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Introduction of a procedure to objectively quantify spastic movement impairment during freely performed voluntary movements

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ABSTRACT

Spastic impaired limb function is a frequent result of brain lesions. Although its assessment is important for clinical and therapeutical management, it still lacks an objective measure to quantify the functionality of the affected limb. The present paper reports a procedure based on the muscular activation recorded by Surface Electromyography (sEMG), which enables the assessment of the degree of spastic impairment.

15 healthy subjects and 7 patients with impaired upper limb function due to spasticity were included in the study. SEMG was recorded from the biceps and brachioradialis during active elbow extension at different movement velocities. The spastic impairment was clinically assessed by the Tardieu-Test and the Wolf Motor Function Test.

Results of the clinical assessment and parameter values quantifying the muscular activation at different joint positions and movement velocities have been set in relation to one another.

The results show that spastic impairment leads to a changed correlation between the muscular activation and movement velocity as well as to a changed inter-muscular co-ordination of biceps and brachioradialis. These changes, reflected in the sEMG, can be quantified by 5 newly introduced parameters. This way could allow the assessment of spastic impairment in the context of functional everyday tasks, for the first-time.

1. Introduction

Motion is a basis for life. Everyday movements like unlocking a door or zipping up a jacket are freely performed voluntary movements carried out with different ranges of motion and at different movement velocities. In healthy persons these movements are possible due to a fine-tuned coordination between agonistic and antagonistic muscles, which ensure movement regulation.

In the past couple decades, a great variety of research has been carried out on the physiological muscular control and coordination in freely performed movements. In this context, a recent study of von Werder and Disselhorst-Klug (2016) analysed the activation strategy of the two elbow flexors biceps and brachioradialis in healthy persons. Their findings in extension movements of the upper limb indicate a fine-tuning function of the brachioradialis which controls movement velocity and joint position while the biceps has a weight bearing function for holding external weight. Further research mentioned the importance of fibre length, contraction velocity, and the contraction type with respect to the contraction force of a single muscle fibre for freely performed movements (Komi et al., 2000; Herzog, 2014).

However, not all humans are able to freely perform voluntary movements. Neuronal lesions e.g. due to insufficient supply of blood and oxygen can cause movement impairment (Bhimani and Anderson, 2014). A frequently observed movement impairment is spasticity leading to an inability to freely perform voluntary movements (Carr et al., 1995; O'Dwyer et al., 1996). But spasticity is still a problematical term. There is not only a missing consistent definition of spasticity, but also a missing objective assessment (Malhora et al., 2009). Furthermore, there is only little knowledge about the effect of spasticity on muscular control and coordination in freely performed voluntary movements. The most cited definition of spasticity is the description from Lance, specifying spasticity as 'a velocity dependent increase in tonic stretch reflex' (Lance et al., 1980). Yet, it misses the spasticity effects on voluntary movements and the positive features of the Upper Motor Neurone Syndrome (UMNS) occurring in skeletal muscle after a brain lesion. In 2005, Pandyan et al. (2005) defined spasticity as a

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Table 1
Patients' basic data and clinical tests' results.

Patient	A	B	C	D	E	F	G
Basic data							
Aetiology	Cerebral palsy	Internal carotid artery dissection with media ischemia	Ischemia after clipping of the middle cerebral artery	Middle cerebral artery infarction	Cerebral sinus venous thrombosis with associated congestive bleeding	Internal carotid artery thrombus with middle cerebral artery infarction	Internal carotid artery occlusion with ischemia of the middle cerebral artery
Time from stroke onset (in month)	436	21	12	12	4	22	105
Tadieu Test							
Score		2	0	2	2	2	2
WMFT							
Score	53	26	71	26	46	20	14

result from upper motor neuron lesion causing a disordered control presented as an involuntary activation of muscles.

This review reveals that spasticity is still defined inconsistently. Another problem is the subjectivity of spastic measures, which often do not correspond to the description of clinical key features (Malhora, 2009). Even common spasticity tests used in clinical practice like the Tardieu-Test, assessing the muscle's response to stretch at various given velocities (Morris and Williams, 2018; Haugh et al., 2006), or the Modified Ashworth Scale (MAS), ranking spasticity within six degrees, have a limited meaning (Fleuren et al., 2010). On the one hand, they are passive tests which do not reflect everyday dynamic movements, and, on the other hand, they are not reliable due to the subjectivity of the evaluating physician. Only a poor correlation between the clinical measures, like the Tardieu- Test or the MAS, and increased muscular activity, measured by means of sEMG, during passive stretch has been found (Lebiedowska and Fisk, 1999; Pandyan et al., 2006). A commonly used functional performance test is the Wolf Motor Function Test (WMFT) quantifying the upper extremity motor ability by means of daily motions. This test is not, however, a specific test quantifying spastic impairment (Hartwig, 2011).

More objective ways to quantify individual spastic impairment methods like the sEMG assessment of the Hoffmann reflex or the stretch reflex were used, but have proven to only be moderately sensitive (Voerman et al., 2005), until McGibbon et al. (2013) combined a kinematic model with Surface Electromyography (sEMG) capturing data of the muscular activation during passive stretch reflex testing. This system was finally able to investigate the relationship between biometric results and different clinical measures providing an objective tool to analyse spastic movement impairment.

The systematic review by Bar-On et al. (2014) revealed a wide range of various electrophysiological and biomechanical instrumented parameters for the assessment of spasticity and consequently a missing consensus of the optimal parameter quantifying spasticity. They also pointed out that biomechanically and/or electrophysiological instrumented assessment supports a better differentiation of spastic impairment and advances the clinical practice and treatment planning.

Based on these findings Lei et al. (2017) recently proposed a new surface EMG-based index for the assessment of spasticity. They captured sEMG data from agonistic and antagonistic muscles during passive stretch and used the ratio between the Root Mean Square (RMS) of the agonistic and muscle and the mean of the RMSs of the agonistic and the antagonistic muscles as an index for spasticity. Although this work presents an sEMG-based method reducing inter-rater reliability to assess spasticity, it is limited to assisted, passive movements and gives no information about freely performed voluntary movements.

