Motorized versus manual instrumented spasticity assessment in children with cerebral palsy

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ABBREVIATIONS

GAS	Gastrocnemius medialis
SOL	Soleus
ROM	Range of motion
EMG	Electromyography

AIM We compared the outcomes of manual and motorized instrumented ankle spasticity assessments in children with cerebral palsy (CP).

METHOD Ten children with spastic CP (three males, seven females; mean age 11y [standard deviation 3y], range 6–14y; Gross Motor Function Classification System levels I–III) were included. During motorized assessments, fast (100°/s) rotations were imposed around the ankle joint by a motor-driven footplate; during manual assessments, rotations of comparable speed were applied by a therapist using a foot orthotic. Angular range of motion, maximum velocity, acceleration, work, and muscle activity (electromyography [EMG]) of the triceps surae and tibialis anterior were compared during passive muscle stretch between motorized and manual assessments. Both movement profiles were also compared to CP gait ankle movement profile.

RESULTS The imposed movement profile differed between methods, with the motorized assessment reaching higher maximum acceleration. Despite equal maximum velocity, the triceps surae were more often activated in motorized assessments, with low agreement of 44% to 72% ($\kappa \leq 0$) for EMG onset occurrence between methods. The manually applied ankle velocity profile matched more closely with the gait profile.

INTERPRETATION The differences in acceleration possibly account for the different muscle responses, which may suggest acceleration, rather than velocity-dependency of the stretch reflex. Future prototypes of instrumented spasticity assessments should standardize movement profiles, preferably by developing profiles that mimic functional tasks such as walking.

Cerebral palsy (CP) is the most common physical disability among children.[1] Its main subtype, spastic CP, is generally characterized by increased resistance to motion in affected joints, which is caused by either neural or tissue-related impairments. Neural impairments comprise spasticity, defined as velocity-dependent hyper-excitability of stretch-reflexes,[2] and increased background muscle activation.[3] Tissue impairments include abnormal shortening and increased stiffness of the muscle fibres, tendons, or connective tissues.[3] Because the underlying aetiology guides treatment selection, objective quantification of these neuromuscular characteristics in children with CP is warranted.

Current clinical assessment of joint resistance is based on the subjective feeling of resistance to manual passive stretching at different velocities. Resistance during slow movement is assumed to be indicative of increased tissue stiffness, while a difference between slow and fast movements is considered to be spasticity-related.[4] However, these clinical tests possess low resolution, do not control for the stretch velocity or applied force, and cannot discriminate tissue from neural contributions.[5,6] Continued use of clinical tests may therefore lead to an erroneous definition of symptoms and misdirected treatment.[7]

Manual instrumented tests that include measurement of joint velocity, imposed force, and muscle activity have been shown to considerably improve objectivity, resolution, and precision of the clinical tests.[8] Instrumented measurements facilitate quantification of the muscle response, standardization of the imposed movement by providing feedback, and the possibility to apply neuromuscular models that estimate neural- and tissue-related contributions.[9,10] Aside from manual instrumented tests, motorized alternatives are available.[9] Their additional advantage is that they allow for highly-controlled imposed movements with reduced out-of-plane movements and standardized profiles.

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Both manual and motorized instrumented assessments have been separately examined in rehabilitation environments.[9,10] This raises the question whether these different methods measure joint characteristics that are close enough to yield the same clinical conclusions. For instance, despite reaching similar maximum velocity, the movement profile as well as the interaction between patient and motor versus examiner may vary, and thus affect the assessment of spasticity. Furthermore, even though the fast stretches are applied to provide an indication of altered reflex activity during functional tasks such as walking,[11] the relationship between the imposed movements and movement during gait remains unknown.

Therefore, the aim of the current study was to compare spasticity-related outcomes of a motorized with a manual instrumented assessment of the ankle joint, with matched maximum velocity, in children with CP. In addition, the movement profiles of both motorized and manual assessments were compared with typical ankle kinematic profiles during walking.

