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ORIGINAL RESEARCH

Measuring Mechanical Properties of Spastic Muscles After Stroke. Does Muscle Position During Assessment Really Matter?

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Abstract

Objective: To investigate the influence of muscle position (relaxed vs stretched) on muscle mechanical properties and the ability of myotonometry to detect differences between sides, groups, and sites of testing in patients with stroke. We also analyzed the association between myotonometry and clinical measures of spasticity.

Design: Cross-sectional study.

Setting: Outpatient rehabilitation units including private and public centers.

Participants: Seventy-one participants (20 subacute stroke, 20 chronic stroke, 31 controls) were recruited (N=71).

Intervention: Muscle mechanical properties were measured bilaterally with a MyotonPRO at muscle belly and musculotendinous sites during 2 protocols (muscle relaxed or in maximal bearable stretched position).

Main Outcome Measures: Muscle tone and stiffness of the biceps brachii and gastrocnemius. Poststroke spasticity was evaluated with the Modified Tardieu Scale (MTS). A mixed-model analysis of variance was used to detect differences in the outcome measures.

Results: The analysis of variance showed a significant effect of muscle position on muscle mechanical properties (higher tone and stiffness with the muscle assessed in stretched position). Measurements with the stretched muscle could help discriminate between spastic and nonspastic sides, but only at the biceps brachii. Overall, there was a significant increase in tone and stiffness in the chronic stroke group and in myotendinous sites compared with muscle belly sites (all, $P<.05$). No correlations were found between myotonometry and the MTS.

Conclusions: Myotonometry assessment of mechanical properties with the muscle stretched improves the ability of myotonometry to discriminate between sides in patients after stroke and between people with and without stroke.

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Spasticity is a frequent and disabling poststroke sequela, with an estimated prevalence of 25%.[1] Despite being a well-known disorder, there is little consensus on how to measure spasticity.[2] Subjective scales are common in the clinical setting, with limited evidence to support their use because they lack proper validity,[3] reliability, and reproducibility.[4] Clinical measures cannot discriminate between the neural and nonneural (peripheral) components of spasticity,[4] except the Modified Tardieu Scale (MTS). The peripheral contribution to poststroke spasticity (PSS) can be quantified for clinical and research purposes using objective, noninvasive methods, for example, shear-wave elastography and myotonometry.[4,5] Myotonometry represents a valid, reliable, and convenient tool[4,6] that has proven to be useful to monitor PSS after conservative or invasive treatments.[7] However, current evidence on the ability of myotonometry to discriminate between spastic and nonspastic muscles after stroke is scarce and conflicting.[6] It

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has been recommended to conduct myotonometry measurement of PSS at several muscle sites of testing and in different muscle positions, that is, relaxed or stretched,[6] to get a clear picture of how muscle mechanical properties may change after stroke[8] and in response to rehabilitation programs.

This study aimed to investigate the differences in myotonometry scores for muscle tone and stiffness in patients with stroke, comparing sides (affected vs nonaffected), sites (muscle belly [MB] vs musculotendinous [MT]), and groups (subacute stroke, chronic stroke, control), during 2 evaluation protocols (relaxed or stretched muscle). As a secondary goal, we analyzed the possible associations between myotonometry and the MTS. We hypothesized differences between protocols in myotonometry scores and that measuring tone and stiffness in stretched position would help to better distinguish between the affected and nonaffected sides in patients with stroke and between individuals with or without stroke.

Methods

Design

We conducted a multicenter, cross-sectional study, including adults with subacute (6-36 weeks after the event)[9] or chronic (more than 36 weeks) stroke[10] and participants without stroke. The protocol of the study respected the ethical guidelines set in the Helsinki Declaration and was approved by the Junta de Andalucía Ethical Committee for Biomedical Research (CI 1222-N-16). It followed the Strengthening the Reporting of Observational Studies in Epidemiology framework for observational studies. All participants provided verbal and written informed consent.

