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Myotonometric Measurement of Muscular Properties of Hemiparetic Arms in Stroke Patients

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1. Introduction

Stroke is the leading cause of functional disability. The most significant impairment developed in individuals with stroke is the loss of normal skeletal muscle tone on the affected side, which leads to the lack of normal, controlled movements and further limits the individual's ability to carry out tasks of daily living. Session 1 of this chapter describes skeletal muscle changes after stroke and defines functional roles of muscle tone, elasticity, and stiffness. Session 2 discusses methods for measuring muscle tone, elasticity, and stiffness, including common clinical measure, laboratory measure, and a new novel myotonometer. Session 3 presents metric properties of the myotonometric measurements in previous studies. Session 4 provides an overview of myotonometric measurement relevant to stroke motor rehabilitation and future research directions, with special attention on the reliability, validity, and sensitivity to treatment-induced change of using the myotonometer to measure muscle properties of relaxed extensor digitorum, flexor carpi radialis, and flexor carpi ulnaris muscles in patients with stroke. Session 5 concludes the clinical value of myotonometric measurements in stroke rehabilitation.

1.1 The definition and functional role of muscle tone, elasticity, and stiffness

Muscle tone involves active tension and passive (resting) intrinsic viscoelastic tone (Ditroilo et al., 2011; Masi & Hannon, 2008; Simons & Mense, 1998). Human resting muscle tone was defined as the passive tonus or tension of skeletal muscle that derives from its intrinsic molecular viscoelastic properties (Masi & Hannon, 2008); that is, resting muscle tone is the viscoelastic stiffness without contractile activity (Simons & Mense, 1998). The functional roles of passive muscle tone are for maintaining balanced stability posture and for achieving energy-efficient costs for prolonged duration without fatigue (Masi & Hannon, 2008).

Muscle elasticity is defined as the property of a muscle to return to its original form or shape after removing a deforming force, and muscle stiffness is a muscle's resistance to deformation (Masi & Hannon, 2008; Panjabi, 1992; Simons & Mense, 1998). Factors that affect resting muscle tone, elasticity, and stiffness include neuromuscular disorders (Alhusaini et al., 2010; Hafer-Macko et al., 2008; Ratsep & Asser, 2011), massage (Huang et

al., 2010), stretching maneuvers (Magnusson, 1998; Reisman et al., 2009), aerobic exercise (Hafer-Macko et al., 2008), the length of skeletal muscle (Ditroilo et al., 2011; Hoang et al., 2007), and eccentric exercise (Hoang et al., 2007; Whitehead et al., 2001). Decreased muscle elasticity brings on easier fatigueability and limited movement speed (Gapeyeva & Vain, 2008). Muscle performing the movement (agonist) stretches out the antagonist muscle. Antagonist muscles with higher stiffness require greater effort for stretching, which leads to worse economy of movement (Gapeyeva & Vain, 2008).

1.2 Skeletal muscle changes after hemiparetic stroke

Evidence has revealed that the mechanisms of abnormal muscle tone in stroke patients include physiologic as well as mechanical (viscoelastic) properties of muscle (Dietz et al., 1981; Katz & Rymer, 1989; Pandyan et al., 1999; Rydahl & Brouwer, 2004). Significant changes in structural and mechanical properties of the paralyzed muscle occur after a stroke (Sjostrom et al., 1980; Svantesson et al., 2000). Muscular atrophy and muscle phenotype shift to fast-twitch fiber proportions in the hemiparetic leg muscle after a stroke and relate to muscle fatigue, poor fitness, poor physical performance, and neurologic gait deficit (Hafer-Macko et al., 2008). Spasticity (hyperactivity of stretch reflexes) and hypertonia (i.e., increased stiffness and viscosity) are common impairments after stroke (de Vlugt et al., 2010; Katz & Rymer, 1989). Spasticity is attributed to increased muscle tone related to hyperreflexia according to Lance (1980) who defined spasticity as a velocity-dependent increase in tonic stretch reflexes (muscle tone) with exaggerated tendon jerks, resulting from reflex hyperexcitability (Lance, 1980). Hypertonia, i.e., increased resistance to passive stretch, was more associated with intrinsic changes of the muscles than increased reflex activity (O'Dwyer et al., 1996). Moreover, the muscle stiffness of the affected leg was much higher than that of the contralateral leg after a stroke, suggesting a difference in the passive mechanical properties of the muscles of the spastic limb compared with the normal limb (Svantesson et al., 2000).

