ORIGINAL ARTICLE

Reliability, Validity, and Responsiveness of Myotonometric Measurement of Muscle Tone, Elasticity, and Stiffness in Patients With Stroke

Li-ling Chuang, PhD, PT, Ching-yi Wu, ScD, OTR, Keh-chung Lin, ScD, OTR

ABSTRACT. Chuang L-L, Wu C-Y, Lin K-C. Reliability, validity, and responsiveness of myotonometric measurement of muscle tone, elasticity, and stiffness in patients with stroke. Arch Phys Med Rehabil 2012;xx:xxx.

Objective: To assess the metric properties of a myotonometer.
Design: Metric study.
Setting: Three medical centers.
Participants: Stroke patients (N=67).
Intervention: Upper-extremity rehabilitation programs.
Main Outcome Measures: The tone, elasticity, and stiffness of relaxed extensor digitorum, flexor carpi radialis, and flexor carpi ulnaris were measured using the myotonometer. Fifty-eight patients completed the myotonometer measures twice at pretreatment. The myotonometric measurement and the criteria measures, including hand strength (grip, lateral pinch, and palmar pinch strength) and Action Research Arm Test (ARAT) were administered at pretreatment and posttreatment.

Results: The myotonometer showed high test-retest reliability for muscle properties in 3 muscles. Significant correlations existed between the tone and stiffness of the 3 muscles and palmar pinch strength, between those of the flexor carpi muscles and lateral pinch strength, and between those of the flexor carpi radialis and the ARAT at posttreatment. The posttreatment elasticity of the 2 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 the ARAT. The responsiveness of the extensor digitorum was higher than that of the flexor carpi radialis and ulnaris. Muscle stiffness was more responsive than tone and elasticity in 3 muscles.

Conclusions: Myotonometry can be a reliable, valid, and responsive outcome measure for assessing muscle properties after stroke rehabilitation.

Key Words: Muscles; Rehabilitation; Reproducibility of results; Stroke.

SPASTICITY and hypertonia (ie, increased stiffness and viscosity) are common impairments after stroke that may interfere with function and lead to functional disability.[1,2] Spasticity is the most common condition of increased muscle tone, characterized by velocity-dependent resistance to passive stretch and exaggerated tonic stretch reflexes in the muscle.[3] Mechanisms that contribute to muscle tone include reflex excitability, the viscoelastic properties of the musculotendinous unit, and the intrinsic properties of the contractile elements.[2,4-6] Understanding the properties of the muscles may lead to the development of more rational interventions to treat patients with spasticity. In recent decades, new methods have been used in stroke patients to treat increased muscle tone; thus, adequate tools that are reliable, valid, and responsive to measure the progression and success of interventions become important.[7]

The most widely accepted clinical measures of muscle tone are the Ashworth Scale (AS) and the Modified Ashworth Scale (MAS), where the resistance perceived to passive stretch of the muscle is categorized on a 5- or 6-point ordinal scale, respectively.[5,8,9] However, these measures have been criticized for not standardizing stretch velocity in manual testing,[1] not quantifying resistance in absolute units,[5] not providing an assessment of activated muscle tone,[10] subjectively grading and clustering of scores,[2,5] only being applicable for the extremities,[11] and lacking sensitivity for detecting smaller degrees of changes in spasticity.[3]

The reliability and validity of both scales have also been questioned.[2,5,12-14] The MAS is reliable for measuring muscle tone in certain muscle groups in stroke patients such as the elbow, wrist, and knee flexors.[15] The AS has only been validated for measuring spasticity around the elbow after stroke.[16] These limitations, combined with poor discrimination between increased muscle tone and soft-tissue stiffness,[1,17] as well as the lack of correlation with functional changes after treatment,[18] reaffirm the need for suitable clinical tools that reliably and accurately assess the biomechanical properties of muscle, including tone, elasticity, and stiffness.[5]

List of Abbreviations

ARAT	Action Research Arm Test
AS	Ashworth Scale
CI	confidence interval
ICC	intraclass correlation coefficient
MAS	Modified Ashworth Scale
SRM	standardized response mean
UE	upper extremity

From the School of Occupational Therapy, College of Medicine, National Taiwan University, Taipei (Chuang, Lin); Division of Occupational Therapy, Department of Physical Medicine and Rehabilitation, National Taiwan University Hospital, Taipei (Lin); Department of Occupational Therapy and Graduate Institute of Clinical Behavioral Science, College of Medicine, Chang Gung University, Taoyuan, (Wu), Taiwan.

Chuang and Wu contributed equally to this manuscript.

Supported by the National Science Council (grant nos. NSC 97-2314-B-002-008-MY3, NSC 99-2314-B-182-014-MY3, and NSC100-2811-B-002-131), and the National Health Research Institutes (grant nos. NHRI-EX100-10010PI and NHRI-EX100-9920PI) in Taiwan.

No commercial party having a direct financial interest in the results of the research supporting this article has or will confer a benefit on the authors or on any organization with which the authors are associated.

Clinical Trial Registration No.: NCT00780533 and NCT00917605.

Correspondence to Keh-chung Lin, ScD, OTR, 17, F4, Xu Zhou Road, Taipei, Taiwan, e-mail: *kehchunglin@ntu.edu.tw*. Reprints are not available from the author.

0003-9993/12/xxx-00442$36.00/0
doi:10.1016/j.apmr.2011.09.014

A hand-held myotonometer, uses painless and noninvasive means to provide quantitative and objective assessments of muscle properties. Mechanical characterization of the skeletal muscle, as measured by the myotonometer, may provide new insights into muscle function and help to diagnose the stage of pathologic processes taking place in the muscles.[19] Previous studies have indicated that the myotonometer is highly reliable for measuring skeletal muscle viscoelastic parameters in healthy individuals,[13,20-24] children with cerebral palsy,[12,25] and patients with Parkinson's disease.[21,26] However, the reliability of the myotonometer has yet to be investigated in stroke patients. Reliability should be established for all patient populations for which the instrument is intended.[27]

The construct validity of the myotonometer has been established in healthy individuals,[28] in patients with upper motorneuronal disorders,[11] and in stroke survivors.[6] Myotonometric measures of rectus femoris muscle compliance (displacement per unit force, inverse of stiffness) were highly correlated to muscle strength and activation levels during a voluntary isometric knee extension task.[28] Tissue compliance of the ankle plantarflexor muscle was related to total ankle stiffness in stroke patients.[6] Muscle stiffness increased with increasing contractile force and levels of muscle activation, indicating that tissue displacement during contracted conditions provided an indirect measure of muscle strength.[6,11,12,22,28] Moreover, Katz and Rymer[2] 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 to further validate myotonometric measures.

