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ORIGINAL ARTICLE

Shear wave elastography in the assessment of gastrocnemius spastic muscle elasticity: influences of ankle position and muscle contraction

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ABSTRACT

BACKGROUND: Following upper motor neuron syndromes (UMNS), intrinsic viscoelastic muscle properties such as elastic stiffness may be altered, which leads to muscle hyper-resistance to passive mobilization. So far, no gold standard assessment of hyper-resistance, whether clinical or instrumental, is available. Shear wave elastography (SWE) has been increasingly used for non-invasive evaluation of elastic stiffness of skeletal muscles in people with hyper-resistance.
AIM: Our study aimed to evaluate the validity of SWE at ankle neutral resting position (ANRP). Additional objectives included assessing the influence of ankle position, muscle contraction, and laterality on elastic stiffness, and evaluating the reproducibility and responsiveness of SWE.
DESIGN: Observational cohort study.
SETTING: Outpatients of the physical and rehabilitation medicine department of a university hospital in Brussels.
POPULATION: Thirty hemiparetic patients following UMNS with hyper-resistance in gastrocnemii muscles.
METHODS: Elastic stiffness was quantified by shear wave velocity (SWV) measurements of gastrocnemii muscles. A higher SWV corresponds to a higher elastic stiffness. Measurements were performed on the affected and less-affected limbs in ANRP, in passive dorsiflexion and during isometric contraction. Assessments were performed 3 times. Criterion validity, reproducibility, and responsiveness were evaluated. A linear mixed model was used to study position and laterality effect.
RESULTS: In ANRP, reproducibility was excellent and SWV was significantly higher in the affected limb than in the less-affected limb. This laterality effect disappeared in passive dorsiflexion and was even reversed during isometric contraction. SWV was significantly higher on both sides in passive dorsiflexion and during contraction than in ANRP.
CONCLUSIONS: Our results suggest that SWE measurements in ANRP are reliable and may provide a more valid measurement of gastrocnemii elastic stiffness following UMNS.
CLINICAL REHABILITATION IMPACT: SWE may be a useful clinical tool as an extension of the physical exam for longitudinal monitoring of passive muscle elastic stiffness, to assist with treatment decisions and to better quantify the therapeutic effect of procedures to reduce muscle overactivity. However, a standardized protocol should be used. ANRP seems to be the most valid position for assessing gastrocnemius elastic stiffness in neurological populations. This should be kept in mind for the choice of positioning in further studies.

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KEY WORDS: Muscle spasticity; Elasticity; Elasticity imaging techniques.

Muscle overactivity is one of the consequences of upper motor neuron syndromes (UMNS) that affects children and adults. This often leads to functional loss, limitations in the ability to perform activities of daily living, and decreased quality of life.[1] Hyper-resistance is one of the clinical features of muscle overactivity. It is still too often referred to as "spasticity," despite a European consensus recommending the use of the term hyper-resistance to describe the phenomenon of impaired neuromuscular response during passive stretch.[2] This model distinguishes 2 main components of hyper-resistance: a non-neural (tissue-related) component and a neural (central nervous system related) component. The non-neural component consists of muscular adaptations such as muscle stiffness (loss of extensibility). Muscle stiffness can be further divided into elasticity (the deformability of a muscle tissue as a result of an external impulse and the capability of returning to its original state) and viscosity (the internal resistance of muscle tissue to motion or deformation). Neural components include velocity dependent stretch hyperreflexia (spasticity stricto sensu) and non-velocity dependent spastic dystonia and co-contractions. Evaluation of muscle hyper-resistance is mostly based on clinical assessments, such as the Modified Ashworth scale (MAS) and Modified Tardieu scale (MTS). They are easy to use and require no equipment, but these measurements have poor intra-/inter-rater reliability.[3, 4] Moreover, these measurements cannot distinguish neural from non-neural components.[5] So far, no gold standard assessment of hyper-resistance, whether clinical or instrumental, is available.