2. Methods for measuring muscle tone, elasticity, and stiffness

In recent decades, new methods, such as botulinum toxin, have been increasingly used to treat spasticity due to stroke (Shaw et al., 2011). Thus, the need for a quantitative measurement of muscle tone in the clinical setting has been highlighted. The development of an adequate tool that is reliable, valid, and responsive to measure the progression of muscle properties and success of treatments becomes urgent (Haas & Crow, 1995).

2.1 Common clinical measure of muscle tone

The Ashworth Scale (AS) and the Modified Ashworth Scale (MAS) are the most common clinical measures of muscle tone, rating the resistance perceived to passive stretch of the muscle with a 5- or 6-point ordinal scale, respectively (Ashworth, 1964; Bohannon & Smith, 1987; Pandyan et al., 1999). Although they are useful in the clinic, these two measures have been criticized for:

- not standardizing stretch velocity in manual testing (de Vlugt et al., 2010),
- not quantifying resistance in absolute units (Pandyan et al., 1999),
- not providing an assessment of activated muscle tone (Sommerfeld et al., 2004),

- subjectively grading and clustering of scores (Katz & Rymer, 1989; Pandyan et al., 1999),
- only being applicable for the extremities (Leonard et al., 2001),
- lacking sensitivity for detecting smaller degrees of changes in spasticity (Lance, 1980),
- poor discrimination between increased muscle tone and soft-tissue stiffness (de Vlugt et al., 2010; Sheean & McGuire, 2009), and
- lacking correlation with functional changes after treatment (Ward, 2000).

The reliability and validity of both scales have also been questioned (Aarrestad et al., 2004; Katz & Rymer, 1989; Leonard et al., 2003; Pandyan et al., 1999; Pomeroy et al., 2000).

The AS has only been validated for measuring spasticity around the elbow after stroke (Lee et al., 1989). The MAS is reliable for measuring muscle tone in certain muscle groups, such as the elbow, wrist, and knee flexors, in stroke patients (Gregson et al., 2000). These critiques and limitations reaffirm the need for identifying suitable clinical tools that reliably and accurately assess the biomechanical properties of muscle, including tone, elasticity, and stiffness (Pandyan et al., 1999).

2.2 Laboratory measure of mechanical properties of muscle

The mechanical properties of muscle are generally assessed in laboratories with expensive and heavy equipment, such as isokinetic and ultrasound machines (Ditroilo et al., 2011). Ultrasonography is limited to superficial structures and does not assess specific muscle mechanical properties (Nordez et al., 2008).

2.3 A new novel instrument for measuring muscle tone, elasticity, and stiffness simultaneously

For clinical applications, mechanical properties, such as muscle elasticity and stiffness, may not be accurately estimated by the clinical scales. A novel hand-held myotonometer, the Myoton myometer (Müomeetria AS, Tallinn, Estonia) device, provides painless and noninvasive means to obtain quantitative and objective assessments of mechanical properties of muscles (Gapeyeva & Vain, 2008; Roja et al., 2006). The Myoton myometer was primarily developed for testing the superficial skeletal muscles (Gapeyeva & Vain, 2008). The principal differences between myotonometry and traditional measures of muscle tone are that the former measures the tone, elasticity, and stiffness simultaneously and quantitatively (Gapeyeva & Vain, 2008), is not affected by tester strength (Leonard et al., 2003), and is more sensitive to detect small changes (Aarrestad et al., 2004; Leonard et al., 2001). The myotonometer has the additional advantages of an appropriate size for being portable, relatively inexpensive and convenient to use, and relatively easy to administer over a wide range of postural or extremity musculature (Aarrestad et al., 2004; Ditroilo et al., 2011; Gapeyeva & Vain, 2008; Gubler-Hanna et al., 2007; Ianieri et al., 2009).

