A Practical Post-Stroke Elbow Spasticity Assessment Using an Upper Limb Rehabilitation Robot: A Validation Study

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***Abstract*— Spasticity is a motor disorder characterised by a velocity-dependent increase in muscle tone, which is critical in neurorehabilitation given its high prevalence and potential negative influence among the post-stroke population. Accurate measurement of spasticity is important as it guides the strategy of spasticity treatment and evaluates the effectiveness of spasticity management. However, spasticity is commonly measured using clinical scales which may lack objectivity and reliability. Although many technology-assisted measures have been developed, showing their potential as accurate and reliable alternatives to standard clinical scales, they have not been widely adopted in clinical practice due to their low usability and feasibility. This paper thus introduces an easy-to-use robotic based measure of elbow spasticity and its evaluation protocol. Preliminary results collected with one post-stroke patient and one healthy control subject are presented and demonstrate the feasibility of the approach.**

I. Introduction

Spasticity is an upper neuron motor disorder in which affected muscles involuntarily contract. It is characterised as "a velocity dependent increase in tonic stretch reflexes (muscle tone) with exaggerated tendon jerks, resulting from hyperexcitability of the stretch reflex" [1]. It is a common sequela following stroke with a prevalence rate of 30-80% [2]. Upper-limb spasticity is strongly correlated with post-stroke pain [3], and it also limits patient engagement in rehabilitation [4]. Furthermore, spasticity could lead to activity limitations and participation restrictions of stroke survivors [5] and causes a higher socioeconomic burden for stroke survivors compared to those without spasticity [6]. Different options including oral medications, intervention, surgery and rehabilitation are used as the treatment of spasticity [7] and accurate measurement of spasticity is needed to direct the therapist toward an adequate spasticity treatment, as well as to evaluate the effectiveness of the management strategies of spasticity [8], [9].

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Currently, the Modified Ashworth Scale (MAS) and Modified Tardieu Scale (MTS) are two widely used clinical scales to measure spasticity [10]. The MAS is a 6-point scale to assess muscle resistance torque by a manual stretch at a single and vague velocity, which means MAS may not be a specific tool considering spasticity is velocity dependent and may confound spasticity with hypertonicity. Besides, MAS has only moderate intra-rater and inter-rater reliability, affecting its validity as a spasticity measure [11]. Similarly, the MTS is a 5-point scale to rate the reaction of affected muscles to manual stretching at two velocities, which are defined "as slow as possible" and "as fast as possible" [12]. Although MTS seems to be a more specific tool to measure spasticity [13] as it considers different stretching velocities, the sensitivity and reliability may depend on the ability and experience of the raters [14].

To address this issue of relatively poor clinical scales, attempts have been made to investigate technology-assisted measures of spasticity, which are expected to be more objective, accurate and reliable compared to the MAS and MTS. To monitor the response of spastic muscles to stretching, surface electromyography (sEMG) along with angle measurement has been employed for the quantification of spasticity. Alves's study [8] used a single-channel sEMG sensor and a flexible optical goniometer to obtain Tonic Stretch Reflex Threshold (TSRT) as an outcome measure to quantify spasticity which had a positive and strong correlation with MAS. Meanwhile, Frenkel-Toledo's study [15] showed good inter-rater reliability of spasticity measurement with sEMG sensors and electrogoniometer. However, both studies still rely on a number of manual stretching to elicit reflex responses which may cause the boredom and fatigue of both testers and subjects [16]. The complexity of sEMG sensor placement also leads to a deficiency in the practicability of this spasticity measure.

To avoid the use of sEMG sensors, force/torque measurements during controlled stretching by robotic devices have also been used to evaluate spasticity. This is aligned with the increasing popularity of robotic devices in rehabilitation settings. Lee et al. designed and built a robotic exoskeleton which showed the possibility of identifying spasticity by measuring the resistive torque [17]. In addition, end-effector based robots which employ force measurement with controlled velocities have also been used to provide an evaluation of spasticity [18]. Moreover, a more recent study [19] used a Biodex device to impose 50 repetitions of controlled elbow stretching at velocities up to $150^{\circ}.s^{-1}$. The results suggested

the promise of an accurate robotic spasticity assessment by only force measures.