Ultrasound elastography has been increasingly used for non-invasive evaluation of elastic stiffness of skeletal muscles in people with hyper-resistance. SWE generates a transient shear wave propagating in the tissue. In the medical literature, the shear wave velocity (SWV) (displayed in meter per second), the shear modulus (expressed in kPa) and the Young modulus have been used in reporting outcomes.[6]

Some studies have shown that muscle elasticity is also joint angle specific. Saeki *et al.*[7] and Lee *et al.*[8] showed that elastic stiffness increases respectively with ankle dorsiflexion and during active voluntary contraction in healthy volunteers. However, to our knowledge, no study has evaluated the influence of the ankle position and muscle contraction on the elasticity of gastrocnemius muscle in the affected and less-affected leg simultaneously in neurological adults suffering from hyper-resistance.

The first objective of our study was to evaluate the validity of SWE at ankle neutral resting position (ANRP) in hemiparetic subjects with hyper-resistance in gastrocnemii muscles. Our second objective was to assess the influence of ankle position and muscle contraction on the elasticity of gastrocnemius muscle in the affected and less-affected leg simultaneously. Our third objective was to evaluate the reproducibility and responsiveness of SWE.

Materials and methods

This study was registered in ClinicalTrials under NCT05510726.

Subjects

In this observational single-center cohort study, patients were prospectively enrolled at the Department of Physical Rehabilitation Medicine of the "Cliniques universitaires Saint-Luc" (Brussels, Belgium) between September 2022 and May 2023. Inclusion criteria were as follows: 1) age ≥18 years old; 2) hemiparesia/-plegia following upper motor neuron syndrome; 3) at least 3 months after injury; 4) muscle overactivity in affected lower limb. We excluded patients with 1) any other neurological or orthopedic condition that might interfere with the affected limb function; 2) aphasia or major cognitive impairment limiting functional assessment; 3) previous BoNT-A injection in the last 3 months; 4) previous treatment of muscle overactivity with surgical procedures in the affected limb. This study was approved by the relevant ethics committee and all patients signed a written informed consent after comprehensive explanation of the procedures, according to the Declaration of Helsinki.

Evaluations

All evaluations were performed by the same physician. Assessments on T1 and T2 were performed consecutively (short-term reliability) and assessment on T3 was performed after a 10-day interval, at the same time of the day (long-term reliability). Measurements were taken at T1, T2, and T3 in the gastrocnemii medialis and lateralis, bilaterally. Participants were asked to lie prone with their feet sticking out from the examination table to prevent contractions. Measurements were performed in the neutral position, in passive dorsiflexion as well as during muscle contraction. During passive dorsiflexion, a constant external force of 80 kPa was applied bilaterally by a second investigator using a MicroFet dynamometer. During muscle contraction, the patient was asked to apply a force of 50 kPa on the Microfet dynamometer bilaterally when possible. If the patient could not achieve à force of 50 kPa,

he was asked to perform the maximal force possible on the affected leg. The same force was then applied with the less-affected leg.

SWE

Ultrasound elastography examinations of the patients were made with SWE (DIAGNOSTIC ULTRASOUND SYSTEM Canon Aplio i800) using a linear probe (5-14 MHz) PLT 1005 BT. Those measurements were conducted by a physician (M.D.) with 3 months training in SWE and US. Transmission gel was applied. The transducer was placed parallel to the longer axis of the muscles with as little compression as possible (as any additional pressure may lead to overestimation of muscle stiffness). A region of interest that was approximately 10 mm in diameter was placed in the middle depth of the muscle units such that muscle fascia borders, tendon, and blood vessels were excluded. SWV (displayed as meters per second) were measured in the region of interest after a shear wave quality map automatically generated by the software revealed homogeneous color. Three measurements were made for each position, and the mean values were used for further analysis. SWV is influenced by material properties, with shear wave traveling faster through stiffer tissues.