Proper evaluation of muscle properties is important in monitoring the progression of individuals during rehabilitation therapy, in making appropriate clinical decisions, for planning optimal treatment, and for assessing the efficacy of therapeutic interventions.[5,29] The responsiveness of the myotonometer has not yet been reported, and the sensitivity of the myotonometric measurement in detecting small changes in muscle properties associated with stroke rehabilitation remains unknown. Gaining knowledge about the metric properties of the myotonometer after stroke rehabilitation is crucial for clinicians and researchers. The myotonometer was primarily developed for testing the superficial skeletal muscles,[30] and previous reliability and validity studies applied the myotonometer on large muscles of the trunk and extremities.

Given that wrist and finger control is the motor function most likely to be impaired after stroke and is a key precursor for prehensile activity, loss of this capability is a primary disabler for hand function. Proper hand function is vital for manual exploration and manipulation of the environment. The aim of this study was to investigate the test-retest reliability, validity, and responsiveness of the myotonometer for measuring muscle tone, elasticity, and stiffness of the forearm muscles under a relaxed state in stroke rehabilitation.

METHODS

Participants

We recruited 67 participants from 3 medical centers who were enrolled in ongoing research projects investigating the efficacy of robot-assisted training and mirror therapy. The inclusion criteria were (1) onset of a first-ever stroke, (2) demonstration of Brunnstrom stage III or above for the proximal and distal upper extremity (UE),[31] (3) no excessive spasticity in the UE (MAS≤2 in any joint) that might preclude the functional movements,[9] (4) no cognitive impairment (Mini-Mental State Examination score≥24),[32] (5) no UE fracture within 3 months, (6) no participation in any experimental rehabilitation or drug studies and no use of antispasticity drugs for UE musculature (eg, botulinum toxin type A) during the study period, (7) able to follow instructions to self-rate the measures included and perform therapeutic activities, and (8) willing to provide written informed consent. Institutional review board approval was obtained from the study sites, and written informed consent was obtained from each patient before inclusion.

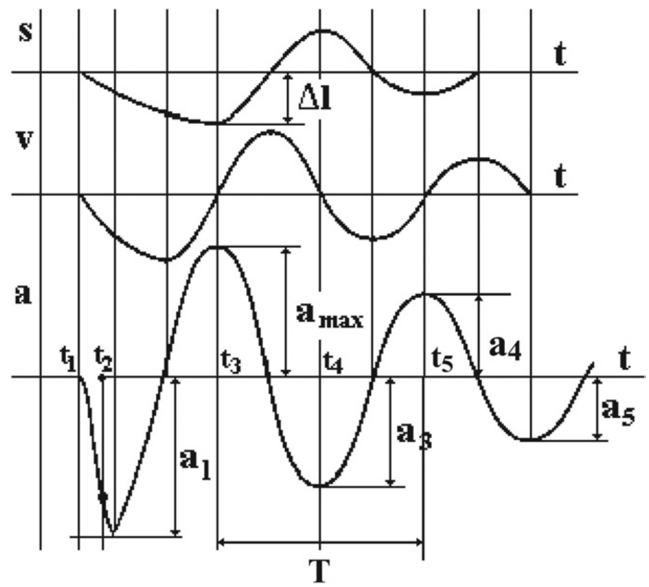

Fig 1. Oscillation graphs show the acceleration (*a*), velocity (*v*), and displacement (*s*) produced in the process of damped natural oscillation performed by the testing end of the myometer.

Interventions

Eligible participants received 1 of the 4 UE rehabilitation therapies: robot-assisted training, mirror therapy, mirror therapy with mesh-glove electrical stimulation, or conventional rehabilitation.[33] All participants received a 1.5-hour therapy session 5 times per week for 4 weeks. The interventions were provided at the participating hospitals under the supervision of 3 certified occupational therapists. Trained raters, whose competence was assessed by a senior certified occupational therapist, administered the outcome assessment to all participants at baseline and after the 4-week intervention. The raters were blinded to the individual's group.

Instrument and Procedure

Myoton-3 myometer. The functional state of skeletal muscle was assessed by using myotonometric measurements with the Myoton-3[a] device, created at the University of Tartu in Estonia.[34] The working principles of the Myoton-3 were as follows: the testing end of the Myoton-3 was placed perpendicular to the skin surface above the muscle to be measured, a brief mechanical impulse was applied, shortly followed by a quick release to the muscle through an acceleration probe, and the damped oscillations of the muscle response were recorded by the acceleration transducer at the testing end of the device. The oscillation graph created during the measurement expresses the acceleration of the testing end (fig 1).

The myotonometric measurements assess oscillation frequency, decrement, and stiffness. The acceleration value of the first period of oscillations characterizes the deformation of the muscle and that of the next oscillation period provides the basis for calculating the oscillation frequency (Hz). The frequency of the damped oscillations characterizes the muscle tone, which was calculated as: Frequency (Hz) = $1/(t_5 - t_3) = 1/T$, where t_5 and t_3 indicate the duration of the impact of the testing end on the muscle, and T is the oscillation period in seconds (see fig 1). The oscillation frequency is usually 11 to 16Hz in the functional state of relaxation and 18 to 40Hz in contraction, depending on the muscle.[30]

The logarithmic decrement of the damping oscillations characterizes muscle elasticity, which is the ability of the muscle to restore its initial shape after contraction. The logarithmic decrement of damping was calculated as: Decrement = $\ln(a_{max}/a_4)$, where a_{max} is the maximal amplitude of oscillation and a_4 is the oscillation amplitude. Elasticity is inversely proportional to the decrement (see fig 1). If the decrement of trained muscles decreases, the muscle elasticity increases. Decreased elasticity brings on quicker muscle fatigue, and the speed of a movement is limited if the muscle is less elastic.[30] The decrement values are usually 1.0 to 1.2, depending on the muscle.

