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ORIGINAL ARTICLE

Biomechanical and electromyographic assessment of spastic hypertonus in motor complete traumatic spinal cord-injured individuals

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Study design: Between-groups design with repeated measures.
Objective: To quantify spastic hypertonia in spinal cord-injured (SCI) individuals.
Setting: Rehabilitative Center, Italy.
Subjects: 29 individuals with a motor complete SCI (American Spinal Injury Association impairment scale grade A or B) and 22 controls.
Methods: According to the modified Ashworth scale (MAS), patients were subgrouped as SCI-1 (MAS = 1, 1 +) and SCI-2 (MAS = 2, 3). Passive flexo-extensions of the knee were applied using an isokinetic device (LIDO Active) at 30°, 60°, 90° and 120° s^{-1}. We measured the peak torque, mean torque (MT) and work. Simultaneous electromyography (EMG) was recorded from leg muscles.
Results: At the speed of 120° s^{-1} all SCI-2 patients presented EMG reflex activities in the hamstring muscle. All biomechanical parameter values increased significantly according to speed, but analysis of variance revealed a significant interaction between the angular velocity and group ($F(d.f.\ 6, 138) = 8.89$, $P < 0.0001$); *post hoc* analysis showed significantly greater torque parameter values in the SCI-2 group compared with the SCI-1 group and the control group at 90° and 120° s^{-1}. Receiver operating characteristic curves showed that using peak torque values the probability of correctly classifying a patient into SCI-1 and SCI-2 was 95%, compared with 70% for MT and 68% for work.
Conclusions: The isokinetic device is useful for distinguishing individuals with a high level of spastic hypertonus. Examination of EMG activity may help ascertain whether increased muscle tone is caused by reflex hyper excitability and to determine whether muscle spasm is present. Peak torque and simultaneous EMG assessment should be considered for the evaluation of individuals with SCI in the rehabilitative context, that is, in measuring therapeutic interventions.
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Keywords: isokinetic dynamometry; torque; spasticity; spinal cord injury; stretch reflex; knee

Introduction

An important aim in the treatment of spinal cord-injured (SCI) individuals is to minimize the spasticity and improve daily living activities. The evaluation of hypertonus is usually performed by testing limb resistance to passive movement using specific clinical scales (modified Ashworth scale, MAS), but the inter- and intra-individual variabilities are yet to be observed. The low sensitivity of the scale results in the majority of patients being assigned intermediate scores (for example, grade 2–3 using the MAS). Problems occur when the MAS is used in longitudinal (natural evolution; pre- and post-treatment) or cross-sectional evaluations (controls versus patients), wherein it is important to identify slight changes in muscle tone. Furthermore, to select appropriate therapeutic interventions, it is crucial to separate the non-reflex components from the reflex ones in the measurement of hypertonus, but clinical measures are unable to accomplish this aim.

These observations have sparked efforts to develop objective evaluation methods based on a readily controlled and reproducible stimulus that can provide a simple measure of the resistance of passive joint movements, such as neurophysiological and biomechanical methods. Unfortunately, most of these evaluation techniques fail to reflect the clinical status of the patient's muscle tone.[1,2] The use of

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isokinetic dynamometry has been proposed as a valuable tool for assessing and quantifying spasticity and other types of hypertonus.[3–7] Erroneous recordings caused by poor limb relaxation and/or inappropriate positioning limit the applicability of the torque measure. Electromyography (EMG) activity recorded during isokinetic tests can be used to overcome those inconveniences.

We used isokinetic dynamometer, simultaneous torque and EMG activity assessment in SCI patients and controls to identify a more sensitive biomechanical parameter that can help discriminate individuals with varying degrees of hypertonus and to assess EMG's usefulness in estimating the 'neural' contribution to tonus increase.

