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Pendulum Test: Quantified Assessment of the Type and Level of Spasticity in Persons with Central Nervous System Lesions

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Abstract: The development of a comprehensive computational model of the pendulum test which is appropriate for the analysis of the pathologic behavior of the leg in humans with the central nervous system (CNS) lesion is presented in this review. The model relates to the pendulum movement of the lower leg (shank and the foot) in the lateral plane due to the gravity and involuntary contractions of the muscles. The viscous damping and elastic stiffness reflect the soft tissues and friction in the knee joint. To quantify the pathologic activity of paralyzed muscles a reflex torque was added to the gravity generated knee joint torque. The knee joint encoder, accelerometers and gyroscopes positioned along the shank and thigh, and EMG amplifiers were used to acquire data for the illustration of the validity of the model. We show that the linear model of the movement of the lower leg is not a good representation of the motor impairment. We show that the model expanded with the reflex torque affecting the movement is well suited for the pendulum analysis. The timing of the reflex torques can be determined from the EMG recordings.

Keywords: Pendulum test, Spasticity, Three-component muscle model, Nonlinear pendulum model.

1 Introduction

Motor impairment is a frequent consequence of a diminished communication between the peripheral systems and the upper motor neuron in a person with a central nervous system (CNS) lesion. Motor impairments can be divided into behaviors which include muscle activity through hyper-excitability of the stretch reflex, rigidity and spasticity; and those of insufficient muscle activity (weakness and paralysis) reducing the motor function.

Biomechanical and electrophysiological measures revealed significant changes in the passive properties in the motor systems of subjects with CNS lesions [1 – 5]. The “passive” resistance to the externally induced movement

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comprises: a) an increase in the stiffness of tendons, joints, or muscles [2], b) change of the intrinsic stiffness of the contracting muscle fibers [6], and c) the evolution of the rigidity mediated by the stretch reflex [3, 7]. The changes in the intrinsic muscle properties are considered as the cause for spastic hypertonia [6, 8, 9]. An accepted reason for spasticity is related to the stretch reflex [3, 7].

We listed motor impairments to illustrate the spectrum of the symptoms which follows a CNS lesion. A quantified assessment of the symptoms is essential for the selection of the best therapeutic modality. The quantification can come from the pendulum test [10 – 14] in addition to the Ashworth modified scale [15]. We present in this review paper an expanded biomechanical model of the lower leg for the detailed analysis of results from the pendulum test.

2 Modeling of the Movement of the Lower Leg in Patients with CNS Lesion

Wartenberg [10] studied the gravity induced movement of the tibial part of a leg in the sagittal plane for quantifying the spasticity and rigidity in Parkinsonian patients. He reported, "irregular zigzag movements" that are out of the sagittal plane. The test was quantified by analyzing the movie recorded during the "pendulum test".

Bajd and Bowman [11] used a mathematical model of the leg (1) for the analysis of the pendulum movement of the lower leg termed pendulum test (Fig. 1).

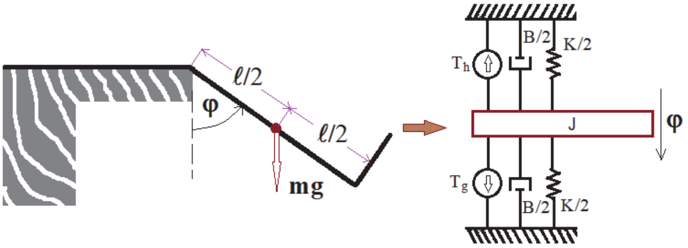

Fig. 1 – *The model of the tibial part of the leg for the analysis of the pendulum test (modified from [11]).*

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

Bajd and Bowman used the electro-goniometer to measure the knee joint angle during the pendulum movements of the tibial part of the leg. In parallel, they recorded EMG from the quadriceps muscle to determine the onset and time course of the reflexive or voluntary knee extensor activity.

Fig. 2 shows the recordings from the case series study with spinal cord injured patients [12].

