

Research Article

Comparison of Modified Ashworth Scale with Systems and Techniques for Quantitative Assessment of Spasticity- Literature Review

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Abstract

Spasticity is a disorder commonly found in people having upper motor neuron lesion and whose involvement can happen at different levels. The Modified Ashworth Scale (MAS) is the most routinely used instrument in clinical practice to assign spasticity levels. However, due to its inherent subjectivity, inter-evaluator discrepancies arise. Therefore, there are systems that quantitatively evaluate spasticity. This study is a literature review which aims to describe technologies for quantitative assessment of spasticity and discuss their effectiveness compared to MAS. The 27 selected papers were retrieved from PubMed, CAPES Portal, SciELO, MEDLINE and IEEE Xplore databases. Most of them had clinical goals involving patients with disorders of unique etiology. Thus, 48% and 30% of the surveyed papers included only patients with spasticity caused by stroke and cerebral palsy, respectively. Only 11% of the papers involved more than one etiology in the same trial. The remaining papers (11%) did not detail spasticity etiology. The results revealed different evaluative approaches including biomechanical data based on torque, joint angle, angular speed and muscle vibration, as well as neurophysiological approaches that analyzed electromyography signals of agonist and/or antagonist muscles. The integration of both approaches was also observed. Although MAS is widely used, quantitative assessment methods are more sensitive than MAS and, therefore, they are more suitable and safe for classifying spasticity. In conclusion, MAS should be replaced by quantitative tools, but it was not possible to determine the most effective measure for its replacement.

ABBREVIATIONS

SCI: Spinal Cord Injury; CP: Cerebral Palsy; MAS: Modified Ashworth Scale; EMG: Electromyography; CSA: Commercial Stiffness Analyzer; PMT: Passive Movement Torque; MMG: Mechanomyography; WTP: Wartemberg's Pendulum Test; HRL: Hoffmann Reflex Latency; SR: Stretch Reflex; SRTS: Stretch Reflex Threshold Speed; ISI: Passive Stiffness Index; TSI: Total Stiffness Index; MQS: Mechanical Quantification System; MSI: Muscle Stiffness Index; AM: Amplitude of Movement; AMSI: Average Muscle Stiffness Index; TSRT: Tonic Stretch Reflex Threshold; MSM: Montreal Spasticity Measurement; ML0: Modified Ashworth Scale Level 0; ML1: Modified Ashworth Scale Level 1

INTRODUCTION

Spasticity is a common disorder that affects people having upper motor neuron lesion [1] like stroke [2], spinal cord injury (SCI) [3], head trauma [4], non-progressive chronic encephalopathy or cerebral palsy (CP), and multiple sclerosis [5]. Even today, spasticity leaves gaps regarding the complete understanding of its physiopathology [6]. However, there is

consensus on its characterization by muscle tone changes due to the exacerbation of deep myotendinous reflex [7] caused by the increase in speed of stretch reflex response [8]. Physical manifestations of spasticity include involuntary contractions (e.g. when one needs to urinate, the triceps surae presents clonus), abnormal postures and pain [9]. In some cases, spasticity may bring advantages. Mention is made to functional spasticity, that is, patient learns to use extensor spasticity to stand and assist in walking.

Despite health professionals identify the spasticity clinical condition, the process of assigning levels is still difficult [10]. The exact assessment of spasticity level is required both during initial diagnosis and in the follow up monitoring. The Modified Ashworth Scale (MAS) is the most used scale to determine spasticity. During MAS application, the evaluator performs passive movements on and assigns levels of spasticity to joints of interest according to the perceived muscle resistance to passive stretching [11]. Even though MAS is the most used scaling method, it has limitations. It does not consider that spasticity is dependent on stretch speed. Moreover, MAS presents both

low sensitivity and reliability as the assigned level depends exclusively on evaluator sensitiveness and interpretation. Thus, the need for more reliable and reproducible methods stimulates the development of technologies that allow for measuring more precisely the spasticity levels. In this scenario, the main goal of this work is to present new technologies for quantitative evaluation of spasticity. With this review, we intend to answer the following question: are quantitative spasticity assessment protocols more effective than MAS? The initial hypothesis is that new technologies can provide more reliable evidences regarding spastic muscle condition and can be more feasible related to MAS.

MATERIALS AND METHODS

The reviewed papers were retrieved from PubMed, Capes Portal, Scientific Electronic Library Online (SciELO), MedLine and IEEE Xplore scientific databases. The search was performed using the following query filter: “quantify measurement spasticity or quantify assessment spasticity”; “objective assessment spasticity or device or approach to quantify spasticity” and “comparison between clinical and objective assessment of spasticity”, published between 2000 and 2017 and written in either English or Portuguese.