In clinics, emerging trends demand to classify spastic impairment in the context of functional movements of everyday life (Rekand, 2010). A method to measure the impact of spastic impairment on freely performed movements is requested as this is the only way to get insight into spasticity related impairments resulting in loss of ability to perform everyday tasks. Here, sEMG could be an option since it allows the non-invasive detection of the muscular activation even during freely performed movements.

Although sEMG allows the pain-free assessment of muscular activation it is still based in laboratory tests. As sEMG tools and application procedures need to be developed enabling the sEMG to meet the needs of physicians our pilot study with clinical and laboratory tests should serve as a preliminary in the development of an objective sEMG spasticity assessment during activities of daily living.

Due to these demands on spasticity assessment, the purpose of this work is to introduce a procedure based on sEMG which enables the objective assessment of spastic impairment during freely performed voluntary movements which consequently reflects patient's everyday life performance. In this pilot study, *a* procedure has been utilized exemplarily for elbow extension movements based on the activation of biceps and brachioradialis. We hypothesized that spastic-movement

Table 2
Inclusion criteria.

1.	Spastic movement impairment due to congenital spasticity, such as cerebral palsy, or unilateral stroke (infarct or haemorrhage, diagnosed by an experienced neurologist by clinical presentation, clinical diagnosis and imaging) with post- stroke spastic movement impairment
2.	No further progression or spontaneous recovery of neurological deficits for at least three months before enrolment
3	Ability to move the arm with little or without assistive device
4	Stable general health status and free from pain
5	No-pre-existing functional limitations of the affected upper extremity
6	No contracture of the elbow joint
7	No visuospatial, cognitive or attentive deficits and a sensory form of aphasia

impairment leads to a modified inter-muscular coordination of the elbow flexors. We anticipated that these changes can be seen in the sEMG signal and we expected that the degree of change correlates with the results of common clinical tests. We aimed to find parameters derived from the sEMG signals, which allow the prediction of the patient's results in these clinical tests or even predict and assess spastic movement impairment objectively.

2. Material & methods

2.1. Participants

15 healthy subjects and 7 patients with spasticity in an upper limb took part in the study after giving written informed consent. One patient had spastic movement impairment due to cerebral palsy and six others due to stroke (Table 1). The selection of patients was dependent on special inclusion criteria (Table 2). Additionally, details such as age, time from stoke onset, or stroke type were noted.

2.2. Clinical tests

For clinical information about the individual severity of spastic movement impairment, the Tardieu-Test, as a commonly used spasticity assessment in clinics, was performed prior to the experiments. The muscle's response was tested and scored according to the procedure described in literature (Marks, 2009). Each patient's biceps muscle of the affected arm was tested.

For quantifying the motor ability of the affected arm, the functional tasks of a modified WMFT were carried out (Wolf et al., 2001). The WMFT as a test containing daily tasks resembles the patients 'everyday impairment'. The test included six items of time functional tasks and the nine items for analyzing movement quality while completing various tasks. Focussing on the functional ability of the impaired arm, the strength tasks and the time keeping were left out. Every task was rated with regard to the limbs functionality on a 6-point scale and the results were added to a score according to literature (Hartwig, 2011).

So, with choosing these two tests, evaluating the severity of spasticity (Tardieu-Test) and the resulting functionality of the arm (WMFT), two tests were selected physicians are familiar with. Therefore, they can relate our results to their everyday routine on a ward. Relating these two tests commonly used in clinics to the laboratory test results with sEMG, makes it possible to present a preliminary in the development of an sEMG based test to evaluate spasticity in functional movements during work on a ward.

2.3. Instrumentation

Muscular activation of biceps brachii and brachioradialis were recorded during freely performed elbow flexion and extension movements.

Constant torque of 1Nm along the full range of motion and supporting the extension of the elbow, was given by a deflection pulley

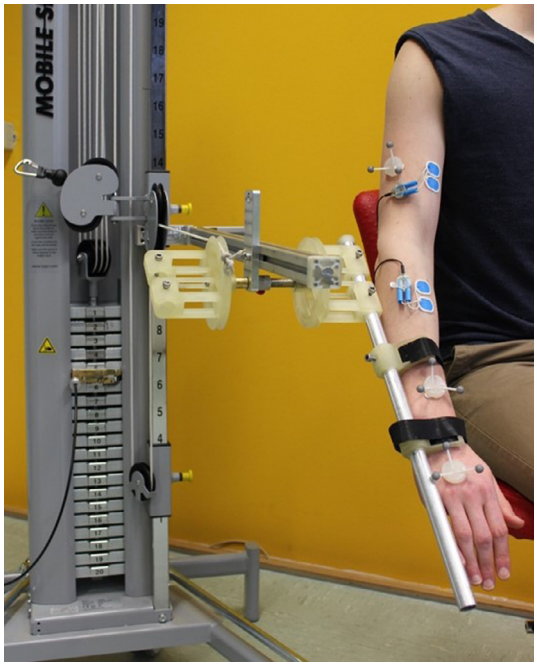

Fig. 1. Measuring set-up with pulley machine.

1 kg to which the affected arm was connected (Fig. 1).

An optical feedback should animate the patient to perform elbow flexion and extension movements in different velocities. To personalize the feedback and adapt it to the patient's range of motion, an individual reference curve of a single flexion and extension movement was recorded at a constant angular velocity of 20°/s. The reference curve showed the elbow angle as a function of time. The reference curve has been duplicated multiple times and for each duplication the duration has been scaled differently. In this way the duplication represents different movement speeds between 20°/s and 140°/s. Afterwards the doublets were assembled in a random order into a feedback path (Fig. 2). To avoid sequence effects, the order of movement velocities was randomized. The generated feedback path and the current elbow angle were both visualized simultaneously on a screen (Fig. 2). As subjects were advised to follow the feedback path, they flexed and extended their elbows in different angular velocities.