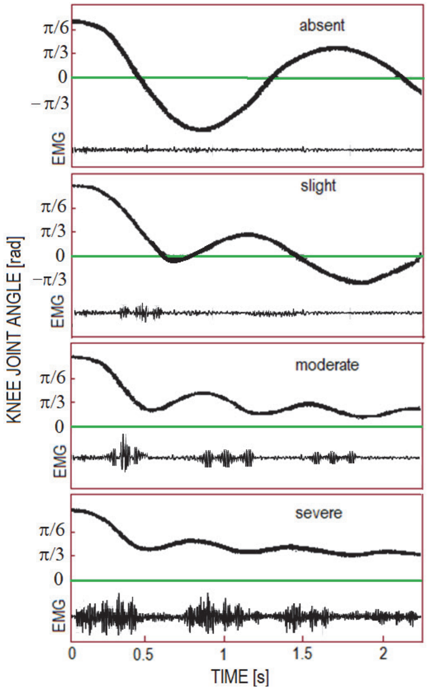

Fig. 2 – *The goniograms and EMG recordings from four subjects with a spinal cord lesion. The degrees of spasticity were: absent, slight, moderate and severe. An increase of the frequency of oscillations and decrease of the knee joint angles is shown from the top to the bottom of four panels. Modified from [12].*

The more detailed study by Bajd and Bowman [12] analyzed a simplified model of the tibial part of the leg as a single rod with the moment of inertia $J = m\ell/3 = 0.6\,\mathrm{Nms}^2/\mathrm{rad}$ (m = 5 kg, ℓ = 0.6 m). They linearized the model assuming that $\sin\varphi \approx \varphi$ ($\varphi \in \pm 1\,\mathrm{rad}$). In the absence of reflexive muscle activity, (1) becomes the homogenous second order differential (2):

$$\ddot{\varphi} + 2\beta\dot{\varphi} + \omega_0^2\varphi = 0\,, \tag{2}$$

where $\beta = B/2J$, ${\omega_0}^2 = (K + mgl/2)/J$. The analytic solution of the (2) is

$$\varphi = \mathrm{e}^{-\beta t}(C\sin\omega t + D\cos\omega t)\,, \tag{3}$$

where $\omega^2 = {\omega_0}^2 - \beta^2$.

The computational result for the healthy subjects outputs the values for the viscous damping B = 0.5 Nms/rad and elasticity K = 0.5 Nm/rad. These values were used for the determination of the reflexive torque T_h in patients. In the case of patients the assumed function of the knee joint angle was:

$$\varphi = C_1 + C_2\,e^{-at} + C_3\,e^{-bt}\sin\omega_1 t\,. \tag{4}$$

The fitting of the experimental curve for the case of severe spasticity resulted with the following values: C_1 = 0.28, C_2 = 0.66, C_3 = 0.19, ω_1 = 12.5 s^{-1}, a = 3 s^{-1} and b = 1.5 s^{-1}. In the study [12] the input muscle torque T_h was calculated from the output goniograms presented in Fig. 2 by using an algorithm solving the integral equation appertaining to the linear model [16].

In a later study, that included 10 SCI and five stroke patients, Bajd and Vodovnik [13] defined new measures of spasticity from the pendulum test. Patients were seated at a tilt table, and their lower leg was free to rotate about the knee joint. The lower leg was released from the fully extended knee (horizontal direction of the lower leg) allowing a free swing due to the gravity. Surface EMG was recorded to estimate the onset and offset of the knee extensors. Fig. 3 shows the goniogram and tachogram during the pendulum test of a healthy person. Eight parameters were selected for assessment of spasticity: 1) relaxation index ($R_{2n} = A_1/1.6A_0$), 2) number of swings, 3) area between goniogram and the resting angle, 4) the first maximum of the goniogram after the release of the leg ($A_0 - (A_1 - A_2)$), 5) relaxation index at the half swing (relaxation index in the case where the starting position for the pendulum movement was about one radian), 6) average relaxation index of ten successive swings, 7 and 8) first maximum and minimum of the tachogram [13].

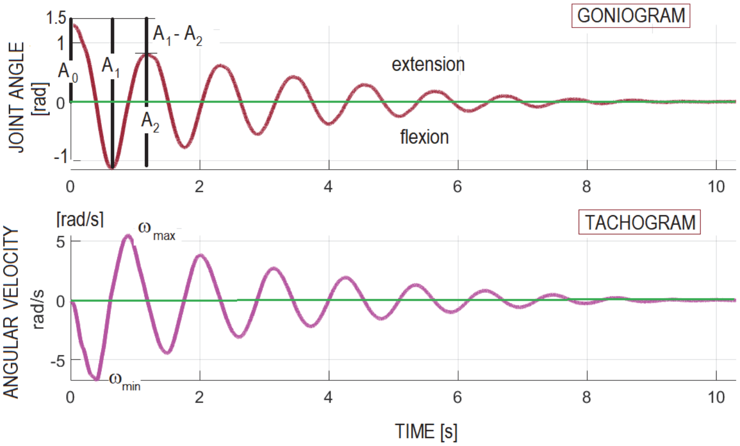

Fig. 3 – *The pendulum test (goniogram and tachogram) from a healthy subject. Angles A_0, A_1 and A_2 are used to calculate the parameters [13].*