All abstracts were read and duplicates, papers involving non-clinical trials, reviews and papers describing evaluative technologies for comparison of treatment efficacy were removed. The quality of the selected papers was evaluated through the Physiotherapy scale Evidence Database (PEDro), but the score obtained did not consist of eligibility criteria for this review.

RESULTS

The search retrieved 67 papers. After applying the exclusion criteria 27 papers remained. This study joined to the results other relevant papers that describe the spasticity physiopathology as well as very prominent papers in the scientific area related to changes in muscle morphology in order to underlie the introduction, totaling 37 reference papers.

Table 1 summarizes the main studies that were reviewed and shows (neurophysiological or biomechanical) approaches, measurement modes and features used in the assessment of spasticity, the evaluated joint and the subjective scale to which the system was correlated with or compared to.

DISCUSSION

The correct determination of the spasticity level is essential for both initial diagnosis and follow up monitoring. Table 1 shows most of the reviewed studies focused on selecting patients with spasticity of unique etiology for clinical trials. About 48% of the evaluation procedures inspected in this review were performed in patients with a diagnosis of stroke. Other 30% evaluated patients with CP. Only 11% investigated patients with different etiologies during the same trial, including stroke and CP. The remaining 11% did not provide information on the spasticity etiology of patients. Since spasticity can affect both neural and non-neural components depending mainly on causal factors, the developed technologies should test their efficacy in patients with different etiologies, because the assessment could be effective for some patients and unusable for others. Therefore, the developed systems should prove the assessment efficacy for all causes of spasticity.

One can also notice that 15% of the papers studied the ankle, 7% the wrist, 22% the knee, 8% both elbow and knee, and most of them (48%) exclusively the elbow. According to Dantas, the anatomy and biomechanics of the joints are different from one another and the choice for the same joint aims obtaining more effective features to compare among different techniques [27].

The reviewed studies presented different approaches for spasticity assessment including neurophysiological, biomechanical, hybrid and the integration of multiple signals. All of them are discussed in the next sections.

Neurophysiological approach

The neurophysiological approach for assessing spasticity investigates neuromuscular electrical activity of agonist, antagonist or both muscles during active or passive movements acquired by surface electromyography (EMG) [33]. Basically, this mechanism of evaluation involves the excitability analysis of motoneurons and tendon reflexes, observed by signs of electromyography. However, it has no defined correlation between the clinical condition of spasticity and trial results. Since MAS does not consider spasticity dependence on stretch speed [32], the use of EMG alone with MAS has limitations. This happens because it does not provide muscle resistance information [33].

In this review, the studies that acquired EMG signals also registered biomechanical data like torque or resistance to passive movement and/or angle displacement. They are described in the section of hybrid approaches because there is involvement of two assessment mechanisms.

Biomechanical approach

In a biomechanical approach, joint position, angular speed, and reactive/resistive torque quantify muscle behavior especially during movements with controlled speed. Isokinetic devices and/or speed control motors measure the stretch reflex resistance during passive movements [15,16,19,22]. The advantage of these devices is that they allow the standardization and control of velocities and amplitudes while evoking the stretch reflex. Thus, they can quantify the resistance speed dependent on the muscle to the passive movement. However, these devices are expensive, they demand specialized training for their operation and require special rooms for installation, all in all, characteristics that raise the price of assessment procedures and complicate their use by health professionals.

To mitigate this issue and facilitate its use in clinical practice, new research groups have emerged in order to implement portable technologies [19,25,27,30]. It is difficult to compare efficacy among the proposed methods because, although most of the studies reviewed use similar instrumentation, quantitative spasticity analysis methodologies are developed in different ways, as described below.

Lee et al., compared the reaction torque of 15 healthy people with that of 15 people with spasticity during passive elbow flexion and extension movements [19]. Figure 1 illustrates the experimental setup. Pressure sensors were coupled into a wrist cuff and measured the muscular resistance imposed on passive movement. A gyroscope at the elbow picked up the angular speed whereas an electrogoniometer measured the angular displacement. Data were then sent to a differential pressure

Table 1: Summary of quantitative technologies investigated in spasticity assessment