Stiffness (newton per meter [N/m]) reflects the resistance of the muscle to the force deforming the muscle.[19] Stiffness was calculated as: Stiffness = $a_{max} \times m/\Delta l$, where m is the mass of the testing end of myometer, a_{max} is the maximal amplitude of oscillation, and Δl is the deepest tissue displacement of the testing end (see fig 1). Greater effort is required from the antagonist to stretch a stiff muscle, which leads to worse economy of movement.[30] The usual range of stiffness values is 150 to 300N/m for resting muscle and may exceed 1000N/m for contracted muscles.[30]

The Myoton-2 myometer[a] has good to excellent test-retest reliability for measuring viscoelastic stiffness of resting leg muscles (ie, rectus femoris, biceps femoris, and gastrocnemius muscle) in healthy individuals.[22]

Myotonometric testing of the bilateral extensor digitorum, the flexor carpi radialis, and the flexor carpi ulnaris was conducted before and after interventions. Before measurement, subjects were informed about standard measurement procedure. The UE was bent at the elbow joint, at 30° to 45° from the longitudinal axis of the upper arm, with the palm downward for measurement of the extensor digitorum and palm upward for flexor carpi and ulnaris measurements.[30]

The location of the measured muscles was first determined on the left side, thereafter on the right side. The subject was requested to make an effort with the individual muscle (applying resistance to the investigator's hand), and at the same time, the investigator established the location of the muscle belly by the visual-palpatory test. After the muscle had relaxed, the particular measuring point was marked with a marker; for example, the measuring point for the extensor digitorum was at the line of the proximal one-third of the UE, in the middle of the muscle belly. The muscles of the left side of the body were measured first. The subjects 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 both sides with the same procedure, 30 minutes apart, on the same day.

Outcome Measures

The outcome measures of the Myoton-3 and criterion measures, including hand strength—grip strength, lateral pinch strength, and palmar pinch strength—and the Action Research Arm Test (ARAT) were performed before and after interventions.

Hand strength. The Baseline digital hydraulic hand dynamometer and pinch gauge[b] were used for measurement of grip and pinch strength. Participants were evaluated in the standard testing position suggested by the American Society of Hand Therapists[35] and Mathiowetz et al.[36,37] Participants were seated with their shoulder adducted and neutrally rotated, elbow flexed to 90°, and forearm and wrist in a neutral position.

For the grip strength measurement, participants were instructed to squeeze the dynamometer with their hand as hard as they could. For the lateral pinch strength measurement, the pinch gauge was positioned between the pad of the thumb and the radial side of the middle phalanx of the index finger. For palmar pinch strength measurement, the pinch gauge was grasped between the pad of the thumb and the pad of the index finger. Participants were told to pinch as hard as they could. Three consecutive measurements with 2- to 3-minute intervals were performed for each assessment, and the arithmetic mean value of the 3 trials was used for statistical analysis. This method shows high repeatability, according to Haidar et al.[38]

Action Research Arm Test. The ARAT assesses the hemiplegic arm function of handling objects differing in size, weight, and shape, with 19 items divided into 4 domains of grasp, grip, pinch, and gross movement. A 4-level ordinal scale ranging from 0 (no movement) to 3 (normal movement)[39] is used, and a maximum total score of 57 points indicates normal performance. The ARAT has excellent clinimetric properties in stroke patients.[40-44]

Data Analysis

Statistical analyses were performed using SPSS 16.0 software.[c] For all analyses except the paired t test, the significance level was set at P less than .05. Mean data are presented with the SD. The 9 paired t tests were performed to test the differences in muscle tone, elasticity, and stiffness of the 3 muscles between the affected and unaffected limbs at pretreatment and posttreatment, respectively. The other 9 paired t tests were used to analyze the change of muscle tone, elasticity, and stiffness of the 3 muscles between pretreatment and posttreatment for the affected and unaffected limbs, respectively. Therefore, the Bonferroni correction was applied to set the significance level at $P<.006$ (.05/9) for the paired t test. Test-retest reliability of the myotonometer was determined by using the intraclass correlation coefficient (ICC) with 95% confidence intervals (CIs). The ICC was calculated using a 2-way mixed-effect model, with an agreement coefficient. ICC values vary from 0 (no relationship) to 1 (perfect relationship). For test-retest reliability, an ICC value exceeding .80 indicated high reliability.[45]

Concurrent and predictive validity of the Myoton 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. For concurrent validity, the pretreatment and posttreatment values of the muscle tone, elasticity, and stiffness were correlated with their respective pretreatment and posttreatment scores on the criterion measures. To assess the predictive validity of the Myoton, the pretreatment values of muscle properties were correlated with the posttreatment scores on the criterion measures. The strength of correlations was interpreted as low (.00–.25), fair (.25–.50), moderate to good (.50–.75), and good to excellent ($>.75$).[46]

The standardized response mean (SRM) was used as the index of the responsiveness of the Myoton according to changes of the affected and unaffected limbs from pretreatment to posttreatment. The SRM was estimated as the ratio of the

Table 1: Demographic and Clinical Characteristics of the Participants (N=67)