2.4. Measuring procedure

Bipolar sEMG was recorded. Therefore, Ag-AgCl gel surface electrode pairs with a 2 cm inter-electrode distance (Ambu® Blue Sensor N) were placed on the tested muscles biceps and brachioradialis. The biceps' electrodes were located according to SENIAM (Surface

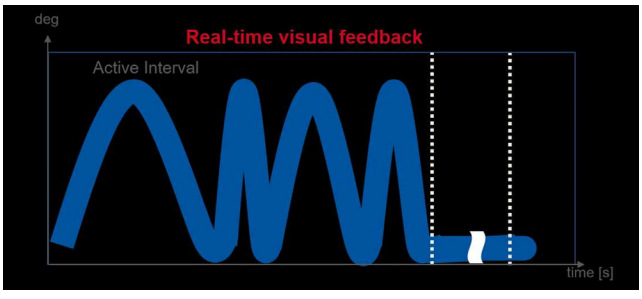

Fig. 2. Optical feedback: Generated path with randomized movement velocities (green) and currently performed movements by the patient/healthy test person (blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

ElectroMyoGraphy for the Non-Invasive Assessment of Muscles) recommendations (Hermens et al., 2000). Due to missing recommendations for electrode placing in the brachioradialis, electrodes were placed on the muscle belly one third from the fossa cubiti.

SEMG recording was performed with a sampling rate of 2000 Hz. The measurement chain of the recording comprised differential amplification with an overall gain of 1000, an analog bandpass filter between 1 and 500 Hz, and a 16 Bit A/D converter.

To record the kinematics of the elbow movements a VICON MX motion capture system (ten cameras) with a sampling rate of 200 Hz was used. Optical marker tracking was done via four segmental triplet-markers and five joint markers which were placed accordingly to the biomechanical model of Williams and Schmidt (Williams et al., 2006) to determine the actual elbow joint angle. The infrared light reflecting markers were placed on six anatomical landmarks of the upper extremity, precisely on acromion, olecranon, radial styloid process, ulnar styloid process, epicondyle lateral and epicondyle medial. The midpoint between both epicondyles and styloid processes were estimated as the joint centres of elbow and wrist, respectively. Three rigid triplet-markers were places on the upper body segments (thorax, upper arm, forearm, hand). Through the exact position of recorded segment marker triplets relative to computed elbow joint centres were synchronously measured to the sEMG recording of biceps and brachioradialis.

During measurement, the subjects were seated in a height-adjustable chair in front of the pulley machine (Fig. 1). The extension axis of the impaired arm's elbow was placed in the centre of the deflection pulley while the upper arm was straight, and the shoulder relaxed. The forearm was fixed to the pulley in the most suitable position, depending on the spastic orientation of the affected hand. One measuring trial compromised 45 s of flexion and extension tasks with different movement velocities. Subjects were asked to perform as many repetitions of the flexion and extension tasks as possible during one trail. Maximum was set to eight trials have been recorded with a break of 60 s between the different trails.

2.5. Signal processing

The sEMG envelopes were built through digital band pass-filtering (Butterworth, 9th order, 10–500 HZ), full wave rectifying and smoothing (moving average filter window length 80 ms). The envelopes were normalized to the 75% percentile of the maximum amplitude of the envelope to prevent negative effects of outliers (Praagman et al., 2010).

Additionally, the elbow joint angles and the angular velocities of the joint were assessed. A spline filter of third order filtered the marker trajectories (Schmidt et al., 1999). Elbow joint angles were calculated from the marker trajectories based on the above-mentioned biomechanical model of Williams and Schmidt (Williams et al., 2006). The calculated elbow angles as a function of time were low pass filtered with a cut-off frequency of 2.2 Hz. Afterwards, for each separate movement cycle between 25° and 125° elbow joint angle the slope of the processed angle course was calculated separately for flexion and extension movements. This measure represents the average angular velocity for either the flexion phrase (positive velocity values) or extension phase (negative velocity values) of a single motion cycle.

2.6. Data categorization

For data categorization a combination of an angle interval and angular velocity interval was defined as a category. To match each sample of the normalized sEMG envelope to a category a decision tree algorithm was used (Fig. 3). First, phases of eccentric muscular contraction have been separated from phases of concentric muscular activation by means of the average angular velocity. In the case of the biceps muscle and the brachioradialis muscle there is an eccentric contraction during extension movements of the elbow, which is characterized by a negative averaged angular velocity. Concentric contraction corresponds to the flexion movements of the elbow going along with a positive averaged angular velocity. Hereafter, sEMG envelope data points representing concentric activation of the muscle received no further consideration, whereas sEMG envelope data points representing eccentric contractions were further categorized (Fig. 3).

In a next step, sEMG envelope samples have been categorized with respect to joint angle. Phases of movement in which the elbow angle was less than 25° and higher than 125° were excluded from further consideration. This was done to exclude the turning points of the movement and to achieve constant angular velocities and constant moment of inertia. The remaining range between 25° and 125° was divided into equal intervals of 20° each. Depending on the corresponding elbow angle each sEMG envelope assigned to one of these 5 angular intervals. After categorization with respect to joint angle categorization with respect to movement velocity takes place (Fig. 3). For this purpose, four velocity intervals between 20°/s and 140°/s were formed. sEMG envelope data points of each joint angle interval were split again and assigned to one of these velocity intervals depending on the corresponding averaged velocity. IN this way, it was ensured that each category contains only sEMG envelope data points resulting from movements with comparable constraints in terms of contraction type, joint position and movement velocity (Von Werder et al., 2015). To finalize the categorization process, all sEMG envelope data points belonging to one category were averaged. In the following, this value is called 'categorized sEMG value ($CsEMG_{value}$)' representing the muscular activation under different movement constrains.

After categorization for each subject a matrix ($[CsEMG_{value}]^{i,j}$) of categorized sEMG values, exists with i = 5 = number of angle intervals and j = 4 = number of velocity (Figs. 3 and 4). The categorized sEMG values of healthy subjects were averaged for each category separately. Thus, a reference matrix of categorized sEMG values representing physiological muscular activation was built and patient data was compared to this reference matrix individually.

2.7. Data analysis

To quantify the correlation between muscular activation and movement performance, five different newly developed parameters are introduced and calculated from the categorized sEMG values.