Author / Year	Approach		Measured variables	Subjective Scale used to compare	Etiology of spasticity	Joint Involved			
	B	N				W	E	K	A
Pisano <i>et al.</i> (2000)[12]	X	X	EMG and force	MAS	S	X			
Pandyan <i>et al.</i> (2001)[13]	X		RPM and force	MAS	S		X		
Leonard <i>et al.</i> (2001)[14]	X		Displacement and force	MAS	CP and S		X		
Damiano <i>et al.</i> (2002)[15]	X	X	EMG and torque	MAS	CP			X	
McCrea <i>et al.</i> (2003)[16]	X		Torque	MAS	S		X		
Aarrestad <i>et al.</i> (2004)[17]	X		Displacement and force	***	CP		X	X	
Rydahl and Brouwer (2004) [18]	X		Displacement and force	MAS	S				X
Lee <i>et al.</i> (2004)[19]	X		Torque	MAS	***		X		
Kim <i>et al.</i> (2005)[20]	X	X	Torque, Angular Threshold	MAS	S				X
Rabita <i>et al.</i> (2005)[21]	X		Torque	MAS	***				X
Pierce <i>et al.</i> (2006)[22]	X		Torque and RPM	MAS	CP			X	
Gordon <i>et al.</i> (2006)[23]	X	X	Torque and EMG	MAS	CP		X		
Kumar <i>et al.</i> (2006)[24]	X		Torque	MAS	S		X		
Calota <i>et al.</i> (2008)[25]		X	EMG (TSRT)	MAS	S		X		
Malhotra <i>et al.</i> (2008)[26]	X	X	Torque, EMG	MAS	S	X			
Dantas (2008)[27]	X	X	Torque and EMG	MAS	S		X		
Lidström <i>et al.</i> (2009)[28]	X		Displacement and force	***	CP			X	
Fleuren <i>et al.</i> (2010)[29]	X	X	EMG and Displacement and force	MAS	***		X	X	
Kim <i>et al.</i> (2011)[30]		X	EMG (TSRT)	MAS	S		X		
Krüeger <i>et al.</i> (2012)[31]		X	MMG	MAS	DE			X	
Sterpi <i>et al.</i> (2013)[5]	X		Displacement	WPT and MAS	DE			X	
Silva (2013)[32]		X	EMG (TSRT)	MAS	S		X		
Bar-On <i>et al.</i> (2013)[33]	X	X	Integration of multidimensional signals	MAS	CP			X	
Jonnalagedda <i>et al</i> (2016)[34]	X		Force	MAS	CP		X		
Misgeldet <i>al</i> (2016)[35]	X	X	EMG	MAS	CP				X
Li <i>et al.</i> (2017) [36]	X		Displacement and force	MAS	S		X		
Eby BS <i>et al.</i> (2107)[37]	X		Elastography	MAS	S		X		

Legend: B: Biomechanics; N: Neurophysiological; EMG: Electromyography; MMG: Mechanomyography; TSRT: Tonic Stretch Reflex Threshold ; RPM: Resistance to Passive Movement; CP: Cerebral Palsy; S: Stroke; MAS: Modified Ashworth Scale ; WPT : Wartenberg Pendulum Test ; W: Wrist; E: Elbow; K: Knee; A: Ankle; DE: Different etiologies *** = Not reported.

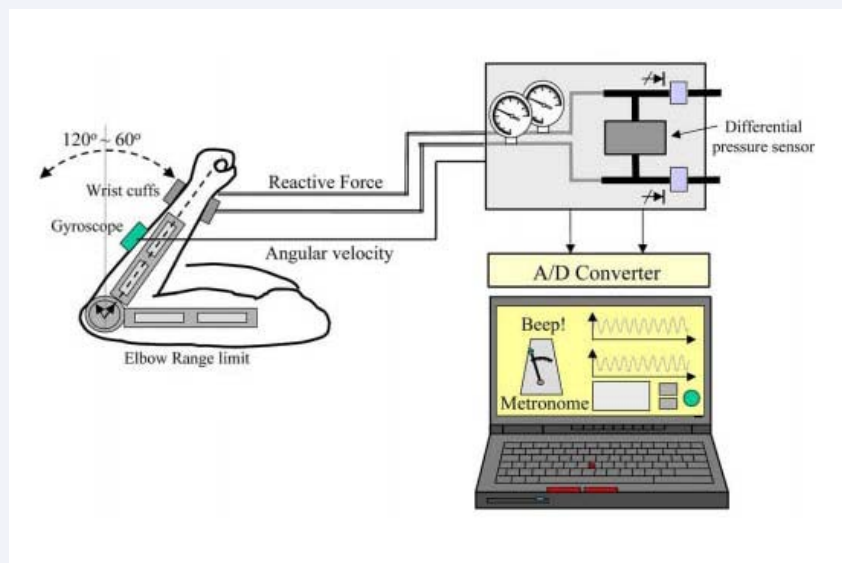


Figure 1 Model of a quantitative spasticity assessment system. Pressure sensors were coupled into a wrist cuff and measured the muscular resistance imposed on passive movement. The gyroscope at the elbow picked up the angular speed whereas the electrogoniometer measured the angular displacement. Data were sent to a differential pressure system which recognized the changes and processed information. Subsequently, the analog signals were converted into digital signals to be displayed on the computer. A digital metronome helped maintaining movement speed. Extracted from Lee et al.[20].

system which detected changes and processed information. Subsequently, the analog signals were converted to digital signals to be displayed on the computer display. A digital metronome helped to maintain movement speed. Results show that the imposed resistance was greater for individuals with spasticity, indicating correlation with MAS. However, the mechanism has limitations since the imposed resistance solely refers to muscle structures, i.e., only non-neural aspects of spasticity. The resistance to passive movement observed in individuals with spasticity is influenced by viscoelastic property changes of soft tissues and joint structures as well as by neuronal activities (stretch reflex) [13]. As the methodology used by Lee et al., focuses mechanical aspects, there is no support to conclude that it can replace MAS.

