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Spastic dystonia in stroke subjects: prevalence and features of the neglected phenomenon of the upper motor neuron syndrome

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HIGHLIGHTS

- 74% of stroke subjects was affected by spastic dystonia in their hypertonic wrist flexor muscles.
- Only a minority of stroke subjects was affected by spasticity in their hypertonic wrist flexor muscles.
- Evaluation of EMG activity during static muscle stretch is pivotal to assess spastic dystonia.

ABSTRACT

Objective: Spastic dystonia is one of the positive phenomena of the upper motor neuron syndrome (UMNS). It is characterised by the inability to relax a muscle leading to a spontaneous, although stretch-sensitive, tonic contraction. Although spastic dystonia is a recognized cause of muscle hypertonia, its prevalence among hypertonic muscles of stroke subjects has never been investigated. Differently from spasticity, which is an exaggerated stretch reflex, spastic dystonia is viewed as an efferent phenomenon, due to an abnormal central drive to motoneurons.
Methods: In 23 hemiparetic stroke subjects showing increased muscle tone of wrist flexors, surface EMG was used to investigate the presence of spontaneous, stretch-sensitive EMG activity in *flexor carpi radialis*.
Results: Spontaneous, stretch-sensitive EMG activity was found in 17 subjects. In the remaining 6 subjects, no spontaneous EMG activity was found.
Conclusions: The majority of stroke subjects is affected by spastic dystonia in their hypertonic wrist flexor muscles. Only a minority of subjects is affected by spasticity.
Significance: To stop spastic dystonia from being the neglected aspect of UMNS, it is essential to link its definition to increased muscle tone, as occurred for spasticity. Recognizing the real phenomena underling muscle hypertonia could improve its management.

1. Introduction

Spastic dystonia and spasticity are two positive phenomena (i.e. those characterized by muscle over-activity) of the upper motor neuron syndrome (UMNS) (Trompetto et al., 2014). Both phenomena occur while the subject attempts to keep the muscles relaxed.

Spastic dystonia can be described as a spontaneous tonic muscle contraction occurring at rest, i.e. in the absence of any muscle stretch or any voluntary command (Gracies, 2005b). Although not evoked by muscle stretch, spastic dystonia increases when the muscle is stretched, even though prolonged stretch can reduce it (Sheean and McGuire, 2009). Therefore, the *stretch-sensitive spontaneous tonic muscle contraction* is the basic trait of spastic dystonia, the spastic component being its stretch sensitivity, whereas the dystonic component being the spontaneous activity at rest and the inability to stop it at command (Gracies, 2005b; Sheean and McGuire, 2009).

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Spastic dystonia is usually viewed as an efferent phenomenon, mediated by a tonic supraspinal drive to spinal motor neurons (Sheean and McGuire, 2009). The supposed efferent nature of spastic dystonia is based on the observations of Denny-Brown, who coined the term spastic dystonia to indicate the spontaneous limb postures displayed by monkeys after specific cortical lesions. He demonstrated that these postures did not result from overactivity in spinal reflex circuits since they were not abolished by dorsal root section (Denny-Brown, 1966). Subsequently, other Authors noted the similarities between the postures described by Denny-Brown in monkeys with the hemiplegic postures in UMNS subjects leading to the adoption of the concept of spastic dystonia in the clinical field (Burke, 1975; Lance, 1981; Burke, 1988). However, it must be stressed that the pathophysiology of spastic dystonia has never been investigated in humans and, therefore, dedicated neurophysiological studies are needed (Lorentzen et al., 2018). In a recent review on spasticity, we suggested that the prolonged firing of α-motoneurons after a muscle contraction, a well-documented phenomenon in UMNS subjects (Zijdewind and Thomas, 2003), is likely to play an important role in producing spastic dystonia (Trompetto et al., 2014).

Unlike spastic dystonia, spasticity is a phenomenon whose pathophysiology is well known. It is a stretch reflex disorder, manifested clinically as an increase in muscle tone that becomes more apparent with more rapid stretching movement. Spasticity is due to a pathological stretch reflex, i.e. a tonic stretch reflex present in a relaxed muscle (Lance, 1980; Sheean, 2002). In healthy subjects at rest, in fact, no tonic stretch reflex (i.e. the reflexes elicited by the rather slow stretches performed during muscle tone assessment) is evoked. The basic trait of spasticity is that it is a dynamic phenomenon, i.e. the tonic stretch reflex ceases as soon as the passive movement stops (Burke, 1975; Thilmann et al., 1991; Sheean, 2002).

Muscle hypertonia is a frequent clinical sign in UMNS subjects. It can hinder function, produce pain and several complications, limiting the potential success of rehabilitation. Muscle hypertonia is a complex phenomenon due to several factors, including spasticity (Thilmann et al., 1991) and secondary soft tissue changes (mainly due to limb immobilization) in muscles, tendons and ligaments (Dietz et al., 1981; Gracies, 2005a). Hypertonia due to secondary soft tissue changes is often referred as intrinsic hypertonia.

Besides spasticity and intrinsic hypertonia, it has been suggested that increased muscle tone in UMNS subjects could also be due to spastic dystonia (Gracies, 2005b; Bakheit et al., 2011; Lorentzen et al., 2018). Recently we had the chance to test this hypothesis. Using surface electromyography (s-EMG) in a group of subjects suffering from multiple sclerosis with increased muscle tone in the quadriceps, we found a tonic stretch reflex at rest in all of them. However, in some subjects the muscle was actually relaxed prior to muscle stretch, indicating the presence of spasticity (73% of the sample). In the remaining subjects, there was an irrepressible spontaneous tonic contraction prior to muscle stretch, indicating the presence of spastic dystonia (Marinelli et al., 2017).