Materials and methods

SCI individuals admitted to the Rehabilitation Centre of S. Maria agli Ulivi (Pozzolatico, Florence, Italy) and to the Spinal Cord Unit of Azienda Ospedaliera Universitaria Careggi (Florence, Italy) for rehabilitative treatment between 1 January 2006 and 30 December 2007 were screened according to the following inclusion criteria: (a) spinal trauma that occurred at least 3 months before; (b) a minimum pain-free passive range of motion of 80° at the knee; (c) the absence of previous knee fractures or severe articular blocks; (d) the absence of paraosteoarticular ossification evaluated by means of hip and knee X-ray; and (e) stable dosage of oral antispastic drugs for 30 days before the evaluation. Lesional level was assessed by neuroradiological examinations. Clinical assessments were performed by two experienced assessors (AP and CF), who were blinded to the biomechanical measurements. Impairment was assessed by the American Spinal Injury Association (ASIA) impairment scale.[8] Spasticity of the knee extensors and flexors was assessed by MAS.[1,9] Spasms, defined as sudden involuntary muscle contractions in the affected limb, were assessed using the Penn spasm frequency score.[10] Healthy subjects with no history of neurological disease or knee injury and normal muscle tone (MAS = 0) were studied as a control group. All individuals were advised about the experiment's procedures and aims and they gave their consent to participate in the study, which had the approval of the local ethics committee.

Two of the authors (AG and RC), blinded to clinical evaluation, carried out isokinetic tests using a computerized isokinetic dynamometer (LIDO Active, Officine Rizzoli, Bologna, Italy). The patients were examined with an empty bladder before they underwent therapeutic activity. The patient was positioned in the dynamometer's seat and the back was tilted to 85°, with the chest and thighs restrained by straps. The lower limb was attached to the active arm of the dynamometer 4–5 cm above the lateral malleolus.

We recorded the EMG activity of the quadriceps and hamstring muscles using pairs of surface electrodes (Bionen, Florence, Italy) placed according to Freriks *et al.*[11] A Medelec synergy machine (Oxford Instruments, Surrey, UK) with a sampling rate of 1024 Hz, sweep rate of 100 ms div^{-1} and sensitivity of 500 μV–2 mV div^{-1} was used. EMG was synchronized with torque–angle curve data.

Protocol

Knee movements were imposed over 80° range of motion starting at 85° and ending at 5° of knee flexion. To allow for subject familiarization with the isokinetic machine and avoid warm-up effects, the subject's knee was cycled through the range of motion at least 20 times at 30° s^{-1}. Ten consecutive knee flexions and extensions were performed at 30°, 60°, 90° and 120° s^{-1} with 60 s of rest between trials. To minimize the temporal and sequence effects, the tested leg (right/left) and the four speeds were randomly arranged across individuals.

Data analysis

On-line EMG activity recordings were used to identify the relaxation status during the trials. Stretch response was considered to be present when the mean root mean square value exceeded the mean baseline resting level plus 2.5 standard deviations in trials in which muscle activity was absent during the 250 ms before movement onset. Resistance to passive motion was determined by measuring the peak torque (PT N m), defined as the greatest resistance measured during the passive movement, mean torque (MT, N m), defined as the sum of torques on the defined window divided by time, and work (*W*, Joule), calculated as the area below the torque–angle curve. The PT, MT and *W* of each repetition were calculated over a ± 30° window centred on the middle of the range of motion, and the average values of the 10 repetitions were used for statistical analysis. Cycles of activity where spasms occurred, as indicated by EMG activity unrelated to limb position, were eliminated.

Statistical analysis

All statistical procedures were carried out using the StatView software package (Version 5.0.1, 1998). Descriptive statistics (means and s.d.'s) were calculated for instrumental parameters. Biomechanical parameters were used as dependent variables in univariate analysis of variance for repeated measures to analyse the differences between patients and controls. The within-subject factors were velocity (30°, 60°, 90° and 120° s^{-1}), side (right and left) and movement (extension and flexion). Those variables showing significant main effects or significant interactions ($P<0.05$) were subjected to Fisher's *post hoc* test using an α level <0.05. The accuracy of biomechanical parameters in predicting the MAS score was evaluated by plotting receiver operator characteristic (ROC) curves, which combine both the sensitivity and specificity achieved by the diagnostic test at several cut-off points.[12]

Results

We selected 29 SCI patients classified according to MAS in SCI-1 (MAS = 1, 1 +) and SCI-2 (MAS = 2, 3) (Table 1). Sixteen SCI individuals were taking antispasticity medications (Baclofen, 30–70 mg). Twenty-two healthy subjects (13 male; mean age 40 years; range 22–68) were included in the control group.