Gordon et al., evaluated spasticity and dystonia in children with CP using a commercial stiffness analyzer (CSA) composed of pressure sensors coupled to a cuff and a gyroscope [23]. However, they did not report which torque was measured, namely operator or muscle torque (or both) [27]. They investigated 13 children with spasticity caused by CP and 8 healthy children. All volunteers were evaluated with MAS before the assessment protocol with the commercial device. The CSA was placed on the volunteer's forearm. The evaluator used a metronome to perform elbow flexion and extension movements at 25, 100 and 175 beats per minute (bpm) in three cycles. Gordon et al., measured torque during EMG signal acquisition of deltoid, biceps brachii, triceps brachii, and wrist extensors and flexors. For every cycle movement the peak speed was found. Spasticity was determined as the ratio between force and speed. Results have shown that average force was greater for CP children than for healthy ones. Moreover, at higher speeds, spastic muscles required greater force to be passively stirred. Although the torque variables showed a significant correlation with MAS, the data presented by the authors did not allow us to conclude that the method

could replace MAS, since reliability and cost-benefit trials for clinical use were not included. This is because the authors, in this research, also classified muscle behavior with dystonia, which may have left the evaluation of spasticity itself vague.

Pierce et al., investigated spasticity in CP individuals and assessed test and retest reliability of peak resistance of both knee flexor and extensor muscles with a dynamometer [22]. They concluded there was reliability for the peak torque method at angular speed of 180°/s. Nevertheless, the peak resistance as a spasticity level rank system should be employed carefully [22] when based on test and retest method, because authors limited reliability investigation at a single speed (180°/s). As spasticity depends on stretch speed, new studies trying to correlate peak torque at other rates should be performed and include slow (80 and 120°/s) and fast tests (240 and 260°/s).

Pandyan et al., investigated elbow spasticity of 16 post stroke individuals using a biomechanical device consisting of load cell and electrogoniometer, as illustrated in Figure 2 [13]. They analyzed passive movement torque (PMT). Results indicated that PMT decreased as speed and movement cycle increased. Additionally, a weak correlation was detected between PMT and MAS. Damiano et al. [15], and Rabita et al. [21], also studied PMT and MAS. Their results were likewise inconsistent regarding the correlation between quantitative data and MAS. This finding corroborates that MAS alone is not enough for reliable spasticity assessment. In this context, Fleuren et al., tried to unveil the real MAS reliability using strength, range of motion and EMG data [29]. The authors stated that MAS is not enough to assess spasticity. Such statement justifies the importance of instigating health professionals to avoid using only the subjective scale during spasticity assessment and it emphasizes the need for reliable, modern and commercially available systems that guarantee patient safety.

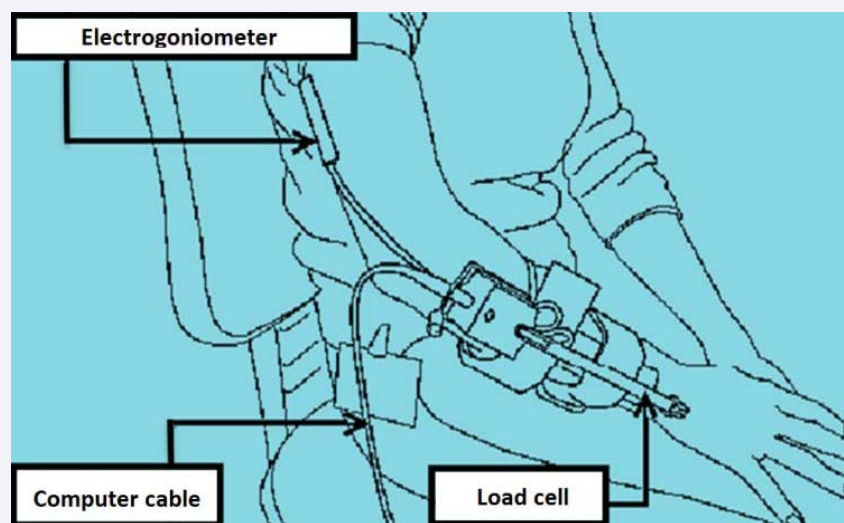


Figure 2 System for assessing spasticity using load cell. In this system, there is a flexible electrogoniometer positioned at the elbow joint and load cell positioned at the forearm region. In the test, the evaluator performs elbow extension movements while the data is acquired and sent to the computer.