As far as we know, there are no studies in the literature investigating the prevalence of spasticity and spastic dystonia in hypertonic muscles of stroke subjects. Up to now, all subjects affected by muscle hypertonia are referred to as having spasticity without investigating their ability to maintain the muscles relaxed prior to muscle stretch.

This is a relevant issue since muscle hypertonia often requires to be treated, and several treatments are currently available. Knowing whether muscle hypertonia is due to an exaggerated stretch reflex (spasticity) or to a different phenomenon whose pathophysiology is elusive (spastic dystonia) could be relevant in selecting the most appropriate treatment for each single subject.

To our knowledge, this study represents the first attempt to investigate the prevalence of spasticity and spastic dystonia in hypertonic muscles of post-stroke subjects.

2. Materials and methods

2.1. Subjects

Recruitment occurred from outpatient clinics of the Department of Neuroscience, IRCCS Ospedale Policlinico San Martino, Genova, Italy. Inclusion criteria were: (1) clinical presentation of a hemispheric stroke leading to unilateral motor deficit at least 6 months prior to enrolment; (2) brain CT or MRI documenting a single vascular lesion in the middle cerebral artery territory; (3) presence of hypertonia in the wrist flexor muscles with a Modified Ashworth Scale (MAS) score ranging from 1 to 3; (4) no previous treatment with botulinum toxin and drugs acting on muscle tone; (5) no severe cognitive impairment.

All subjects provided their written informed consent to participate in the study, which was approved by the local ethical committee.

2.1.1. Clinical assessment

Muscle tone of the wrist flexor and extensor muscles was measured by means of the MAS. Furthermore, a 0–10 numeric rating scale (NRS) for muscle stiffness of the wrist experienced by the patients was used (0 = no muscle stiffness; 10 worst possible muscle stiffness). Deep tendon reflexes of the upper limb (biceps reflex, triceps reflex, brachioradialis reflex) were graded as follows: 0 = no response; 1+ = a slight but definitely present response; 2+ = a brisk response; 3+ = a very brisk response; 4+ = a tap elicits a repeated reflex. Muscle strength of wrist flexor and extensors muscles was rated according to the Medical Research Council (MRC) for muscle strength. Finally, wrist postures were assessed while the subject, sitting on a chair with their back supported and the arms over their lap, was asked to stay completely relaxed in their most natural position. After visual assessment, wrist was considered flexed, extended or neutral (Hefter et al., 2012).

2.1.2. EMG and kinematic recordings

A surface preamplified electrode with fixed inter-electrode distance (TSD150B, Biopac Systems Inc, USA) was placed over the muscle belly of *flexor carpi radialis* (FCR) following SENIAM (Surface Electromyography for Non-Invasive Assessment of Muscles) guidelines (Hermens, 1999). The excursion of wrist joint was recorded by a twin-axis electronic goniometer placed across the joint (TSD130B, Biopac Systems Inc, USA). All signals were acquired by an MP150 unit (Biopac Systems Inc, USA) with a 2 KHz sampling rate and underwent a Blackman −61 dB 10–350 Hz band-pass filter for offline processing (AcqKnowledge 3.8.1 software by Biopac Systems Inc, USA).

2.1.3. Experimental protocol

Subjects were seated in a chair with their back supported. For the entire duration of the recording session, subjects were instructed to stay completely relaxed and in silence. They were examined through the following 3 phases:

- *Phase 1: looking for the presence of spontaneous EMG activity at rest.*

After placing the electrode and the goniometer, subjects' arms were arranged over their lap in the most natural position. Then, the EMG signal was recorded for approximately 120 seconds (s).

In the case of tonic EMG activity, subjects were urged to stay relaxed every 10 s.

- *Phase 2: dynamic stretch of wrist flexors.*

The examiner (CT, medical doctor) grasped the subject's hand and moved it from the natural position of phase 1 to maximal extension in 1 s (dynamic phase of the stretch). To control the velocity of the passive displacement, a method developed in our laboratory was used (Marinelli et al., 2013).

- *Phase 3: static stretch of wrist flexors.*

After the dynamic phase of the stretch, the subject's hand was kept in the extended position for approximately 120 s (static phase of the stretch).

2.1.4. Analysis of data

The angle values detected by the electronic goniometer were used to calculate onset and termination times of the dynamic phase of the stretch (phase 2). Onset and termination times were visually detected on the goniometer trace displayed on the computer screen, using a display gain of 20°/cm and a temporal window of 340 ms/cm (Marinelli et al., 2017).

Single subject analysis. Visual examination of unrectified EMG signal was carried out to look for muscle activity at phase 1, phase 2 and phase 3. Average Rectified Value of the EMG signal (ARV) (Hermens, 1999) at phase 1, phase 2 and phase 3 was measured only when muscle activity was detected in the corresponding phase by visual examination. Both phase 1 and phase 3 were divided into 4 bins of 30 s each (bin 1: 0–30 s; bin 2: 30–60 s; bin 3: 60–90 s; bin 4: 90–120 s). For each bin, ARV was calculated.

Analysis across subjects. A paired t-test was used to compare ARVs obtained at phase 1 to those obtained at phase 3. In order to compare ARVs in the 4 bins of phase 1, a repeated measure ANOVA was performed followed by Bonferroni/Dunn post-hoc analysis. Similarly, to compare ARVs in the 4 bins of phase 3, a repeated measure ANOVA was performed followed by Bonferroni/Dunn post-hoc analysis.

3. Results

According to the inclusion criteria, 23 hemiparetic subjects (8 women; mean age ± SD 68 ± 8 years, range 43–80 years) were enrolled. Demographic and principal clinical characteristics are shown in Table 1.