Muscle properties can be measured with the myotonometer without the muscle being moved, which might be helpful with patients who have limited range of motion or pain with movement (Leonard et al., 2003). Its application leads to a more objective assessment of numeric parameters of muscle tone, elasticity, and stiffness within minutes (Aarrestad et al., 2004). Therefore, the myotonometer appears to be clinically applicable without compromising the precision related to more complex laboratory methods and ensures a better pathophysiological vision of all three muscle properties.

From discerning muscular properties using myotonometric measurements, clinicians would be able to have a better understanding of the pathologic processes of muscle functions in individuals with spastic muscle secondary to stroke, design a specific rehabilitation program for each patient, make appropriate clinical decision, plan a more targeted and customized treatment specifically for each patient with abnormal muscle properties, and assess the efficacy of specific therapeutic treatment (Pandyan et al., 1999; Wade, 1992). This chapter will illustrate the metric properties of myotonometric measurement based on previous studies and our recent research in stroke rehabilitation.

3. Metric properties of the myotonometric measurements: Reliability and validity

Metric properties of the myotonometric measurements, such as reliability, validity, and responsiveness are the prerequisites of a useful measurement. From literature review, previous studies focused on examining reliability and validity of myotonometric measurement. The results of previous reliability studies have indicated that myotonometry is highly reliable for measuring skeletal muscle viscoelastic parameters in healthy individuals (Bizzini & Mannion, 2003; Ditroilo et al., 2011; Gavronski et al., 2007; Leonard et al., 2004; Leonard et al., 2003; Viir et al., 2006), children with cerebral palsy (Aarrestad et al., 2004; Lidstrom et al., 2009), and patients with Parkinson's disease (Marusiak et al., 2010; Ratsep & Asser, 2011). There is no study investigating the reliability of the myotonometer in stroke patients, which may limit the interpretation of the change for myotonometric measurements.

The construct validity of the myotonometer has been established in healthy individuals (Gubler-Hanna et al., 2007), patients with upper motor neuronal disorders (Leonard et al., 2001), and stroke survivors (Rydahl & Brouwer, 2004). Studies have shown that muscle stiffness increased with increasing contractile force and muscle activation, indicating that muscle stiffness during contracted conditions provides an indirect measure of muscle strength (Aarrestad et al., 2004; Bizzini & Mannion, 2003; Gubler-Hanna et al., 2007; Leonard et al., 2001; Rydahl & Brouwer, 2004). Moreover, Katz and Rymer (1989) demonstrated that extending a limb against passive resistance may be more related to the viscoelastic properties of the soft tissues than to spasticity, indicating that biomechanical measures correlate most closely with motor function. These findings provide the theoretic basis for use of muscle strength and motor function measures to further validate myotonometric measures.

4. Metric properties of the myotonometric measurements: Reliability, validity, and responsiveness of the Myoton-3 myometer in patients with stroke

Previous metric studies of myotonometry have not yet reported the responsiveness. The responsiveness of the instrument is its ability to detect change over time, which is an important quality to detect small changes in muscle properties and assess the effectiveness of specific treatment. Additionally, previous reliability and validity studies applied the myotonometer on large muscles of the trunk and extremities. Wrist and finger control is the motor function most likely to be impaired after stroke. Proper function of the muscles involved in hand movements is crucial to manual exploration and manipulation of the environment.

Our recent study (Chuang et al., 2012) addressed the test-retest reliability, validity, and responsiveness of the Myoton-3 myometer used for assessing tone, elasticity, and stiffness of the affected forearm muscles under a relaxed state in stroke rehabilitation. The Myoton-3 myometer represents a new technology to quantify mechanical properties of resting and contractile muscles. To the best of our knowledge, this was the first report to show the metric soundness of the Myoton-3 myometer for assessing muscle tone, elasticity, and stiffness of the extensor digitorum, flexor carpi radialis, and flexor carpi ulnaris muscles in patients with stroke. Information reported in this study that is relevant to purposes of this book chapter is summarized below.