Adapted from Pandyan et al. [13].

Mechanomyography (MMG) was also used for quantification of spasticity. MMG is a technique that allows observing muscle mechanical vibration (therefore assumed as biomechanical approach) during contraction and stretching, acquiring signals by means of superficial sensors fixed on the skin [31]. Krueger et al., assessed the spasticity of thigh muscles. Regarding the spasticity level, they gathered volunteers into two groups: MAS level 0 and MAS level 1. The integral of MMG was greater in MAS level 1 than in MAS level 0. Thus, this feature can be assumed as sensitive for distinguishing spasticity levels. Consequently, MMG can be used in spasticity assessment in both clinics and offices. However, since the study was performed with a small group of individuals and focused only on lower limbs, new research is required with more people and joints.

Serpi et al., executed an experimental protocol verifying the applicability of inertial sensors (another biomechanical approach) during spasticity quantitative assessment of quadriceps muscles simultaneously with Wartemberg's pendulum test (WPT) [5]. The study involved 20 healthy subjects and 11 patients in vegetative condition with spasticity of different etiologies. Six features were investigated: (i) initial knee angle (initial angle during maximal extension); (ii) final knee angle (at the end of oscillation); (iii) first reverse angle (angle in which the first change occurs from flexion to extension); (iv) area under a curve (the area between the knee angle and the complementary angle during oscillations); and (v) time to first reversal (interval between the beginning of flexion and the first change from flexion to extension). Correlation proved significant to both intra and inter-evaluators during WPT application. A weak correlation occurred between MAS and WPT. Therefore, even though in a promising way, this study indicated the possibility to assess spasticity quantitatively. In order to incorporate the device to daily practice it will require studying different spasticity levels.

Spasticity can be assessed using force sensors and inertial measurement as described by Jonnalagedda et al. The

authors coupled the sensors into a glove and interconnected to a mechanism for adjusting arm stiffness, a load cell and a potentiometer. The health professional dressed in the glove and performed flexion and extension movements on the patient's elbow. The glove recorded the force applied by the professional to perform the movements. Preliminary results showed that the glove based system proved to be effective and able to detect variations in spasticity when compared with subjective scales. The study involved simulated movements and evaluated only one joint therefore there it has limitations. Thus, improvements in instrumentation should be added and a larger number of patients should be included for more conclusive data [34].

Myotonometry is another biomechanical measurement technology. Myotonometer is a computerized device that quantifies muscle tone by analyzing muscle tissue displacement during contraction. This displacement represents an indirect measurement of force as muscle stiffness increases linearly with contractile force and muscle activation level. The validity of myotonometer measurements was studied by Leonard et al. who investigated biceps brachii displacement [14]. Two groups were formed: (i) control group with 10 participants and (ii) increased muscle tone group with 10 participants. Results showed that significant differences between both groups and myotonometry measurements showed correlation with MAS. Rydahl et al., also used myotonometry to assess the ankle plantar flexor muscle and compared the results to MAS and muscle stiffness [18]. They concluded that there are significant differences in muscle tissue movements between the muscle tone of healthy people and the increased muscle tone of 23 post stroke patients. Moreover, myotonometry showed intra and inter-evaluator reliability in investigations with CP children [17,28].

More recently, Liet al., studied myotonometry in 14 post stroke people. Their results showed a high sensitivity to assess spasticity, with significant differences in muscle displacement and adhesion in the spastic muscles compared to the contralateral side.

This finding suggests that myotonometry may be an effective technique to assess spasticity. However, the myotonometer is not easily accessible to health professionals and both acquisition and maintenance can be expensive [36].

In another line of research, shear wave elastography was investigated to characterize the spastic reflex in the brachial biceps during passive extension of the elbow in a 42-year-old male patient with spasticity. The authors asserted that the technique showed sensitivity to detect increased stiffness of brachialis muscle (compared with the muscle in the contralateral limb), especially when performing elbow extension movements at high speed. In spite of the promising results and easy operability by clinicians, the use of elastography in this task still requires a wider inspection because a single subject was studied. Similar results may not occur in limbs of other subjects whose spasticity is caused by other mechanisms of action [37].