Characteristic	Value
Sex, men/women (n)	40/27
Age, mean ± SD (y)	54.67±10.90
Side of stroke, right/left (n)	36/31
Months after stroke, mean ± SD	21.12±13.63
Brunnstrom stage of upper limb, median (range)	
Proximal part	4 (3–5.5)
Distal part	4 (3–5.5)
MAS, mean ± SD	
Pretest	0.53±0.31
Posttest	0.43±0.25
Mini Mental-State Examination scores, mean ± SD	28.20±2.11
Intervention (n)	
Robot-assisted training	38
Mirror therapy	8
Mirror therapy with mesh-glove electrical stimulation	7
Conventional rehabilitation	14

mean change scores to the SD of the change scores from patients whose myotonometric measures improved after interventions (ie, the change score from pretreatment to posttreatment was negative in muscle properties), and the values were categorized as large (>.80), moderate (.50–.80), and small (.20–.50).[47] Patients who did not benefit from the treatment (ie, change score≥0) were excluded from the estimation of responsiveness. It was recommended to calculate responsiveness only for the improved patients[48] because a measure that has negative and positive change scores will have a small mean change score that results in a higher level of variability in change score and a small SRM value. The bootstrap resampling procedure was used to estimate 95% CIs for the SRMs and to examine the level of significance of the SRM differences among the 3 muscles.[49] A significant SRM difference among the 3 muscles was determined if the value 0 was not included between the 25th and the 975th observations taken from the 1000 paired bootstrap samples of the 2 paired muscles.[50]

RESULTS

The study comprised 67 stroke patients (40 men and 27 women) who were a mean age ± SD of 54.67±10.90 years. The mean time since stroke onset ± SD was 21.12±13.63 months, and 31 patients had left hemiplegia. Table 1 reports the demographic and clinical characteristics of the participants. Table 2 summarizes the mean ± SD myotonometric measurements for muscle tone, elasticity, and stiffness in the affected and unaffected forearm muscles. The paired *t* tests showed significant differences between the affected and unaffected side in pretreatment and posttreatment muscle elasticity of the extensor digitorum ($P<.001$, $P<.001$, respectively) and posttreatment elasticity of flexor carpi ulnaris ($P<.001$), and in pretreatment muscle tone and stiffness of the flexor carpi radialis ($P=.004$, $P=.001$, respectively). The posttreatment muscle tone and stiffness of the flexor carpi radialis in the affected limb was not significantly different from that of the unaffected limb ($P=.327$, $P=.256$, respectively), indicating muscle tone and stiffness of the affected flexor carpi radialis were close to that of the unaffected limb after interventions.

Multiple paired *t* tests were performed to confirm if statistically significant differences in mean scores had occurred from pretreatment to posttreatment among muscle properties. We

Table 2: Mean and SD of the Myotonometric Properties of the 3 Muscles of the UEs

		Pretest Mean ± SD		P*	Posttest Mean ± SD		P†	P<!---->‡	
Muscle	Variable	Affected	Unaffected	Affected-Unaffected	Affected	Unaffected	Affected-Unaffected	Affected: Pre-Post	Unaffected: Pre-Post
Extensor digitorum	Tone	17.60±2.82	17.31±2.99	.416	17.03±2.64	16.73±2.21	.292	.033	.077
	Elasticity	1.89±0.27	1.68±0.29	<.001	1.84±0.34	1.62±0.30	<.001	.167	.054
	Stiffness	354.90±62.16	343.37±62.99	.090	341.24±51.02	331.36±44.45	.100	.023	.081
Flexor carpi radialis	Tone	14.78±3.01	15.84±2.19	.004	15.03±3.19	15.37±1.92	.327	.394	.046
	Elasticity	1.31±0.31	1.24±0.28	.117	1.31±0.40	1.24±0.27	.056	.898	.930
	Stiffness	297.85±65.47	326.97±52.34	.001	309.26±74.09	318.89±46.19	.256	.101	.141
Flexor carpi ulnaris	Tone	13.45±2.80	13.55±2.19	.760	13.39±2.40	13.52±2.11	.667	.827	.891
	Elasticity	1.35±0.33	1.27±0.33	.016	1.40±0.34	1.25±0.32	<.001	.165	.603
	Stiffness	272.85±57.72	278.30±62.92	.456	268.94±55.05	271.60±50.94	.714	<.001	.326

*Associated with the paired *t* test between the affected side and unaffected side at pretest.
†Associated with the paired *t* test between the affected side and unaffected side at posttest.
‡Associated with the paired *t* test between the pretest and posttest on the affected and unaffected sides.

Table 3: Test-Retest Reliability of Myotonometric Properties of the 3 Muscles of the UEs

Muscle	Variable	Affected (95% CI)	Unaffected (95% CI)
Extensor digitorum	Tone	0.93 (0.89–0.96)	0.86 (0.78–0.92)
	Elasticity	0.86 (0.77–0.91)	0.75 (0.62–0.85)
	Stiffness	0.92 (0.87–0.95)	0.86 (0.77–0.91)
Flexor carpi radialis	Tone	0.96 (0.93–0.97)	0.93 (0.88–0.96)
	Elasticity	0.92 (0.87–0.95)	0.93 (0.88–0.96)
	Stiffness	0.94 (0.90–0.97)	0.92 (0.86–0.95)
Flexor carpi ulnaris	Tone	0.93 (0.88–0.96)	0.89 (0.82–0.93)
	Elasticity	0.90 (0.83–0.94)	0.89 (0.82–0.93)
	Stiffness	0.90 (0.84–0.94)	0.87 (0.80–0.92)

found significant changes in muscle stiffness of the flexor carpi ulnaris on the affected side ($P<.001$). The P values for muscle stiffness of all 3 muscles on the affected side were smaller than those for tone and elasticity.

Table 3 lists the reliability coefficients for measurements of the affected and unaffected forearm muscles. The test-retest reliability was performed on a subset of 58 participants who underwent 2 pretreatment measurements. The Myoton-3 myometer showed high to very high test-retest reliability for muscle properties in affected and unaffected extensor digitorum, flexor carpi radialis, and flexor carpi ulnaris (ICCs, .75–.96).