Torque

The mean and s.d. of the biomechanical parameters are reported in Table 2. The preliminary analysis of variance showed no significant effect of side, neither overall nor according to the between (group) and within (velocity and movement) factors. For this reason, the analyses of variance were done using the average value of both legs for each subject.

The amount of increase in biomechanical parameters according to speed was significantly different among groups (velocity × group interaction, Table 3). *Post hoc* analysis showed significantly greater PT and *W* values in SCI-2 compared with SCI-1 and the control group at 90° and 120° s^{-1}. MT values were significantly higher in SCI-2 only at 120° s^{-1}.

PT values were significantly greater in SCI-2 compared with the other groups both during extension and during flexion at the speed of 120° s^{-1} (group × movement × speed) (Figure 1).

Figure 2 shows the sensitivity and specificity in ROC curves of PT, MT and *W* at the speed of 120° s^{-1}. The PT–ROC curve passes closer to the upper left corner with respect to MT and *W* curves, showing both a high sensitivity and high specificity (area under the ROC curve = 0.95), whereas the ROC curves for MT and *W* intersect and overlap (areas under ROC curves 0.70 and 0.68, respectively).

Table 1 Individuals' characteristics

Characteristic	*SCI-1 (n = 14)*	*SCI-2 (n = 15)*
Mean age, year (range)	36 (27–70)	47 (28–68)
Gender (male/female)	8/6	9/6
Months since trauma, mean (range)	7.3 (3–24)	7.6 (4–24)
Injury level		
Cervical	2	6
Thoracic	12	9
AIS		
A	11	6
B	3	9
PSFS median (IQR)	1 (1)	1 (2)

Abbreviations: A, Complete: No motor or sensory function is preserved in the sacral segments S4–S5; AIS, American Spinal Injury Association Impairment Scale; B, Incomplete: Sensory but no motor function is preserved below the neurological level and includes the sacral segments S4–S5; PSFS, Penn spasm frequency score; SCI, spinal cord injured; SCI-1 (modified Ashworth scale = 1, 1+); SCI-2 (modified Ashworth scale = 2, 3).

Table 2 Resisting peak torque (N m), mean torque (N m) and work (J) values for knee motion in the SCI and control groups at different angular velocities (mean ± s.d.)