Hybrid approach

As Table 1 describes, some systems involved both biomechanical and neurophysiological assessment methods. However, they are hybrid systems that do not always analyze the signal simultaneously. Kim et al., used EMG, an isokinetic device and MAS during spasticity assessment [20]. They assessed the ankle muscles of 20 subjects that had post stroke spasticity and compared results to a group of healthy people. After subjective analysis using MAS, the subjects seated on the isokinetic device and performed passive movements at 60, 120, 180 and 240°/s. Torque, angular threshold and work were acquired simultaneously with the gastrocnemius EMG signal. Results revealed torque, angular threshold, work and EMG activity were significantly greater in the group of subjects with spasticity than in the control group. Additionally, peak torque in post stroke group decreased as the angular speed increased from 60°/s to 180°/s. Observed increase were more noticeable during the first change (60 to 120°/s). Regarding work, the post stroke group did not show a linear increase like the one observed in control group. Angular threshold and the integral of EMG activity increased significantly with increasing speed in both groups. Therefore, assessment characteristics obtained with the isokinetic device were significantly correlated with MAS, however EMG did not show significant correlation with MAS. From the results of Kim et al., it is noted that the parameters evaluated by the biomechanical approach would be better indicated for determining the spastic condition, whereas the neurophysiological approach by the EMG would not present viability. However, Malhotra et al., compared the results of MAS (Clinical approach) with EMG (neurophysiological approach) and resistance imposed to passive movement (biomechanical approach) and the result was different [26]. According to Malhotra et al., there was a sensitivity of 0.5 and the specificity of 0.92 between MAS and EMG, while biomechanical measurements did not present a consistent relation with other measures (MAS or EMG). Such disagreements between the results show that biomechanical evaluation technologies, based only on the variables of muscle resistance imposed on the movement, are not feasible to determine the degree of spasticity.

Pisano et al., tried to correlate computerized (biomechanical) indexes with MAS and EMG (neurophysiological) [12]. They tried

to characterize intrinsic muscle tone and neural components of patients with spasticity. There were observed the Hoffmann reflex latency (HRL), Hmax/Mmax ratio, stretch reflex threshold speed (SRTS), stretch reflex (SR) latency and area, passive stiffness index (ISI) and the total stiffness index (TSI). Protocol was applied to wrist muscles. Results indicated the latent H reflex was not significant between spastic and healthy individuals. Hmax/Mmax, SR area, ISI and TSI were significantly greater for people with spasticity than with healthy people. The SRTS was significantly smaller in the spasticity group than in the healthy one. HRL and Hmax/Mmax did not correlate significantly with MAS. Patients with the same spasticity level (as determined with MAS) showed different H reflexes. In opposition, reflexes having similar intensities might occur in patients with different MAS levels of spasticity. One could observe MAS showed significant correlation with the mechanical stretching, mainly SRTS and TSI, although ISI did not present significant correlation with MAS.

Pisano et al. [12], associated EMG with biomechanics and they observed increased precision during assessment, mainly because EMG had changed linearly with spasticity levels. Moreover, EMG signals did not allow conglomerates because volunteers were gathered into six MAS-oriented level groups. Thus, EMG allowed determining slight changes in stiffness even though volunteers were ranked in a same MAS level. The authors claimed this assessment were more reliable. As limitations one could list the small number of patients assessed in the essay and the biomechanics device's lack of portability. Only laboratory assessments were performed.

Dantas used a load cell to measure muscle resistance, EMG to assess myoelectric activity of biceps and triceps brachii muscles and an electrogoniometer to analyze the range of motion [27]. The device is known as spasticity mechanical quantification system (MQS) and has its block diagram depicted in Figure 3. His work evaluated MQS functionality by means of a comparative study with MAS and it was observed dependence between passive muscle resistance and test application speed. Dantas determined the muscle stiffness index (MSI) calculating the ratio between the amplitudes of muscle force normalized mean and the angular speed. Conversely to Pandyan et al. [13], and Kumar et al. [24], who adopted only 1 s to periodicity of the cycle speed, the MQS uses three periodicities (1, 2 and 3 s). He used the greatest amplitude of movement (AM) allowed without causing pain. However, there was similarity regarding the adopted AM. Dantas' work differs from Lee et al., s research [19] which used four Periodicities (0.3, 0.5, 1.0 and 1.5 s), and movements were performed in the 60° - 120° range. Additionally, it also differed from the study of Gordon et al. which employed periodicities of 0.34, 0.6 and 2.4 s and AM of 50° [23].

The different periodicities used in the different papers can be explained by the tendency of patients with greater spasticity to show smaller AM. Therefore, according to Dantas, the periodicity of these patients has to be smaller than the others. Moreover, since stretch speed interferes with the assignment of spasticity levels, using a single periodicity could be efficient for same spasticity levels or could be feasible only when assessing slower or faster movements. In order to overcome such limitations, one could argue in favor of different periodicities. However, the investigations of Dantas [27], Pandyan et al. [13], Kumar et