3 The Nonlinear Model of the Pendulum Test

The model of a pendulum test used by Bajd and Bowman [14] was modified by Le Cavorzin et al. [17, 18]. Le Cavorzin et al. [19] added a reflexive component (1) in the model suggested by Bajd and Bowman. The block diagram of the model for the joint torque is shown in Fig. 4.

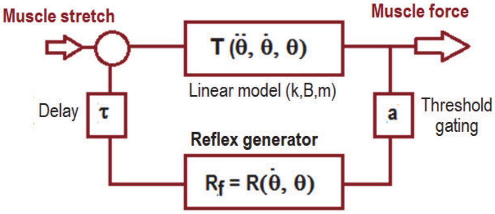

Fig. 4 – *The model of the spastic response of the muscles which follows the spinal cord injury. Modified from Le Cavorzin et al. [19].*

The reflex generator uses into account the biological behavior of the threshold and the delay that lumps together the agonist and antagonistic muscles (Fig. 4), pointing mostly on the contribution of the quadriceps activation.

$$R_f = J\ddot{\varphi} + C\dot{\varphi} + K\varphi + mgl_C \sin\varphi\,, \tag{5}$$

where R_f is:

$$R_f = B\mathrm{e}^{D|t-t_0|^n}\,, \tag{6}$$

where B is the magnitude of the reflex mediated torque, t_0 its onset. D and n describe the shape of the generated torque. The additional member R_f follows the experimental work (Fig. 5) and the heuristics. Fitting was done by using the neural parameter R_f as a function of the leg inertia (J).

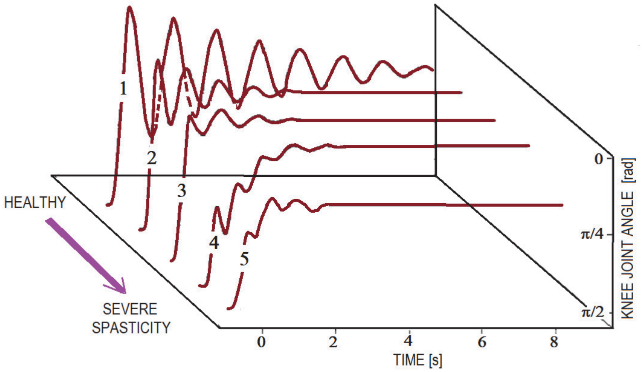

Fig. 5 – *Set of the recordings in patients with spinal cord injury. Modified from Le Cavorzin et al. [19].*

The conclusion was that there is a high correlation between the R_f and the Ashworth grade as shown in Fig. 6. Le Cavorzin et al. [19] presented results from ten healthy subjects and 15 SCI spastic patients.

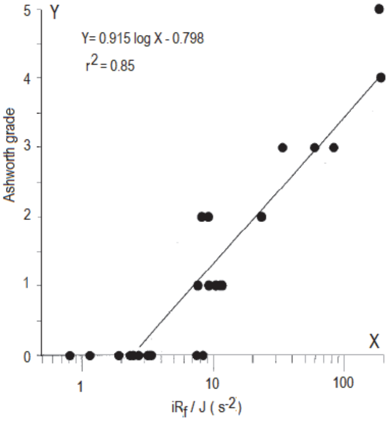

Fig. 6 – *Correlation between the integral of the reflex-mediated torque and the clinically- assessed muscle hypertonia (Ashworth). Modified from [19].*

In the recent retrospective study of evaluating the spasticity [20, 21], we used the pendulum test and found that the pathologic behaviors cannot be simulated well enough with the models presented above.