	Angular velocity (° s^{-1})							
	30		*60*		*90*		*120*	
	Ext	*Flex*	*Ext*	*Flex*	*Ext*	*Flex*	*Ext*	*Flex*
				Peak torque				
Right								
Controls	0.8 ± 1.9	0.4 ± 0.9	5.1 ± 1.8	5.7 ± 1.7	6.9 ± 1.4	6.3 ± 1.2	7.8 ± 2.6	7.9 ± 1.6
SCI 1	0.9 ± 2.0	0.7 ± 1.9	4.9 ± 1.2	5.6 ± 1.5	6.4 ± 1.8	6.2 ± 1.4	7.0 ± 1.7	7.1 ± 1.3
SCI 2	1.5 ± 0.9	1.4 ± 1.0	6.4 ± 2.4	5.2 ± 0.9	11.4 ± 7.6	8.4 ± 3.9	14.0 ± 6.8	11.4 ± 4.5
Left								
Controls	0.7 ± 1.6	0.5 ± 1.0	5.2 ± 1.0	5.6 ± 1.7	6.5 ± 1.3	7.0 ± 1.8	7.6 ± 1.7	8.2 ± 1.9
SCI 1	0.2 ± 0.4	0.4 ± 0.5	4.5 ± 0.6	5.9 ± 1.6	6.0 ± 1.5	7.0 ± 1.5	7.4 ± 1.6	7.7 ± 1.3
SCI 2	1.9 ± 3.1	1.7 ± 2.5	6.7 ± 2.7	5.3 ± 2.0	10.9 ± 4.6	7.9 ± 3.0	14.1 ± 6.2	11.1 ± 5.6
				Mean torque				
Right								
Controls	0.6 ± 1.6	0.1 ± 0.4	0.9 ± 1.7	0.9 ± 1.1	2.4 ± 1.6	1.4 ± 0.9	2.7 ± 2.2	1.9 ± 0.6
SCI 1	0.4 ± 0.9	0.3 ± 1.0	0.5 ± 0.8	0.9 ± 0.8	1.6 ± 1.1	1.2 ± 0.8	1.6 ± 1.2	1.7 ± 0.8
SCI 2	0.5 ± 0.6	0.4 ± 0.6	1.5 ± 0.9	0.7 ± 0.7	3.6 ± 3.6	2.1 ± 2.7	4.9 ± 3.2	3.2 ± 2.7
Left								
Controls	0.3 ± 0.8	0.1 ± 0.3	0.5 ± 0.7	0.8 ± 0.6	1.9 ± 0.8	1.5 ± 0.8	2.2 ± 0.6	1.8 ± 0.6
SCI 1	0.1 ± 0.3	0.2 ± 0.4	0.1 ± 0.3	0.4 ± 0.6	1.8 ± 0.4	1.4 ± 0.7	1.6 ± 0.7	1.9 ± 0.7
SCI 2	0.9 ± 1.0	0.6 ± 0.6	1.5 ± 1.1	0.8 ± 0.7	3.4 ± 2.0	1.9 ± 0.8	4.8 ± 2.5	3.1 ± 1.7
				Work				
Right								
Controls	2 ± 0.3	1 ± 0.3	12 ± 1.1	10 ± 1.1	23 ± 2.1	18 ± 1.5	38 ± 2.4	37 ± 1.4
SCI 1	2 ± 0.2	3 ± 0.2	7 ± 0.8	8 ± 0.8	18 ± 1.6	19 ± 1.2	36 ± 2.7	34 ± 1.3
SCI 2-3	8 ± 0.4	3 ± 0.5	17 ± 1.0	9 ± 0.5	53 ± 5.2	30 ± 4.1	91 ± 6.8	58 ± 4.9
Left								
Controls	2 ± 0.2	1 ± 0.2	8 ± 0.6	8 ± 0.5	19 ± 1.1	19 ± 1.3	40 ± 1.4	38 ± 1.4
SCI 1	1 ± 0.1	2 ± 0.2	3 ± 0.2	7 ± 0.4	15 ± 0.4	21 ± 1.1	35 ± 1.4	35 ± 1.3
SCI 2-3	7 ± 0.7	5 ± 0.5	5 ± 1.1	9 ± 0.5	56 ± 2.9	29 ± 1.0	96 ± 4.8	57 ± 3.2

Abbreviations: Ext, eccentric torque in extension movement; Flex, eccentric torque in flexion movement; SCI, spinal cord injury.

Individual PT values in controls and SCI patients are plotted in Figure 3. At the speeds of 30° and 60° s^{-1}, individual values of SCI patients have the same distribution as controls. At 90° s^{-1}, some SCI-2 patients showed PT values greater than controls. At 120° s^{-1}, all SCI-2 individuals showed PT values greater than controls.

Table 3 *F* values for ANOVA with between-subject (group) and within-subject factors (speed and movement)

	d.f.	*PT*	*MT*	W
Main effects				
Group	2, 48	7.2**	4.1*	5.7*
Movement	1, 2	0.7	2.3	2.4
Speed	3, 6	186****	59****	90****
Two-factor interactions				
Group × speed	6, 144	8.0***	3.8**	4.8*
Group × movement	2, 48	5.0**	3.0	2.8
Three-factor interactions				
Group × movement × speed	6, 144	3.5**	2.3	1.6

Abbreviations: d.f., degrees of freedom; MT, mean torque; PT, peak torque; *W*, work.
*$P<0.05$; **$P<0.01$; ***$P<0.001$; ****$P<0.0001$.

EMG response

The presence of EMG reflex responses in the study populations, according to the muscle and speed tested, is shown in Figure 4. No control or SCI-1 subject showed a stretch response at any of the velocities tested. A threshold value of velocity had to be exceeded before a stretch reflex was produced in either muscle in SCI-2 individuals (that is, 30° s^{-1} for hamstring and 90° s^{-1} for quadriceps). At the speed of 120° s^{-1}, phasic EMG activity was present in all SCI-2 individuals but more frequently in hamstring than in quadriceps (Figure 5).

In two SCI-2 individuals, EMG activity lasted many seconds (25–30). However, this was not related to limb position but was an EMG expression of spasms occurring during testing (with a Penn spasm frequency score of 4). These individuals showed highly variable torque parameters during repetitions (for example, PT range 7–22 N m). In the torque–angle curve of cycles with high values, PT and MT had similar values, indicating resistance to movement independently from limb position.