4.1 Study sample

We recruited 67 patients (40 men and 27 women) who were a mean age of 54.67 (SD, 10.90) years. The mean time since the stroke onset was 21.12 (SD, 13.63) months, and 31 patients had left hemiplegia. All participants had sustained a first-ever stroke, Brunnstrom stage III to V for the proximal and distal upper extremity (UE) (Brunnstrom, 1970), MAS ≤ 2 in any joint of the UE (Bohannon & Smith, 1987), no cognitive impairment (Mini-Mental State Examination score ≥ 24) (Folstein et al., 1975), not participated in any experimental rehabilitation or drug studies, and not used anti-spasticity drugs for the UE musculature (e.g., botulinum toxin type A) during the study period. Institutional Review Board approval was obtained from the study sites, and written informed consent was obtained from each patient before inclusion.

4.2 Instrument

The functional state of the participants' skeletal muscles was assessed by using myotonometric measurements with the Myoton-3 myometer, created at the University of Tartu in Estonia (Vain, 1995).

The Myoton-3 myometer has a two-armed lever. On the long lever is the testing end and on the short lever is the core of the electromagnet. The essence of the method lies in giving the muscle a short mechanical impulse to evoke decaying oscillations of the muscle because of the elastic behavior of the muscle. The working principles of the Myoton-3 myometer were as follows: the testing end of the Myoton-3 was placed perpendicular to the skin surface above the muscle to be measured and a brief mechanical impulse was applied, shortly followed by a quick release to the muscle through an acceleration probe. The characteristics of the muscle deformation and also the damped oscillations of the muscle evoked after the quick release of the testing end were recorded by the acceleration transducer at the testing end of the device. At the moment the Myoton-3 myometer pickup has created the maximum compression of the tested muscle, the corresponding acceleration a_{\max} characterizes the resistance force of the muscle for the deformation depth Δl (Figure 1).

The parameters of the graph characterize the functional state of the muscle. Displacement (s) is the difference in the initial position of the tested muscle and its final position. The relationships between position, velocity, and acceleration form an important application of the definite derivative. The velocity is defined by the derivative of position at a given time; whereas the acceleration is defined by the derivative of velocity at a given time. The average velocity of the muscle is the total displacement during an extended period of time, divided by that period of time. Average acceleration is the total change in velocity over an extended

period of time, divided by the duration of that period. In Figure 1, time moment 1 (t_1) denotes the beginning of the mechanical impulse to the muscle. The maximum of the deformation speed is obtained at time moment 3 (t_3) and from that moment the muscle deformation speed decreases and at time moment 4 (t_4) the acceleration transducer of the device has reached the maximum depth of its trajectory inward the muscle. At time moment 5 (t_5) the forces of muscle elasticity have given to the transducer its maximum speed upwards. At time moment 6 (t_6) this speed has decreased to zero under the influence of gravity. The above-described process repeats itself until the oscillation has decayed completely.