In this study we introduced the pendulum test (PT) score as the normalized sum of the following parameters R_{2n} – the normalized relaxation index, N – the number of swings, $\varphi_{\max}$ – the first maximum of the goniogram after releasing the leg, and $\omega_{\max}$ and $\omega_{\min}$ – the absolute maximum and minimum angular velocity of the shank as defined in [24], the frequency of oscillations (f) and the absolute difference between the positive and negative areas between the goniogram and neutral line, $\left|P^+ - P^-\right|$, starting from the first minimum. The PT is a global measure of the spasticity:

$$PT_i = \left|\frac{\overline{R}_{2n_i} - \hat{R}_{2n_H}}{7\cdot\hat{R}_{2n_H}}\right| + \left|\frac{\overline{N}_i - \hat{N}_H}{7\cdot\hat{N}_H}\right| + \left|\frac{\overline{\varphi}_i - \hat{\varphi}_H}{7\cdot\hat{\varphi}_H}\right| + \left|\frac{\overline{\omega}_{\max_i} - \hat{\omega}_{\max_H}}{7\hat{\omega}_{\max_H}}\right|$$

$$+\left|\frac{\overline{\omega}_{\min_i} - \hat{\omega}_{\min_H}}{7\cdot\hat{\omega}_{\min_H}}\right| + \left|\frac{\overline{f}_i - \hat{f}_H}{7\cdot\hat{f}_H}\right| + \left|\frac{\overline{\left|P^+ - P^-\right|}_i - \widehat{\left|P^+ - P^-\right|}_H}{7\cdot 100}\right|,$$

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). Each member in the equation is divided by the all seven parameters used to calculate *PT* to normalize *PT* score. The study suggested that there is a high correlation between the Ashworth scale score and the *PT* score [21].

Additional elements can be extracted from the data recorded during the pendulum test. Fig. 7 illustrates the differences in the data recorded during the pendulum test in three chronic SCI patients: Nº1 (Ashworth score = 1), Nº2 (extension type spasticity, Ashworth score = 4), and Nº3 (flexion type spasticity, Ashworth score = 4).

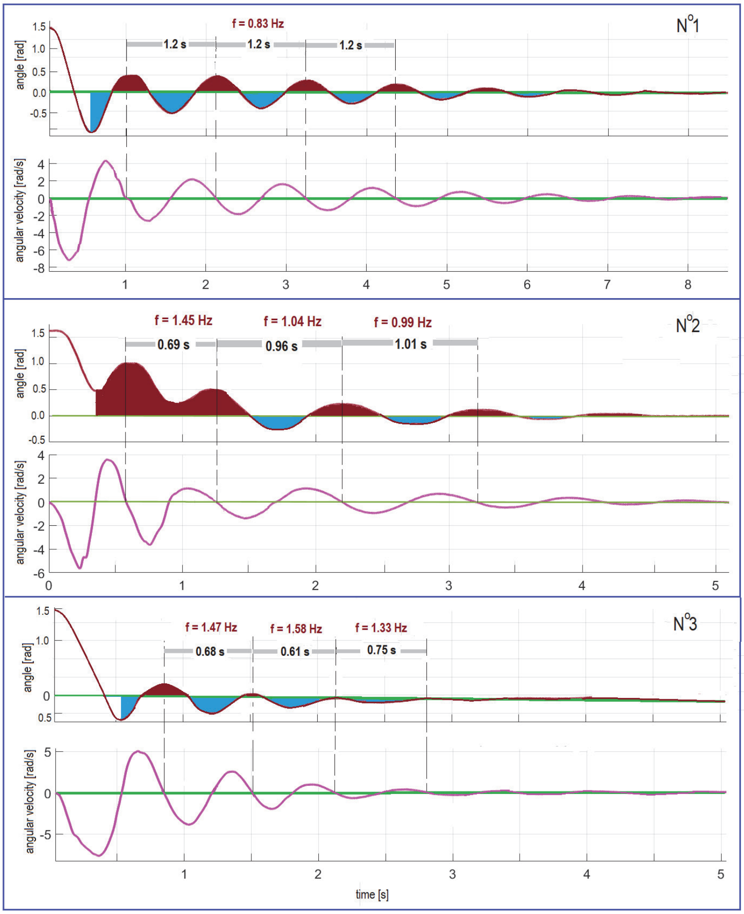

Fig. 7 – *Goniogram and tachogram for three chronic SCI patients: Nº1 with mild spasticity (top panel), Nº2 with strong extension spasticity (middle panel), and Nº3 with strong flexion spasticity (bottom panel). The joint angle for the patient with mild spasticity is balanced around the neutral line (dark red and blues areas), and the periods of oscillations are constant. The duration of subsequent swings (period of oscillations) for patients with severe spasticity is time-varying. The areas between the goniogram and the neutral joint angle are not balanced (middle and bottom panels).*

The simulation (5) of the behavior for the cases shown in Fig. 7 is in Fig. 8. The graphs indicate that the model is applicable for the case when the spasticity is mild (Fig. 8a), while the fit of the model in the cases with severe spasticity suggests that the model is not appropriate (Fig. 8b and 8c).