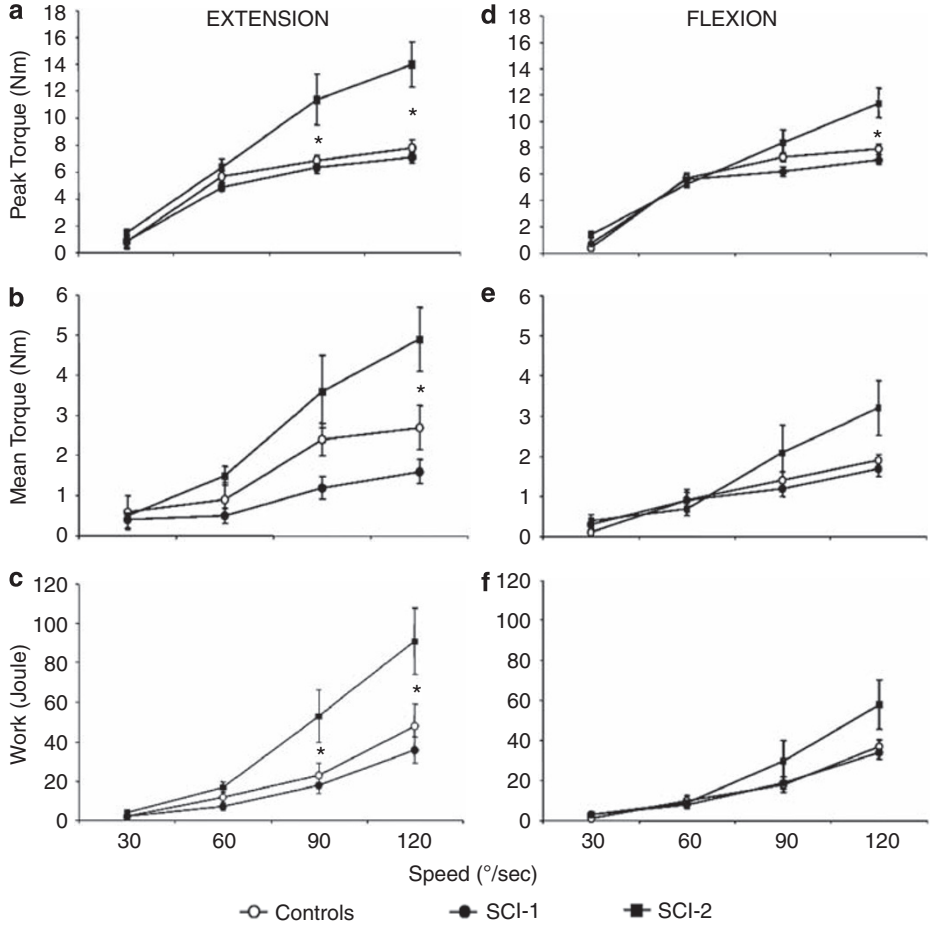

Figure 1 PT (**a**, **d**), MT (**b**, **e**) and *W* (**c**, **f**) in passive isokinetic knee movements during extension (left column) and flexion (right column) of controls (open circles), SCI-1 (filled circles) and SCI-2 individuals (filled squares). All values refer to mean ± standard error of the mean at different speed (30°, 60°, 90° and 120° s^{-1}). **post hoc* test $P<0.05$.

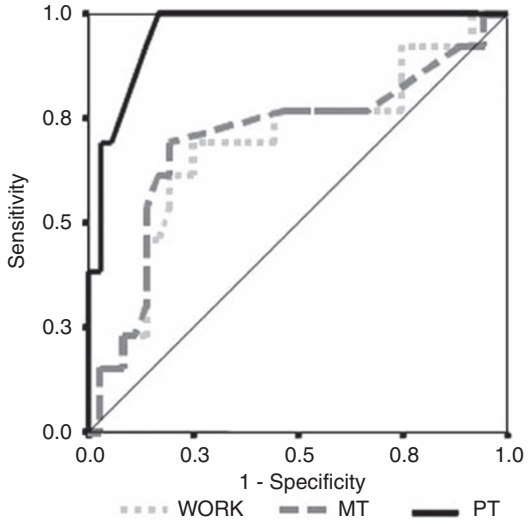

Figure 2 Receiver operator characteristics (ROC) curves of (PT), (MT) and *W* ($120^\circ s^{-1}$) to predict a MAS score $\geqslant 2$. The ordinate axis shows the sensitivity of the tests, ranging from 0 to 1.0, whereas the abscissa shows the percentage of false-positive results (1-specificity). Tests with good discriminatory power produce a ROC curve, which closely follows the left-hand axis and the top margin of the graph.