2.7.1. Maximum velocity (v_{max})

The parameter '*maximum velocity*' (v_{max}) is defined by the maximum velocity interval (j), reached during the movement task (Eq. (1.1)).

$$(\boldsymbol{v_{max}}) = MAX\,(v_j) \tag{1.1}$$

2.7.2. Mean categorized sEMG value ($Mean\_CsEMG_{value}$)

To compare the correlation between the amount of muscular activation and the results of the clinical tests, the parameter $Mean\_CsEMG_{value}$ was computed. Therefore, the mean of all categorized sEMG values was calculated (Eq. (2.1)). Only those joint angles intervals and velocity intervals reached by the subject during the movement task were regarded

$$\boldsymbol{Mean\_CsEMG_{value}} = \frac{\sum_{i=min}^{i=max}\sum_{j=min}^{j=max}\boldsymbol{CsEMG_{value\_i,j}}}{(\boldsymbol{i_{max}}-\boldsymbol{i_{min}})+(\boldsymbol{j_{max}}-\boldsymbol{j_{min}})} \tag{2.1}$$

i = Number of joint angel intervals
j = Number of velocity intervals

2.7.3. Correlation between muscular activation and movement velocity (MA_v)

Velocity dependency is the basis of the usual spasticity definition. Thus, for comparing and describing the changes in muscular activation

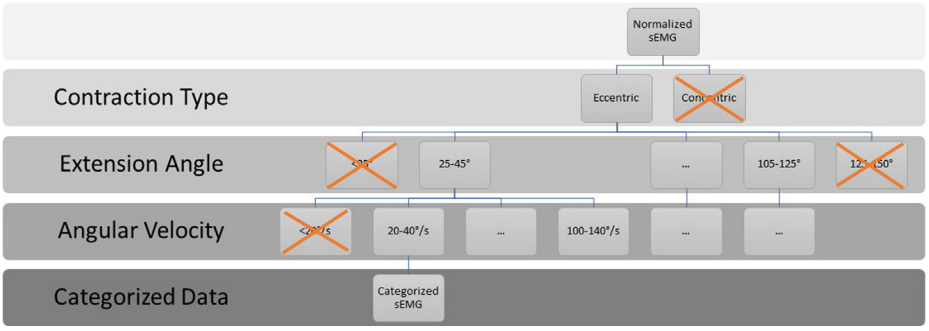

Fig. 3. Decision algorithm assigning every sampling point of the processed sEMG to a combination of five angle intervals and four different angular velocity intervals.

with respect to changing movement velocity, the parameter '*Correlation between Muscular Activation and Movement Velocity*' (*MA_v*) was introduced. For this purpose, the maximal gradient of the categorized sEMG value with increasing movement velocity was calculated separately for each joint angle interval (i) (Eq. (3.1)), in which the subject reached at least two velocity intervals. (Eq. (3.1)). This means that a subject had to be able to conduct a certain degree of extension in at least two different velocities. Subsequently, the mean value over all reached joint angle intervals was calculated to determine the value *MA_v* (Eq. (3.2)).

$$MA\_v_i = \frac{MAX\,(CsEMG_{value}) - MIN\,(CsEMG_{value})}{v_{max} - v_{min}} \tag{3.1}$$

$$MA\_v = \frac{1}{n}\sum_{i=min}^{i=max} MA\_v_i \tag{3.2}$$

2.7.4. Divergence of muscular activation of biceps and brachioradialis with respect to joint angle and movement velocity (DIVERMA$_{flexor}$_av)

The study of von Werder and Disselhorst-Klug (von Werder and Disselhorst-Klug, 2016) *revealed in physiological conditions an oppositional activation strategy of both elbow flexors to perform elbow extension. The muscular activation strategy in patients with spastic movement impairment was expected to diverge from this physiological activation strategy. Therefore, the divergence of the muscular* activation strategy respecting movement velocity and joint angle in non-physiological conditions was examined in this study. Therefore, the parameter *DiverMA$_{flexor}$_av* was introduced.

With this in mind, the difference $\Delta BiBra_{ij}$ between the categorized sEMG value of both muscles, biceps and brachioradialis, was built for each category separately (Eq. (4.1)), with 'i' identifying the joint angle interval and 'j' identifying the velocity interval. Secondly, the minimum value ($MIN(\Delta BiBra_{ij})$) and the maximum value ($MAX(\Delta BiBra_{ij})$) of all differences $\Delta BiBra_{ij}$ was determined.

Since categorized sEMG values of the biceps increase while those of the brachioradialis decrease with an increasing velocity (von Werder and Disselhorst-Klug, 2016), values of $\Delta BiBra_{ij}$ can be both negative and positive. Therefore, absolute values of the maximum $\Delta BiBra_{ij}$ and the minimum $\Delta BiBra_{ij}$ were built before subtracting both measures from each other (Eq. (4.2)) to eliminate effects of sign. Finally, to calculate *DiverMA$_{flexor}$_av* the difference of the absolute values was normalized to the number of joint angle categories plus the number of velocity categories between the category with the maximum and the minimum $\Delta BiBra_{ij}$.

Due to subtracting absolute values, maximal divergence exists when the value of *DiverMA$_{flexor}$_av* approaches zero.

$$\Delta BiBra_{ij} = CsEMG_{value\_ij}\_Biceps - CsEMG_{value\_ij}\_Brachioradialis \tag{4.1}$$

$$Diver\mathbf{MA}_{flexors}\mathbf{\_av} = \frac{|MAX\,(\Delta_{BiBraij})| - |MIN\,(\Delta BiBra_{ij})|}{i_{MAX\,(\Delta BiBra_{ij})} - i_{MIN\,(\Delta_{BiBraij})} + j_{MAX\,(\Delta BiBra_{ij})} - j_{MIN\,(\Delta BiBra_{ij})}} \tag{4.2}$$