Participants

Individuals with a first-ever stroke were selected from public and private centers. Participants should have at least a slight increase of biceps brachii and gastrocnemius muscle tone. This was identified with a score ≥1 in the Modified Ashworth Scale,[11] which addresses the involuntary muscle activation feature of spasticity[12] as the resistance to a passive movement.[13] The exclusion criteria were as follows: cognitive impairtment (score >24 in the Mini-Mental State Examination),[14] diagnosed mood disorder or other neurologic condition, prior severe upper or lower limb trauma, changes in medication for PSS in the previous 48 hours, treatment with botulinum toxin injections within 12 weeks or during the study period, and an epileptic crisis during the previous week. Those in the control group without stroke were recruited from the same population-based cohort.

Outcome measures

Muscle tone and dynamic stiffness of the biceps brachii and gastrocnemius were assessed with a MyotonPRO.[6,a] The device contains a probe that applies an initial load of 0.18 N to the skin and then adds up consecutive short impulses (0.40N) to the subcutaneous tissue to characterize mechanical properties. The MyotonPRO calculates muscle tone (tension) by measuring the natural frequency of the acceleration signal and muscle stiffness by measuring the damped natural oscillation response, using an accelerometer.[15] Measurements were taken bilaterally at MB and MT sites, with the muscle relaxed or in the maximum bearable stretched position. The mean score of the 2 consecutive measures was used for the analysis. Regarding the biceps brachii analysis, participants started in relaxed supine position, with the elbow flexed at 45° and forearm in neutral position. For measuring the gastrocnemius, participants lied in prone with approximately 45° of knee flexion. Three sites of muscle testing were included, namely 1 MT location and 2 MB sites. For MB, the mean value at the 2 sites was used in the analysis.

The level of PSS was measured with the MTS,[16] which adresess the muscle response to a manual stretch elicited as slow as possible (V1) and as fast as possible (V3). At fast stretch, muscle tone reflex increases and it is felt at a so-called "catch angle." V1 denotes the passive joint range of movement, whereas V3 denotes the catch angle used to assess spasticity. V1 and V3 were quantified with an electrogoniometer.[b] At V3, the quality of muscle reaction was scored from 0-5, where 0 represents no resistance during passive motion and 5 represents that the joint cannot be moved.[17] To conduct the MTS at the biceps brachii, participants were supine, and the elbow was initially positioned in maximal flexion and supination. For the lower limb, participants remained prone with knees fully extended and feet outside the table.

All outcomes were collected by the same examiner, who had more than 10 years of experience in neurorehabilitation using clinical measures and was previously trained with the MyotonPRO. The examiner remained unaware of the study aims and the participants' allocation group.

List of abbreviations:

MB	muscle belly
MT	musculotendinous
MTS	Modified Tardieu Scale
PSS	poststroke spasticity

Statistical analysis

Sample size was calculated with the G*Power software v. 3.1.9.2.[c] We assumed an α level of 0.05, an 80% statistical power, and a high effect size (η^2 = 0.15) for differences between groups on muscle tone and stiffness. This generated a sample of 19 participants per group.

Statistical processing was conducted with the PASW Advanced Statistics version 26.0.[d] Normal distribution of the data were evaluated with the Shapiro-Wilk test. We used a mixed-model analysis of variance to compare differences in tone and stiffness of the biceps brachii and gastrocnemius, using muscle position (relaxed vs stretched), side (affected vs nonaffected), and site (MB vs MT) as the within-participant factors and group (subacute stroke, chronic stroke, controls) as the between-participant factor. The Spearman rank test or the Pearson product-moment correlation coefficient analysis were used to test for associations between myotonometry measurement and the MTS. The level of significance was set to P<.05.

Data availability

The data that support the study findings are available from the corresponding author on request.