Discussion

We used an isokinetic device to move the knee joint passively and measure the movement-provoked resistive torque and EMG activity in SCI individuals and healthy controls. Biomechanical parameters were able to classify individuals with different MAS scores. PT is superior to the other two torque parameters (MT, *W*) for detecting SCI-2 patients. In more detail, a PT value greater than 8.7 N m, measured at $120^\circ s^{-1}$ during limb extension, represented the best trade-off between sensitivity and specificity to identify individuals with an MAS score $>1+$. EMG activity was absent in healthy controls or in SCI-1 individuals at all of the angular velocities tested. All SCI-2 individuals showed stretch responses in at least one muscle at maximal speed. Moreover, the maximal PT measured followed the onset of EMG activity. The velocity-dependent behaviour of biomechanical parameters and EMG activity suggested that resistance, measured during passive movement, was mainly because of hyperactive phasic stretch reflexes. Therefore, the hypertonus measured in SCI-2 individuals had a neural contribution.

Biomechanical tests, such as the pendulum[13] and ramp-old tests[2] among others, are not regularly used in daily practice because they require special equipment and do not provide information easily interpreted by the clinician. Many authors tried to determine whether the parameters of isokinetic dynamometer measurement were appropriate for the quantification of spasticity.[3,4,6,9,14] However, conflicting and inconclusive data were reported for the heterogeneity of patients examined (aetiology of spasticity, MAS score) and isokinetic protocol (speed, order of testing, EMG activity recording).

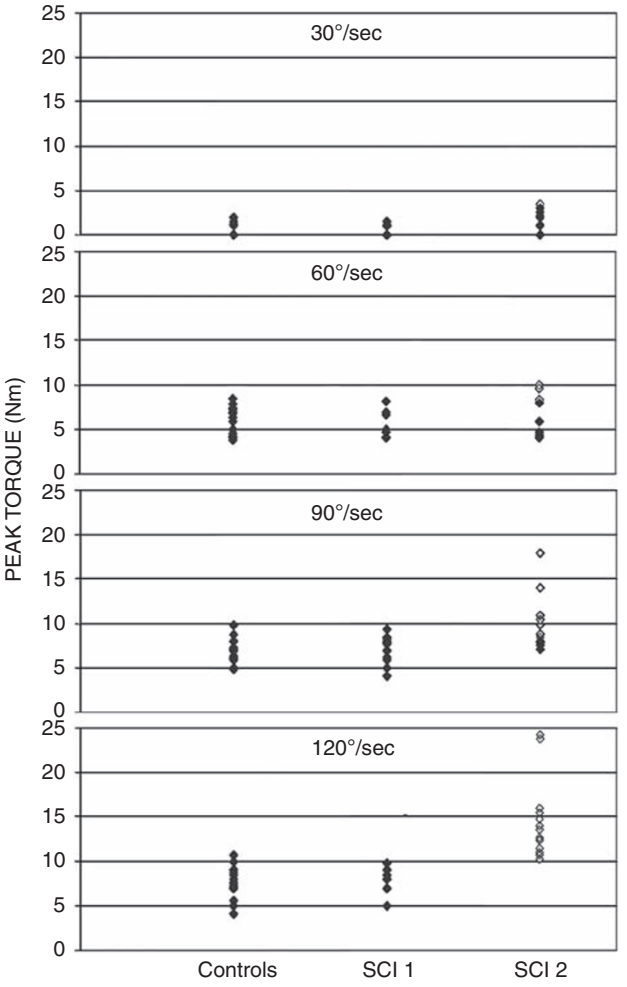

Figure 3 Comparison of PT values at all velocities assessed in the controls and spinal cord injured individuals (SCI-1 and SCI-2). Each point represents PT mean value during stretch at different speed (30°, 60°, 90° and $120^\circ s^{-1}$). Open symbol indicates those subjects who showed EMG activity in hamstring muscle.