MyotonPro

The Myoton (Myoton AS, Tallinn, Estonia) is a noninvasive hand-held myotonometer device aimed at recording, among others, the elastic stiffness of myofascial tissues.[9] It produces a series of damped oscillations induced by a single external mechanical impulse. The probe of the MyotonPro was placed perpendicularly where SWV had previously been obtained. With a pre-force of 0.18 N, a quick mechanical impulse of 0.4 N was released for 15 ms. The total force applied to the structure was 0.58 N. Following the single external mechanical impulse, free oscillations were recorded for 400 ms. Then, the device needed 10 ms for processing raw signals and five more to compute all the parameters. The sequence was looped five times for a total duration of 2.15 s. The mean value of the five sequences corresponds to one assessment allowing the calculation of stiffness (displayed as Newton per meter). One measurement was made for each position.[10, 11]

Clinical assessment

The following clinical assessments were performed for the affected leg at T1 and T3: MAS, MTS, passive range of motion, and Fugl-Meyer Assessment.[12] Hyper-resistance of the calf muscles was evaluated using the MAS and MTS in the supine position with both a flexed and extended knee. The passive range of motion of ankle dorsiflexion was measured in the supine position while extending and flexing the knee using a manual goniometer. The muscles and soft tissues were stretched at slow speed to avoid a stretch reflex. Regarding the Fugl-Meyer Assessment, only the subscale of motor function (/34 points) of lower extremity was performed.

Statistical analysis

Statistical analyses were performed using SPSS Statistics, v. 28 (IBM, Armonk, New York, NY, USA). Continuous data are presented as mean and standard deviation or median and first-third quartile. Categorical data are presented as counts and percentages. Normal distribution of variables was evaluated with statistical (Shapiro-Wilk) and graphical approaches (Q-Q plot). In order to validate SWE, we followed the standards proposed by the Consensus-Based Standards for the Selection of Health Measurement Instruments (COSMIN) checklist.[13] We assessed the criterion validity, reliability, internal consistency, and responsiveness.

Criterion validity was assessed by studying the correlation between muscle elasticity measured with SWE and 1) myotonometer; 2) clinical assessments of hyper-resistance and function. Spearman correlation was considered good, moderate, or poor if the correlation coefficient (r) was >0.6, 0.3<r>0.6, <0.3, respectively.[14]

A linear mixed model with random subject effect was used to compare SWV and search for interactions. SWV was considered as dependent variable while side, muscle, position and time were considered as factors. Fixed effects with non-nested build terms were used. Residuals were saved to check for normality based on graphical approaches (Q-Q plot and histogram).

Test-retest reliability (reproducibility) was assessed using intraclass correlation coefficients (ICCs), which were calculated with average measures, two-way random-effects model for absolute agreement with 95% confidence intervals (CI). ICCs<0.50 were considered poor, 0.50-0.75 moderate, 0.75-0.90 good, and >0.90 excellent.[15] ANOVA Friedman analyses were performed to see whether more than two related groups differed.

Measurement error was evaluated by use of the standard error of measurement (SEM).[16]

Responsiveness was estimated using the minimum detectable change (MDC). The MDC, which represents the magnitude of change necessary to exceed the measurement error of 2 repeated measures at a specified CI was

calculated for the 95% CI (MDC95).[16] MDC95 was also expressed as a percentage (MDC95%).

The power calculation based on the results of a previous SWE study,[17] estimated that a sample size of 28 patients was needed to obtain a power of 80% with a first type error of 0.05. Missing data were not replaced. For all tests, the statistical significance was set at P<0.05.

Results

We included 30 participants in our study. Of those 30 patients, 24 were males (80%), 20 (69%) suffered from stroke, and median age was 56 (47-64.75) years. Ten (33.3%) patients had already received past BoNT-A injection in the gastrocnemius muscle with a median duration since last BoNT-A injection of 17.5 (9.5-26.25) months. The detailed sample characteristics are shown in Table I. All variables were abnormally distributed except for Fugl-Meyer Assessment. SWV of every measurement can be found in Table II.

