The pendulum test for assessing spasticity based on smart phone movie and passive markers

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***Abstract*— For humans with central nervous system lesion the spasticity is an important indicator of the impairment and the course of the recovery. The pendulum test was accepted as the quantification method of spasticity. We present a new, easy to use inexpensive pendulum apparatus for estimation of spasticity. The new system uses smart phone camera and markers positioned at the leg segments for measuring the knee joint movement. We compared results obtained with the new camera-based system with the system that uses knee joint angle encoder and inertial measurement units. The differences (errors) between the two systems are within the acceptable margin for clinical applications (5%). The first tests in the clinical environment suggest that the applicability of the system and the overall acceptance are appropriate (donning, doffing, setup time, precision, repeatability, ease of results interpretation).**

***Index Terms*—spasticity assessment, pendulum test, image processing, smart phone**

I. Introduction

CLINICIANS need to quantify the level of impairment to select the most appropriate treatment for patients after spinal cord injury or stroke. One of the impairment is an uncontrolled response to stretch, called spasticity [1]. A clinician assesses spasticity using the modified Ashworth scale by manually estimating the increased resistance of a particular muscle group [2]. To reduce the subjective component of the assessment, the pendulum test was introduced [3, 4]. The knee joint angle *vs.* time data, collected during the pendulum motion are used to calculate a set of parameters that reflect the intensity and type of spasticity. Recently, we modified the instrumentation for the pendulum test and introduced new parameters for a more appropriate classification of spasticity [5].

A standard method to measure joint angles are camera-based systems in motion laboratories with passive/active markers [6, 7]. The smart phones 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 [8, 9].

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].

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II. The Method

A. Instrumentation

Two systems were used in the measurements to document the validity of the method: 1) the system with passive markers and the smart phone, and 2) the system with the goniometer and inertial movement units [5].

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

A system with the goniometer and inertial movement units (Fig. 1). A scissors-like system made of thin graphite bars was fixed at the thigh and shank cuffs by using the Velcro [5]. The bars are connected by a low friction hinge joint [1]. A Hall-effect 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 all four kinematic sensors.

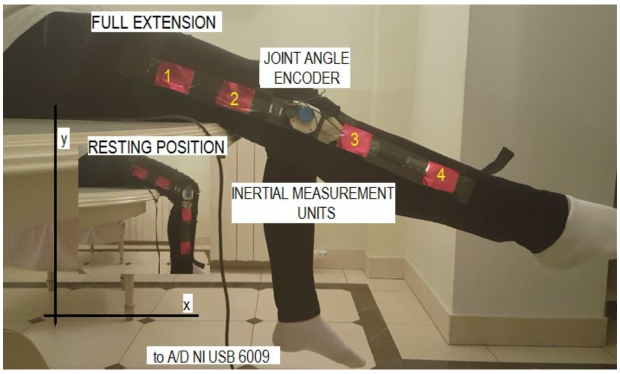

Fig. 1. The neutral position of the leg (insert) and the fully extended leg. Four red markers are used for the image based estimation of the movement. Hall-effect based absolute angle encoder and spatial inertial measurement units (accelerometers and gyroscopes) are components of the pendulum test apparatus described in Popović-Maneski et al. [5].

The sampling frequency was set at 1kHz since we simultaneously measured also the activity of muscles (electromyography) to document that there was no voluntary effort to control the movement of the shank (not shown in this presentation).

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B. 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. For analysis, only red component of the image was processed. The threshold for processing was obtained from an image histogram. Different morphology operations were tested. First operation fill 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 neighbors white were set to white if they were previously black. Finally, erosion and dilatation were applied. Dilatation was made with a segment of 15 x 22 pixels and erosion was applied using a 17 x 17 pixel segment. After morphological processing, centroids of the detected markers were calculated. Then, the centroids were sorted by y scale, for line detection. The first line is defined as a line that contains first two centroids with smaller values on y scale. The second two centroids, with higher values on a y scale, were detected as the second line. Further angle calculations were made using analytical geometry. The line coefficients were calculated using Eq. 1 and 2 respectively, and angle was calculated using Eq. 3.

$$k_1 = \frac{y_2 - y_1}{x_2 - x_1} \quad (1)$$

$$k_2 = \frac{y_4 - y_3}{x_4 - x_3} \quad (2)$$

$$\phi = arctg\left(\frac{k_2 - k_1}{1 + k_2 * k_1}\right) \quad (3)$$

The signals from the Hall-effect angle encoder were filtered with the moving average filter of 20 samples as described in [5]. The results measured by the Hall-effect angle encoder and the estimated from the series of images were compared. First, the data from the Hall-effect angle encoder was resampled from 1 kHz to 30 Hz to allow the comparison of two time series. The beginning of the data for processing was heuristically synchronized since the recordings come from two systems that cannot be automatically synchronized. The errors were calculated by subtracting the data from the two recordings.