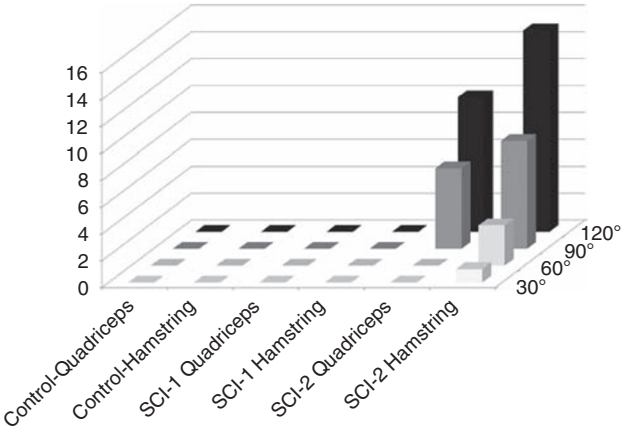

Figure 4 Number of subjects (ordinate axis) presenting EMG reflex responses in the study populations according to muscle (abscissa axis) and speed tested (z axis).

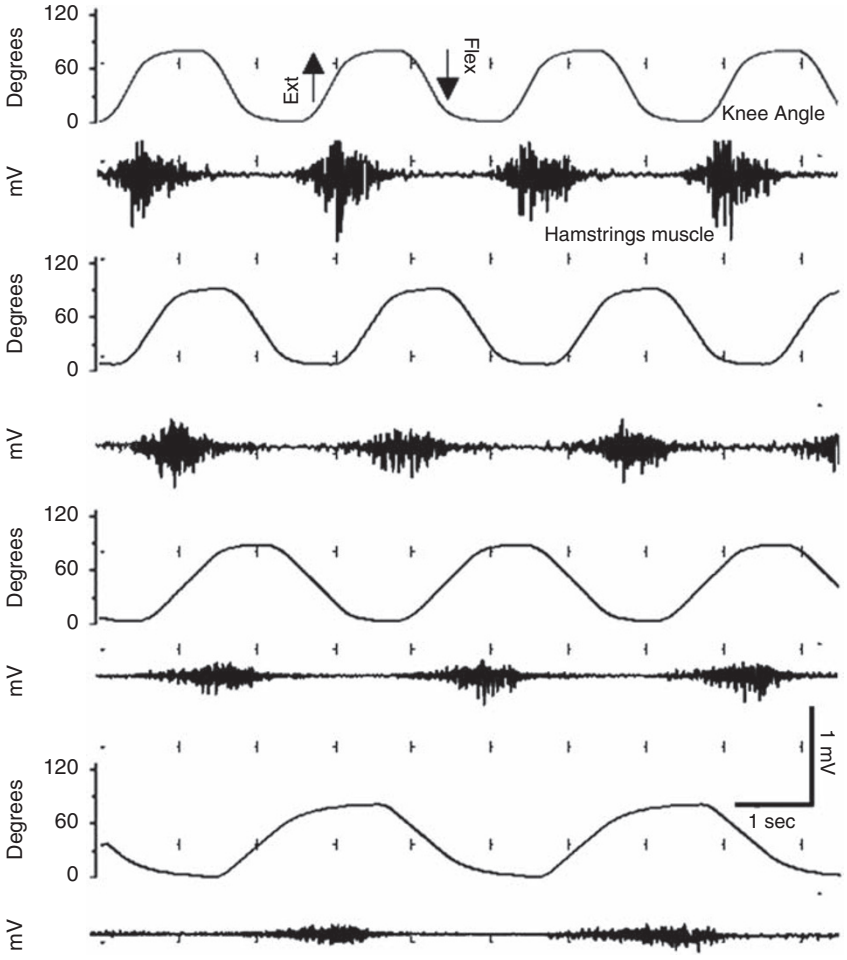

Figure 5 Angular position and EMG data during passive knee extension/flexion in a SCI patient with MAS = 3 at 120°, 90°, 60° and 30° s^{-1} (from top to bottom). The odd traces represent knee angle moving into extension and then moving back into flexion. The even traces represent the raw EMG activity recorded from the hamstring muscles of the stretched limb.