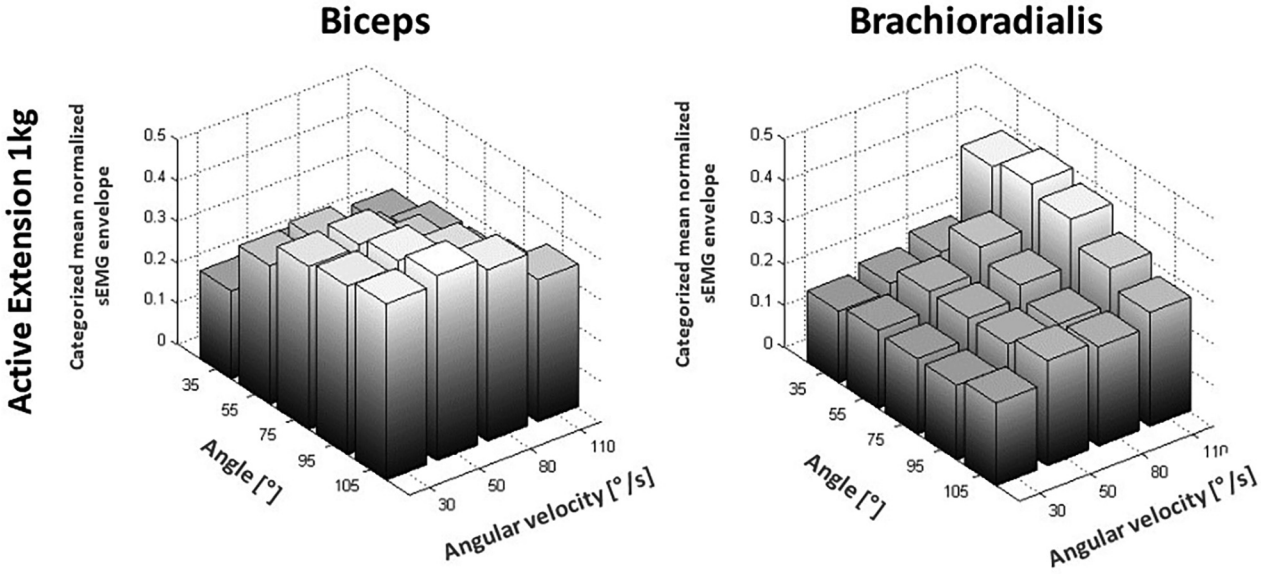

Fig. 4. Mean Muscular Activation pattern from a data set with healthy volunteers during active extension with 1 kg (von Werder and Disselhorst-Klug, 2016). The mean normalized sEMG, is sorted to the different categories of combinations of elbow angle and angular velocity.

2.7.5. Averaged relative difference of patient's categorized sEMG value from those of healthy controls (Mean_ΔCsEMGv$_{alue}$ Patient/Control)

The deviation of the patients' categorized sEMG value from that of the healthy controls is described by the parameter *Mean_ΔsEMG$_{value}$ Patient/Control*. The relative difference *rel_ΔPatRef$_{jj}$* in each category was calculated by subtracting the categorized sEMG values of the reference matrix from the patient's matrix and normalizing to the reference matrix values afterwards (Eq. (5.1)). Subsequently, the mean of all relative differences was computed (Eq. (5.2)).

For each muscle and every patient separately, only those combinations of angle interval and angular velocity which the subject was able to perform were regarded. The particular categories of joint angle and velocity the individual subject was not able to perform were disregarded.

$$\boldsymbol{rel\_\Delta PatRef_{i,j}} = \frac{(\boldsymbol{CsEMG_{value\_ij}\_Patient} - \boldsymbol{CsEMG_{value\_ij}\_Reference})}{\boldsymbol{Mean\_CsEMG_{value}\_Reference}} \quad (5.1)$$

$$\mathbf{Mean\_\Delta CsEMG_{value}\_Patient/Control} = \frac{\sum_{i=min}^{i=max}\sum_{j=min}^{j=max} \boldsymbol{rel\_\Delta PatRef_{i,j}}}{(\boldsymbol{i_{max}} - \boldsymbol{i_{min}}) + (\boldsymbol{j_{max}} - \boldsymbol{j_{min}})} \quad (5.2)$$

3. Results

3.1. Clinical appearance

Patients' clinical appearance, e.g., motivity of the affected arm, or the clinical data revealed great variations, although in most cases the supply area of the middle cerebral artery was affected (Table 1). Especially no relation between time since onset and the developed parameters was recognisable, so no recovery effect was existent (see Table 2)

Also, the results of the passive Tardieu -Test, showed no great variations within 6 out of 7 patients with a score of 2 (Table 1). Testing the functionality of the affected arm with the WMFT, patients reached different scores (Table 1) allowing a higher degree of differentiation between the patients than the Tardieu Test.

3.2. Maximum velocity (v_{max})

The maximum velocity in healthy subjects was generally higher than in the patients (Fig. 5).

Comparing v_{max} with the reached WMFT-Score, patients with higher scores were able to achieve higher extension velocities than patients who reached minor scores. A strong correlation (r = 0.9; p = 0.0058) between the reached maximum velocity and the reached WMFT-Score has been found (Fig. 5).

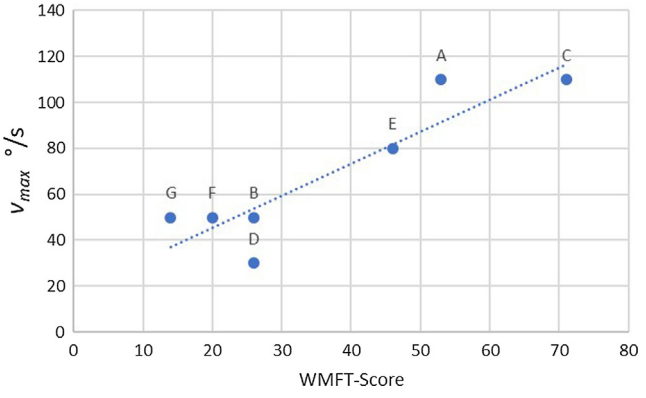

Fig. 5. Maximal reached extension velocity (v_{max}) as a function of WMFT-Score (letters inside the following figures as code for the tested patients, compare Table 1).

As v_{max} differs between the patients while the Tardieu-Score is identical in 6 out of 7 patients, no significant correlation between v_{max} and the Tardieu-Score could be found.