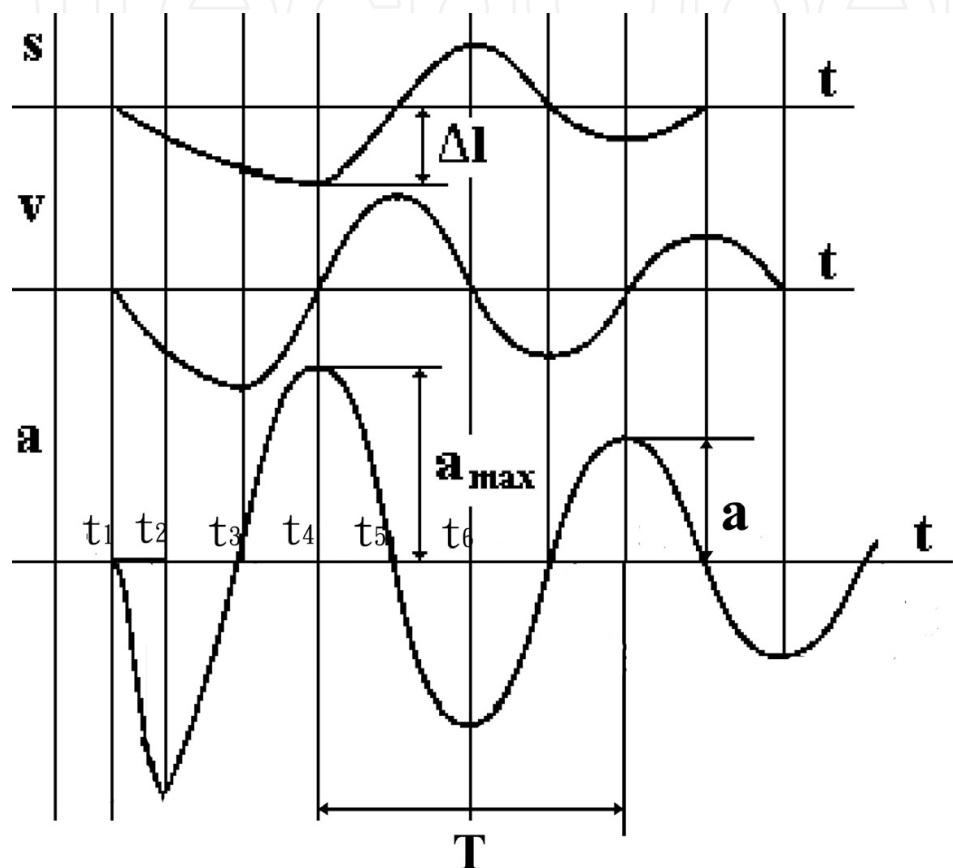


Fig. 1. An oscillation graph of the muscle shows the acceleration (a), velocity (v), and displacement (s) of the muscle produced in the process of damped natural oscillation measured by the Myoton-3 myometer.

The parameters measured by the myotonometer are oscillation frequency, decrement, and stiffness. The acceleration value of the first period of oscillations characterizes the deformation of the muscle, and the value of the next oscillation period provides the basis for calculating the oscillation frequency (Hz). The oscillation frequency is usually 11 to 16 Hz in relaxation and 18 to 40 Hz in contraction, depending on the muscle (Gapeyeva & Vain, 2008). The frequency of the damped oscillations characterizes the muscle tone, the mechanical tension in a relaxed muscle. The higher the value, the more tense is the muscle. The frequency of the damping was calculated as:

$$\text{Frequency (Hz)} = 1 / T$$

where T is the oscillation period in seconds (Figure 1).

The logarithmic decrement of the damping oscillations characterizes muscle elasticity, which is the ability of the muscle to restore its initial shape after contraction. Elasticity is inversely proportional to the decrement. If the decrement of trained muscles decreases, the muscle elasticity increases. The decrement values are usually 1.0 to 1.2, depending on the muscle. The logarithmic decrement of damping was calculated as:

$$\text{Decrement} = \ln(a_{\max} / a)$$

where a_{\max} is the maximal amplitude of oscillation and a is the oscillation amplitude (Figure 1).

Stiffness (N/m) reflects the resistance of the muscle to the force deforming the muscle (Roja et al., 2006). The usual range of stiffness values is 150 to 300 N/m for resting muscle and may exceed 1000 N/m for contracted muscles (Gapeyeva & Vain, 2008). Stiffness was calculated as a ratio between the force applied and the muscle deformation:

$$\text{Stiffness (N/m)} = f / \Delta l = m \times a_{\max} / \Delta l$$

where f is the force applied, m is the mass of the testing end (kg), a_{\max} is the maximal acceleration of oscillation (meter/second²), and Δl is the deformation depth of the muscle (meter) (Figure 1).

4.3 Procedures

Myotonometric testing of the affected extensor digitorum, the flexor carpi radialis, and the flexor carpi ulnaris in relaxed state was conducted before and after treatments. All participants received a 1.5-hour therapy session 5 times per week for 4 weeks. A senior occupational therapist administered the outcome measures at baseline and after the 4-week treatment. Before measurement, participants were informed about standard measurement procedure with their elbow flexion 30° to 45°, the palm downward for the affected extensor digitorum measurement and palm upward for measurements of the affected flexor carpi radialis and ulnaris muscles (Figure 2) (Gapeyeva & Vain, 2008). The investigator applied resistance to the tested muscles and requested participants to make an effort to resist. At the same time, the investigator established the location of the tested muscles by the visual-palpatory test. Participants were instructed to lie supine and relax the muscles maximally. Three trials were recorded with a 1-second interval, and the average value was used for analysis. To investigate test-retest reliability, 58 of the 67 individuals were tested twice on the affected side with the same procedure, 30 minutes apart, at baseline.