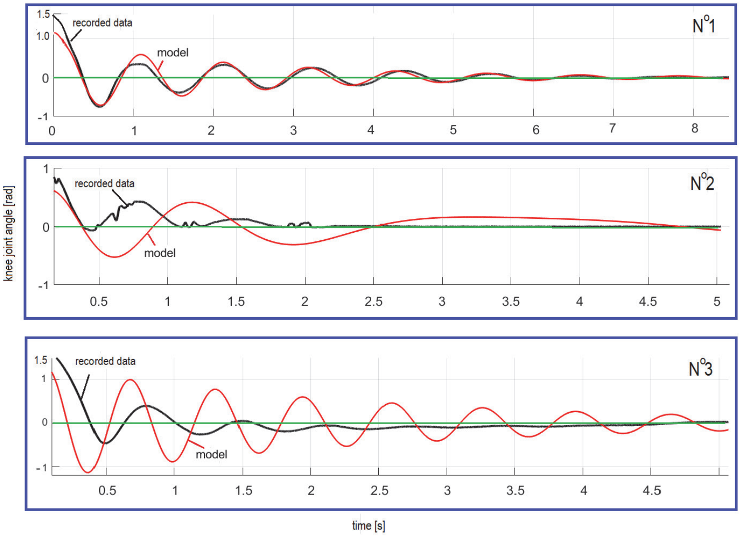

Fig. 8 – *The estimated knee joint angles by using the linear model (red lines) superimposed over the recorded data for the patient with mild spasticity (Ashworth = 1) in the top panel, patient with extension spasticity (Ashworth = 4) in the middle panel, and patient with flexion spasticity (Ashworth = 4) in the bottom panel.*

4 Nonlinear Model with the Three-Component Model of Muscles

We suggest that the more complex model of the pendulum movements could encompass the movement of the lower leg behavior in the cases with severe spasticity. The additional term to the original model that we propose is the multiplicative model of reflex activated muscles. The model which separately includes agonist and antagonistic muscles (T_E – extensors and T_F – flexors) is shown in Fig. 9 and (7):

$$J\ddot{\varphi} = T_E(\varphi,\dot{\varphi}) - T_F(\varphi,\dot{\varphi}) - B(\dot{\varphi}) - K(\varphi) - mgd\sin\varphi \, . \qquad (7)$$

The terms $T_E(\varphi,\dot{\varphi})$ and $T_F(\varphi,\dot{\varphi})$ follow the earlier studies related to the control of walking in subjects with a complete SCI lesion [22, 23]. The three component multiplicative model as described by (8) [22].

$$T_i(\varphi,\dot{\varphi}) = \sum_{k=1}^{M}[h(t-\tau_{0k}) - h(t-\tau_k)]T(\varphi)T(\dot{\varphi})u_{ik} , \quad i = E,F \, ,$$

$$T_i(\varphi) = b_{1i}(\varphi-\varphi_0)^2 + b_{2i}(\varphi-\varphi_0) + b_{3i} \, ,$$

$$T_i(\dot{\varphi}) = \begin{cases} T_i, & \dot{\varphi} < 0, \\ T_i(1 - k_i\dot{\varphi}), & 0 \le \dot{\varphi},\ i = E, F, \\ 0, & k \le \dot{\varphi}, \end{cases} \tag{8}$$

where φ_0 is the joint angle in a resting position and φ when the muscle is stretched. The Heaviside step function is defined by: $h(t) = 1,\ t > 0,\ h(t) = 0,\ t \le 0$. The instants τ_{0k} are determined from the EMG recordings (start of the reflexive responses due to the stretch) and the τ_k the moments when the EMG disappears. M is the number of periods of EMG activities. The parameters b_i and k_i can be determined using methods described in [24]. The term u_{ik} is the output of the second order low passed impulse with $u_{\max} = 1$ and duration: $\tau_k - \tau_{0k}$.

The more appropriate model of the lower leg (the shank and the foot) is a rigid body formed by two cylinders (Fig. 9).