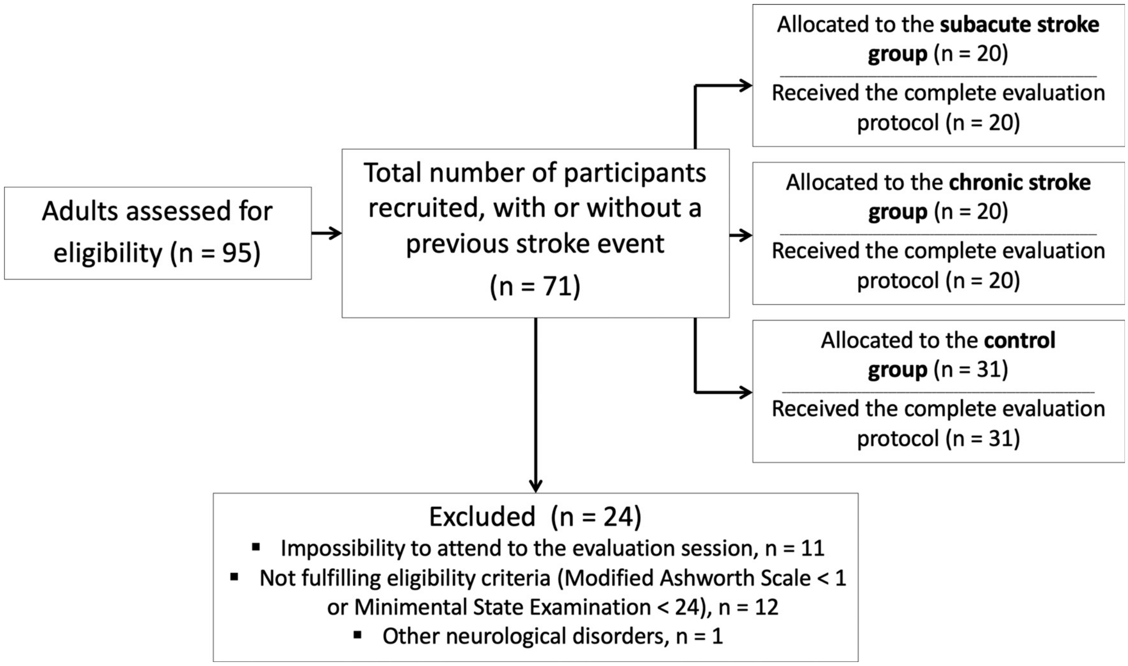

Fig 1 Flowchart diagram of the study participants.

Results

Seventy-one participants (20 subacute stroke, 20 chronic stroke, 31 controls) were recruited (fig 1). The clinical and demographic characteristics of the sample are listed in table 1.

Comparison between measurement protocols

Tables 2 and 3 include the tone and stiffness values at the different sites, sides, and groups during the evaluation protocols. The analysis of variance revealed a significant effect of muscle position during myotonometry assessment (relaxed vs stretched) on muscle mechanical properties for (1) the biceps brachii: tone, F=59.567, $P<.001$, η^2=0.095; stiffness, F=22.808, $P<.001$, η^2=0.039 and (2) the gastrocnemius: tone, F=313.2, $P<.001$; η^2=0.365; stiffness: F=341.57; $P<.001$; η^2=0.386. Overall, scores were significantly higher bilaterally and in most testing sites with the muscle stretched than with the muscle relaxed (with a large effect size).

Discriminative ability between spastic and nonspastic muscles

Myotonometry measurements in relaxed position could not discriminate between the affected and nonaffected sides or between patients with stroke and controls (all, $P>.05$), except for the lower limb, where higher values were found in the chronic stroke and control groups compared with those with subacute stroke (all, $P<.05$). For assessments in stretched position, differences between sides were only reported at the biceps brachii (increased stiffness in the spastic side, P=.020). Furthermore, the comparison between groups demonstrated (1) higher biceps brachii stiffness in the chronic stroke than in the control group (P=.045) and (2) lower gastrocnemius tone and stiffness in participants with subacute stroke compared with controls without stroke (all, $P<.05$).

Discriminative ability between sites of testing

There was a significant muscle position*sites interaction, with a moderate to large effect size, for (1) the biceps brachii: tone, F=8.158, $P<.004$, η^2=0.015; stiffness, F=6.330, $P<.012$, η^2=0.012 and (2) the gastrocnemius: tone, F=6.089, $P<.014$, η^2=0.011; stiffness: F=39.847, $P<.001$, η^2=.068. Differences between sites of testing were found in the 2 protocols, with higher tone and stiffness at MT sites than MB sites (all $P<.05$), except for the biceps brachii when measured in relaxed position that showed the opposite trend.