Table 4 reports concurrent validity of outcome measures at pretreatment and posttreatment. A significant correlation was found between the grip strength and elasticity of the flexor carpi radialis (r=–.30) and ulnaris (r=–.35) at posttreatment. Significant correlations existed between the elasticity of the extensor digitorum and lateral pinch strength (r=–.24) and between the tone (r=.37) and stiffness (r=.35) of the extensor digitorum and palmar pinch strength at posttreatment. Significant correlations existed between the elasticity of the flexor carpi radialis (r=–.30) and ulnaris (r=–.35) and grip strength at posttreatment. The tone and stiffness of the flexor carpi radialis were significantly correlated with lateral pinch strength at posttreatment (r=.27, r=.27, respectively), palmar pinch strength at pretreatment (r=.48, r=.48, respectively) and posttreatment (r=.42, r=.48, respectively), and the ARAT at pretreatment (ρ=.27, ρ=.30, respectively) and posttreatment (ρ=.29, ρ=.36, respectively). The tone and stiffness of the flexor carpi ulnaris were significantly correlated with lateral pinch strength at posttreatment (r=.28, r=.25, respectively) and palmar pinch strength at pretreatment (r=.28, r=.52, respectively) and posttreatment (r=.57, r=.52, respectively).

As summarized in table 5, the elasticity of the flexor carpi ulnaris at pretest significantly correlated with grip strength at posttest (r=−.32). Muscle tone and stiffness of the flexor carpi radialis at pretest were significantly correlated with palmar pinch strength (r=.45, r=.40, respectively) and the ARAT (ρ=.25, ρ=.32, respectively) at posttest.

Table 6 demonstrates the responsiveness of the muscle tone, elasticity, and stiffness measurements by the Myoton in the affected and unaffected extensor digitorum, flexor carpi radialis, and ulnaris for the patients who demonstrated beneficial effects after stroke interventions. The responsiveness of the Myoton-3 was 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: −.57 vs −.39 vs −.35; elasticity: −.75 vs −.44 vs −.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, .44; 95% CI, −.78 to −.11). The responsiveness of muscle stiffness was high for the affected extensor digitorum (−.83) and moderate for the affected flexor carpi radialis (−.71) and ulnaris (−.77). The responsiveness of the muscle tone, elasticity, and stiffness of the unaffected extensor digitorum, flexor carpi radialis, and flexor carpi ulnaris was small (−.26 to −.48).

DISCUSSION

The present study was primarily an investigation of the reliability, validity, and responsiveness of the Myoton-3 in stroke rehabilitation. The Myoton-3 represents a new technology to quantify mechanical properties of resting and contractile muscles. To our knowledge, this is the first report that the Myoton-3 myometer can be reliable, valid, and responsive for assessing muscle tone, elasticity, and stiffness of the extensor digitorum, flexor carpi radialis, and flexor carpi ulnaris muscles in patients with stroke. Myotonometric measurements with sound metric properties may have diagnostic as well as therapeutic significance.

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 and unaffected forearm muscles of stroke patients. These findings are similar to those reported of myotonometers for different muscles and study

Table 4: Concurrent Validity of the Myoton-3 Measurements and Grip Strength, Lateral Pinch Strength, Palmar Pinch Strength, and ARAT Score

		Grip Strength		Lateral Pinch Strength		Palmar Pinch Strength		ARAT Score	
Muscle	Variable	Pretest	Posttest	Pretest	Posttest	Pretest	Posttest	Pretest	Posttest
Extensor digitorum	Tone	−.07	−.05	.02	.14	.01	.37*	−.03	−.19
	Elasticity	−.24	−.23	−.21	−.24*	.06	−.01	−.03	−.11
	Stiffness	−.04	−.06	.00	.18	.03	.35*	−.01	−.07
Flexor carpi radialis	Tone	−.05	.02	.24	.27*	.48*	.42*	.27*	.29*
	Elasticity	−.16	−.30*	.10	−.01	−.20	.10	.02	.03
	Stiffness	.12	.10	.27*	.27*	.48†	.48†	.30*	.36†
Flexor carpi ulnaris	Tone	−.17	.06	.05	.28*	.28*	.57†	.01	.11
	Elasticity	−.32†	−.35†	−.19	−.18	−.24	−.23	−.07	−.18
	Stiffness	−.12	−.03	.12	.25*	.52†	.52†	.10	.07

*$P<.05$; †$P<.01$.

Table 5: Predictive Validity of the Myoton-3 Measurements

Muscle	Variable	Grip Strength	Lateral Pinch Strength	Palmar Pinch Strength	ARAT Score
Extensor digitorum	Tone	−.03	.11	.32	−.13
	Elasticity	−.20	−.22	.05	−.03
	Stiffness	−.02	.07	.27	−.12
Flexor carpi radialis	Tone	−.02	.20	.45†	.25*
	Elasticity	−.10	.19	.13	.06
	Stiffness	.15	.18	.40*	.32†
Flexor carpi ulnaris	Tone	−.20	.04	.26	.02
	Elasticity	−.32†	−.12	−.16	−.05
	Stiffness	−.12	.09	.45†	.04

*$P<.05$; †$P<.01$.

populations. The reliability of the myotonometer was high in the biceps brachii, rectus femoris, biceps femoris, and gastrocnemius in healthy individuals[13,21,22]; the biceps brachii in patients with Parkinson's disease[21]; and in the brachii, gastrocnemius, and rectus femoris in children with cerebral palsy.[12,25] In general, the Myoton-3 myometer is reliable for measurements in healthy individuals as well as for various patient populations.

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.[22] In this study, the elasticity of the 2 wrist flexors tended to increase with greater grip strength after interventions. At posttreatment, the elasticity of the extensor digitorum and muscle tone and stiffness of the 2 wrist flexors tended to increase with greater lateral pinch strength. The muscle tone and stiffness of the extensor digitorum and the 2 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.

A possible reason for the lack of consistency in concurrent validity of measures across muscles might be that the grip and pinch strength and ARAT were tested under muscle contraction but the myotonometric properties were measured in a relaxed condition. A power grip is the result of forceful flexion of all finger joints with the maximum voluntary force that the subject is able to exert. A strong pinch requires contractions of the abductor pollicis brevis and opponent pollicis muscles of the thumb. The synergistic action of flexor and extensor muscles might also be an important factor in grip and pinch strength, resulting in less correlation with myotonometric measurements. The ARAT, consisting of 4 subscales of grasp, grip, pinch, and gross movement, requires coordination between the distal and proximal parts of muscles. This might contribute to the low correlations between the ARAT scores and myotonometric measurements of the forearm muscles.