What this paper adds

- Different methods of ankle spasticity assessment evoke different muscle responses, despite equal peak velocity.
- Differences in acceleration profile possibly account for different muscle responses.
- The manual assessment better matched the ankle velocity during gait than motorized assessments.

METHOD

Participants

We included a convenience sample of 10 children with spastic CP (three males, seven females; mean age 11y [standard deviation 3y], range 6–14y; Gross Motor Function Classification System levels I–III) from our department (Table I). Inclusion criteria were a clinical diagnosis of spastic uni- or bilateral CP and no clinical signs of dystonia; less than 20° knee flexion contracture; absence of severe cognitive deficits; and no additional medical problems interfering with joint mechanics. Informed consent was provided and the study approved by the Dutch Central Committee on Research Involving Human Subjects.

Protocol

Because motorized and manual assessment protocols have previously been tested for reliability and validity,[9,12] these protocols were retained, with the exception that in manual assessments, maximum velocity was decreased and participants were seated rather than supine, to match motorized assessments as much as possible. Both methods measured the ankle of the most affected leg. Surface electromyography (EMG) electrodes were placed on the gastrocnemius medialis (GAS), soleus (SOL), and tibialis anterior muscles according to SENIAM guidelines (http://www.seniam.org/), and remained in place during both measurements. For motorized assessments, participants were seated in an adjustable chair with 20° knee flexion (Fig. 1a). This knee position was attainable for all participants, allowed for assessment of spasticity simultaneously in both the GAS and SOL muscles, and was similar to how measurements have been collected previously.[9,10] During manual assessments, participants were seated on an examination table with the back semi-inclined and the lower leg on a stand to induce 20° knee flexion (Fig. 1b). The order of manual and motorized measurements was randomized.

During motorized assessments, the passive range of motion (ROM) was determined by imposing age-dependent maximal dorsiflexion (6–10Nm) and plantarflexion (4–7.5Nm) moments.[9] Next, the motorized footplate imposed two fast (100°/s) position-controlled ramp-and-hold rotations towards dorsiflexion within the ROM. During manual assessments, two to four fast movements were applied by the same trained examiner. Before data collection, the examiner practiced matching the motorized velocity. To account for performance variability between stretch repetitions in manual assessments, and for any variability inherent to the phenomenon of spasticity, the first two successful trials were selected and averaged for further analysis. In both types of assessment, measurements started at a random time instant, with at least 20 seconds' rest between measurements. Participants were instructed to remain relaxed. A stretch was repeated if any EMG activation of agonist and/or antagonist occurred before or at an unexpected time during stretch.

Sagittal ankle angle and moment as well as muscle activity were measured or derived. For motorized assessments, a force transducer measured the net ankle moment and a

Table I: Patient characteristics

Patient	Sex	Age, y	Weight, kg	Height, m	Involvement	GMFCS level	Leg
P1	M	14	60	1.57	Bilateral	II	L
P2	F	6	19	1.15	Bilateral	II	L
P3	F	11	38	1.37	Bilateral	III	L
P4	F	7	19	1.20	Bilateral	II	L
P5	M	11	49	1.44	Bilateral	III	L
P6	F	14	38	1.48	Bilateral	II	L
P7	F	10	34	1.33	Bilateral	II	L
P8	M	10	50	1.45	Bilateral	I	R
P9	F	14	40	1.61	Bilateral	II	R
P10	F	8	26	1.30	Bilateral	II	R

GMFCS, Gross Motor Function Classification System; Leg, most affected leg; M, male; F, female; L, left; R, right.