Table 1 Baseline clinical and demographic features of participants

Characteristic	Subacute Stroke (n=20)	Chronic Stroke (n=20)	Control Group (n=31)	*P* Value
Age (y), mean ± SD	60.2±9.7	61.45±9.7	60.8±10.6	.926
Sex (female), n, (%)	7 (35)	7 (35)	14 (45.2)	.689
Time after stroke (wk), median (IQR)	17 (6-34)	242.5 (58-1108)	NA	<.001
Affected side, left, n (%)	11 (55)	15 (75)	NA	.289
Hand dominance (right; left; ambidextrous), n (%)	20 (100)	17 (85); 1 (5); 2 (10)	25 (80.6); 6 (19.4)	.131
Leg dominance (right; left; ambidextrous) n (%)	19 (95); 1 (5)	16 (80); 1 (5); 3 (15)	26 (83.9); 5 (16.1)	.319

Abbreviation: NA, Not applicable.

Table 2 Muscle tone (Hz) and stiffness (N/m) for the biceps brachii at the different sites, sides, and groups during the 2 measurement protocols

Measurement Side		Muscle Position	Subacute Stroke Group Tone	Subacute Stroke Group Stiffness	Chronic Stroke Group Tone	Chronic Stroke Group Stiffness	Control Group Tone	Control Group Stiffness
MB sites	Dominant/nonaffected	Relaxed	14.2±1.8	259.1±53.3	14.8±1.5	271.6±40.7	14.7±2.1	271.2±48.7
		Stretched	15.0±1.9*	267.6±50.7	15.3±1.9*	276.4±44.8*	15.7±2.4*	289.3±53.4*
	Nondominant/affected	Relaxed	15.8±2.5	312.3±74.2	15.6±2.1	301.5±60.2	14.6±1.8	276.3±44.6
		Stretched	16.2±2.3	309.2±64.3	16.7±2.7*	315.9±68.3	15.6±2.0*	291.9±43.4*
MT sites	Dominant/nonaffected	Relaxed	14.3±1.3	245.6±33.2	15.1±2.9	275.7±75.2	14.3±1.5	253.4±39.7
		Stretched	16.4±1.8*	285.3±48.7*	16.4±2.3*	290.7±51.8	16.2±1.7*	282.41±36.0*
	Nondominant/affected	Relaxed	14.4±2.5	251.9±54.2	14.2±1.7	259.9±39.1	14.5±1.9	258.4±48.4
		Stretched	16.2±2.3*	285.3±62.7*	16.3±2.5*	307.9±58.7*	16.3±2.1*	288.4±50.1*

* Significant differences in the within-groups analysis when comparing scores at the same site and side between the 2 different protocols (muscle relaxed vs stretched).

Table 3 Muscle tone (Hz) and stiffness (N/m) for the gastrocnemius at the different sites, sides, and groups during the 2 measurement protocols

Measurement Side		Muscle Position	Subacute Stroke Group Tone	Subacute Stroke Group Stiffness	Chronic Stroke Group Tone	Chronic Stroke Group Stiffness	Control Group Tone	Control Group Stiffness
MB sites	Dominant/nonaffected	Relaxed	14.8±1.3	281.8±28.7	16.4±1.9	291.8±35.8	15.3±1.1	285.6±18.1
		Stretched	18.8±2.6*	348.4±50.8*	20.1±3.4*	387.9±93.7*	19.8±2.2*	383.3±65.2*
	Nondominant/affected	Relaxed	15.1±1.9	283.3±24.7	16.7±2.9	321.0±58.2	15.6±1.4	286.2±21.4
		Stretched	19.0±3.1*	350.2±56.4*	19.7±3.3*	386.6±106.2*	19.8±2.5*	375.4±64.4*
MT sites	Dominant/nonaffected	Relaxed	21.9±2.4	442.2±56.3	22.8±4.0	468.5±94.5	23.9±3.3	483.2±58.6
		Stretched	26.8±4.4*	594.6±123.7*	27.6±3.1*	620.1±103.4*	30.3±4.6*	697.6±128.5*
	Nondominant/affected	Relaxed	21.8±2.9	433.3±63.9	23.0±3.1	459.4±75.9	23.5±2.6	482.5±56.5
		Stretched	27.0±4.7*	577.6±132.8*	27.1±3.3*	599.2±104.2*	28.9±3.7*	659.8±113.5*