3.1. Subjects showing spontaneous EMG activity at phase 1 (subjects 1–17 in Table 1)

Spontaneous, tonic EMG activity was found at phase 1 in 17 subjects (1–17). This activity was present throughout the recording time (120 s) in 11 subjects (1–11). In the other subjects (12–17), EMG activity was present at the beginning of the recording, but lasted less than 120 s, with a duration ranging from 20 s (subject 17) to 90 s (subject 12). Mean ± SD ARV at phase 1 was 4.25 ± 3.53 μV. ARV decreased across the 4 bins ($F[3,48] = 6.0$, $p < 0.0015$) (Fig. 1), indicating a gradual decrease of EMG activity during phase 1. Post-hoc analysis confirmed a significant difference between bin 1 and bin 3 and between bin 1 and bin 4. However, when only the first 11 subjects (those in whom EMG activity lasted for the entire duration of phase 1) were included in the analysis, the decrease of AVR across the 4 bins of phase 1 was no longer significant ($F[3,48] = 2.8$, $p < 0.06$).

Both dynamic stretch (phase 2) and static stretch (phase 3) of wrist flexors produced a clear EMG activity in all the 17 subjects, both in those activated (subjects 1–11) and in those relaxed (subjects 12–17) prior to muscle stretch. Mean ± SD ARV during phase 2 and phase 3 was respectively 24.73 ± 20.86 μV and 11.90 ± 8.28 μV. Statistical analysis showed that ARV at phase 3 was higher than ARV obtained at phase 1 ($p < 0.0001$). ARV decreased across the 4 bins ($F[3,48] = 27.2$, $p < 0.0001$) (Fig. 1),

Table 1
Patients' demographic and clinical features.

Subject	Gender	Age (years)	Lesion/affected side of the body	Time since stroke (months)	MAS		MRC		NRS		DTR			Rest posture
					Ext	Flex	Ext	Flex	Ext	Flex	BR	TR	BrR	
1	F	43	Haemorrage/L	13	0	2	5	3	6	6	3	3	3	N
2	F	75	Infarction/R	11	1	3	3	1	2	10	4	3	3	F
3	F	68	Haemorrage/R	108	1	3	3	0	8	10	3	3	3	F
4	M	68	Haemorrage/L	49	0	3	4	2	2	6	3	3	3	N
5	M	78	Infarction/R	11	2	3	3	1	3	5	3	3	3	F
6	M	61	Infarction/L	6	0	2	5	3	0	5	3	2	3	N
7	M	71	Haemorrage/L	45	0	1	5	4	5	5	3	3	3	N
8	F	79	Infarction/R	22	0	1+	5	4	0	2	3	3	3	N
9	F	80	Haemorrage/R	124	0	2	0	0	0	0	3	3	3	N
10	M	74	Infarction/R	21	1	3	0	0	0	8	3	3	3	F
11	M	70	Infarction/L	20	0	3	0	0	2	5	4	3	3	F
12	M	66	Haemorrage/L	15	0	1+	3	1	5	5	3	2	3	F
13	M	59	Haemorrage/L	11	1	2	4	1	2	2	3	3	3	F
14	M	75	Infarction/R	9	0	3	0	0	0	9	3	3	3	N
15	M	67	Infarction/L	6	0	1+	5	4	0	1	3	2	3	N
16	F	74	Infarction/R	9	2	3	0	0	0	0	3	3	3	F
17	M	61	Infarction/L	32	0	3	5	4	1	0	3	3	3	F
18	M	71	Haemorrage/R	62	0	2	5	4	2	1	3	3	3	N
19	M	66	Infarction/L	36	0	1+	5	4	0	2	3	3	3	N
20	F	58	Infarction/R	34	2	2	0	0	2	5	3	3	3	F
21	M	68	Infarction/L	8	0	1	5	4	0	0	3	2	3	N
22	M	66	Infarction/L	36	0	1+	5	4	0	2	3	3	3	N
23	F	69	Infarction/R	49	0	1	5	5	0	0	3	3	3	N

Subjects' number does not refer to recruitment order. Time since stroke refers to the number of months between stroke onset and recruitment in the study. Ext = wrist extensors; Flex = wrist flexors; MAS = Modified Ashworth Scale; MRC = Medical Research Council (scale for muscle strength); NRS = numeric rating scale for muscle stiffness; DTR = Deep Tendon Reflexes; BR = biceps reflex; TR = triceps reflex; BrR = brachioradialis reflex; N = neutral position (wrist neither flexed nor extended); F = flexed position (wrist in flexion).

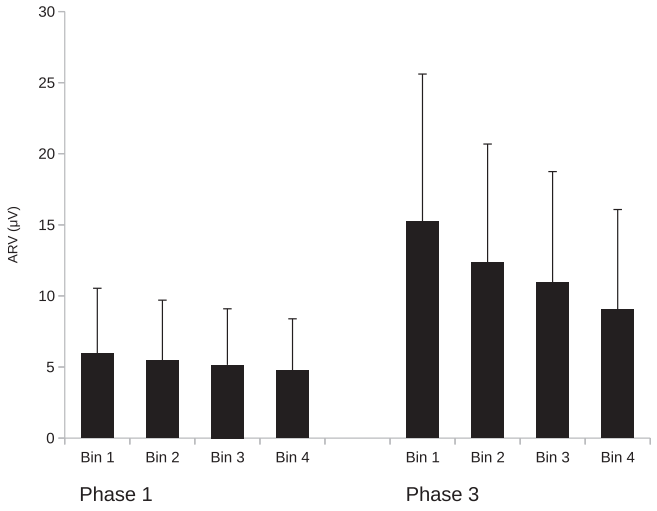

Fig. 1. Mean data (±SD) of the average rectified value of the EMG signal (ARV) obtained during phase 1 and phase 3 in subjects 1–17. Bin 1: 0–30 s; bin 2: 30–60 s; bin 3: 60–90 s; bin 4: 90–120 s. ARV obtained during phase 1 significantly decreases over time ($p < 0.0015$). ARV obtained during phase 3 significantly decreases over time ($p < 0.0001$).

indicating a gradual decrease of EMG activity during phase 3. Post-hoc analysis confirmed a significant difference between bin 1 and the other bins, as well as from bin 2 and bin 4. Although EMG activity during phase 3 was characterized by a gradual reduction over time, in all the 17 subjects muscle activity persisted for the entire duration of phase 3.