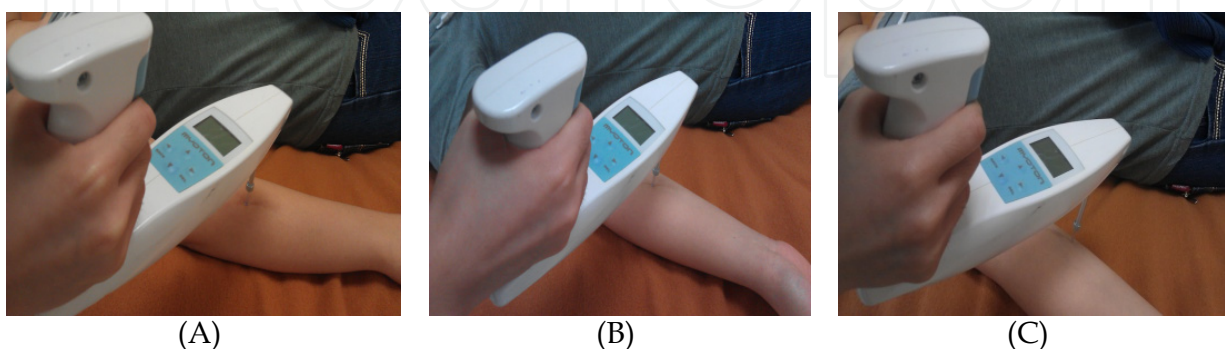


Fig. 2. The standard measurement location of the measured muscles: (A) extensor digitorum, (B) flexor carpi radialis, and (C) flexor carpi ulnaris

4.4 Criterion measures

The Myoton-3 measures, as well as criterion measures for hand strength, including grip strength, lateral pinch power, and palmar pinch power, the Action Research Arm Test (ARAT), and Brunnstrom stage were performed before and after treatments.

4.5 Data analysis

Statistical analyses were performed with SPSS version 16.0 software (SPSS Inc, Chicago, IL USA) and values of $P < 0.05$ were considered statistically significant. The analysis of variance (ANOVA) was used to compare the baseline and posttreatment characteristics of the 3 affected muscles. The Bonferroni method was used for post hoc pairwise comparisons.

Test-retest reliability of the Myoton-3 was determined by using the intraclass correlation coefficient (ICC) with 95% confidence intervals (CIs); an ICC value exceeding 0.80 indicated high reliability (Weir, 2005).

Concurrent validity of the Myoton-3 was determined using the Pearson correlation (r) test to establish relationships with hand strength and the Spearman rho (ρ) test to calculate the degree of correlations with the ARAT and Brunnstrom stage, respectively. The strength of correlations was interpreted as low (0.00-0.25), fair (0.25-0.50), moderate to good (0.50-0.75), and good to excellent (>0.75) (Portney, 2009).

The standardized response mean (SRM) was used as the index of the responsiveness of the Myoton-3 according to changes of the affected and unaffected limbs from pretreatment to posttest. The SRM was estimated as the ratio of the mean change scores to the standard deviation of the change scores from patients whose myotonometric measures improved over time (i.e., the change score from pretreatment to posttreatment was negative in muscle properties), and the values were categorized as large (>0.8), moderate (0.5-0.8), and small (0.2-0.5) (Cohen, 1988).

