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A New Method For Reflex Threshold Estimation in Spastic Muscles

Matthieu Chardon, Student Member, IEEE, Nina L. Suresh and W. Zev Rymer, Senior Member, IEEE

Abstract— **Many clinical measures of spasticity, such as Ashworth tests and tendon tap responses, are linked to stretch reflex thresholds but these methods are relatively imprecise and unreliable. To address this deficit, we examined the utility of a system that relies on a small position controlled actuator to better estimate this threshold. We compared the reflex threshold estimates in the passive spastic and contralateral elbow flexor muscles of 4 hemiparetic spastic stroke survivors. We propose that the use of controlled indentation of the tendon may be a practical and accurate method of estimating stretch reflex threshold as well as passive muscle properties.**

I. INTRODUCTION

Hyperactive stretch reflexes are routinely observed in stroke survivors. Research studies have shown that in stroke survivors, the stretch reflex threshold is significantly reduced in spastic muscles, and this reduction is correlated with increases in reflex joint torque [1]. Many clinical measures of spasticity, such as Ashworth tests and tendon tap responses are linked to stretch reflex thresholds. In the context of estimating stretch reflex threshold, these methods are relatively imprecise and unreliable, primarily because these methods are based on qualitative assessments.

To address this deficit, we examined the utility of a system that relies on a small actuator to better estimate this threshold, using small amplitude dynamic muscle stretches superimposed upon progressively increasing muscle pre-load in passive muscle.

We used a position-controlled linear actuator (Linmot, Inc.) to apply controlled indentations of the tendon of the biceps brachii. The actuator was positioned at approximately 90 degrees to the long axis of the biceps brachii while the limb was fully stabilized. A Sensotec single axis load cell recorded the static preload applied to the tendon, the stimulus force (i.e, tap force) as well as the (dynamic) load produced by the reflex response. The static preload was used as a marker for tendon (and muscle stretch) relying on the assumption that tendon stress is linearly related to tendon strain, for small perturbations. Surface EMG of the biceps brachii and triceps was also recorded. To estimate reflex threshold we imposed successive position changes of the tendon. We then, using muscle indentation. We recorded the stretch reflex response (EMG and force) to five successive pulses at each indentation position. We compared the reflex threshold estimates in the passive spastic and contralateral elbow flexor muscles of 4 hemiparetic spastic stroke survivors.

Our findings were that both reflex force and EMG responses to the pulses were elicited at much lower initial loads on the spastic side as compared to the contralateral side, however the stimulus force was similar between the two sides. We propose that the use of controlled indentation of the tendon may be a practical and accurate method of estimating stretch reflex threshold as well as passive muscle properties and thereby quantifying spasticity in a simple, rapid and cost effective manner.

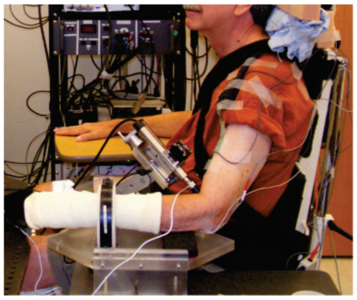

Fig. 1. Experimental set up: a position-controlled linear actuator (Linmot, Inc.) was placed perpendicular to the tendon of the biceps brachii. The actuator was lowered onto the tendon sequentially relative to the skin and then used to tap the tendon according to a tap sequence. Both EMG from the biceps brachii and the force from the tendon where measured during the whole procedure. These measurements were the bench mark for the reflex threshold estimations.

II. METHODS

The stretch reflex is an involuntary muscle contraction elicited by a brief stimulus to muscle receptors, such as a tap on the patellar tendon. If the arm and muscle are immobilized (i.e., no joint movement), the result will be a measurable change in the tension of the tendon attached to the muscle. We quantified the reflex response by eliciting a reflex and then measuring the associated electromyogram (EMG) as well as recording the tendon force of the biceps brachii of stroke survivors.

A. Experimental Setup

Two measures were used to quantify the reflex responses: 1) the force trace measurement of the tension in stimulated muscles tendon and 2) the EMG activity of that muscle. Both measurements required different methods, as explained below.