Although the robotic measure has the potential to be accurate, specific and reliable to evaluate spasticity, it has not been routinely adopted in clinical settings due to its low feasibility and practicability. Firstly, the self-developed exoskeleton and the Biodex device used in previous studies are laboratory systems, so they are not typically available in clinical practice as they have not been developed as rehabilitation devices. Then, the radical stretching velocities could be risky to patients with severe spasticity when an intense spastic muscle response is elicited by a high velocity. Moreover, the large amount of passive stretching repetitions is time consuming, even causing the decrease of spasticity in trials which could affect the assessment accuracy [16]. Therefore, a safe and easy-to-use robotic measure of spasticity is required to be better adopted and significantly improve spasticity assessment in clinical settings.

This study aims to validate a practical force-based measure of spasticity in the elbow flexors for chronic stroke survivors using a clinically available rehabilitation robot. We report the developed procedure (apparatus and methods), study protocol and preliminary results obtained to date with this method.

II. Methods

A. Subjects

This is a multicenter study which recruited patients in both Royal Melbourne Hospital (Melbourne, Australia) and Ruijin Hospital (Shanghai, China). Participants were from 18 to 75 years old and in the chronic phase (at least 3 months post onset) of stroke recovery with the following inclusion criteria: upper limb hemiparesis due to a unilateral single stroke; spasticity in the elbow flexors as identified by treating clinicians; adequate cognition to provide informed consent. Individuals with any following conditions were excluded from the study: co-morbid neurological conditions; a painful shoulder or elbow; significant non-neurological upper limb pathology; contractures in the affected upper limb. Healthy subjects were recruited as a control group in parallel with patient recruitment. The ethical approval was obtained from the Melbourne Health HREC and Ruijin Hospital CTEC. Written informed consent was collected from all participants.

B. Experimental Setup

The experiment was performed on a commercially available rehabilitation robot ArmMotus-M2 (Fourier Intelligence, Shanghai, China) shown in Fig.1. The original controller of ArmMotus-M2 was replaced by a self-developed CANOpen Robot Controller (CORC) [20] to implement the protocol of robotic assessment and record the kinematic and interaction force data at a sampling rate of 500Hz. A safety protection mechanism was embedded in the controller which will interrupt the robot when the measured interaction force exceeds 80N. A Unity-based user interface was developed for clinicians to control the whole experimental procedure without additional training. Surface EMG sensors (Delsys, Natick, USA) were used to record the muscle activity from

Fig. 1: Fourier Intelligence ArmMotus-M2 (www.fftai.com).

elbow flexors and extensors, which was not analysed in this paper but will be used for further investigation. Both centers had the same experimental setup.

C. Procedure

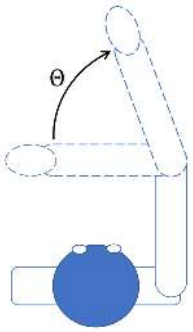
The participants undertook a clinical assessment and a robotic assessment to evaluate elbow spasticity in a single session in which the sequence of assessments was randomised. During the clinical assessment, a MAS and an MTS measurements in the supine posture were performed by a trained clinician. The control group did not undertake the clinical assessment.

At the beginning of the robotic assessment, the participants were seated in front of the ArmMotus-M2 on a chair or a wheelchair. The impaired forearm of patients or the dominant side of control subjects was attached to the end-effector with an initial posture of approximately 90° shoulder elevation and 90° elbow flexion shown in Fig.2a. Then, the participants were instructed to fully relax their upper limb, and the clinician stretched the participant's arm to perform an elbow extension movement from the initial posture to the maximum range of motion (ROM) as illustrated in Fig.2b. This movement trajectory was recorded and then performed by the robot in a ROM of 80° at 9 different angular velocities (from $10°.s^{-1}$ to $90°.s^{-1}$) in a randomised order. This conservative maximum stretching velocity was determined based on the results of previous study [19] where the increase of reflex torque resulting from spasticity could be observed. In order to investigate the repeatability of the robotic assessment, the entire procedure was repeated after a 10-minute break.