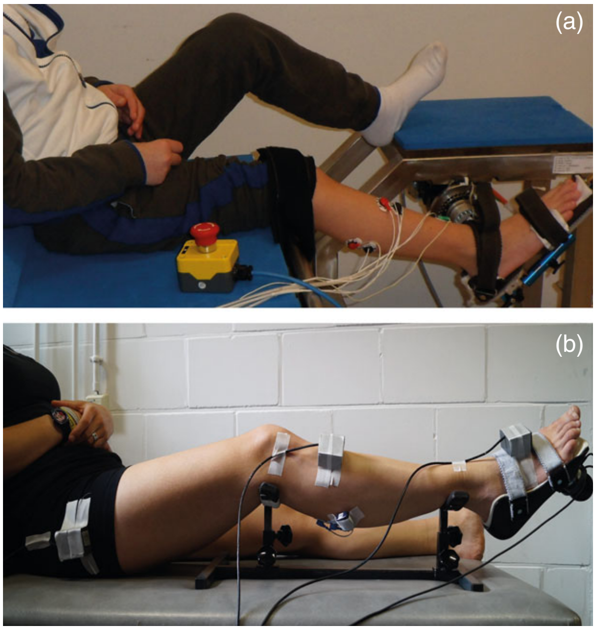

Figure 1: Participants were seated with 70° hip flexion to limit posture-dependent reflex activity and to allow for a comfortable position, and 20° knee flexion to allow for small knee contractures and to measure spasticity simultaneously in both the gastrocnemius medialis and soleus muscles. Participants were seated in an adjustable chair for the assessment with motorized (a) and on an examination table with a semi-inclined back and the lower leg on a stand for manual assessment (b).

potentiometer the footplate's position, both at 1024Hz (Moog BV, Nieuw-Vennep, the Netherlands). EMG was measured at 1024Hz (Porti7; TMSi, Enschede, the Netherlands). For manual assessments, applied forces and moments were measured using a 6 degrees of freedom hand-held force transducer (ATI mini45; Industrial Automation, Apex, NC, USA) attached to a foot orthotic. Two inertial measuring units (IMUs; Analog Devices, ADIS16354, Norwood, MA, USA) were used to track the foot segment with respect to the lower leg. The points of application of the force transducer with respect to the lateral malleolus as well as the tibia and foot lengths, were measured with a tape measure. Force and motion data were sampled at 200Hz and EMG at 2000Hz (Zerowire; Cometa, Milan, Italy).

Analysis

Motorized ankle angle was derived from the measured footplate's position that was calibrated using manual goniometry at a plantarflexion angle of 30°. Manual ankle angle was derived from the IMU data, calibrated similarly at an angle of 0° and using predefined motions in the sagittal plane, and finally filtered with a Kalman smoother.[10] Manual net ankle moment was calculated using inverse dynamics from the measured forces and moments and an anthropometric ankle model based on segment-lengths, moment-arms, bodyweight, and age.[10]

Electromyography data were filtered (40–60Hz notch filter and 20–500Hz band-pass filter) and its root-mean-square was taken to represent the EMG intensity. Electromyography, angle, and moment data were low-pass filtered at 30Hz and down-sampled to 200Hz. All filters were sixth-order zero-phase Butterworth implementations. Because EMG data were measured with different systems for motorized and manual assessments, an EMG-equipment tester (Whisper; Roessingh Research & Development, Enschede, the Netherlands) was used to calibrate the gain factor per EMG channel. An example of measured data is given in Figure S1 (online supporting information).

Several outcome parameters were calculated. First, the movement profiles of motorized and manual assessments were compared, based on maximum angular velocity and acceleration, as well as ROM, maximal dorsiflexion and stretch duration. In addition, the positive amount of work delivered at the ankle joint was quantified as the area under the moment-angle curve, taken from 0Nm up to 90% of the ROM to exclude initiation or termination artefacts.

Second, the muscle response was examined. Electromyography was selected from 10% to 90% of the ROM after subtracting the baseline EMG (i.e. average EMG measured 0.5s before start of the stretch). Maximum EMG was calculated as the 95th centile to correct for outliers. The presence of spasticity was based on the occurrence of bursts in the EMG signal (EMG onset) detected according to the method of Staude and Wolf,[13] with the additional condition of peak EMG exceeding two standard deviations of the signal. Onset detection was visually inspected and manually corrected in 9.9% of the trials, similar in motorized and manual assessments. All parameters were averaged over the two stretch repetitions per method.