4.6 Results

4.6.1 Comparison of the muscular properties of the extensor digitorum, flexor carpi radialis, and flexor carpi ulnaris at pretreatment and posttreatment

Table 1 summarizes the mean (SD) of the myotonometric measurements for muscle tone, elasticity, and stiffness of the extensor digitorum, flexor carpi radialis, and flexor carpi ulnaris muscles at pretreatment and posttreatment.

| | Muscular properties | Extensor digitorum | Flexor carpi radialis | Flexor carpi ulnaris |
|-------------------------|---------------------|--------------------|-----------------------|----------------------|
| Pretreatment Mean (SD) | Tone (Hz) | 17.60 (2.82) | 14.78 (3.01) | 13.45 (2.80) |
| | Elasticity | 1.89 (0.27) | 1.31 (0.31) | 1.35 (0.33) |
| | Stiffness (N/m) | 354.90 (62.16) | 297.85 (65.47) | 272.85 (57.72) |
| Posttreatment Mean (SD) | Tone (Hz) | 17.03 (2.64) | 15.03 (3.19) | 13.39 (2.40) |
| | Elasticity | 1.84 (0.34) | 1.31 (0.40) | 1.40 (0.34) |
| | Stiffness (N/m) | 341.24 (51.02) | 309.26 (74.09) | 268.94 (55.05) |

Table 1. Mean and standard deviation of the myotonometric measurements for muscular properties of the 3 affected forearm muscles

Results of the ANOVA showed a significant difference in muscle tone, elasticity, and stiffness among the 3 affected muscles before and after treatment ($P < 0.0001$). Post hoc analyses revealed that muscle tone and stiffness of the extensor digitorum were significantly higher than those of the flexor carpi radialis and flexor carpi ulnaris at both pretreatment and posttreatment (pretreatment tone and stiffness: $P < 0.0001$, posttreatment tone: $P < 0.0001$, posttreatment stiffness: $P = 0.008$, $P < 0.0001$, respectively). Muscle tone of the flexor carpi radialis was significantly higher than that of flexor carpi ulnaris at pretreatment and posttreatment ($P = 0.025$, 0.002 , respectively). Muscle stiffness of the flexor carpi radialis was significantly higher than that of flexor carpi ulnaris at posttreatment ($P = 0.001$). Muscle elasticity of the extensor digitorum was significantly lower than the elasticity of flexor carpi radialis and flexor carpi ulnaris at both pretreatment and posttreatment ($P < 0.0001$, $P < 0.0001$, respectively). In general, the extensor digitorum showed higher tone and stiffness with lower elasticity compared to the flexor carpi radialis and ulnaris muscles.

4.6.2 Reliability of the Myoton-3 myometer in patients with stroke

The test-retest reliability was performed on a subset of 58 participants who underwent two pretreatment measurements. The Myoton-3 myometer showed high to very high test-retest reliability for muscle properties in affected extensor digitorum, flexor carpi radialis, and flexor carpi ulnaris (ICC, 0.86-0.96).

Our study indicated that the Myoton-3 is a highly reliable measurement tool with high test-retest reliability under relaxed conditions in measurements of affected forearm muscles of stroke patients. These findings are similar to those reported of the myotonometer for different muscles and study populations. The reliability of the myotonometer was high in the biceps brachii, rectus femoris, biceps femoris, and gastrocnemius in healthy individuals (Bizzini & Mannion, 2003; Ditroilo et al., 2011; Leonard et al., 2003; Marusiak et al., 2010); the biceps brachii in patients with Parkinson's disease (Marusiak et al., 2010); and in the brachii, gastrocnemius, and rectus femoris in children with cerebral palsy (Aarrestad et al., 2004; Lidstrom et al., 2009). In general, the Myoton-3 myometer is reliable for measurements in healthy individuals as well as for various patient populations.

4.6.3 Validity of the Myoton-3 myometer in patients with stroke

Significant correlations existed between the tone and stiffness of the 3 muscles and palmar pinch strength, between those of the flexor carpi radialis & ulnaris muscles and lateral pinch strength, and between those of the flexor carpi radialis and the ARAT at posttreatment. The posttreatment elasticity of the two flexor carpi muscles was significantly correlated with grip strength. The pretreatment elasticity of the flexor carpi ulnaris was significantly correlated with posttreatment grip strength, and the pretreatment muscle tone and stiffness of the flexor carpi radialis were significantly correlated with palmar pinch strength and ARAT. There was no significant correlations existed between the Brunnstrom stage and muscle properties of the 3 muscles at pretreatment. Posttreatment extensor digitorum tone and flexor carpi radialis stiffness were significantly correlated with the Brunnstrom stage.