Perell[5] reported a slope of regression curve for the spastic group lower than that of the controls, whereas other authors[6,15] found no torque increase with increasing movement speed. These negative findings are probably because of the different populations studied and kinds of data analyses. In Akman's study,[6] despite the correlation between Ashworth grades and average torque values, the relationship between angular velocity and torque was studied for all patients without subgroup analysis. Similarly, Skold *et al*.[15] studied patients with a wide range of MAS scores, but did not analyse EMG activity and torque according to the MAS score. This might have weakened the correlation between torque and clinical condition. During movements at low speeds (30–60° s^{-1}) we found no significant differences among SCI and control groups. Only at 120° s^{-1} did all SCI-2 individuals show different PT values in comparison with the individuals of the other groups studied (Figure 3). Our findings agree with those of Perell,[5] who recommended 120° s^{-1} to show differences in the resistive torque between groups with spastic and normal muscles. These results emphasize the speed control gain using an isokinetic machine, whereas it is not possible to control the velocity when using the MAS in routine clinical practice.[16]

We found higher torque values for extension movement than flexion, in agreement with Kakebeeke *et al.*,[17] and a greater excitability of the flexor than the extensor muscles, as expressed by the EMG activation. These data were probably related to the patient's position during the isokinetic test. Muscle length has an important role when testing spasticity. In the sitting position, knee flexor muscles are more lengthened during extension than are extensor muscles during flexion. Anyway, the sitting position is more comfortable for testing patients and does not affect the isokinetic test's sensibility.

In the isokinetic technique, both reflex response and passive mechanical properties contribute to the measured torque. In our opinion, EMG activity recording is useful for correctly interpreting biomechanical parameters and assessing neural contribution to tonus increase. As SCI individuals with complete lesions (ASIA impairment scale grade A or B) might present only involuntary muscle contractions, measured torque is a putative reliable measure of hypertonus. In evaluating biomechanical parameters, the absence of interference on the passive movement of the dynamometer is assumed. In the absence of EMG recording, this condition would be hardly verified both in patients with hypertonus

and in control populations. At a low velocity, EMG recordings validate the use of the isokinetic dynamometer for the evaluation of the non-reflex components of hypertonus. At a high velocity, reflex responses could be elicited in most individuals with an MAS $>1+$.

Recently, there has been much emphasis on objectively assessing the rehabilitation outcomes, but few reliable measurement tools are available. Regarding spasticity, the MAS has a subjective component and inadequate reliability.[18] However, MAS is the current standard for clinical assessment and is the clinical scale against which new assessment tools of spasticity are evaluated in scientific literature.

Quantitative assessment using an isokinetic machine is more sensitive to small changes that go undetected using an ordinal scale such as MAS that shows a limited resolution, with clustering of results towards the midrange, and a lack of sensitivity for measuring and detecting small changes in spasticity.[9] Many investigators have stated that changes in the intrinsic mechanical muscle properties are largely responsible for hypertonus, and that not all hypertonus are spastic.[19] The MAS measures passive resistance to motion but is unable to distinguish between resistance caused by biomechanical and neural factors, such as changes in soft tissue length and spasticity.[14] Patients with mid-range MAS scores, because of passive stiffness alone, could be incorrectly judged to have mild-to-moderate spasticity, and in patients with contracture[20] spasticity might be overestimated and, consequently, treated inappropriately. The isokinetic dynamometry, but not the MAS, provides a measure of resistive torque that reflects both the reflex and the non-reflex muscle tone components.

The isokinetic dynamometer is a reliable instrument for measuring the spastic hypertonus in SCI patients and facilitates intra- and inter-operator assessments. PT could be used with sufficient confidence as an indirect marker of spastic hypertonus in SCI individuals. Implementation with EMG recording might help identify the intrinsic factors that have a role in resistance to joint motion. Even though the method is time consuming for application in a diffuse clinical contest, it would be worth investigating the usefulness of isokinetic measures in longitudinal evaluations for detecting changes in hypertonus as a result of therapeutic interventions.

Conflict of interest

The authors declare no conflict of interest.

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