Regarding the results of the mixed model (Figure 1), no time effect was observed (P>0.05). Interaction muscle-side was not statistically significant (P>0.05) and thus removed from the mixed model. On the contrary we found a statistically significant effect of muscle, side and ankle position on SWV. Moreover, the interactions muscle-position and side-position were statistically significant (Table III). Residuals were normally distributed according to the graphical approaches.

TABLE I.—*Demographic and clinical characteristics of the sample.*

Gender	
Males, N. (%)	24 (80)
Females, N. (%)	6 (20)
Age, median [Q1-Q3] (years)	56 [47-64.75]
Disease	
Stroke, N. (%)	21 (70)
Brain tumor, N. (%)	4 (13.5)
Multiple sclerosis, N. (%)	3 (10)
Cerebral palsy, N. (%)	2 (6.5)
Disease duration, median [Q1-Q3] (months)	25 [13.25-48.75]
BoNT-A naive patients, N (%)	20 (66.7)
Number of past BoNT-A injections/patient in the gastrocnemius muscle, median [Q1-Q3]	2.5 [1.25-3.75]
Duration since last BoNT-A injection, median [Q1-Q3] (months)	17.5 [9.5-26.25]
Motor function score Fugl-Meyer Assessment (/34), mean±SD	20.9±5.5
Modified Ashworth Scale, N. (1/1+/2/3)	4/8/17/1
Modified Tardieu Scale, N. (1/2/3/4)	3/16/9/2

BoNT-A: botulinum neurotoxin type A; N: NUMBER; Q: quartile; SD: standard deviation.

TABLE II.—*Shear wave velocities.*

Position	Muscle	Side	SWV (m/s), median [Q1-Q3]
ANRP	GL	A	2.33 [2.14-2.61]
		NA	2.22 [2.05-2.36]
	GM	A	2.53 [2.34-2.99]
		NA	2.33 [2.16-2.43]
MC	GL	A	5.08 [3.47-6.25]
		NA	6.12 [5.18-6.67]
	GM	A	4.49 [3.41-6.21]
		NA	6.39 [5.21-6.93]
PDF	GL	A	5.10 [4.18-6.37]
		NA	5.67 [4.93-6.76]
	GM	A	6.90 [5.76-7.69]
		NA	7.15 [5.97-7.65]

A: affected; ANRP: ankle neutral resting position; GL: gastrocnemius lateralis; GM: gastrocnemius medialis; MC: muscle contraction; NA: non-affected; PDF: passive dorsiflexion; SWV: shear wave velocity.

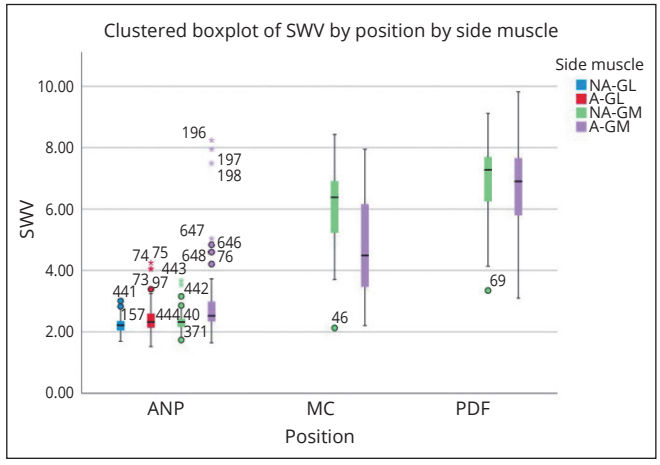

Figure 1.—Effect of position, side, and muscle on shear wave velocity. A: affected; ANRP: ankle neutral resting position; GL: gastrocnemius lateralis; GM: gastrocnemius medialis; MC: muscle contraction; NA: non-affected; PDF: passive dorsiflexion; SWV: shear wave velocity.