Figs. 2 and 3 show EMG recordings from respectively subject 11 and subject 15.

3.2. Subjects showing no spontaneous EMG activity at phase 1 (subjects 18–23 in Table 1)

No spontaneous EMG activity was found in the remaining 6 subjects (18–23).

Dynamic stretch of wrist flexors (phase 2) produced a clear EMG activity in all the 6 subjects. Mean ± SD ARV during phase 2 was 7.14 ± 8.28 μV.

Static stretch of wrist flexors (phase 3) produced EMG activity only in 3 subjects (18–20). This activity, characterized by a gradual reduction over time in all the 3 subjects, lasted 45.50 s in subject 18, 14.60 s in subject 19 and 9.20 s in subject 20. Mean ± SD ARV during phase 3 in these 3 subjects was 2.33 ± 0.42 μV. Fig. 4 shows EMG recordings from subject 20.

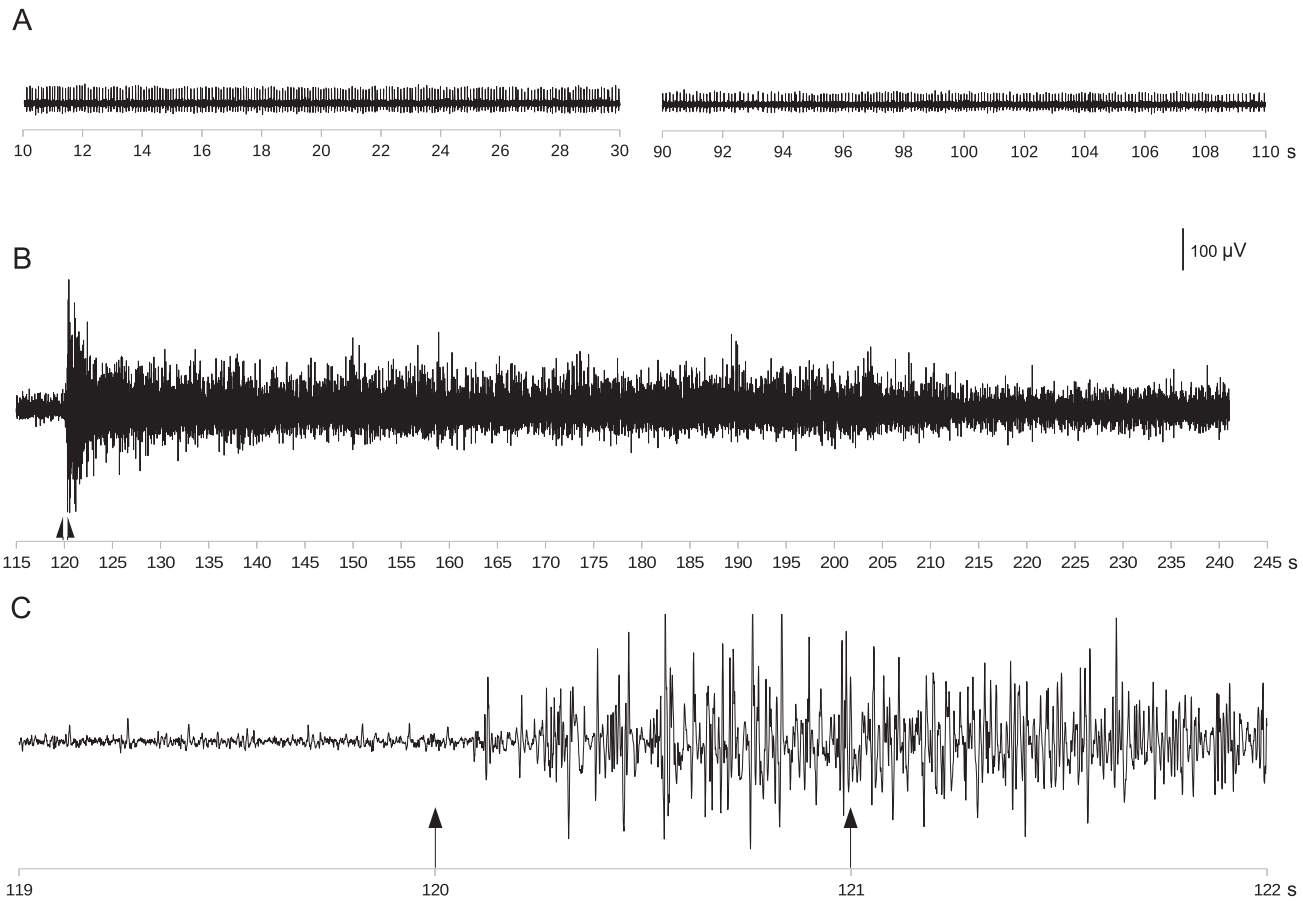

Fig. 2. Involuntary EMG activity from subject 11 is shown. In A, tracing on the left shows EMG activity from the first part of phase 1 (from 10 s to 30 s), while tracing on the right shows EMG activity from the last part of phase 1 (from 90 s to 110 s). B refers to the last part of phase 1 (from 115 s to 120 s), the whole phase 2 (from 120 s to 121 s) and the whole phase 3 (from 121 s to 241 s). C is a focus on the tonic stretch reflex reported in B (from 119 s to 122 s). In B and C, first arrow indicates the beginning, while second arrow indicates the end of passive wrist displacement. A shows that spastic dystonia is present as long as the patient attempts to stay completely relaxed, in the absence of any muscle