* Significant differences in the within-groups analysis when comparing scores at the same site and side between the 2 different protocols (muscle relaxed vs stretched).

Table 4 Descriptive data for the clinical measure of spasticity with the Modified Tardieu Scale in the subacute and chronic stroke groups

Measure	Subacute Stroke Group V1	Subacute Stroke Group V3	Subacute Stroke Group V1-V3	Subacute Stroke Group X	Chronic Stroke Group V1	Chronic Stroke Group V3	Chronic Stroke Group V1-V3	Chronic Stroke Group X
Biceps brachii	172.7±3.6	118.1±6.2	54.5±5.9	2.1±0.1	172.1±3.4	120.0±5.8	52.1±5.3	1.9±0.1
Gastrocnemius	83.1±2.7	65.5±2.4	17.6±2.6	2.3±0.1	78.5±3.5	60.1±4.1	18.4±2.3	2.4±0.1

Abbreviations: V1, joint angle at slow passive stretch (degrees); V3, "catch angle" at fast passive stretch (degrees); X, quality of muscle reaction at V3, from 0-5.

Correlations

Table 4 lists the clinical data for the measure of spasticity with the MTS in the stroke groups. No significant correlations were observed between myotonometry and the level of PSS, as assessed with the MTS (all $P>.05$).

Discussion

The present findings partly agree with our hypotheses. Tone and stiffness values changed among the 2 protocols, and myotonometry measurements with the muscle stretched could discriminate between the spastic and nonspastic sides, although only for the biceps brachii. When comparing groups, our results differed depending on the protocol and the assessed muscle. This distinct behavior has been explained on the basis of the different activation patterns of flexor and extensor muscles.[18]

Comparison between measurement protocols

Myotonometry is a valid and easy-to-use approach to objectively quantify muscle mechanical properties in people after stroke.[4,6] However, its high environmental sensitivity[4] and the large within- and between-participants variability[19] together with assessment-related aspects, such as muscle position and operator's experience,[4,20] stress the importance of agreeing on a standardized evaluation protocol.

Most previous research in patients with stroke has been conducted carrying out myotonometry measurements with the muscle relaxed. Our findings support the notion that muscle position, relaxed or not, can affect myotonometry scores, which depend on the tissue displacement-force relation.[21] In our study, we mostly observed higher tone and stiffness during evaluation with the muscle stretched. There are plausible reasons to understand this observation. Motor neuron responsiveness to passive stretch is increased after stroke,[22] which may become more evident with the muscle stretched than relaxed.[23] PSS is also related with shorter muscle fascicles and more compliant tendons that do not respond properly to stretch, increasing tone and stiffness.[24] Additionally, thixotropy, as the influence of movement and time of recovery after movement on mechanical properties,[25] is altered after stroke[26] and can modify muscle stiffness[25] and contribute to intrinsic hypertonia.[27] All in all, changes in mechanical properties after stroke are linked to changes in muscle morphology and composition.[28] This needs to be considered when assessing PSS with myotonometry. It could also explain the lack of association between myotonometry and clinical measures of spasticity, in line with former research[21] but in contradiction with studies that used myotonometry with the muscle contracted.[29,30] The scarce and contradictory literature on this issue, as well as the differences among studies in myotonometry devices and muscle position, can account for the lack of agreement.