The results of the concurrent validity showed partly significant associations between forearm muscle properties and hand strength and UE motor function, especially at

posttreatment, which indicates that they might measure similar constructs. Our present findings were compatible with those from a previous study reporting a correlation between muscle stiffness and muscle strength of the quadriceps (Bizzini & Mannion, 2003). In this study, the elasticity of the two wrist flexors tended to increase with greater grip strength at posttreatment. At posttreatment, the elasticity of the extensor digitorum and muscle tone and stiffness of the two wrist flexors tended to increase with greater lateral pinch strength. The muscle tone and stiffness of the extensor digitorum and the two wrist flexors appeared to increase with greater palmar pinch strength. The pretreatment and posttreatment muscle tone and stiffness of the flexor carpi radialis were correlated to palmar pinch strength and ARAT.

4.6.4 Responsiveness of the Myoton-3 myometer in patients with stroke receiving rehabilitation

The responsiveness of the extensor digitorum was higher than those of the flexor carpi radialis and ulnaris, with moderate to high for the affected extensor digitorum and small to moderate for the affected flexor carpi radialis and ulnaris. The responsiveness of the muscle tone and elasticity was moderate for the affected extensor digitorum and small for the affected flexor carpi radialis and ulnaris (tone: -0.57 vs -0.39 vs -0.35 ; elasticity: -0.75 vs -0.44 vs -0.31). The responsiveness of the elasticity of the affected extensor digitorum was significantly higher than that of the affected flexor carpi ulnaris (difference in SRM, 0.44 ; 95% CI, -0.78 to -0.11). The responsiveness of muscle stiffness was high for the affected extensor digitorum (-0.83) and moderate for the affected flexor carpi radialis (-0.71) and ulnaris (-0.77).

The responsiveness of the Myoton-3 is an important outcome measure and may serve as the foundation for therapy guidance and evaluation. The responsiveness to change of myotonometric measurements can be calculated through numeric data, provide a basis for estimates of whether the changes of muscle parameters over time are in the desired direction, and thus permit rehabilitation therapies to be adjusted accordingly. Our SRM calculations showed the affected extensor digitorum appears to be more responsive than the affected flexor carpi radialis and ulnaris in muscle tone, elasticity, and stiffness, and especially elasticity (-0.75 vs -0.44 vs -0.31). This result may arise from an emphasis on activation of wrist and finger extensor muscles elicited by the rehabilitation program the patients received. Thus, the extensor digitorum was much facilitated after treatments, and the flexor carpi muscles were not as sensitive as the extensor digitorum. Given that the ability to sustain finger extension is necessary in most functional hand activities; active finger extension is an important prognostic determinant and an early valid indicator of favorable UE function after stroke (Fritz et al., 2005; Nijland et al., 2010). Stroke patients with early finger extension after onset had a 98% probability of regaining some dexterity and a 60% probability of achieving full functional recovery of the hemiplegic arm at 6 months after stroke (Nijland et al., 2010).

4.6.5 Future directions

- Different treatment effects across treatment groups could adversely affect variability. Future studies with a larger sample size may analyze changes after specific treatment.

- Resting muscle tone during the relaxed condition does not fully quantify spasticity, which is characterized by a velocity-dependent and should be adequately performed under a dynamic state. Further studies may compare biomechanical properties of the resting muscles with the contracted muscle.
- With a sufficient sample size, a comparison of change in the myotonometric measures between patients who improved and those who did not should be analyzed separately.
- Further substantiation and generalization of these findings in larger and more diverse samples are warranted to determine clinical value of the Myoton-3.

5. Conclusion

The Myoton-3 myometer measures mechanical properties of the skeletal muscle, which may provide new insights into muscle functions to diagnose and treat muscle pathophysiology. In clinical practice and research settings, performance documented by the Myoton-3 myometer might be a useful indicator of muscle changes. This overview showed that the Myoton-3 myometer could be applied as a reliable, valid, and responsive device for objectively quantifying muscle tone, elasticity, and stiffness of resting forearm muscles in patients with stroke. These findings support the use of myotonometric measurement in stroke rehabilitation and further clinical trials.

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