In order to utilize tendon tension as a measure of the reflex response, an isometric condition is established using

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M. Chardon is with Biomedical Engineering, Northwestern University `matthieuchardon@gmail.com`

N. Suresh is with the Rehabilitation Institute of Chicago `n-suresh@northwestern.edu`

W. Rymer is with the Rehabilitation Institute of Chicago and Northwestern University, Department of Biomedical Engineering and The Feinberg School of Medicine, Northwestern University, Department of Physical Medicine and Rehabilitation `w-rymer@northwestern.edu`

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a mechanical frame to stabilize the limb. Subjects were strapped to a chair, with the arm and wrist casted, and clamped on a magnetic base, assuring the relative immobility of the elbow joint (Figure 1). The arm position was optimized such that the elbow and shoulder joint angles ensured a maximal reflex response from the biceps. Our subjects had approximately 45 degree wrist supination, a 110 degree elbow extension, a 45 degree shoulder abduction and a 10 degree shoulder flexion. Subjects were placed as closely as possible to the ideal joint angles. These angles were recorded for all subjects so to ensure repeatability on the contralateral side.

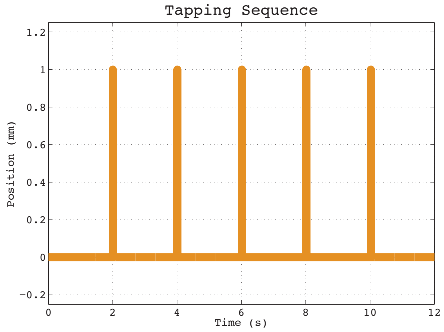

Fig. 2. Tap sequence: this tap sequence was delivered on the tendon at different indentation depth relative the initial position (the skin). The tap sequence was composed of five one millimeter taps spaced by one second.

A position controlled linear actuator, the Linmot, was mounted on the mechanical frame directly above the patients tendon and used to elicit the reflex response. The linear actuator was placed at an angle of 90 degrees to the tendon and the position zeroed at the surface of the skin visually. The tapper was then methodically lowered in increments of 1 mm, using a micrometer attached to the actuator. The position of the linear actuator was constantly monitored, guaranteeing repeatability in the stimuli and in the measurements of the reflex. In addition, the load cell enabled us to measure the tension in the tendon at rest and during a reflex response, using a high precision load cell mounted between the linear actuator and a rubber bumper that interfaced with the patients skin.

Each position was treated as a new trial. At each position, five transient taps indented the tendon for 1mm in 1 ms, every 5 seconds (Figure 2). The taps were administered over a distance of 25 mm indentation into the tendon. In some subjects, the number of trials was limited on the affected side by the large force generated by the reflex response, which could shut the actuator controller off. The controllability of the linear actuator insured the repeatability of the stimuli over duration of each experimental session.. Additionally, since the actuator is placed so as to pre-stretch the tendon, constant contact between the tendon and the actuator was ensured.

The second measure used was EMG. We placed 3 active delsys electrodes on the medial and lateral heads of the biceps brachii muscle at about the center of the muscle (i.e. half way between anatomical landmarks at the shoulder and the elbow), and one on the triceps brachii.

B. Study Participants

We examined the stretch reflexes of the biceps brachii in both sides of four (4) hemi-spastic stroke individuals. A clinical assessment was performed by a physical/occupational therapist, upper arm impairment was assessed using the Fugl-Meyer test and the Chedoke-McMaster assessment. All participants gave informed consent via protocols approved by the Institutional Review Board under the Office for the Protection of Human Subjects at Northwestern University. Stroke participants were adults who had sustained a hemiparetic stroke at least six months prior to experimental testing.

C. Data Collection

The Delsys preamplifier has a bandwidth of 20-450 Hz for surface recordings with a gain set at 100x for all tested subjects. The surface EMG signal was digitized at a rate of 2 kHz (CED, Power 1401). Sensotec force or force applied/generated at the biceps tendon was filtered with a bandwidth of Hz and sampled at a rate of 1000 Hz. The data was collected using the software program from CED, Spike2 (version 6), and stored on a computer for subsequent analysis.

D. Data Analysis

Two parameters were extracted from the recorded force trace, 1) the maximum tap force and 2) the maximum reflex response. The maximum tap force is the calculated as follows,

$$F_{tap} = F_t - F_i, \tag{1}$$

where F_{tap} is the relative force between the absolute force applied on the tendon by the transient tap: F_t and the pre-stretched force on the tendon: F_i (Figure 3). Ftap is interpreted as the passive visco-elastic properties on the muscle.

The second value is the maximum reflex force which is calculated as follows,

$$F_{max} = F_r - F_i, \tag{2}$$

where F_{max} is the relative force between absolute reflex force F_r and the pre-stretch force on the tendon F_i (Figure 3).

To quantify the surface EMG activity of the biceps, we computed the average rectified EMG (RIEMG). It was calculated as follows,

$$RIEMG = \frac{\Sigma V - b}{\Sigma V_{pre}} \tag{3}$$

where V is the voltage of the reflex, b is the base line voltage and V_{pre} the voltage prior to a stimulation. It is understood that the summation window are equivalent for both V and V_{pre}.