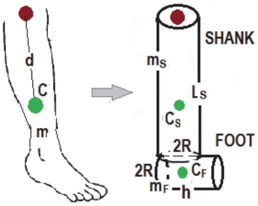

Fig. 10 – *Model of the lower leg of the pendulum test.*

The lengths L_s and h can be measured and the radius R calculated from the perimeter of the shank above the ankle joint. The masses m_S and m_F are determined based on the volume of the shank and foot and the density of the tissue from the literature (≈ 1100 kg/m^3). The distance of the center of mass of the shank and foot complex from the knee (d) and the moment of inertia (J) can be estimated from (9):

$$d = \frac{m_S L_S + 2m_F\left(L_S + R\right)}{2(m_S + m_F)},$$
$$J = \frac{4m_S L_S^2 + 3(m_S + m_F)\mathrm{R}^2 + m_F \mathrm{h}^2 + 12m_F\left[(h - R)^2 + (L_S + R)^2\right]}{12}. \tag{9}$$

An example of the simulation obtained by heuristic determination of the timing of the EMG activities is shown in Fig. 11 for the subject N$^{\mathrm{o}}$3.

Fig. 11 includes the timing when the reflexive activity contributed to the joint torque for both flexor and extensor muscles. The use of the nonlinear model requires the use of patient characteristic parameters; therefore, it does not have a direct application for daily clinical use. However, the use of the appropriate model is the prerequisite for the assessment of the motor status.

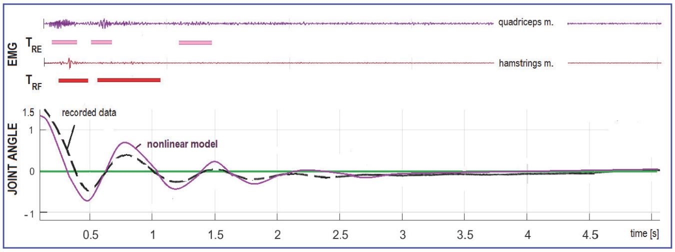

Fig. 11 – *The original joint angles, simulation of the linear model and heuristic simulation of the nonlinear model for the subject as defined in (8).*

By analyzing how to maximize the use of the goniograms and tachograms an alternative for quantifying the spasticity was noticed [20]. The exponential curves (Fig. 12) were obtained by fitting the absolute values of the recorded joint angles with the sign determined from the comparison of the positive and negative areas between the goniogram and the neutral angle.

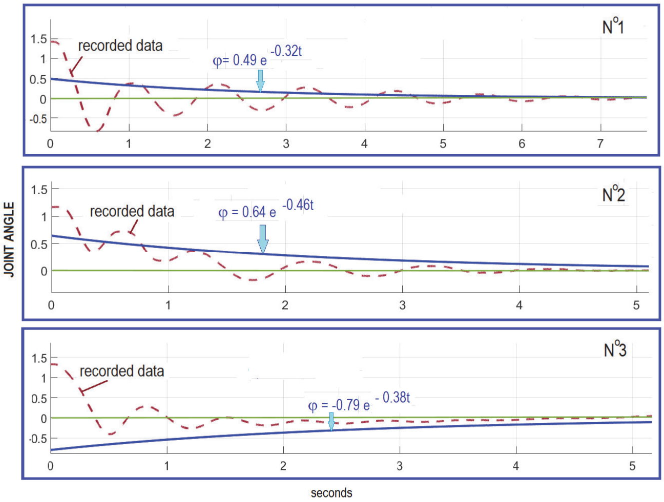

Fig. 12 – *Fitted exponential curves through absolute values joint angles multiplied with the sign function of the sum of the positive and negative areas between the goniogram and the neutral knee joint angle. The exponential fits* $\varphi = C e^{-\sigma t}$ *are characterized by the values* C *and* σ. *Negative values* C *show that the flexion spasticity is expressed and vice versa positive value* C *means that the extension spasticity is expressed.*

The exponential fit is also characterized by the time constant σ. This parameter shows how fast the reflexive behavior deteriorates. The more prominent is the parameter σ, the stronger is the spasticity.

5 Message to Take Home

Best rehabilitation medicine practice requires the quantified and validated measures of the impairment. The pendulum test is a practical noninvasive method [20, 21] which with the user-friendly software allows clinicians to get better insight into the pathologic behavior caused by the CNS lesion. Further research and use of models that are based on the more profound understanding of complex neural mechanisms will allow better assessment. The better evaluation of the motor status is the prerequisite for the decision which treatment is optimal.

6 Acknowledgment

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