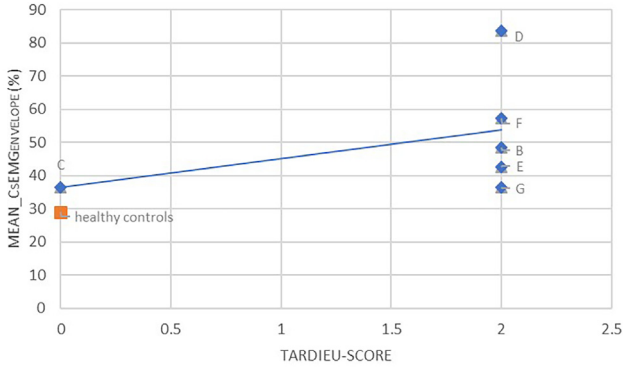

Fig. 6. Correlation between Averaged categorized sEMG values (Mean_CsEMG$_{value}$) and the Tardieu-Score.

3.3. Mean categorized sEMG value (Mean_CsEMG$_{value}$)

The *Mean categorized sEMG Value* (*Mean_CsEMG$_{value}$*) of the biceps differs in different patients during the voluntary performed elbow extension. *Mean_CsEMG$_{value}$* of the healthy controls was 29% (Fig. 6).

Here again, no correlation between *Mean_CsEMG$_{value}$* and the Tardieu-Score was possible, as patients with the same Tardieu-Score differ in *Mean_CsEMG$_{valuee}$* indicating different levels of muscular activation (Fig. 6).

Also, no correlation between the *Mean_CsEMG$_{valuee}$* and the WMFT results could be found (r = −0.36; p = 0.4827) (Fig. 7). However, as a tendency, a decreased *Mean_CsEMG$_{valuee}$* of the biceps has been found with increasing WMFT-Score (Fig. 7).

Taking the results of v_{max} and *Mean_CsEMG$_{valuee}$* into account, the WMFT-Score was used to evaluate the clinical significance of the different parameters further on, as it correlates better with the distinguished levels muscular activation of the elbow flexors.

3.4. Correlation between muscular activation and movement velocity (MA_V)

In 6 out of 7 patients the muscular activation of the biceps muscle increases with increasing movement velocity (positive parameter '*Correlation between Muscular Activation and Movement Velocity*' (*MA_V*) value) (Fig. 8). In contrast, healthy controls showed a negative *MA_V* value, indicating a decrease in muscular activation with increasing

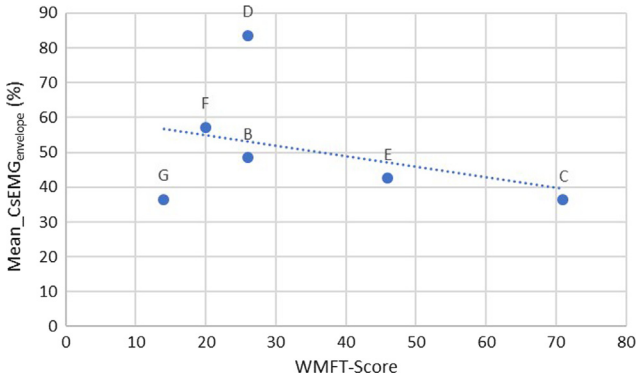

Fig. 7. Averaged categorized sEMG value (Mean_CsEMG$_{value}$) as a function of WMFT-Score. Example is given for the biceps muscle.

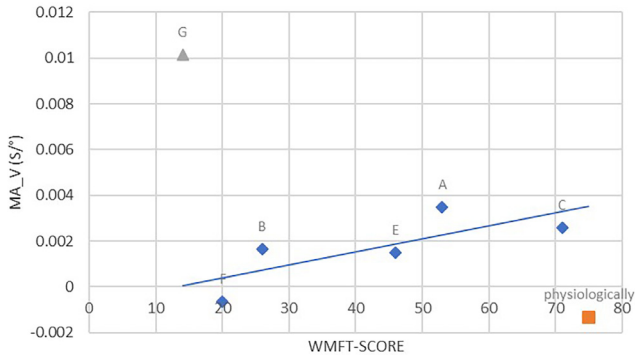

Fig. 8. Correlation between muscular activation of the biceps and movement velocity (MA_V) as a function of WMFT-Score Annotation: the value 'physiologically' is taken from a reference data set generated from healthy volunteers and therefore mirrors the correlation in healthy, unaffected test persons.

movement velocity in eccentric contractions.

Interestingly, in both flexors *MA_V* increases with increasing WMFT-Score. Concerning both flexors, patients with lower WMFT-Scores (20–26) showed smaller *MA_V* values (0.001661–0.003471 s/°) closer to the physiological value (−0.001288 s/°), whereas patients with higher WMTF-Score (53–75) deviated increasingly from the physiological value and showed higher *MA_V* values (0.0034715–0.0025802 s/°) (Figs. 8 and 9).

A stronger correlation between the WMFT-Score and the correlation between muscular activation and movement velocity was shown for the biceps (r = 0.7582; p = 0.1375) than for the brachioradialis (r = 0.4875; *p = 0.4875*) (Fig. 9).

3.5. Divergence of muscular activation of biceps and brachioradialis (*DiverMA$_{flexors_}$av*)

Concerning the '*Divergence in Muscular Activation of Biceps and Brachioradialis*' (*DiverMA$_{flexors_}$av*) in patients' extension movements, no difference in activation strategy of the two muscles with respect to joint angle and movement velocity was found. Both flexors did not oppose each other like in physiological movements but were activated synchronously. This is reflected in the *DiverMA$_{flexors_}$av* values which are in 6 out of 7 patients higher compared to healthy controls (Fig. 10).

Due to the parameter *DiverMA$_{flexors_}$av* 's definition, the physiological value was approaching zero (0.0047 s/°). With increasing WMFT-Score the *DiverMA$_{flexors_}$av* value decreases (r = −0.4045; p = 0.4264) indicating an increasing degree of *divergence* in muscular activation and becoming more conform with the physiological activation strategy.