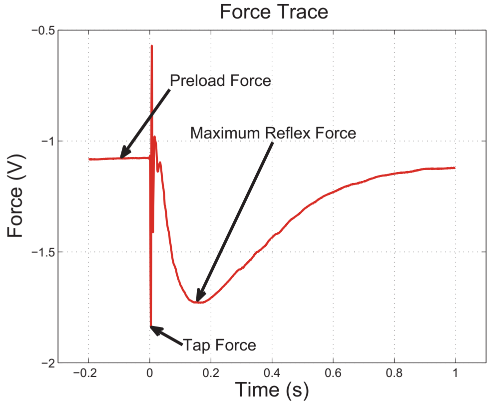

Fig. 3. Force trace: the force trace was the continuous resultant force of the actuator on the tendon. It was measured by a force sensor mounted at the end of the tapper. In this study we extracted three different information from the trace: the preload force which is the force at which the tendon is initially loaded at, the tap force which is the force exerted by the tap and the maximum reflex force which is the maximum measurement delivered by a reflex response.

III. RESULTS

A. Threshold: EMG and Maximum Reflex Force

Using our tendon tapping method we were able to detect distinct EMG and force threshold differences between the affected and contralateral side of all four tested stroke subjects (Table I). Further, the threshold values derived from the EMG and force traces in the same subject were consistent with each other (Table I).

In three of our four subjects, the EMG recording shows that the threshold of the stretch reflex was markedly lower for the spastic side as compared to the contralateral side (Figure 4 and Table I).

TABLE I

POSITION OF THRESHOLD FOR EACH SUBJECT

Subject	EMG (mm)		Max Reflex Force (mm)	
	Spastic	Contralateral	Spastic	Contralateral
1	5	13	6	13
2	7	14	9	14
3	10	11	10	11
4	12	-	12	-

B. Characterization

Additionally, since we were able to collect data over a fairly large range of tendon indentations, we were also able to quantify and characterize the relation between input tap force and indentation, a relation that was approximately linear (Figure 4). We were also able to characterize the relation between the reflex force and tendon indentation, which was also approximately linear. In contrast, the relation between EMG and tendon indentation was approximately sigmoidal in shape (Figure 4).

C. Tap Force

In three of our four subjects, the forces elicited by the taps were identical on the two sides, over the range of tested indentations. In the fourth subject, the tap force was similar over a large part of the range. When tapping force is plotted against tapper indentation position the relationship is linear in all four of our subjects. The tap force is therefore also a measure of the passive properties of the musculotendinous apparatus, and this constancy implies that for matched initial tap responses, we are delivering comparable stimuli to the tendons on both sides of the subject.

Another advantage of this method is that we can readily separate tendon mechanical from reflex force responses. This is because the stimulus time window does not overlap the time of the reflex response (Figure 3).

IV. DISCUSSION AND CONCLUSION

Our major findings were that a linear position controlled actuator could be used to indent the tendon of spastic muscle, as a way to produce controlled muscles stretch, without moving the whole limb. When we use tendon force as a surrogate measure of stretch, and superimpose sharp tendon taps to generate responses, we find that the threshold muscle lengths were systematically longer in spastic as compared with contralateral or normal control muscles.

A. Tendon Strain Measurements: Benefits and Costs

There are many potential benefits to this tendon loading/tapping technique. First, the input to the system is controlled and repeatable, making it possible to set a base line level of stretch and to stimulate the system with a broad range of input amplitudes and bandwidths. Second, unlike EMG measurements, which are often non-linear, tendon strain measurements are able to quantify the activity of the muscle as a whole in a relatively linear manner. Third, because we are able to obtain input force measures, the force trace provides information on reflex activity and also on the passive muscle properties. Finally, in the spectrum of reflex stimulators, when its design is finalized, our tendon tapper is potentially more portable and lower in cost than are large-scale actuated systems used to manipulate whole limbs. With limited additional effort this tool could potentially be used by the medical community for standard reflex measurements.

In order to reliably elicit and measure a reflex with the device, the joint has to be immobilized and the device has to be placed on the tendon accurately. Hence the limitations of the device are mostly mechanical. If this device were to be transferred to the clinic, a thoughtful design would have to be undertaken to minimize its size and to increase its portability. Furthermore, we need to be able to measure reflexes from different joints, adding further complexity to the design.