Comparison to movement profiles during walking

To compare motorized and manual assessment movement profiles to typical functional ankle movement profiles, data from standard clinical gait analysis of 14 children with CP were examined (informed consent was provided). Three-dimensional kinematic data were collected at preferred walking speed using a motion capture system (Optotrak; Northern Digital, Waterloo, ON, Canada) that tracked technical clusters attached to the trunk, pelvis, and leg. Sagittal ankle angles were calculated from virtual anatomical markers that were related to the clusters using open-source software (www.BodyMech.nl) and time-normalized to stride cycles using initial-contact and toe-off events derived from forward foot velocity.[14] Ankle angular velocity and acceleration were derived from the ankle angle.

Statistical analysis

Systematic differences and correspondence between parameters from motorized and manual assessment were examined with Wilcoxon's signed rank tests and Spearman's rank correlations coefficients (ρ), with significance at $p<0.050$. The occurrence of EMG onset was compared using percent exact agreement and Cohen's kappa (κ) and interpreted according to Altman.[15] Finally, Wilcoxon rank-sum tests were used to compare maximum ankle velocity and acceleration during motorized and manual assessments, and during stance and swing phase of gait. All data analyses and statistics were performed in Matlab (Mathworks Inc., Natick, MA, USA).

RESULTS

For one participant, SOL EMG data were unavailable because of technical issues, and manual assessment was uncomfortable and not performed for another.

Motorized versus manual

Overall, manual assessment velocity differed more between trials, and was generally more bell-shaped compared to motorized assessment (Fig. 2). Trials were velocity-matched and had similar ROM and performed work between methods, but motorized assessment imposed on average a two to three times higher maximum acceleration resulting in shorter trials (Table II).

Maximum GAS activity was 93% increased for motorized assessment, and there was no significant agreement between methods (Table II). For both GAS and SOL, EMG onset was detected more often in motorized (94% and 100%) compared to manual trials (44% and 78%), resulting in a generally poor agreement between methods (44% and 72%; $\kappa<0$). There was a fair agreement (61%; $\kappa<0.32$) between methods in onset occurrence in tibialis anterior muscles.

Comparison to movement profiles during walking

The velocity profiles during the stretch phases of stance and swing phase of gait were more similar to the manual assessment profiles, but with smaller ROM (Fig. 2). Both motorized and manual maximum velocities were lower than those reached in both stance and swing (median values [interquartile range]: 104 [27]°/s and 101 [0]°/s vs 171 [72]°/s and 163 [79]°/s respectively, $p<0.001$). Both motorized and manual assessments imposed maximum accelerations in maximum plantarflexion with decreasing accelerations towards dorsiflexion, similar as during both stance and swing, although motorized and manual values were considerably lower (464 [269]°/s^2 and 1019 [5]°/s^2 vs 3201 [1339]°/s^2 and 4975 [1667]°/s^2 respectively, $p<0.001$).

DISCUSSION

This explorative study compared biomechanical and electrophysiological parameters collected with a motorized- and a manual-instrumented spasticity assessment in children with spastic CP. In addition, the movement profiles of these assessments were compared to those seen in gait of children with CP. In general, we found different results between the two measurement set-ups, particularly in maximum acceleration and electrophysiological response to passive stretch. These differences in the measured signals would most likely result in different neural- and tissue-related contributions to increased joint resistance estimated using neuromechanical models.[9,10] The ankle's movement profile imposed during manual assessments seemed to better simulate the profile of the ankle during gait.

The difference between methods in muscle response to fast stretch was illustrated by low correlation and agreement of electrophysiological outcomes. Muscle response seemed consistently larger during motorized trials, reflected in higher median EMG values, although only significant differences were found for GAS because of the large variance. Previous studies also found different responses to manual assessment dynamometry and motorized isokinetic dynamometry, although, in contrast to our findings, manual application was found to evoke more reflex activity.[16,17] These studies, however, did not match the movement velocity between methods and thus the increased stretch-reflex activation can most likely be attributed to the higher velocities imposed by manual assessment.