TABLE III.—*Type III tests of fixed effects.*

Source	F	Sig.
Side	23.62	<0.001
Muscle	50.81	<0.001
Position	939.77	<0.001
Time	1.56	0.212
Side*position	26.10	<0.001
Muscle*position	24.08	<0.001

Ankle neutral resting position

A side effect was observed with a mean SWV of the affected limb significantly higher than the less-affected limb in the GL muscle (+10%, P<0.05) as well as in the GM muscle (+22.5%, P<0.004). Furthermore, a muscle effect was found in the affected limb as mean SWV was signifi-

cantly higher in the GM (+0.429 m/s, P<0.017) than in the GL muscle. No muscle effect was observed in the less-affected limb.

Influences of ankle position and muscle contraction

No side effect was observed in passive dorsiflexion as no significant difference was found between the affected and the less-affected limb, both for the GM and the GL muscle. During muscle contraction, on the other hand, mean SWV was significantly higher in the less-affected limb than in the affected limb, both for the GM and the GL muscle. Furthermore, a position effect was observed as mean SWV was significantly higher during muscle contraction and in passive dorsiflexion than in neutral position, both in the GM and GL muscle of the affected and less-affected limb (P<0.001). No muscle interaction was analyzed in those two positions and only mean SWV of GM muscle are represented in Figure 1.

Criterion validity

Criterion validity was evaluated in ANRP as only ANRP could correctly distinguish the affected- and less-affected limb. A moderate positive correlation was found at T3 between SWV of GL muscle and MAS (r=0.42, P=0.02) and between SWV of GL muscle and number of previous BoNT-A injections (r=0.42, P=0.02). No other correlations were found in neutral position between SWV and clinical assessments (MAS, MTS, Fugl-Meyer, passive range of motion) nor between SWV and elasticity measured with MyotonPro, nor between SWV and demographical and clinical characteristics (disease duration, previous Botulinum-toxin injections).

Reliability

ICCs were calculated for SWE measures of the affected limb in neutral position. Reproducibility was excellent (ICC>90) at short and long term for both muscles. ICCs are shown in Table IV and illustrated in Figure 2. Furthermore, according to ANOVA Friedman's Test, no time effect was observed as the mean SWV was not significantly different (P>0.05) between T1, T2, and T3 in the affected limb in neutral position.

Responsiveness

In neutral position at short term SEM was 0.14 m/s and 0.11 m/s and MDC was 0.38 m/s (16%) and 0.30 m/s (11%) for GL and GM, respectively. At long term, SEM was 0.16 m/s and 0.22 m/s with an MDC at 0.45 m/s (18%) and 0.62 m/s (22%) for GL and GM, respectively (Table IV).

Discussion

The present study evaluated the validity of SWE in ANRP in hemiparetic subjects with hyper-resistance in gastrocnemii muscles. It also assessed the influence of ankle position and muscle contraction on the elastic stiffness of gastrocnemius muscle in the affected and less-affected leg simultaneously. Finally, we aimed to study the reliability and responsiveness of SWE.

Influence of ankle position and muscle contraction

There is currently no consensus regarding which method may be the most optimal for assessing gastrocnemius muscle elasticity among neurological populations. In the present study, the choice was made not to strictly control joint angles in neutral position. We opted for allowing the patient to adopt a natural resting position, which can be more readily replicated during a routine examination, as opposed to fixed-angle "neutral" postures that might necessitate an external device for replication and furthermore would stretch the muscle, thus increasing stiffness. In neutral position, a side effect was observed with a mean SWV of the affected limb significantly higher than the less-affected limb in the GM muscle as well as in the GL muscle, indicating greater elastic stiffness. In the same way, Hong *et al.*[16] and Kesikburun *et al.*[18] observed a significantly higher elasticity index of the spastic GM and GL muscles compared with the unaffected side in stroke survivors. Our results are also in line with studies conducted in upper limb muscles.[18-20] These results suggests that the spastic paretic muscles have altered muscle properties which may result in changes in the elastic characteristics of the muscle. The mechanisms behind muscle stiffness changes in spastic muscle are unclear and current measurements of SWV cannot distinguish between the

TABLE IV.—*Intraclass correlation coefficients and responsiveness SWE of the affected limb in ankle neutral resting position.*

	ICC (T1-T2)	ICC (T2-T3)	SEM Short term (m/s)	SEM long term (m/s)	MDC short term (m/s) (%)	MDC long term (m/s) (%)
GL	0.92	0.88	0.14	0.16	0.38 (16)	0.45 (18)
GM	0.99	0.96	0.11	0.22	0.30 (11)	0.62 (22)

ICC: intraclass correlation coefficient; MDC: minimal detectable change; SEM: standard error of measurement.