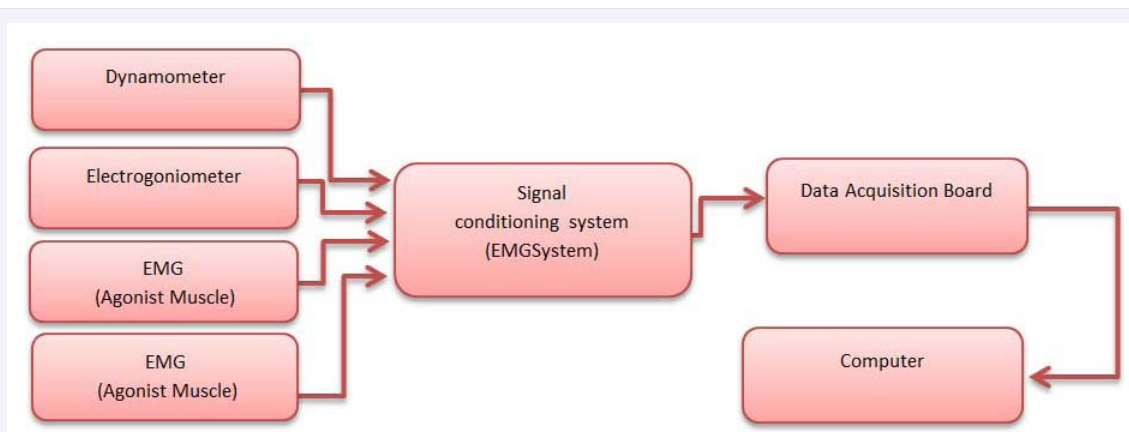


Figure 3 Block diagram of the mechanical quantification system. Adapted from Dantas [27].

al. [24], Gordon et al. [23], and Lee et al. [19], were also limited because their experiments did not take place in laboratory settings and involved a small number of volunteers. Thus, their results present low reliability for large scale reproducibility.

It was attributed to patients and healthy people the average muscle stiffness index (AMSI) for a better comparison between MQS and MAS. The mathematical model of flexion and extension movements considered three biomechanical aspects: inertia, related to forearm mass; viscous friction, related to joint friction; and elasticity, related to the response of muscle fascia. A load cell measured force variations aiming the determination of torque generated in both movements. Both MSI of patients and AMSI of patient group were significantly greater than control group indexes. The comparison between AMSI and MAS revealed correlation with $\rho = 0.81$ ($p = 0.01$).

According to Bar-On et al., interpreted both biomechanical and neurophysiological data simultaneously. The integration of multidirectional signals is not totally clear and has been poorly assessed regarding reliability, although some studies used both approaches in a same trial [33]. Therefore, Bar-On et al., developed a device to measure spasticity using multidirectional signals and they determined measurement properties such as reliability and the relation between MAS and the Tardieu's test. A group of 28 CP and 10 healthy children participated in the tests in which EMG signals from gastrocnemius and hamstrings were recorded. Two inertial measurement unit sensors determined joint position, angular speed and acceleration. A 6-degree of freedom load cell registered torque during joint movements. Children were allowed to seat appropriately, and muscles were stretched during manually controlled limb movements. Movements occurred at low, mean and high speed and with reference to predefined joint angle. Results showed that the reliability of such measurement was high to both muscles. All parameters were greater for children with spasticity than for healthy children, showing a moderate correlation with MAS in both muscles and strong correlation with Tardieu's test for hamstrings. Considering the results, multidirectional signals revealed to be reliable and relevant to assess muscle spasticity and can be clinically feasible. However, data collection only occurred for the knee joint and the protocol involved few volunteers. Thus, new studies are required with other joints and more volunteers.

A new approach for the detection of spasticity was created using the Medit Aachen (IPANEMA) body sensor network (BSN) called Integrated Posture and Activity Network system. For this, EMG was developed and used in the human locomotion of hemiplegic CP patients. The authors developed an algorithm for detecting the co-activation of antagonist muscle groups, during exaggerated stretch reflex and associated joint stiffness. The algorithm applies a cross-correlation function to EMG signals of two antagonist muscles and subsequent weighting using a Blackman window. As results, it was observed that the algorithm was sensitive to detect co-activation of muscles when spasticity was present, correlating with BSN data and with MAS. This form of evaluation is positive because it allows its inclusion in robotic equipment aiming to reduce spasticity or even equipment to favor locomotion. However, when it comes to replacing MAS, further research is needed, mainly involving a greater number of patients and other etiologies [35].

Tonic stretch reflex threshold

The literature describes studies that assessed spasticity levels using the tonic stretch reflex threshold (TSRT). Calota et al., developed a portable device called Montreal Spasticity Measurement (MSM) to investigate intra and inter-evaluator reliability in the quantification of muscle tone degree observing changes in TSRT [25]. They also tried to correlate TSRT with the degree of stretch resistance provided by MAS for post stroke subjects. The elbow joint of 20 men and 4 women was evaluated. The EMG signal of biceps brachii was recorded while the evaluator executed passive elbow flexion and extension movements, at different speeds using a metronome. The joint angles at which the EMG signals increased (above the value obtained at rest) determined the speed dependent dynamic stretch reflex threshold (SDSRT). The TSRT was determined by intercepting the regression line with the angle indicated by SDSRT. The study revealed that intra and inter-evaluator reliability during classification with MSM laid in a range from moderate to good for patients with high level of spasticity, but it does not show the same reliability for patients with low levels of spasticity. The differences between the techniques adopted by evaluators could have contributed to the variability between them.