stretch, with the wrist in a natural position (phase 1). B and C show that dynamic passive stretch of wrist flexors produces a clear EMG activity (tonic stretch reflex), which carries on during the subsequent static stretch of wrist flexors (phase 3). B shows that EMG activity during the static stretch of wrist flexors lasts for the entire duration of phase 3 with a decremental trend in time. Note that prior to passive displacement of the wrist the muscle is activated for the presence of spastic dystonia.

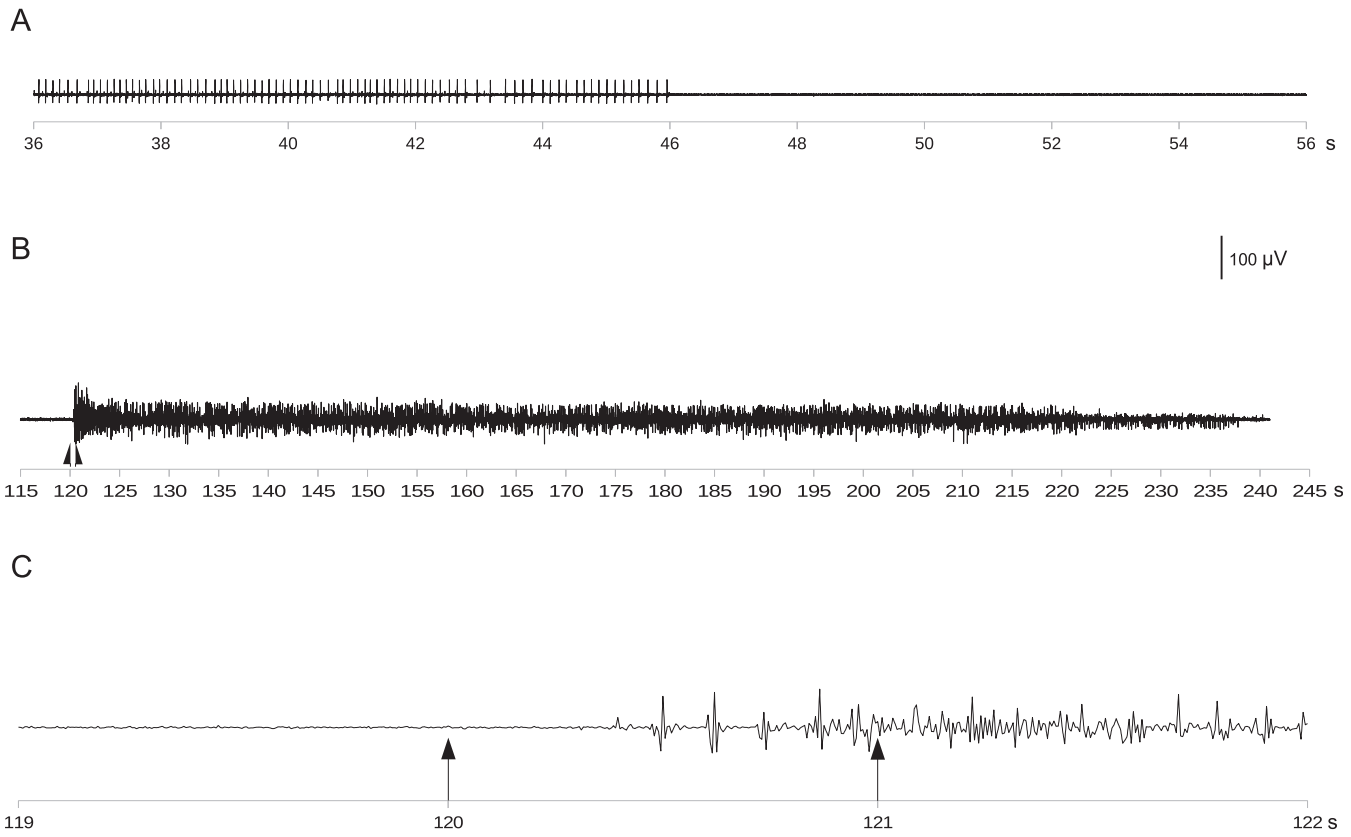

Fig. 3. Involuntary EMG from subject 15 is shown. In A, EMG activity of phase 1 (from 36 s to 56 s) is reported. B refers to the last part of phase 1 (from 115 s to 120 s), the whole phase 2 (from 120 s to 121 s) and the whole phase 3 (from 121 s to 241 s). C is a focus on the tonic stretch reflex reported in B (from 119 s to 122 s). In B and C, first arrow indicates the beginning, while second arrow indicates the end of passive wrist displacement. A shows that spastic dystonia spontaneously extinguishes after 46 s from the beginning of phase 1. B and C show that dynamic passive stretch of wrist flexors produces a clear EMG activity (tonic stretch reflex), which carries on during the subsequent static stretch of wrist flexors (phase 3). B shows that EMG activity during the static stretch of wrist flexors lasts for the entire duration of phase 3 with a decremental trend in time. Note that prior to passive displacement of the wrist the muscle is completely relaxed.