The reason the relationships in the concurrent validity test were more significant at posttreatment than at pretreatment might be because of significant changes in muscle stiffness of the affected flexor carpi ulnaris and normalization of muscle tone and stiffness of the affected flexor carpi radialis after interventions. Normalization of muscle tone and/or stiffness of the affected flexor carpi radialis at posttreatment occurred along with the appearance of lateral and palmar pinch and control over voluntary movement. This agrees with Vain,[34] who proposed that muscle tone was one of the determining factors regarding the functional state of the muscle.

Not surprisingly, a similar tendency existed between muscle tone and stiffness. Muscle tone depends on intrinsic stiffness and is related to the mechanical properties in the muscle.[3] Resistance to a change in length is primarily because of passive/active stiffness and neutrally mediated reflex stiffness.[51] The increase in passive mechanical stiffness explains most of the increased joint stiffness that presents clinically in spastic hemiparetic patients[51]: a muscle with high tone is stiffer than usual and is more difficult to stretch.

The trend of predictive validity was similar to the concurrent validity at pretreatment. If pretest myotonometric measurements were significantly correlated to pretest criteria measures, then they showed better ability to predict posttest criteria measures. Individuals with higher pretest muscle tone and/or stiffness of the flexor carpi radialis appeared to have greater

Table 6: Responsiveness of Myoton-3 Measurements of the 3 Muscles of the Affected and Unaffected Limbs in Participants Who Improved After Interventions

Muscle	Variable	SRM (95% CI) Affected	SRM (95% CI) Unaffected
Extensor digitorum	Tone	−0.57 (−0.82 to −0.38)	−0.27 (−0.50 to −0.03)
	Elasticity	−0.75 (−1.01 to −0.54)	−0.41 (−0.63 to −0.20)
	Stiffness	−0.83 (−1.08 to −0.64)	−0.44 (−0.67 to −0.25)
Flexor carpi radialis	Tone	−0.39 (−0.66 to −0.12)	−0.30 (−0.54 to −0.09)
	Elasticity	−0.44 (−0.65 to −0.22)	−0.26 (−0.47 to −0.03)
	Stiffness	−0.71 (−0.99 to −0.48)	−0.48 (−0.69 to −0.26)
Flexor carpi ulnaris	Tone	−0.35 (−0.55 to −0.15)	−0.26 (−0.51 to −0.01)
	Elasticity	−0.31 (−0.53 to −0.09)	−0.25 (−0.52 to −0.03)
	Stiffness	−0.77 (−1.03 to −0.57)	−0.42 (−0.62 to −0.26)

palmar pinch strength and a higher ARAT score after stroke interventions. Individuals with better pretest elasticity of the flexor carpi ulnaris tended to have greater posttreatment grip strength, and better pretest stiffness of the flexor carpi ulnaris tended to have greater posttreatment palmar pinch strength. These results point out the significant importance of the flexor carpi radialis with palmar pinch strength and UE function and that of the flexor carpi ulnaris with progression of grip and palmar pinch strength. Wrist flexors are essential to perform testing movements of the hand dynamometer and the ARAT. Muscle tone and muscle stiffness have also shown a similar trend of correlations with criteria measures. The validity results provide the strongest direct evidence that the intrinsic stiffness of skeletal muscles was altered with changed muscle tone and that increased stiffness can reflect excessive muscle tone.

The responsiveness of the Myoton-3 is an important outcome measure after interventions as the foundation for therapy guidance and evaluation. The change of myotonometric measurements after interventions 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 (−.75 vs −.44 vs −.31). This result may arise from an emphasis on activation of wrist and finger extensor muscles elicited by robot-assisted training and mirror therapy with or without mesh-glove electrical stimulation, because flexor synergy of the UE is dominant after stroke. Thus, the extensor digitorum was much better after interventions, 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.[52,53] 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.[52]

In addition, an interesting finding of this present study was that the muscle stiffness of all 3 muscles showed better responsiveness than the muscle tone and elasticity. Moreover, the responsiveness of the Myoton-3 to changes in clinical endpoints from baseline to week 4 appeared to be higher for the affected side than the unaffected side, especially in stiffness of the extensor digitorum (−.83 vs −.44). The responsiveness of muscle tone and elasticity of the flexor carpi radialis and ulnaris on the affected side and the unaffected side was small. Our findings indicated that stiffness of the affected forearm muscles was improved more than tone and elasticity after the interventions.

For clinical practice, the findings of the present study suggest that the Myoton-3 myometer is a valuable complementary instrument with good metric properties when assessing muscle properties. Tone and stiffness measurements can be obtained with the myotonometer without the muscle being moved, which might be helpful with patients who have limited range of motion or pain with movement.[13] The myotonometer has the advantages of being portable and relatively easy to administer over a wide range of postural or extremity musculature.[12,28,30]

The principal differences between myotonometry and traditional measures of muscle tone are that it can measure the tone, elasticity, and stiffness simultaneously,[30] it is not affected by tester strength,[13] and it is more sensitive to detect small changes.[11,12] Its application leads to more objective assessment of numeric parameters of muscle tone, elasticity, and stiffness within minutes.[12] Therefore, the myotonometer appears to be clinically applicable without compromising the precision related to more complex laboratory methods. Discerning muscular properties from Myoton-3 measurements would facilitate the diagnosis of muscle functions and the subsequent indication for treatment.

Study Limitations

A prerequisite for using any instrument is knowledge of its performance characteristics and limitations because these are important when analyzing and interpreting the data. This study also needs to account for the limitations that may have affected the experimental results. First, this study is a secondary analysis of the data from ongoing clinical investigations of the efficacy of robot-assisted training and mirror therapy. If there are different treatment effects across treatment groups, this could be adversely affecting variability. Therefore, we performed analysis of variance to examine if there was any significant difference in mean change of myotonometric measurements from pretreatment to posttreatment among treatment groups. The results showed no significant difference in mean change of muscle tone, elasticity, and stiffness of all 3 muscles among the treatment groups ($P>.05$). Future studies with a larger sample size may analyze changes after specific intervention to clarify this issue.