After correlating quantitative data with MAS, the study proved that SDSRT did not present correlation with stretch

resistance observed with MAS; this work's initial hypothesis.

Kim et al., also correlated data based in TSRT and MAS, investigating the elbow joint of 15 subjects [30]. Figure 4 shows the setup with equipment that captures the EMG of biceps and triceps brachii, and electrogoniometer placed at the elbow registering displacement angle. All acquired data (EMG and electrogoniometry) were sent to a sensor module where they were processed and displayed. Participants were ranked into three groups and all showed correlation between spasticity levels given by MAS and TSRT.

More recently, Silva developed spasticity assessment instrument using TSRT [32]. The results indicated that the increase in spasticity produced an increase in TSRT i.e. a greater TSRT implies a higher spasticity level, even when classified in a same MAS level. Thus, Silva emphasizes the idea that TSRT is more sensitive than MAS in the assessment of spasticity because MAS only allows ranking into six levels. Moreover, attributing a MAS level depends on evaluator sensitivity, what is ineffective to graduate very small changes in a same spasticity level as can be observed in the assessment with TSRT. However, even having shown higher sensitivity in the spasticity assessment, the study of Silva [32] allows questionable gaps because it performs experiments on a small group of patients and with patients presenting low to moderate spasticity (MAS 0 to 2, respectively). This fact does not guarantee TSRT is in fact reproducible in large scale or in patients with severe spasticity (MAS 3 or 4).

CONCLUSION

The literature revealed that experiments with quantitative assessment of spasticity involved small number of volunteers. Therefore, there is need of performing more clinical investigations in order to increase the number of volunteers and/or observe different joints in the same experiment.

The initial hypothesis was confirmed showing that quantitative assessment of spasticity is more sensitive to detect spasticity levels if compared to MAS. Therefore, the use of MAS alone for spasticity level ranking is insufficient and unsafe for both professionals and patients. So, it is essential to enhance such assessment equipment for both commercialization and also

to encourage health professionals to replace MAS use.

The retrieved papers employed the following parameters in biomechanical approach: (i) torque or force, (ii) range of motion, (iii) angular speed and, (iv) integral of mechanomyography. The parameters of neurophysiological approach were extracted from electromyography signals of agonist and antagonist muscles. However, most papers integrated both approaches to guarantee differences in neural and non-neural aspects.

FUTURE PERSPECTIVES

The search for an approach and an instrument that fully replace MAS in clinical practice remains because no study performed enough clinical essays that allowed it to be widely diffused and the instrumentation commercialized. In order to be feasible in daily routine of health professionals, the equipment should be easy to use, portable and have low cost.

As future perspectives, we expect to correlate mechanomyography signals with spasticity levels and to determine which signal processing technique allows better correlation. In the case, there is correlation between MMG and spasticity level and enhancements in signal processing techniques, it will be possible to develop mobile (such as smartphones) applications that assign spasticity levels by analyzing muscle vibrations registered by seismic sensors inside these devices during stretch reflex. If the sensitivity of the internal accelerometer is insufficient to detect muscle vibration changes, then an external module consisting of highly sensitive accelerometers or other vibration transducers could be connected to the mobile device and transmit information wirelessly. Moreover, the system should be able to process mechanomyography signals in real time. In this way, the assignment of spasticity levels would be objective, quantitative, precise, reproducible, mitigating divergences between professionals and respecting metrological requirements, ergonomics for ease handling and market low-cost.

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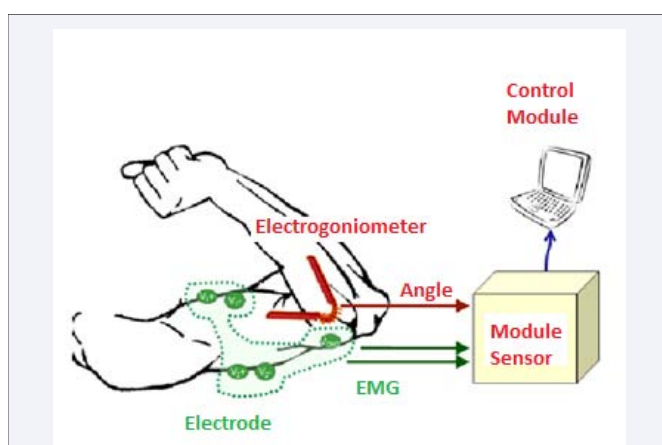


Figure 3 Block diagram of the mechanical quantification system. Adapted from Dantas [27].

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