Parameters for the estimation of the spasticity were calculated as defined in [3] and modified in our recent research [5] (Fig. 2): R_{2n} – the normalized relaxation index, N – the number of swings, α_{max} – the maximum of the goniogram (joint angle *vs.* time) after the release of the leg.

C. Measurements

The subject was sitting on a stable desk with the back support (hip angle ≈ 135^0). Two series of measurement were made: 1) the leg of the subject was ten times passively extended from the relaxed position (Fig. 1, left) to the full extension (Fig. 1, right); and 2) the shank was allowed to oscillate as the physical pendulum from the knee extended.

The examiner fully extended the knee joint and then released it (pendulum test) which resulted with oscillatory movement of the shank eventually stopping in the vertical position. The other examiner was holding a camera parallel to the subject and recording a video.

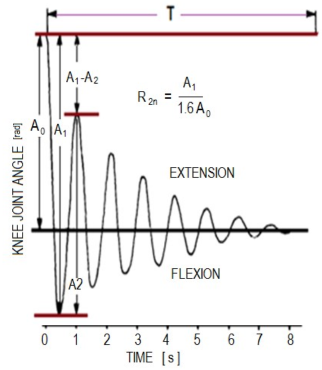

Fig. 2: The sketch of the goniogram of the knee joint and the parameters that are quantifying spasticity [3, 5]

III. Results

Figure 3, left panel shows a representative image from a series forming the movie that was used for image processing.

Fig. 3. A selected frame for image processing (left panel) and the grey scale of the same image (right panel)

Figure 4 shows the histogram of the selected image. The threshold needs to be greater than 25 (red oval).

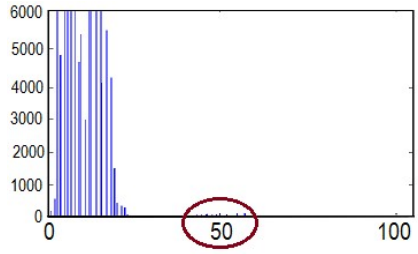

Fig. 4: A histogram of the representative image shown in Fig. 3 with a circled position of detected red markers.

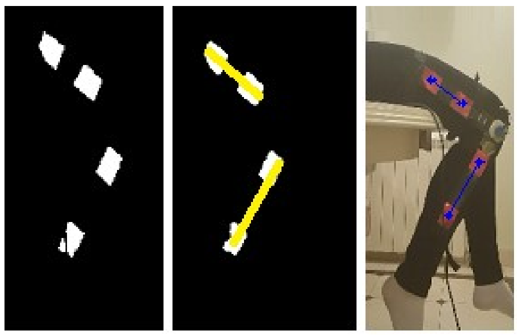

Fig. 5. The reconstructed image after the threshold=30 was applied and the same image after morphological operations (left panels). The image shown in Fig. 3 with the centroids detected and the lines defining the directions of the thigh and the shank

Fig. 6 shows camera detected angle (red line) and the signal from the Hall effect encoder (blue line).

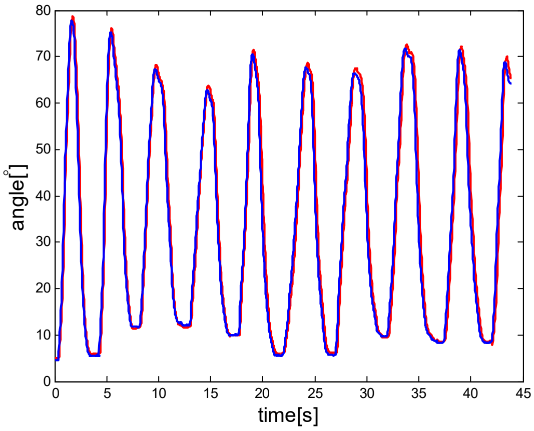

Fig. 6. Angle detected from camera and joint angle encoder for ten repetitions of a full knee extension. A red line shows the camera detected angle and the blue line are signals from the joint angle encoder.

Figure 7 shows the absolute error for ten repetitions of the first test when the knee was pulled to full extension.