Discriminative ability between spastic and nonspastic muscles

In patients with stroke, myotonometry could only discriminate between sides with the muscle stretched and at the upper limb. In agreement with most literature on the topic,[21,31-33] we observed higher stiffness at the spastic biceps brachii than the nonspastic side. It has been argued that stretching of the biceps brachii evokes higher resistance to elbow extension,[23] and this can make the muscle stiffer and increase tone.[34,35] Nonetheless, evidence on this issue is still preliminary and inconsistent.[36] For the gastrocnemius, myotonometry revealed no differences between sides in any of the protocols. These results agree with previous research using myotonometry to analyze the mechanical properties of different lower limb muscles[33,37-39] in individuals with acute[39] or chronic stroke.[33,37,38] Bilateral adaptations of the lower limbs, especially in those who remain nonphysically active after stroke,[40] could explain the lack of discriminative ability at the gastrocnemius.

Regarding the comparison between spastic and control group muscles, higher tone and stiffness are often expected in chronic poststroke stages,[37,38] although the changes in mechanical properties seem to depend on the assessed muscles.[37,38] As in the present study, biceps brachii tone and stiffness have shown to be increased in patients with chronic stroke.[23,41] Our findings, however, differed for the lower limb, with no differences between the control and chronic stroke groups and with lower tone and stiffness in those with subacute stroke. The reduced stiffness at early stages after stroke has been attributed to a low level of functional recovery.[42] Therefore, the clinical implications may be different for the upper and lower limbs and in patients with different levels of functionality. Future research should include subgroups of participants with different PSS severity and presentation to answer this question.[33]

Discriminative ability between sites of testing

Current literature suggests that spatial distribution of mechanical properties may not be homogeneous in spastic muscles. Consistent with this, tone and stiffness were significantly different at MT than at MB sites for both muscles and assessment protocols. The general trend was toward higher tone and stiffness at the tendon, as already observed for the biceps brachii in people with Parkinson disease[43] and for the gastrocnemius in patients with spinal cord injury[44,45] and in healthy volunteers,[46,47] with conflicting evidence for the lower limb.[48] Structural adaptations associated with PSS, for example, lower MB tension with respect to the tendon[49] and lack of muscle strain during stretch[50] and with limb disuse after stroke[51] can help to support these results. Additionally, soft tissue mechanical properties may behave differently, depending on joint position during assessment,[47,52] which highlights again the importance of measuring different spots within the muscle to characterize PSS.[6]

Study limitations

Several limitations need to be acknowledged. First, the subacute group included patients up to 9 months after stroke, in accordance with previous research on the topic.[9] Despite new standards describing chronic as more than 6 months,[53] endogenous plasticity persists beyond this period,[53] and the chronic stage starts when spontaneous recovery is reduced.[9,54] Therefore, one of the main recommendations for stroke research is to report the time from stroke onset.[53] Second, there was a wide time range after stroke for participants in the chronic group. Third, it could be argued that the MTS would have been more accurate than the Modified Ashworth Scale to screen participants for eligibility.[55] However, in the absence of sufficient psychometric evidence to recommend 1 specific clinical measure,[3] the Modified Ashworth Scale is easy and quick to complete,[13] is highly responsive,[56] and remains the common tool to quantify spasticity after stroke, despite its limitations.[3] Lastly, manual stretch was conducted slowly during evaluation in stretched position to avoid the stretch reflex, although the procedure was not time controlled, and possible muscle activation was not monitored by electromyography. Moreover, the time spent in maximum stretch before evaluation was similar for all participants, but it was not standardized.

Conclusions

Myotonometry measurements of tone and stiffness can discriminate better between the affected and nonaffected sides in people with stroke and between these and controls without stroke when myotonometry is performed with the muscle stretched. Clinical measures of spasticity were not correlated with myotonometry, regardless of the muscle position during evaluation.

Suppliers

a. MyotonPRO; Myoton AS.
b. Electrogoniometer; Biometrics Ltd.
c. G*Power software v. 3.1.9.2; Heinrich-Heine University.
d. PASW Advanced Statistics version 26.0; SPSS Inc.

Keywords

Muscle spasticity; Outcome assessment, health care; Rehabilitation; Stroke

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