Because angular velocity was matched in this study, the different electrophysiological responses to passive stretch may be related to large differences in the magnitude and timing of maximum acceleration between motorized and manual assessments. Motorized showed high initial accelerations, while a more intermittent acceleration was found in manual application. This dependence on acceleration is supported by strong correlations found between muscle response and maximum acceleration in the literature.[18,19] In addition, variations in the magnitude and timing of maximum acceleration results in a variation in the relation between maximum velocity and muscle length, i.e. muscle length dependency of the reflex threshold.[20] Thus, the profile of the imposed accelerations, including muscle length–velocity relationship, might be as important as the maximum velocity for muscle response. This is a very innovative finding and, if confirmed by larger studies, may require alteration of the definition of spasticity. The notion that the imposed movement profile, including acceleration, is for an important part responsible for the muscle response to passive stretch, questions the use of ramp-and-hold rotations imposed with motorized assessments. Although such rotations at constant velocity are common for motorized footplates,[16,17,21,22] comparison with manual and thus clinical tests would benefit from more bell-shaped movements.[16] Future research should focus on deciphering the mechanisms that trigger stretch-reflexes, to contribute to further development of spasticity assessment protocols. This is best achievable with controlled motorized systems that apply different velocity and acceleration profiles.

Furthermore, the imposed movement profile should preferably match the ankle characteristics during gait, i.e. an iso-functional measurement,[11] which was more the case for the average manual assessment velocity profile compared with motorized assessment (Fig. 2). Even though gait differs considerably between patients, maximum velocity and acceleration of both motorized and manual assessment were considerably lower than those seen in the ankle during stance and swing measured in a heterogeneous group. For better representation of altered reflex activity during gait, velocity and/or acceleration during