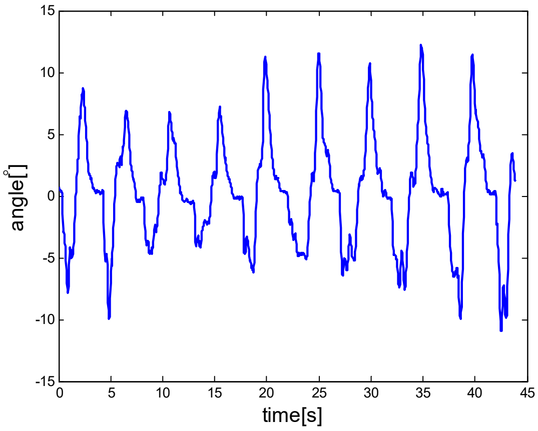

Fig. 7. Error during ten repetitions for the first of two measurements: passive movement to the full knee extension.

Figures 8 and 9, and Table 1 show results from the pendulum test.

Fig. 8 shows the image based (red line) and encoder based (blue line) knee joint angle superimposed, and they basically overlap completely. Fig. 9 shows the absolute error of the pendulum test that was only about 2.5^0 (relative error <3%).

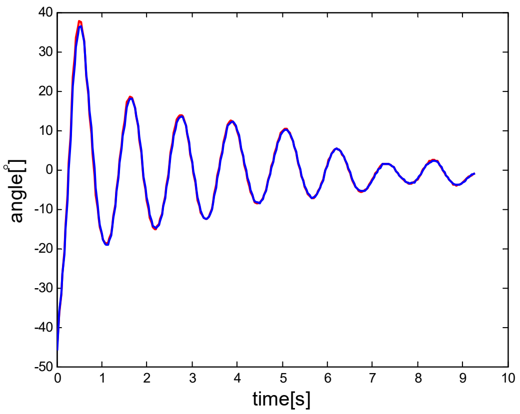

Fig. 8. An example of the knee joint goniogram estimated by image analysis of the movie recorded (red) and the signals from the joint angle encoder (blue) for the pendulum test.

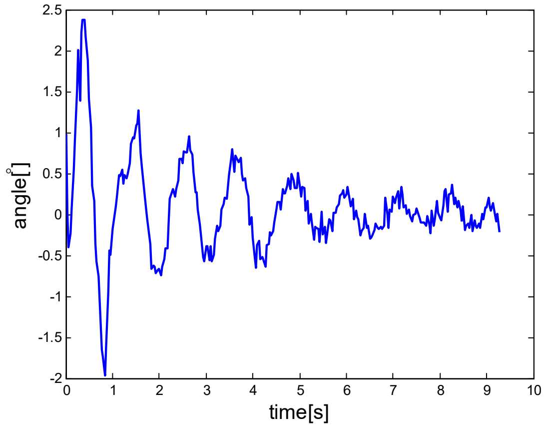

Fig. 9. An example of the error during the pendulum test: the difference between the goniograms from the image analysis and the joint encoder.

Table 1 presents the estimated parameters defined in [3, 5] for both of the signals: images from the movie and the joint angle encoder.

TABLE 1.PARAMETERS DEFINING SPASTICITY [3] OBTAINED FROM THE IMAGE ANALYSIS AND THE JOINT ANGLE ENCODER SIGNALS

	R_{2n}	N	α_{max}
Image analysis	0.93	6	0.33
Joint angle encoder	0.95	6	0.32

TABLE 2. MEAN AND STANDARD DEVIATION OF THE ERROR

	Mean [°]	St. dev. [°]
Pendulum test	1.15	0.55
Passively extending the knee	0.22	4.42

IV. DISCUSSION

The aim of this presentation is to demonstrate that it is possible 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 [8, 10]. Applying the appropriate threshold and the correct morphological operations are of highest importance. As shown in Fig. 10, it is impossible to correctly detect the marker without the appropriate usage of the morphological operations.

Fig. 10: False detected markers due to inadequate background marked with asterisks.

Fig. 5 shows a case with good detection of the markers. The background of the leg with markers is important, since elements in the background can be false detected. The method was designed for the clinical environment which in many cases is white; thereby, the background is light decreasing the contrast. The most important element is that the background does not comprise elements that are red, since we use red for the detection of markers on the leg.

Table 1 shows the parameters determined from signals coming from the processed camera data and joint angle encoder. The table suggests that the pendulum test can be performed by only a simple hand held smart phone and the set of four red markers positioned on the lateral side of the shank and thigh. The software we developed directly provide data to the clinician. The size of the absolute error and its standard deviation suggest that the camera based goniometry is sufficiently accurate; thereby, appropriate method for the knee angle estimation for planar movements being of interest in the assessment of spasticity.

V. Conclusion

In this study, we confirmed that a camera-based system is a practical method for the knee joint angle measurement during sagittal plane movements. The smart phone camera was chosen for the movie acquisition because it is inexpensive and generally available. Signal processing was developed for the Windows platform, and its complexity is not visible for the user. The future research needs to consider different markers (size, reflection level, contrast) to prevent the interference from background.

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