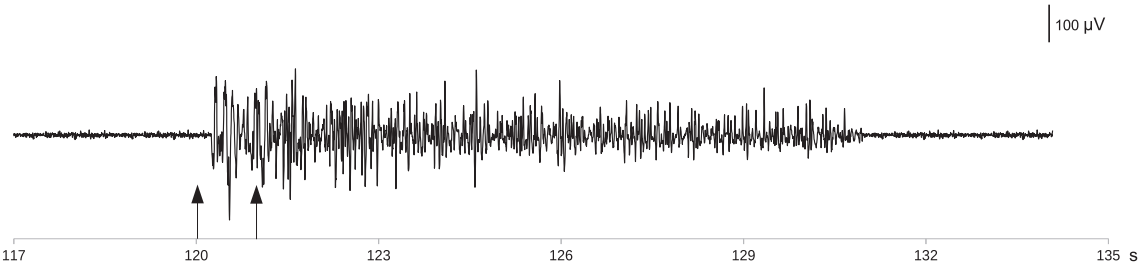

Fig. 4. Involuntary EMG from subject 20 is shown. EMG activity from the last part of phase 1 (from 117 s to 120 s), phase 2 (between the arrows) and phase 3 (from 121 s to 134 s) is reported. The first arrow indicates the beginning, while the second arrow indicates the end of passive wrist displacement. Spastic dystonia is not present. The muscle is completely relaxed prior to passive stretch. Dynamic passive stretch of wrist flexors produces a clear EMG activity (tonic stretch reflex), which carries on only for a few seconds during the subsequent static stretch of wrist flexors (phase 3).

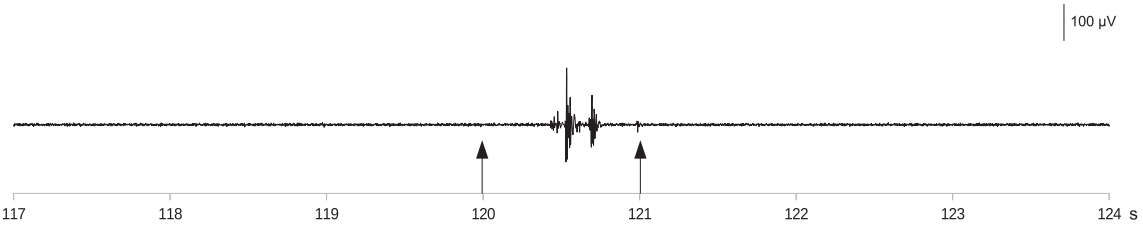

Fig. 5. Involuntary EMG from subject 23 is shown. EMG activity from the last part of phase 1 (from 117 s to 120 s), phase 2 (between the arrows) and phase 3 (from 121 s to 124 s) is reported. The first arrow indicates the beginning, while the second arrow indicates the end of passive wrist displacement. Spastic dystonia is not present. The muscle is completely relaxed prior to passive stretch. Dynamic passive stretch of wrist flexors produces a clear EMG activity which ceases as soon as passive movement stops.

Static stretch of wrist flexors (phase 3) induced no EMG activity in subjects 21–23. Fig. 5 shows EMG recordings from subject 21.

4. Discussion

The s-EMG protocol used in this study has been designed to search for involuntary EMG activity (both spontaneous and stretch-induced) in the FCR of stroke subjects showing hypertonic wrist flexor muscles. Spontaneous EMG activity was searched for 120 s, while the subjects were sitting on a chair at rest, with their back supported and with their arms positioned over their lap in the most natural position (phase 1). To investigate the effects of dynamic and static stretch on this spontaneous activity, subject's wrist was passively extended (dynamic stretch, phase 2) and kept in this position for 120 s (static stretch, phase 3). Dynamic phase of stretch (phase 2) was performed in 1 second in order to investigate the tonic stretch reflex in wrist flexor muscles.

Stretch reflexes can be classified as phasic or tonic according to the duration of the dynamic stretch. Phasic stretch reflexes are evoked by fast stretches, such as tendon jerks evoked by a tendon tap. Tonic stretch reflexes are elicited by stretches of much longer duration, such as those performed during muscle tone assessment (Sheean, 1998). We chose a duration of passive wrist displacement of 1 second because this velocity of passive movement falls in the range of the velocities commonly used in muscle tone assessment.

We investigated 23 stroke subjects showing hypertonia of wrist flexor muscles.

In 17 subjects (subjects 1–17), we found a spontaneous, tonic EMG activity in their FCR in the absence of any muscle stretch and while, according to the instructions, they were attempting to stay fully relaxed. Both dynamic and static stretch increased this spontaneous activity. With static stretch, EMG activity gradually reduced over time; however, it was present as long as wrist flexors were kept stretched (Figs. 1–3). Therefore, the activity found in subjects 1–17 can be properly described as a *spontaneous, tonic, stretch-sensitive muscle contraction*. It perfectly fits with the description of spastic dystonia (Gracies, 2005b; Sheean and McGuire, 2009).

In 3 subjects (21–23), no spontaneous EMG activity was observed in the 120 s chosen as criterion for presence. Furthermore, in these 3 subjects, EMG activity induced by muscle stretch ceased as soon as the passive movement stopped (Fig. 5). This activity can be described as a *pure dynamic tonic stretch reflex*, which perfectly fits with the classical view of spasticity (Burke, 1975; Thilmann et al., 1991; Sheean, 2002).

In the remaining 3 subjects (18–20), no spontaneous EMG activity was found. However, in these subjects EMG activity induced by dynamic stretch (tonic stretch reflex) did not cease as soon as the passive movement stopped, but it was followed by a tonic EMG activity during the subsequent static phase of the stretch. This activity was rapidly decremental, disappearing well before the end of phase 3 (Fig. 4).