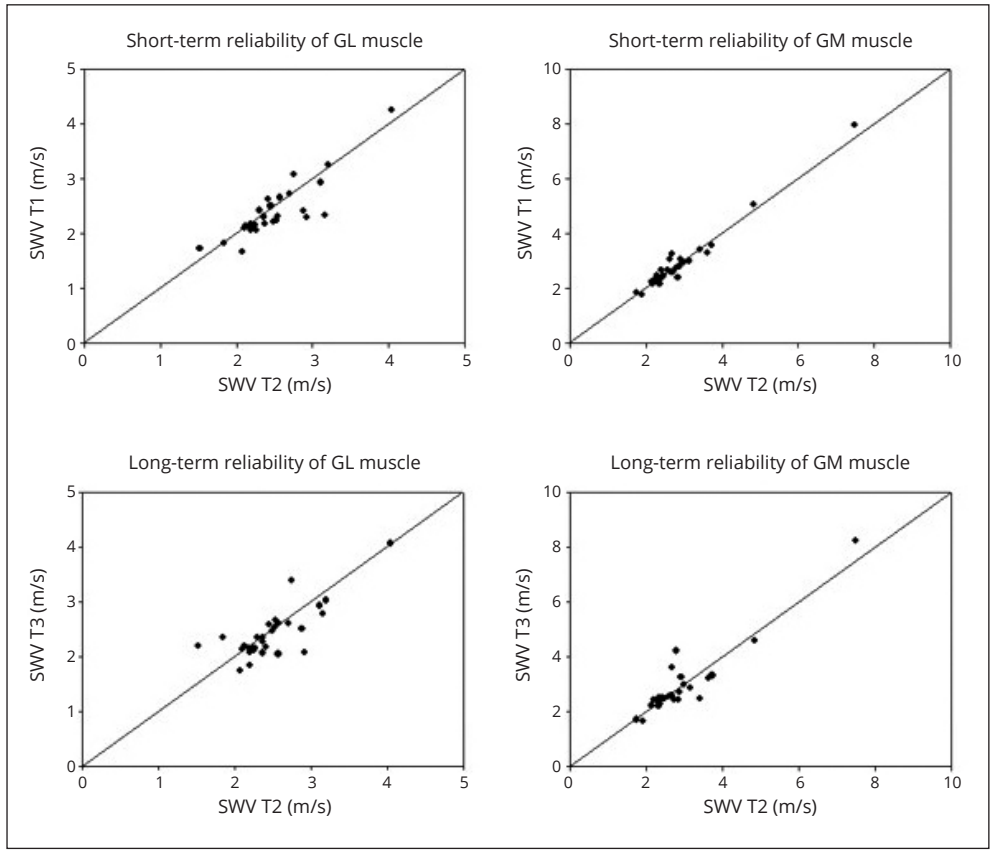

Figure 2.—Agreement plots of short-term and long-term reliability of SWE in the affected limb in ankle neutral resting position.
GL: gastrocnemius lateralis; GM: gastrocnemius medialis; SWV: shear wave velocity.

factors that may contribute to this increased elastic stiffness. However, several potential mechanisms can be highlighted such as muscle composition changes and muscle architectural alteration. Those changes include changes in connective tissue, increased collagen content,[21-24] increased extracellular matrix,[25] stiffer fibers,[24, 26] shorter resting sarcomeres,[16] changes in intracellular proteins such as titin, accumulation of extracellular fat in the muscle,[23] quantifiable fibrosis,[27] and pennation angle and fascicle length changes.[16, 26, 27]

Furthermore, a muscle effect was found in the affected limb as mean SWV was significantly higher in the GM than in the GL muscle. This has never been highlighted before. No muscle effect was observed in the less-affected limb, supporting the concept that GM muscle was probably more affected in our patients than GL muscle.

