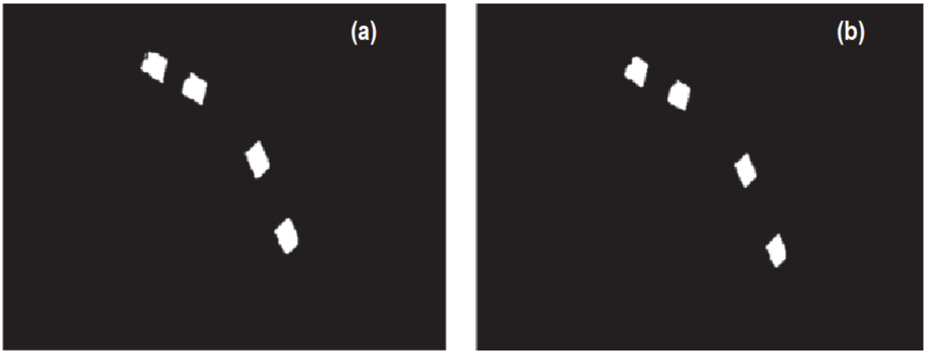


Fig. 6 – *(a) The processed image after the threshold "30" was applied.*
(b) The reconstructed image after morphological operations.

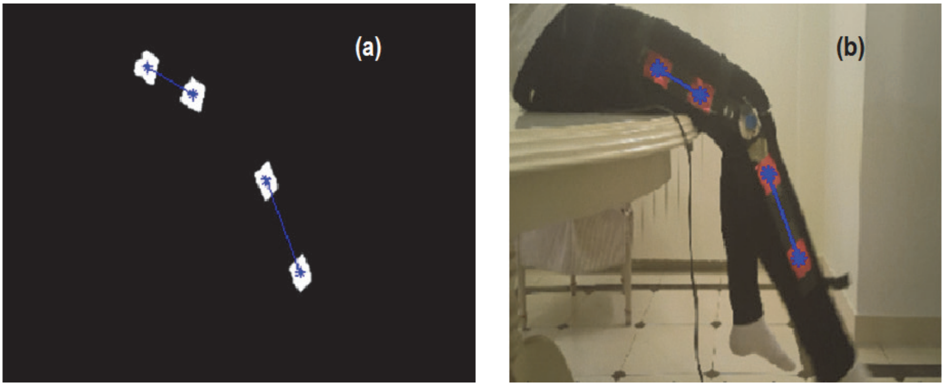


Fig. 7 – *(a) The image after morphological operations and detection of centroids.*
(b) The detected centroids of the markers superimposed onto the original image.

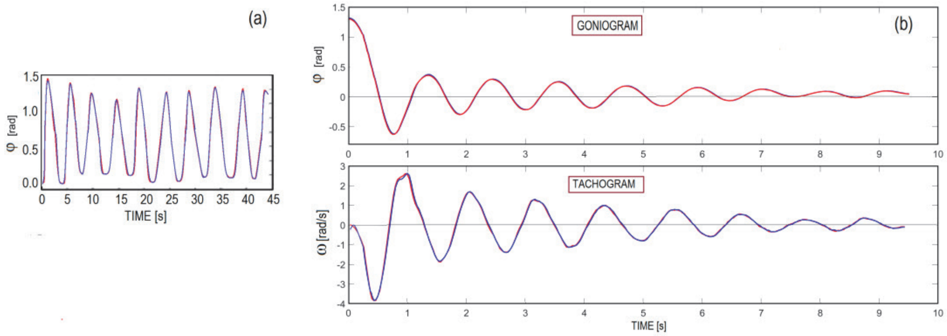


Fig. 8 – *(a) Superimposed angles estimated from the camera data (red line) and the data from the angle encoder (blue line) for ten consecutive voluntary movements of the lower leg from the flexed position to the near full extension and back (Subject 1). (b) Superimposed goniogram and tachogram form two systems for the pendulum test.*

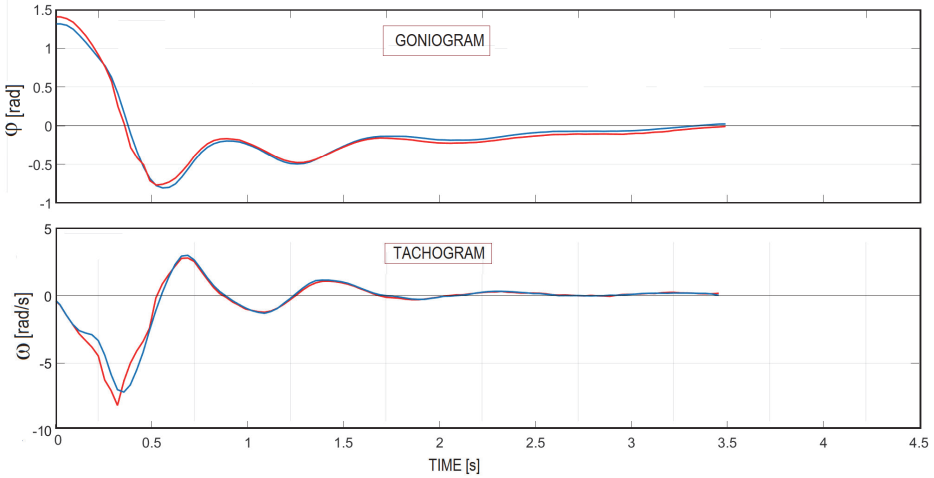


Fig. 9 – *Knee joint goniogram and tachogram for Subject 2 (patient) estimated by image analysis of the movie recorded (red line) and the signals from the joint angle encoder (blue) for the pendulum test.*