Patients with a high WMFT-Score and low *DiverMA$_{flexors_}$av* values showed a stronger activation within the range of high velocities and smaller angles, whereas patients with low WMFT-Score and high

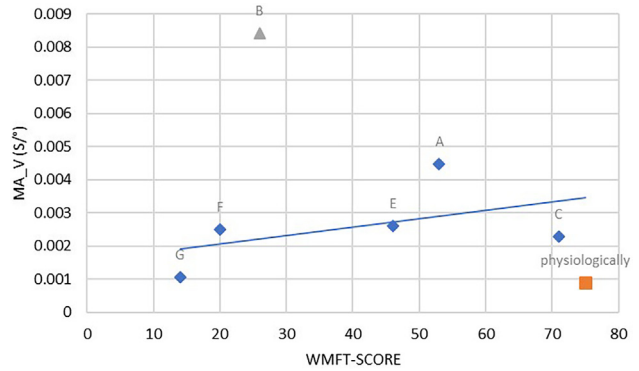

Fig. 9. Correlation between muscular activation of the brachioradialis and movement velocity (MA_V) as a function of WMFT-Score.

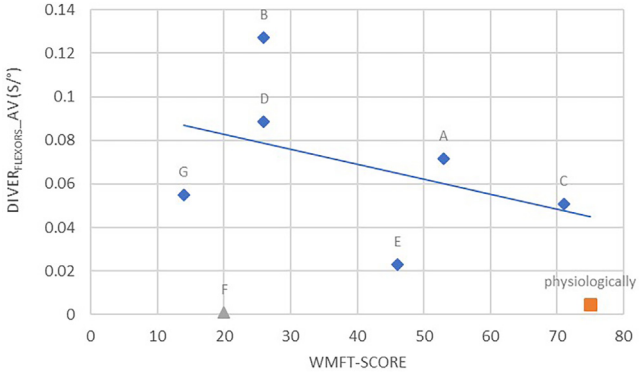

Fig. 10. Divergence of muscular activation of biceps and brachioradialis (DiverMA$_{flexors_}$av) as a function of WMFT-Score. The parameter DiverMA$_{flexors_}$av has been defined in such a way, that lower parameter values indicate higher oppositeness.

DiverMA$_{flexors_}$av values showed a stronger activation of both muscles within the range of minor velocities and higher angles. This synchronous activation pattern could be found in 6 out of 7 patients, only patient E/WMFT 46 did not show this synchronous activation pattern.

3.6. Average relative differences of patient's categorized sEMG value from those of healthy control (*Mean_ΔCsEMG$_{value_}$Patient/Control*)

When calculating the '*Averaged relative difference of patient's sEMG from those of healthy controls*' (*Mean_ΔCsEMG$_{valuee_}$Patient/Control*) no correlation with the WMFT-Score could be found.

6 out of 7 patients showed a higher deviation in the brachioradialis from the healthy controls (*Mean_ΔCsEMG$_{evalue_}$Patient/Control* 1419; r = 0.2365477; *p = 0.6095*) compared to the biceps (*Mean_ΔCsEMGv$_{alue_}$Patient/Control* 0.701; r = 0.3294315; *p = 0.4706*) (Fig. 11).

Patients with minor WMFT-Scores showed higher differences in the *Mean_ΔCsEMG$_{value_}$Patient/Control* values concerning the brachioradialis than patients with higher WMFT-Scores (*Mean_ΔCsEMG$_{value_}$Patient/Control* 2.34397 to 0.87708)

Also, the difference between the Averaged Relative Difference of the biceps and the brachioradialis was higher in patients having lower WMFT-Scores (*Mean_ΔCsEMG$_{value_}$Patient/Control* 2.02 to 0.46).

Patient G had to be excluded from the calculation due to the few reached combinations of angle and velocity.

4. Discussion

After a brain lesion, a patient's life is frequently disturbed through

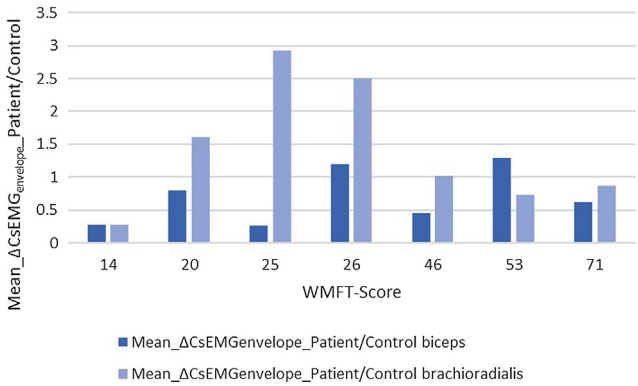

Fig. 11. Averaged Relative Difference of patient's categorized sEMG value from those of healthy controls (Mean_ΔCsEMG$_{value}$Patient/Control).

spastic movement impairment, a disorder still lacking an objective categorization for clinical management. Based on the assumption that spastic movement impairment derives from a change of the stretch reflex, we hypothesized that spasticity causes a changed effect of movement velocity on muscular activation and a changed inter-muscular coordination of the two elbow flexors. From this hypothesis we developed a new procedure which enables the objective assessment of spastic movement impairment during freely performed voluntary movements. Objectivity is ensured by five sEMG derived parameters reflecting the results of clinical tests, which assess the functionality of the impaired limb.

4.1. WMFT as a better tool for clinical classification

Spasticity classifications are a widely-discussed issue. A frequently used clinical test evaluating spasticity is the Tardieu-Test.

Concerning this test and the great variety of clinical appearance, our data indicate that the Tardieu-Test seems not to be specific enough to distinguish the great variability of different muscular activation strategies and study task performances seen in the patient group. These changes in muscular activation are not mirrored in the Tardieu-Score, but in the WMFT. Furthermore, the calculation of $Mean\_CsEMG_{value}$ indicated different levels of muscular activation, also better resembled by the WMFT than by the Tardieu-Score.

These results are supported by earlier studies, which criticize the Tardieu-Test for not being precise enough to evaluate spasticity (Naghdi et al., 2014). Instead, emerging trends demand a spasticity assessment in the context of functional movements of everyday life (Levin et al., 2000). The introduced procedure is a first step in this direction since it assesses voluntary movements. Furthermore, our data supports the demand of including functional everyday life movements in the assessment of spastic impairment, since the WMFT scores of the patients reflect the variability in the muscular activation and study task performance much better than the Tardieu-Test.