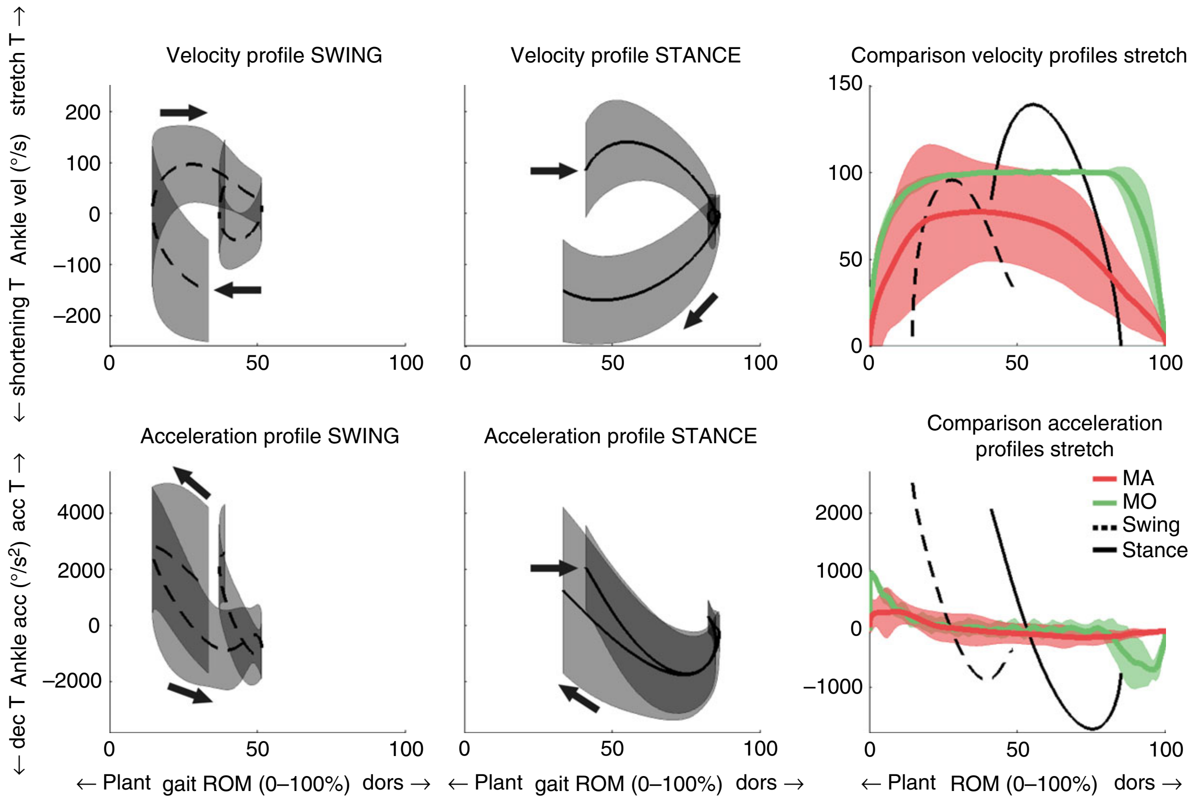

Figure 2: Comparison of ankle movement profiles between instrumented assessment and gait, for both velocity (vel; top figures) and acceleration (acc; lower figures) profiles. The velocity and acceleration profiles as function of the range of motion (ROM) are given for the swing (left figures, dotted lines) and stance (middle figures, solid line) phase of gait based on a representative population of patients with cerebral palsy. These gait profiles are compared to the profiles imposed by manual (MA; red) and motorized (MO; green) in the figures on the right for the phase in which the gastrocnemius medialis and soleus (triceps surea; T) is stretched. Lines indicate averages over all participants, with the standard deviation indicated by the shaded area and the arrows indicating the direction of the movement. Note that peak values are not representative of mean maximum values given in Table II because of a spread in timing of these peak values. In addition, ROM values may differ between gait and passive instrumented assessment, but were normalized to 0% to 100% for comparison between participants. dec, deceleration; plant, plantar; dors, dorsal.

Table II: Outcome parameters manual vs motorized assessment

	Manual		Motorized		Difference	Correlation		Agreement	
Outcome	Median	IQR	Median	IQR	*p*	ρ	*p*	%	κ
Movement									
Max. velocity (°/s)	103.9	27.3	101.5	0.1	0.301	–	–	–	–
Max. acceleration (°/s^2)	463.8	269.4	1018.7	4.7	**0.004**	–	–	–	–
ROM (°)	60.9	4.6	55.5	18.2	0.910	0.32	0.410	–	–
Max. dorsal flexion (°)	16.5	11.0	4.3	13.0	0.098	0.22	0.581	–	–
Stretch duration (s)	1.7	0.4	0.9	0.2	**0.004**	0.37	0.336	–	–
Work (J)	2.4	1.5	2.1	1.7	1.000	0.05	0.912	–	–
Spasticity									
Max. EMG GAS (uV)	10.4	6.3	20.0	44.7	**0.027**	–0.35	0.359	–	–
Max. EMG SOL (uV)	7.7	8.6	8.5	11.8	0.742	0.05	0.935	–	–
Max. EMG TA (uV)	3.4	3.6	5.2	54.4	0.734	–0.18	0.644	–	–
Onset GAS (%)	78		94		–	–	–	72	–0.10
Onset SOL (%)	44		100		–	–	–	44	0.00
Onset TA (%)	33		72		–	–	–	61	0.32

Correlations could not be tested for maximum velocity and acceleration, because there was insufficient variation in the motorized data. Relevant statistics were given per parameter. Differences or correlations are considered significant if $p<0.050$ (indicated in bold). IQR, interquartile range from 25% to 75%; ρ, correlation coefficient of the Spearman's test; κ, Cohen's kappa; ROM, range of motion; Work, positive amount of work; Onset, presence of spasticity in indicated muscle EMG, electromyography; GAS, gastrocnemius medialis; SOL, soleus; TA, tibialis anterior.

instrumented tests should be increased. It should be noted that muscle responses measured during passive assessments differs from those measured during walking, when muscles are active and reflexes modulated.[3] In addition, comparison between passive and functional movement profiles assumes that ankle angular velocity is representative of passive muscle fascicle lengthening velocity. During swing phase, limited triceps surae muscle activation is expected and passive muscle lengthening occurs.[23] During stance, the GAS has been shown to act nearly isometrically in able-bodied adults, but eccentrically in children with CP.[23,24] Therefore, instrumented tests should be improved by better tuning to the movement profile seen during both swing and stance, and possibly by testing during quasi-activation.