D. Data Analysis

The measured interaction force in the transverse plane was filtered by a 2^{nd} order Butterworth low-pass filter with cut-

(a)



(b)

Fig. 2: The initial posture and movement trajectory of this robotic measure of spasticity.

off frequency 10Hz to remove the measurement noise. Then, the elbow torque was obtained by:

$$\tau_{total} = f_{interaction} \times l_{forearm}, \quad (1)$$

where τ_{total} is the total elbow torque, $f_{interaction}$ is the filtered interaction force along the movement direction, and $l_{forearm}$ is the length of the forearm of a participant.

In the absence of voluntary contraction from the subject, the total elbow torque was then considered to be the sum of the neural (stretch reflex), non-neural (passive muscle stiffness), and inertial components [9]. The relevant stretch reflex torque was thus calculated as:

$$\tau_{S.R.}(\dot{\theta}) = \tau_{total} - \tau_K(\theta) - \tau_I(\ddot{\theta}), \quad (2)$$

where θ is the elbow extension angle, $\tau_{S.R.}(\dot{\theta})$ is the velocity-dependent stretch reflex torque, $\tau_K(\theta)$ is the position-dependent passive elastic torque, and $\tau_I(\ddot{\theta})$ is the acceleration-dependent passive inertial torque.

Following the model proposed in [19], the passive elastic torque was modelled as a 5^{th} order polynomial at the lowest angular velocity $10°.s^{-1}$. The passive inertial torque was considered to be 0 when the movement velocity was constant.

Next, the mean value of stretch reflex torque $\bar{\tau}_{S.R.}(\dot{\theta})$ at each velocity was calculated from the remaining torque. We assumed a linear relationship between the average stretch reflex torque and velocity which matched observations from previous studies [18], [19]. Hence, the velocity-dependent stretch reflex torque was modelled as:

$$\hat{\tau}_{S.R.}(\dot{\theta}) = \beta\dot{\theta}, \quad (3)$$

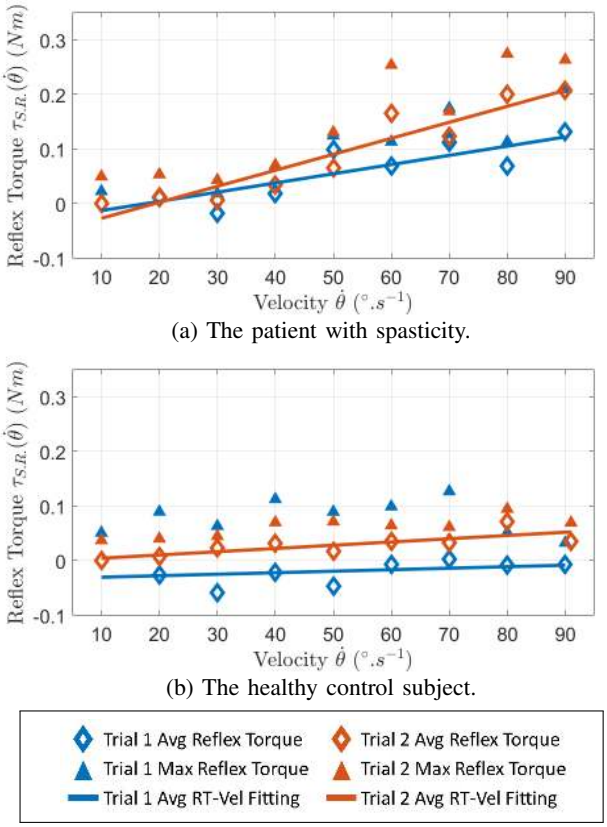
where $\hat{\tau}_{S.R.}(\dot{\theta})$ is the fitted velocity-dependent stretch reflex torque, and the coefficient β is the slope of the reflex torque-velocity curve which represents the spasticity of each participant for each trial.

The coefficient of determination R^2 was also calculated for each linear regression to test the goodness of fit.

III. Results

A 65-year-old male post-stroke patient participated in this study. This patient had an ischemic stroke with an onset time 3 months. Hemiplegia was on the right side. A healthy individual without known neurological or other medical conditions participated in the experiment as a control subject. In the clinical assessment, the patient has a MAS score of 1+ for the elbow flexors. The MTS results of the patient show a quality of muscle reaction score (X) of 2, an angle of catch (R1) of 90° at fast velocity, and a full ROM (R2) of 110° at low velocity.