4.2. Reachable movement velocity as an indicator for remaining function

In our study, patients with higher WMFT-Scores reached higher maximal movement velocity (v_{max}). Additionally, patients with a higher WMFT showed also an increasing muscular activation with increasing movement velocity. Our parameter MA_V verified a correlation between muscular activation and movement velocity depending on the remaining functionality of the arm. This is obvious, since a larger range of possible movement velocities allow higher functionality expressed in a higher WMFT-Score. In contrast to healthy controls, muscular activation of biceps increases with increasing movement velocity. It is likely that this effect can be attributed to a pathological increased stretch-reflex due to a faster stretch of the biceps muscle during extension movements. Surprisingly, in patients with low WMFT-Scores, muscular activation increases less with increasing movement velocity. In these patients a low WMFT-Score indicates a limited range to variate movement velocity. These findings are in accordance to Burke et al. (2013) who showed that an intended movement was limited and slowed down by an increased stretch reflex of the antagonistic muscles.

4.3. Loss of divergent activation strategy of biceps and brachioradialis leads to a loss of fine-tuning and control function

Unlike in healthy volunteers (von Werder and Disselhorst-Klug, 2016), there was no differentiated muscular activation of biceps and brachioradialis in the patients during extension movements in this study. Muscular activation of the two elbow flexors was synchronous, rather than opposed like in the healthy volunteers. This is reflected in a higher $DiverMA_{flexors\_av}$ and seems to be one of the main characteristics of spastic movement impairment as it appears in every single patient regardless to clinical differences. An abnormal increased coactivation of brachioradialis and biceps during extension agrees with the findings of Lum et al. (2004).

von Werder and Disselhorst-Klug (2016) explain the opposed activation strategy of both flexors by different functions of the two muscles. While the biceps bears the weight, the brachioradialis controls movement velocity and joint position resulting in a fine-tuning of the movement. A loss of oppositeness or divergence (higher $DiverMA_{flexors\_av}$ values) leads to a loss of finetuning and control function. Santello and Lang (2015) have shown that stable but fewer patterns of muscular activity arise in patients suffering from stroke resulting in a reduced ability to adapt to demands. The degree of physiological synergy between the muscles correlates with the loss of upper limb ability. This is in accordance with our data, showing simplified muscular coordination patterns of the two elbow flexors during extension movements and upper limbs functionality.

4.4. Interference in the brachioradialis leads to minor functionality of the arm

In our study, the parameter $Mean\_\Delta CsEMG_{value}$ *Patient/Control* revealed differences in the categorized sEMG values between patients and healthy controls. The difference was higher in brachioradialis than in biceps. A higher deviation of the brachioradialis' muscular activation was associated with lower WMFT scores and a minor functionality of the arm. In patients, the brachioradialis already shows a higher activation within the categories of small joint and high velocities, in a range of motion where this muscle is physiologically less active. As a result, the muscle can no longer perform its task as a fine-tuner of the extension movement. Patients in which the brachioradialis is activated in a physiological manner until higher flexion angles and higher movement velocities have a higher WMFT-Score along with a higher capacity to perform fine-tuned movement.

Comparing the meaningfulness of the individual parameter with each other, it turns out that the two parameters describing a dependence of the muscular activation on the movement velocity (v_{max} *and MA_V)* correlate best with the WMFT-Score.

In general, our study data showed that the velocity dependence is an important factor influencing the extent of spasticity. The parameter $Mean\_CsEMG_{value}$ reveals the tendency that a better functionality, resembled in a higher WMFT-Score, is connected to a lower muscular activation the parameter $Mean\_CsEMG_{value}\_Patient/Control$ shows that functionality can only be evaluated by sEMG if the velocity-dependence is considered. Both parameters underline the importance of the factor 'velocity-dependence' for the assessment and categorization of spasticity.

This, too, emphasizes the importance of the study of movement velocity for the assessment of spastic movement restrictions. However, the study itself has some limitations restricting the statements made. The most critical being, that the study is limited by the small sample size of the patient group. As a result, no statistical analysis able of generalization to the population at large could be made. Further and larger studies are needed to investigate this topic, our study itself can only serve as a pilot-study. Nevertheless, we like to publish this study, for despite the small sample size and the variety of clinical appearance similar test results are detectable and therefore first conclusions for our methodical paper can be drawn from this.

Moreover, we like to point out, that although sEMG allows the pain-free assessment of muscular activation, this study it is still based in laboratory tests. As sEMG tools and application procedures need to be developed enabling the sEMG to meet the needs of physicians our pilot study with clinical and laboratory tests serves as a preliminary in the development of an objective sEMG spasticity assessment during activities of daily living.

5. Conclusion

With this paper, we present a new procedure to evaluate spastic movement impairment with objective and reproducible measures. In the present pilot study, our results demonstrate a velocity-dependence of muscular activation during extension movements in spastic impairment which clearly differs from healthy controls. The more severe the impairment, the more different the patients' muscular activation from healthy controls and the more the patients are restricted to lower movement velocities. We propose five parameters derived from the sEMG signal, which allow the quantitative assessment of spastic movement impairment quantitatively and with that objectively. Based on these parameters, spastic movement impairment can be assessed in the context of functional everyday tasks. As an important factor, the velocity-dependence must be considered during the evaluation by sEMG. The introduced procedure associated with the developed parameters might give a more electrophysiological option to label spastic impairment or even replace the WMFT.

6. List of non-standard abbreviations

Vmax	Maximum Velocity
Mean_CsEMG$_{vlue}$	Averaged sEMG values of all categorized sEMG values
MA_V	Correlation between muscular activation and movement velocity
DiverMA$_{flexors_}$av	Divergence of muscular activation of biceps and brachioradialis with respect to joint angle and movement velocity
Mean_ΔCsEMG$_{value_}$Patient/Control	Averaged relative difference of patient's categorized sEMG value from those of healthy controls

Declaration of Competing Interest

The authors declare that there is no conflict of interest

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