Therefore, the results of the present study show that the overwhelming majority of the enrolled subjects was affected by spastic dystonia (74%). Only a minority of subjects was affected by spasticity (13%) or by an intermediate condition in which, notwithstanding the absence of spontaneous EMG activity prior to muscle stretch, the muscle kept on contracting for a few seconds when maintained elongated after the dynamic phase of the stretch (13%). We are tempted to consider this latter condition a transitional phase between spasticity and spastic dystonia. However, further studies are needed to elucidate this issue. In our sample, we find no subjects without involuntary EMG activity since dynamic passive stretch evoked a tonic stretch reflex in all the subjects. This means that in none of the investigated subjects hypertonia of wrist flexors was due to intrinsic hypertonia alone.

The present results suggest that muscles affected by spastic dystonia sooner or later reach a complete state of relaxation. Among the 17 subjects exhibiting spastic dystonia, this form of muscle overactivity ceased spontaneously in 6 subjects (12–17) (Fig. 3). In the other 11 subjects (1–11), spastic dystonia showed a non-significant trend ($p = 0.06$) of reduction over time. Reasonably, also in these later subjects a complete muscle relaxation would have been achieved if the observation period had been longer (for instance 5 or 10 min). That a muscle exhibiting spastic dystonia may spontaneously relax during the examination may cause some difficulty while assessing this form of muscle overactivity. Indeed, this means that, in a subject at rest, transitory absence of EMG activity in a muscle does not definitely rule out spastic dystonia. As we have shown here, the static phase of muscle stretch proves decisive in this context. Muscles exhibiting spastic dystonia (also those relaxed prior to passive muscle stretch, subjects 12–17) were active during the static phase of muscle stretch for at least 120 s (Figs. 2 and 3). On the contrary, muscles not exhibiting spastic dystonia either were not active during the static phase of muscle stretch (subjects 21–23) (Fig. 5) or showed a short activation, lasting no more than 45.50 s (subjects 18–20) (Fig. 4). Therefore, the present data states that the evaluation of EMG activity during static muscle stretch is pivotal to discriminate spastic dystonia from spasticity.

During the static phase of passive muscle stretch, the prolonged activation that we found in subjects 1–17 can be due to at least two different mechanisms. As a first mechanism, this activity could be a static component of the stretch reflex caused by length-dependent muscle afferents, which would be able to activate the α-motoneurons targeting spastic dystonic muscles. Indeed, several studies in UMNS subjects suggested that length-dependent muscle afferents are involved in the stretch reflex, activating the α-motoneurons through an oligosynaptic pathway (Marque et al., 2001; Nardone and Schieppati, 2005; Sheean and McGuire, 2009). Moreover, as a second mechanism, muscle activity during the static phase of passive muscle stretch may be due to the inability to stop the firing of α-motoneurons produced by the preceding dynamic passive stretch (i.e. the inability to stop the tonic stretch reflex). This inability could be connected to the prolonged firing of α-motoneurons which according to this hypothesis would not only follow voluntary muscular activity (Zijdewind and Thomas, 2003), but also involuntary reflex activity (Trompetto et al., 2014). It is possible that both mechanisms (static stretch reflex and inability to stop the firing of α-motoneurons) act concurrently in the same subject.

These data state the importance of sensory feedback in producing spastic dystonia. This is a largely expected result considering that stretch-sensitivity is a pivotal feature of spastic dystonia. Obviously, the fact that sensory feedback can increase spastic dystonia is not in contrast with its efferent nature. From a theoretical point of view, spastic dystonia can be mediated by a tonic supraspinal drive to spinal motor neurons and, at the same time, be modulated by afferent signals from muscle spindles. Physiologically, also spasticity is the result of abnormal descending supraspinal drive and muscle spindles input interacting at the spinal motor neurons. The basic feature that differentiates the two forms of hypertonia is the role played by the peripheral input, which acts as a trigger for motor neuron activation in the case of spasticity, and as a modulator of motor neuron activity in the case of spastic dystonia. This view leads us to consider spastic dystonia as the most severe part of the spectrum of spasticity, where the postsynaptic mechanisms acting onto the α-motor neuron are pushed far enough to enable the motor neuron firing without need of peripheral input. This pathophysiological hypothesis could be

investigated with longitudinal evaluation of EMG activity (both spontaneous and stretch-induced) in the hypertonic muscles of post-stroke subjects.

Another open issue concerning spastic dystonia is dealing with its name. There is no doubt that the term spastic dystonia combines definitions used in the UMNS and in basal ganglia diseases, therefore raising eventual confusion. However, this term was coined 52 years ago by Denny-Brown to indicate the "extrapyramidal" component of spastic hemiplegia that confers the "attitudinal dystonia" resulting in the hemiplegic posture. Since 1960s, the term "spastic dystonia" has been used in many authoritative papers, therefore a possible new definition should emerge from a wide expert consensus. Although we do not consider it immutable, especially over time, we find spastic dystonia a term that reflects perfectly the double nature of this peculiar form of muscle overactivity found in the UMNS (i.e. being a spontaneous contraction difficult to stop at command and being sensitive to muscle length).

The 3 subjects with spasticity (subjects 21–23) were affected by mild muscle hypertonia (MAS 1 or 1+), while in the majority of subjects with spastic dystonia (subjects 1–17) muscle hypertonia was severe (MAS 3 in 9 subjects). This finding suggests that subjects with spastic dystonia are affected by a more severe form of muscle hypertonia than those affected by spasticity. Moreover, eight subjects with spastic dystonia showed no pathological postures at the wrist, while in 1 subject without spastic dystonia the wrist was flexed. These observations lead us to be warned that the simple inspection of clinical posturing can be misleading in the assessment of spastic dystonia (Marinelli et al., 2017). Unfortunately, due to the few subjects affected by spasticity, the sample size was too small to make valid correlations between EMG findings and the clinical picture.