While measurements taken in neutral position offer a physiological baseline, the elastic stiffness observed in contracted or stretched muscles was more variable between pathological and healthy muscles.

Our results showed that during isometric muscle contraction, mean SWV was significantly higher in the less-affected limb than in the affected limb, both for the GM and the GL muscle. Those results raise questions as during muscle contraction, the patient was asked to apply a force of 50 kPa on the Microfet dynamometer bilaterally. Furthermore, a position effect was observed as mean SWV was significantly higher during muscle contraction than in neutral position, both in the GM and GL muscle of the affected and less-affected limb. Thus, SWV is sensitive to muscle activity. Those results are in line with several studies carried out on healthy volunteers where SWV of gastrocnemius muscle increased with active muscle contraction.[8, 28-30] Moreover, our findings align with studies conducted in upper limb muscles.[18, 31]

Regarding stretching in our study, no side effect was observed in passive dorsiflexion as no significant difference was found between the affected and the less-affected limb, both for the GM and the GL muscle. On the other hand, a position effect was observed as mean SWV was significantly higher in passive dorsiflexion than in neutral position, both in the GM and GL muscle of the affected

and less-affected limb. Thus, SWV increases with muscle length. These observations are related to length-dependent structural and mechanical properties of skeletal muscles. Our results are in line with the study of Chernak *et al.*[29] and Dubois *et al.*[32] where average GM SWV increased significantly with passive dorsiflexion in healthy volunteers. Moreover, Jakubowski *et al.*[33] and Lee *et al.*[34] found no significant difference in GM SWV at maximum dorsiflexion between the affected and the less-affected side in chronic stroke survivors and in children with cerebral palsy, respectively.

To summarize, muscle contraction and stretching of gastrocnemius increases SWV but seems to alter the differences between the affected and the less-affected limb. ANRP seems therefore to be the most valid position for assessing gastrocnemius muscle elastic stiffness in neurological populations. This should be kept in mind for the choice of positioning in further studies.

Criterion validity

Criterion validity was assessed by studying the correlation between muscle elastic stiffness measured with SWE and 1) myotonometer; 2) clinical assessments.

No correlations were found between muscle elastic stiffness measured with SWE and with MyotonPro in neutral position, both for GL and GM muscle. These results are conflicting with the results of several studies[8, 28, 35] who observed a moderate but significant correlation in medial gastrocnemius muscle elastic stiffness between measurements of SWE and MyotonPro at rest in healthy volunteers. Several possible reasons could explain this difference. First, those studies showing significant correlations between elastic stiffness measured with SWE and MyotonPro were undertaken in healthy subjects and not in neurological populations. Frölich-Zwahlen *et al.*[36] and Garcia-Bernal *et al.*[37] showed that elastic stiffness measured with the MyotonPro did not differ between the affected and the less-affected gastrocnemius muscles in chronic stroke survivors. The potential validity of MyotonPro for the assessment of gastrocnemius elastic stiffness in neurological populations may thus require further investigation. Secondly, the measurement of muscle elastic stiffness using MyotonPro did not include an assessment of subcutaneous fat. Previous evidence indicates that MyotonPRO is less suitable for measuring elastic stiffness when the muscles are covered by more than 20 mm of subcutaneous fat.[8]