B. EMG vs Force Measurements

Both the EMG and the force measurements are able to show the existence of a reflex threshold (Figure 4). As the tap force is increased incrementally, the RIEMG values often reach a plateau, where the maximum reflex force keeps increasing suggesting saturation in the EMG measurements. This phenomenon may be due in part to the sampling properties of the EMG electrode, which can

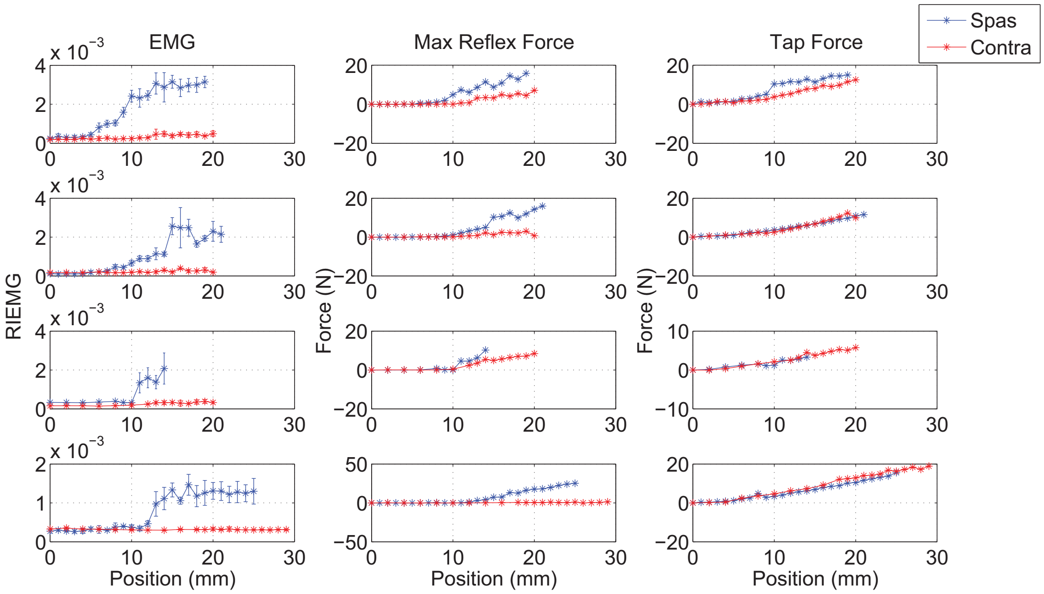

Fig. 4. Results: The tap sequences were administered on both sides of each individuals. One is represented by the blue trace for the spastic side and the other by the red trace for the contralateral side. For the first two columns (EMG & Max Reflex Force) we observed a clear difference between the spastic and contralateral side with regards to EMG activity and reflex force suggesting a difference in reflex susceptibility. For the third column we did not observe a clear difference suggesting similar passive viscoelastic properties for both sides.

only record electrical activity across a given surface area. At higher muscle activation levels, the EMG measurements are underestimating the activity of a muscle and subsequently the motoneuron pool. It also becomes difficult to quantify the system when the relationship between the input and output is non-linear, as compared with steady force measurements.

C. Motor Pool Threshold Estimation

The threshold at which the motor pool responds to a stimulus can be estimated using both EMG and tendon tension measurements. For spastic data, the threshold is clearly discernible, and it can be detected by eye. For the control, we have to rely on mathematical detection methods. In our case we used two standard deviations from the mean as a criteria to determine threshold. The force trace is more suited to determine motor pool threshold than is the EMG due to its linearity. In fact, when two lines are fitted to the data, they intersect at the threshold. For some of the subjects however, EMG processing was able to detect a threshold at a lower stimulus than was discernable on the force race. This apparent dichotomy is probably due to the limited resolution of the load cell that was used. In order to remedy this a more sensitive load will be used in future iterations.

D. Gain vs Threshold of Motoneuron

Our data shows that the tap force delivered on the tendon was (for the most part) the same for the spastic limb as for the control for each subject (Figure 4). This implies that the muscle spindle receptors of the different muscles were stretched equivalently, consistent with previous work [2]. Therefore, the input to the motor neuron pool for both sides was essentially the same. We can look at the spindle afferent information elicited by tap as being proportional to the force delivered on the tendon, with the u=input increasing in size with greater tap force.

E. Predicting Threshold Change

As discussed above, these data suggest that the threshold of the motor neuron pool has declined after a hemiparetic stroke [3] [4]. Using this argument, it is possible to estimate a value for the change in the threshold, expressed as a difference in length or in tendon stress.

F. Conclusion

Three significant results can be extracted from this protocol. The first is that we were able to deliver and measure a reflex response of a single muscle with a small fully embedded tool (actuator and sensor). Second, the force trace results show a linear relationship between tap force and maximum reflex force. Third a simple method was devised to estimate the threshold of a motoneuron pool.

V. ACKNOWLEDGMENTS

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