Second, functional evaluation during dynamic conditions cannot be extrapolated from passive movements, as studied here. Resting muscle tone during the relaxed condition does not fully quantify spasticity. Assessment of spasticity should be adequately performed under a dynamic state because spasticity is characterized by a velocity-dependent increase in tonic stretch reflexes.[3] This highlights the need for further studies that compare biomechanical properties of the resting muscles with the contracted muscle.

Third, our responsiveness estimates of the Myoton-3 were derived from patients whose myotonometric measures improved after interventions, and the results are only applicable for patients who improved. 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.

Finally, the study included patients with a mild to moderate stroke, without major cognitive impairment, and without excessive spasticity in the UE. This might limit the generalization of the present findings to other patients. Further substantiation of these findings in larger and more diverse samples is warranted to determine clinical value of the Myoton-3.

We plan to use the Myoton-3 in a larger cohort of patients to study the effect of different interventions on the biomechanical properties of muscles. Use of the Myoton-3 in larger and more divergent patient groups will demonstrate whether it can be identified in abnormal system properties (eg, enhanced stiffness and muscle tone) as the foundation for therapy guidance.

CONCLUSIONS

Findings from this study indicate that the Myoton-3 myometer can 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. Mechanical characterization of the skeletal muscle measured by the Myoton-3 myometer may provide new insights into muscle functions to diagnose and treat muscle pathophysiology. Thus, performance documented by the Myoton-3 might be a useful indicator of biomechanical tissue changes in clinical practice and research. Further research is needed to study the clinical utility of the instrument based on a larger sample.

References

1. de Vlugt E, de Groot JH, Schenkeveld KE, Arendzen JH, van der Helm FC, Meskers CG. The relation between neuromechanical parameters and Ashworth score in stroke patients. J Neuroeng Rehabil 2010;7:35.
2. Katz RT, Rymer WZ. Spastic hypertonia: mechanisms and measurement. Arch Phys Med Rehabil 1989;70:144-55.
3. Lance JW. Spasticity: disordered motor control. Chicago: Year Book Publishers; 1980.
4. Dietz V, Quintern J, Berger W. Electrophysiological studies of gait in spasticity and rigidity. Evidence that altered mechanical properties of muscle contribute to hypertonia. Brain 1981;104: 431-49.
5. Pandyan AD, Johnson GR, Price CI, Curless RH, Barnes MP, Rodgers H. A review of the properties and limitations of the Ashworth and modified Ashworth Scales as measures of spasticity. Clin Rehabil 1999;13:373-83.
6. Rydahl SJ, Brouwer BJ. Ankle stiffness and tissue compliance in stroke survivors: a validation of myotonometer measurements. Arch Phys Med Rehabil 2004;85:1631-7.
7. Haas BM, Crow JL. Towards a clinical measurement of spasticity? Physiotherapy 1995;81:474-9.
8. Ashworth B. Preliminary trial of carisoprodol in multiple sclerosis. Practitioner 1964;192:540-2.
9. Bohannon RW, Smith MB. Interrater reliability of a modified Ashworth scale of muscle spasticity. Phys Ther 1987;67:206-7.
10. Sommerfeld DK, Eek EU, Svensson AK, Holmqvist LW, von Arbin MH. Spasticity after stroke: its occurrence and association with motor impairments and activity limitations. Stroke 2004;35: 134-9.
11. Leonard CT, Stephens JU, Stroppel SL. Assessing the spastic condition of individuals with upper motoneuron involvement: validity of the myotonometer. Arch Phys Med Rehabil 2001;82: 1416-20.
12. Aarrestad DD, Williams MD, Fehrer SC, Mikhailenok E, Leonard CT. Intra- and interrater reliabilities of the myotonometer when assessing the spastic condition of children with cerebral palsy. J Child Neurol 2004;19:894-901.
13. Leonard CT, Deshner WP, Romo JW, Suoja ES, Fehrer SC, Mikhailenok EL. Myotonometer intra- and interrater reliabilities. Arch Phys Med Rehabil 2003;84:928-32.
14. Pomeroy VM, Dean D, Sykes L, et al. The unreliability of clinical measures of muscle tone: implications for stroke therapy. Age Ageing 2000;29:229-33.
15. Gregson JM, Leathley MJ, Moore AP, Smith TL, Sharma AK, Watkins CL. Reliability of measurements of muscle tone and muscle power in stroke patients. Age Ageing 2000;29:223-8.
16. Lee KC, Carson L, Kinnin E, Patterson V. The Ashworth Scale: a reliable and reproducible method of measuring spasticity. Neurorehabil Neural Repair 1989;3:205-9.
17. Sheean G, McGuire JR. Spastic hypertonia and movement disorders: pathophysiology, clinical presentation, and quantification. PM&R 2009;1:827-33.
18. Ward AB. Assessment of muscle tone. Age Ageing 2000;29: 385-6.
19. Roja Z, Kalkis V, Vain A, Kalkis H, Eglite M. Assessment of skeletal muscle fatigue of road maintenance workers based on heart rate monitoring and myotonometry. J Occup Med Toxicol 2006;1:20.
20. Gavronski G, Veraksits A, Vasar E, Maaroos J. Evaluation of viscoelastic parameters of the skeletal muscles in junior triathletes. Physiol Meas 2007;28:625-37.
21. Marusiak J, Kisiel-Sajewicz K, Jaskolska A, Jaskolski A. Higher muscle passive stiffness in Parkinson's disease patients than in controls measured by myotonometry. Arch Phys Med Rehabil 2010;91:800-2.
22. Bizzini M, Mannion AF. Reliability of a new, hand-held device for assessing skeletal muscle stiffness. Clin Biomech (Bristol, Avon) 2003;18:459-61.
23. Leonard CT, Brown JS, Price TR, Queen SA, Mikhailenok EL. Comparison of surface electromyography and myotonometric measurements during voluntary isometric contractions. J Electromyogr Kinesiol 2004;14:709-14.
24. Viir R, Laiho K, Kramarenko J, Mikkelson M. Repeatability of trapezius muscle tone assessment by a myometric method. J Mech Med Biol 2006;6:215-28.
25. Lidstrom A, Ahlsten G, Hirchfeld H, Norrlin S. Intrarater and interrater reliability of myotonometer measurements of muscle tone in children. J Child Neurol 2009;24:267-74.
26. Ratsep T, Asser T. Changes in viscoelastic properties of skeletal muscles induced by subthalamic stimulation in patients with Parkinson's disease. Clin Biomech (Bristol, Avon) 2011;26:213-7.
27. Pynsent PB. Choosing an outcome measure. J Bone Joint Surg Br 2001;83:792-4.
28. Gubler-Hanna C, Laskin J, Marx BJ, Leonard CT. Construct validity of myotonometric measurements of muscle compliance as a measure of strength. Physiol Meas 2007;28:913-24.
29. Wade DT. Measurement in neurologic rehabilitation. Oxford: Oxford Medical Publications; 1992.
30. Gapeyeva H, Vain A. Methodical guide: principles of applying Myoton in physical medicine and rehabilitation. Estonia: Muomeetria Ltd; 2008.
31. Brunnstrom S. Movement therapy in hemiplegia. New York: Harper & Row; 1970.
32. Folstein MF, Folstein SE, McHugh PR. "Mini-mental state". A practical method for grading the cognitive state of patients for the clinician. J Psychiatr Res 1975;12:189-98.
33. Hsieh YW, Wu CY, Liao WW, Lin KC, Wu KY, Lee CY. The effects of treatment intensity in upper limb robot-assisted therapy for chronic stroke: a pilot randomized controlled trial. Neurorehabil Neural Repair 2011;25:503-11.
34. Vain A. Estimation of the functional state of skeletal muscle. In: Veltink PH, Boom HBK, editors. Control of ambulation using functional neuromuscular stimulation. Enschede: University of Twente Pr; 1995. p 51-5.
35. Fess EE, Moran CA. Clinical assessment recommendations. Indianapolis: American Society of Hand Therapists; 1981.
36. Mathiowetz V, Kashman N, Volland G, Weber K, Dowe M, Rogers S. Grip and pinch strength: normative data for adults. Arch Phys Med Rehabil 1985;66:69-74.
37. Mathiowetz V, Weber K, Volland G, Kashman N. Reliability and validity of grip and pinch strength evaluations. J Hand Surg Am 1984;9:222-6.
38. Haidar SG, Kumar D, Bassi RS, Deshmukh SC. Average versus maximum grip strength: which is more consistent? J Hand Surg [Br]2004;29:82-4.
39. Lyle RC. A performance test for assessment of upper limb function in physical rehabilitation treatment and research. Int J Rehabil Res 1981;4:483-92.
40. Platz T, Pinkowski C, van Wijck F, Kim IH, di Bella P, Johnson G. Reliability and validity of arm function assessment with standardized guidelines for the Fugl-Meyer Test, Action Research Arm Test and Box and Block Test: a multicentre study. Clin Rehabil 2005;19:404-11.
41. Rabadi MH, Rabadi FM. Comparison of the Action Research Arm Test and the Fugl-Meyer Assessment as measures of upper-extremity motor weakness after stroke. Arch Phys Med Rehabil 2006;87:962-6.