The present results are remarkable in the view that all the 23 enrolled subjects might be classified clinically as having spasticity since they exhibited muscle hypertonia in a UMNS context. Unexpectedly, spasticity was present only in a small minority of them, whereas spastic dystonia was markedly prevalent.

Our results show that spastic dystonia and spasticity are not clinical signs, since they cannot be recognized on the sole basis of clinical examination. As a matter of fact, muscle hypertonia is the clinical sign encompassing both spasticity, spastic dystonia and intrinsic hypertonia. To differentiate spastic dystonia and spasticity in hypertonic muscles, s-EMG is essential. Recognizing these two forms of muscle hypertonia could be of clinical significance when planning the management of UMNS patients. A real-life example of this significance comes from observation of the daily practise of physiotherapists, who aim reducing muscle hypertonia by repeated muscle stretching, a procedure known to induce habituation of the tonic stretch reflex. Indeed, in patients with pure spasticity, repeated muscle stretching is invariably followed by reflex habituation, therefore by clinical benefit. In some patients with spastic dystonia, reflex habituation is replaced by paradoxical reflex facilitation (Marinelli, 2017), therefore by exacerbation of muscle hypertonia.

Our results suggest that, to stop spastic dystonia from being the neglected aspect of UMNS, it is essential to link the concept of spastic dystonia to increased muscle tone, as it occurred for spasticity (Lance, 1980).

Conflicts of interest

None.

References

Bakheit AMO, Fheodoroff K, Molteni F. Spasticity or reversible muscle hypertonia? J Rehabil Med 2011;43:556–7.

Burke DJ. An approach to the treatment of spasticity. Drugs 1975;10:112–20.

Burke DJ. Spasticity as an adaptation to pyramidal tract injury. In: Waxman SG, editor. Advances in Neurology, Vol. 47: Functional Recovery in Neurological Disease. New York: Raven Press; 1988.

Denny-Brown D. The cerebral control of movement. Liverpool: Liverpool University Press; 1966 (Sherrington lectures).

Dietz V, Quintern J, Berger W. Electrophysiological studies of gait in spasticity and rigidity. Evidence that altered mechanical properties of muscle contribute to hypertonia. Brain 1981;104:431–49.

Gracies J-M. Pathophysiology of spastic paresis. I: Paresis and soft tissue changes. Muscle Nerve 2005a;31:535–51.

Gracies J-M. Pathophysiology of spastic paresis. II: Emergence of muscle overactivity. Muscle Nerve 2005b;31:552–71.

Hefter H, Jost WH, Reissig A, Zakine B, Bakheit AM, Wissel J. Classification of posture in poststroke upper limb spasticity: a potential decision tool for botulinum toxin A treatment? Int J Rehabil Res Int Z Rehabil Rev Int Rech Readaptation 2012;35:227–33.

Hermens HJ. European recommendations for surface ElectroMyoGraphy: results of the SENIAM project. In: Roessingh Research and Development BV, editor. Enschede: Roessingh Research and Development; 1999 (SENIAM).

Lance JW. Symposium synopsis. In: Feldman RG, Young RR, Koella WP, Spasticity: Disordered Motor Control; 1980. p. 485–94.

Lance JW, Mc Leod JG. A physiological approach to clinical neurology. 3rd ed. London: Butterworth; 1981.

Lorentzen J, Pradines M, Gracies J-M, Bo Nielsen J. On Denny-Brown's "spastic dystonia" - What is it and what causes it? Clin Neurophysiol 2018;129:89–94.

Marinelli L, Currà A, Trompetto C, Capello E, Serrati C, Fattapposta F, et al. Spasticity and spastic dystonia: the two faces of velocity-dependent hypertonia. J Electromyogr Kinesiol 2017;37:84–9.

Marinelli L, Trompetto C, Mori L, Vigo G, Traverso E, Colombano F, et al. Manual linear movements to assess spasticity in a clinical setting. PloS One 2013;8:e53627.

Marque P, Simonetta-Moreau M, Maupas E, Roques CF. Facilitation of transmission in heteronymous group II pathways in spastic hemiplegic patients. J Neurol Neurosurg Psychiatry 2001;70:36–42.

Nardone A, Schieppati M. Reflex contribution of spindle group Ia and II afferent input to leg muscle spasticity as revealed by tendon vibration in hemiparesis. Clin Neurophysiol 2005;116:1370–81.

Sheean G. Spasticity rehabilitation. London: Churchill Communications; 1998.

Sheean G. The pathophysiology of spasticity. Eur J Neurol 2002;9(Suppl 1):3–9. dicussion 53–61.

Sheean G, McGuire JR. Spastic hypertonia and movement disorders: pathophysiology, clinical presentation, and quantification. PM R 2009;1:827–33.

Thilmann AF, Fellows SJ, Garms E. The mechanism of spastic muscle hypertonus. Variation in reflex gain over the time course of spasticity. Brain J Neurol 1991;114:233–44.

Trompetto C, Marinelli L, Mori L, Pelosin E, Currà A, Molfetta L, et al. Pathophysiology of spasticity: implications for neurorehabilitation. BioMed Res Int 2014;2014:354906.

Zijdewind I, Thomas CK. Motor unit firing during and after voluntary contractions of human thenar muscles weakened by spinal cord injury. J Neurophysiol 2003;89:2065–71.