Fig. 9 shows the results of the pendulum test in Subject 2 (person with spinal cord injury).

Table 1 presents the estimated parameters defined in [6] for both of the signals: images from the movie and the joint angle encoder.

Fig. 10 shows the false detection of markers because of the inadequate background.

Table 1

Parameters defining spasticity and the absolute differences obtained from the image analysis and the joint angle encoder signals.

Subject		R_{2n}	N	$\varphi_{\max}$ [rad]	$\omega_{\max}$ [s^{-1}]	$\omega_{\min}$ [s^{-1}]	F [Hz]	$(P^{+}-P^{-})/P_{tot}$ [%]	PT score
1	Image analysis	1.11	8	0.46	2.59	-3.86	1.09	6.68	0.2
	Joint angle encoder	1.09	8	0.48	2.61	-3.85	1.09	6.02	0.19
	|Relative difference| [%]	1.8	0	4.2	0.8	0.3	0	10.9	5.3
2	Image analysis	1.01	4	-0.22	3.8	-8.45	1.35	100	0.73
	Joint angle encoder	1.02	4	-0.23	3.85	-8.14	1.33	97	0.71
	|Relative difference| [%]	1.0	0	0	1.3	3.9	1.5	3.1	2.7

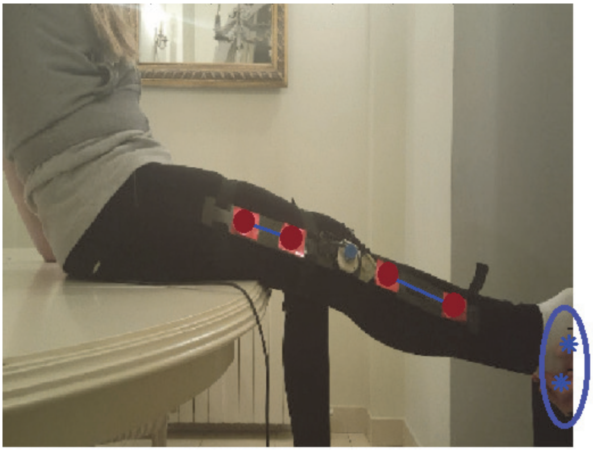


Fig. 10 – *False detected markers due to the inadequate background are shown with asterisks on foot.*

4 Discussion

We demonstrate here that it is feasible to assess spasticity by the pendulum test *via* camera-based angle detection. Image-based methods using a digital camera and a computer with image analysis software have been validated in the knee joint [9, 11]. We confirmed that the appropriate threshold and the correct morphological operations are of highest importance for the accurate estimation of the joint angle. We include an example which shows that it is impossible to correctly detect the marker without the proper usage of the morphological operations (Fig. 10).

Fig. 7 shows a case with proper detection of the markers (no false detection). We found that the background of the leg with markers is essential since elements in the background lead to false detection. In the typical clinical environment, there are many shiny and white objects. Therefore, the recommendation for the use of the camera based system is to select the dark background during the test, if possible. To eliminate this problem, we are finalizing the system which uses reflective passive markers. The use of reflexive markers reduces the artifacts (the threshold can be increased several times in the image analysis).

Table 1 shows the parameters determined from the signals from the processed camera data and the signals from the joint angle encoder. Table 1 shows substantial differences between the healthy and spinal cord injured subjects. We marked the values of these parameters with red numbers. However, the differences between the results of the image analysis and joint encoder data are small. The differences in the PT scores are only 5.3% and 2.7% when comparing the image based estimation and joint encoder data, respectively Based on this result, we suggest that the pendulum test can be performed by only a simple handheld smart phone and two pairs of red markers mounted on the lateral side of the shank and thigh. The software we developed directly provides data to the clinician after the movie is copied to the computer which runs Windows operating system. In future, the application could run possibly on the same smartphone.

5 Conclusion

The results of the study show that a camera-based system is a practical method for the knee joint angle measurement during the pendulum test. The differences in parameters characterizing the spasticity calculated from the image analysis and conventional joint encoder are within few percent. The complex signal processing is not visible to the clinician; hence, she/he can quickly and easily implement the new system for the spasticity assessment in the daily practice. The future camera-based system will use the reflective markers for minimizing the interference with the background and other light sources.

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