The MAS and MTS scores of spastic gastrocnemius muscles didn't show any significant correlation with SWE measurements. MAS and MTS are easy to use clinical assessment of hyper-resistance and require no equipment, but these measurements have poor intra-/inter-rater reliability.[3, 4] Moreover, these measurements cannot distinguish neural from non-neural components.[5] If one of the components is predominant, it will be overlooked by those clinical scales.[38] Thus, MAS and MTS might not be as sensitive as SWE in detecting muscle elastic stiffness which is part of the non-neural component. The degree of involvement of neural and non-neural components is specific to each patient. It may be that our study population had predominant non-neural components. Our results are in the same line as several other studies. Brandenburg *et al.*,[6] Kesikburun *et al.*,[18] and Hong *et al.*[16] did not found any significant correlation between SWE measurements and MAS of the GL and/or GM muscle in children with cerebral palsy and stroke survivors, respectively. Our results are also in line with studies conducted in upper limb muscles such as the biceps brachialis[19, 27, 39] and the flexor carpi radialis[20, 40] of stroke survivors. On the other hand, contrary findings were reported by several studies.[41-44] Moreover, in the systematic review of Roots *et al.*[45] the MAS correlated with ultrasound elastography stiffness in 10 studies and did not correlate in 4 studies. Further studies should be conducted to develop quantitative measurement of hyper-resistance.

Reliability

In healthy volunteers, the intra-rater and inter-rater reliability of SWE has been shown to be good to excellent in several muscles including the gastrocnemius muscle.[8, 32, 44] Prior studies have also highlighted differences in probe orientation. They demonstrated that the longitudinal plane provided the best reproducibility for normal skeletal muscles.[45-47] In a systematic review and meta-analysis of Miller *et al.* published in 2020, reliability varies across neurological populations and assessment conditions (probe orientation, ankle joint, active/passive muscle condition), with most studies indicating moderate to good reliability. Since our results show that ANRP seems to be the most valid position to evaluate gastrocnemius muscle elastic stiffness through SWE, reliability was only analyzed in ANRP. Based on our results, short-term and long-term intra-rater reproducibility of SWE in longitudinal plane is excellent in spastic gastrocnemius muscle in ANRP (ICC>90). In comparison, Mathevon *et al.*[48] found a good intra-rater reproducibility (ICC=0.87) for shear elastic modulus in longitudinal plane of paretic gastrocnemius muscle in neutral position. In the same way, intra-observer agreement on the

use of SWE to measure SWV in post-stroke spastic biceps brachialis was good (ICC=0.82) in the study of Gao *et al.*[39]

Regarding responsiveness of SWE, MDC% results at long term in neutral position were 18% and 22% for gastrocnemius lateralis and medialis respectively. This is an important information to consider in order to evaluate the effectiveness of a treatment for example Botulinum toxin type A injections. A difference of ±20% has to be found before and after the injection to conclude that there is a real improvement in muscle elastic stiffness. Our results are better compared to the results of Mathevon *et al.*[48] with a MDC% of approximatively 30% for gastrocnemius medialis at long-term.

Limitations of the study

Firstly, the sample size is relatively small. Even if the study power is adequate, the generalizability of our results to the neurological population is not warranted.

Secondly, the freehand technique used in SWE leads to technical challenges in reproducing images due to the difficulty of controlling the applied pressure. To decrease the effect of this problem we took the mean of several successive acquisitions.

Finally, most SWE techniques assume that the underlying tissue is isotropic, homogenous and with negligible viscosity. However, muscle is neither isotropic nor homogenous and has known viscous properties, thus caution is advised when interpreting SWE measurements.

Conclusions

SWE is a promising tool for assessing muscle elastic stiffness in spastic gastrocnemius muscles. However, a standardized protocol should be used. Using SWE, we demonstrated that in ANRP, shear waves travel faster in the affected limb than less-affected limb of hemiparetic subjects with hyper-resistance in gastrocnemii muscles. SWV was also demonstrated to increase with increasing ankle angle and with active muscle contraction. However, muscle contraction and stretching of gastrocnemius muscle seems to alter the differences between the affected and the less-affected limb. ANRP seems therefore to be the most valid position for assessing gastrocnemius muscle elastic stiffness in neurological adult populations. In the future, SWE may be a useful clinical tool as an extension of the physical exam for longitudinal monitoring of passive muscle stiffness, to assist with treatment decisions and to better quantify the therapeutic effect of procedures to reduce muscle overactivity.

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