The difference of patient–examiner versus patient–motor interaction may have also influenced our results. First, the impedance most likely differed between methods, with motorized movements deviating less from the planned movement caused by a sudden increase in resistance. Second, patient preference for one or the other method may influence the level of relaxation and hence modulation of the stretch-reflex, and (involuntary background) muscle activity. The motorized footplate can be more intimidating, but imposes a more predictable movement and keeps the foot still before start of the movement. Finally, cutaneous input through skin contact was not expected to differ between methods, for both used a foot orthotic or footplate. By applying a movement with the motorized footplate that matches the manually-applied profile, future research can determine the impact of different interactions versus movement profiles.

It should be noted that the infrequent muscle response found during fast manual assessment trials (44%–78%) is not representative of clinical spasticity assessments, which typically impose rotations as fast as possible in the supine position.[10] Additional manual application measurements performed in supine position showed a negligible effect of the difference in posture (Table SI, online supporting information). Because stretch velocity of 100°/s did evoke muscle responses in motorized assessments, this study innovatively highlighted that high accelerations, rather than velocity, are important for eliciting stretch-reflexes.

Some limitations can be identified that may have affected the relationship between motorized and manual assessments. First, while in manual application the moment was directly measured by the force transducer, in motorized assessment the moment arms were measured with a tape measure. However, work was not found to be significantly different between methods. Second, movements imposed by motorized assessment were more restricted to the sagittal plane than in manual application. However, out-of-plane movements and exerted moments have been found to be negligible for manual assessments.[10] Third, angular parameters could have been affected by the measurement error introduced by the goniometer-based ankle calibration in both methods, the more prominent start of motorized assessment at maximum plantarflexion and pre-defined participant-specific maximum dorsiflexion moment of motorized assessment. However, no consistent differences in ROM were found between methods. Fourth, ROM and muscle lengthening may have been affected by foot deformations occurring during movements. Therefore, the foot was fixated as optimally as possible using an adjustable footplate that allowed for talus repositioning during motorized assessment,[25] and with a custom-made orthotic that fixated the talocrural joint during manual assessment. Despite these efforts, the occurrence of foot deformations in the different footplates and the effect on ROM and muscle lengthening remains unknown. However, it seems unlikely that any of these measurement errors are responsible for the large differences found between methods. Finally, while our findings need to be confirmed on a larger sample group, this small sample size was large enough to consistently show significant differences and high correlations for several parameters (Tables II and SI).

In conclusion, dissimilar muscle responses were found between fast passive rotations imposed during manual and motorized assessments, despite equal maximum velocity. This could be explained by the difference in movement profiles, i.e. timing and magnitude of acceleration. To confirm this, future studies should further examine the effect of different velocity and acceleration profiles imposed by the same instrument. The movement profile imposed with manual assessments better matched functional profiles seen during gait, although lower accelerations and velocities were achieved. Therefore, future prototypes of instrumented spasticity assessments should focus on developing a movement profile which better mimics that of functional tasks such as walking. This is likely to be most meaningful to facilitate treatment planning and outcome evaluation in patients with spasticity.

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SUPPORTING INFORMATION

The following additional material may be found online:

Figure S1: A typical example of two fast stretches for manual (MA, red) and motorized (MO, green) assessment. Both methods measured within a comparable range of motion (*x*-axis) and reached a similar maximum angular velocity (Vel). The maximum acceleration (Acc) was higher for MO, as well as the maximum exerted moment (M). Onsets were detected in the EMG of the gastocnemius medialis (GAS), soleus (SOL) and tibialis anterior (TA) muscles following MO assessment, but only in GAS for MA. EMG, electromyography.

Table SI: Outcome parameters manual sit versus supine

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