The linear regression analysis of the reflex torque-velocity curve of the patient (Fig.3a) and healthy subject (Fig.3b) shows significantly different results. A velocity-dependent increasing trend of reflex torque is seen for the patient in which the spasticity coefficient (β) is $1.7e^{-3}Nm.s.^{\circ^{-1}}$ in the first trial and $2.9e^{-3}Nm.s.^{\circ^{-1}}$ in the second trial. This trend is not observed for the control subject who has significantly lower β values of $0.3e^{-3}Nm.s.^{\circ^{-1}}$ and $0.6e^{-3}Nm.s.^{\circ^{-1}}$ in trial #1 and #2 respectively. A good fitting of the patient



(a) The patient with spasticity.

(b) The healthy control subject.

Fig. 3: Reflex torque-velocity plots and linear regression fitting results.

data can be found as the coefficient of determination (R^2) is 0.74 in trial #1 and 0.90 in trial #2. Whereas, the results of the control subject show an inferior fitting especially in the first trial with a R^2 value of 0.12. In addition, a maximum reflex torque of 0.21Nm (trial #1) and 0.27Nm (trial #2) are observed in the patient data. This is 2-3 times larger than those of the healthy subject with 0.13Nm and 0.10Nm.

IV. Discussion

This study introduced a force-based robotic measure of elbow spasticity for post-stroke patients. The method was proposed to provide an objective and usable elbow spasticity evaluation in clinical practice to resolve the necessity of accurate spasticity assessment and the limitations of widely-used clinical scales. The preliminary results showed a much larger spasticity coefficient with a better fitting of the model in both trials of the patient data compared to that of the healthy control subject, indicating the patient had a velocity-dependent increase of stretch reflex, which is consistent with Lance's definition of spasticity. This approach was further validated by a higher maximum stretch reflex torque of the patient.

A large number of studies investigated the technology-assisted methods for accurate spasticity measurement. However, these measures have not been routinely adopted due to their low practicality and feasibility of both apparatus and protocol. In this study, a commercially available upper limb rehabilitation device was used. Instead of a dedicated

device for spasticity evaluation, this clinically feasible rehabilitation robot is able to perform the assessment by simply adding to a software without extra cost. In addition, the practical assessment protocol was easily performed with a few controlled passive stretches at conservative speeds. The simple setup and procedure ensure a single robotic evaluation can be completed in 10mins without additional training for clinicians prior to the assessment. Furthermore, we believe the same type of apparatus will also be able to perform this spasticity measurement, which could significantly improve the adoption in clinical practice.

The actual values of the stretch reflex torque were small in the patient data, though it showed a clear velocity-dependent increasing trend. It is noted that the patient only had mild spasticity evaluated by the MAS and MTS. Despite the lack of specificity and accuracy of clinical scales to measure spasticity, the clinical results still indicated a low overall resistance to passive stretches of the patient.

So far, only two subjects were recruited and this constitutes only very preliminary results. The clear difference observed between the control and impaired individuals is still promising the relevance of this approach. The planned study aims to recruit a total of 25 patients and 25 age-matched controls to further evaluate the method. This will allow us to estimate its repeatability, through test-retest analysis, and also its discriminability capability. Moreover, the correlation of the robotic measure (the spasticity coefficient β) with the MAS and MTS will be assessed. This is expected to lead to a better acceptance of the proposed method as a potential measure in clinical practice. Finally, the concurrent validity of this method will be further constructed by investigating its correlation with TSRT obtained from the synchronously recorded sEMG measurements.

V. Conclusion

An objective and practical robotic measurement of elbow spasticity for stroke survivors was proposed. This measure intends to perform an accurate spasticity evaluation in a short period of time with a simple setup on a clinically available rehabilitation device. The preliminary results showed the ability of this method to discriminate between one patient with spasticity and one healthy subject based on the velocity-dependent feature of the stretch reflex torque. This approach will be further evaluated with a larger sample size with the aim to be widely adopted in clinical practice due to its practicality and feasibility.

Conflict of Interest

JT is employed by Fourier Intelligence (Shanghai, China). The remaining authors declare no commercial or financial relationships that could constitute a potential conflict of interest.

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