42. van der Lee JH, Beckerman H, Lankhorst GJ, Bouter LM. The responsiveness of the Action Research Arm test and the Fugl-Meyer Assessment scale in chronic stroke patients. J Rehabil Med 2001;33:110-3.
43. Hsieh YW, Wu CY, Lin KC, Chang YF, Chen CL, Liu JS. Responsiveness and validity of three outcome measures of motor function after stroke rehabilitation. Stroke 2009;40:1386-91.
44. Lin KC, Chuang LL, Wu CY, Hsieh YW, Chang WY. Responsiveness and validity of three dexterous function measures in stroke rehabilitation. J Rehabil Res Dev 2010;47:563-71.
45. Weir JP. Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. J Strength Cond Res 2005; 19:231-40.
46. Portney LG, Watins MP. Foundations of clinical research: applications to practice. 3rd ed. Upper Saddle River: Pearson/Prentice Hall; 2009.
47. Cohen J. Statistical power analysis for the behavioral sciences. 2nd ed. Hillsdale: Lawrence Erlbaum Associates; 1988.
48. Husted JA. Cook RJ, Farewell VT, Gladman DD. Methods for assessing responsiveness: a critical review and recommendations. J Clin Epidemiol 2000;53:459-68.
49. Efron B, Tibshirani RJ. An introduction to the bootstrap. New York: Chapman and Hall; 1993.
50. Stratford PW, Kennedy DM. Does parallel item content on WOMAC's pain and function subscales limit its ability to detect change in functional status? BMC Musculoskelet Disord 2004;5:17.
51. Lieber RL, Steinman S, Barash IA, Chambers H. Structural and functional changes in spastic skeletal muscle. Muscle Nerve 2004; 29:615-27.
52. Nijland RH, van Wegen EE, Harmeling-van der Wel BC, Kwakkel G. Presence of finger extension and shoulder abduction within 72 hours after stroke predicts functional recovery: early prediction of functional outcome after stroke: the EPOS cohort study. Stroke 2010;41:745-50.
53. Fritz SL, Light KE, Patterson TS, Behrman AL, Davis SB. Active finger extension predicts outcomes after constraint-induced movement therapy for individuals with hemiparesis after stroke. Stroke 2005;36:1172-7.

Suppliers

a. Muomeetria AS, Peterburi Rd 2F, Tallinn 11415, Estonia.
b. Fabrication Enterprises Inc, 3 Westchester Plz # 111, Elmsford, NY 10523.
c. SPSS Inc, 233 S Wacker Dr, 11th Fl, Chicago, IL 60606.