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ORIGINAL ARTICLE

Abnormal cutaneous flexor reflex activity during controlled isometric plantarflexion in human spinal cord injury spasticity syndrome

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Study design: Although abnormal cutaneous reflex (CR) activity has been identified during gait after incomplete spinal cord injury (SCI), this activity has not been directly compared in subjects with and without the spasticity syndrome.
Objectives: Characterisation of CR activity during controlled rest and 'ramp and hold' phases of controlled plantarflexion in subjects with and without the SCI spasticity syndrome.
Design: Transverse descriptive study with non-parametric group analysis.
Setting: SCI rehabilitation hospital.
Methods: Tibialis Anterior (TA) reflexes were evoked by innocuous cutaneous plantar sole stimulation during rest and ramp and hold phases of plantarflexion torque in non-injured subjects ($n=10$) and after SCI with ($n=9$) and without ($n=10$) hypertonia and/or involuntary spasm activity. Integrated TA reflex responses were analysed as total (50–300 ms) or short (50–200 ms) and long-latency (200–300 ms) activity.
Results: Total and long-latency TA activity was inhibited in non-injured subjects and the SCI group without the spasticity syndrome during plantarflexion torque but not in the SCI spasticity group. Furthermore, loss of TA reflex inhibition during plantarflexion correlated with time after SCI ($\rho=0.79$, $P=0.009$). Moreover, TA reflex activity inversely correlated with maximum plantarflexion torque in the spasticity group ($\rho=-0.75$, $P=0.02$), despite similar non-reflex TA electromyographic activity during plantarflexion after SCI in subjects with (0.11, 0.08–0.13 mV) or without the spasticity syndrome (0.09, 0.07–0.12 mV).
Conclusions: This reflex testing procedure supports previously published evidence for abnormal CR activity after SCI and may characterise the progressive disinhibition of TA reflex activity during controlled plantarflexion in subjects diagnosed with the spasticity syndrome.
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INTRODUCTION

Spasticity was originally defined as an increase in velocity-dependent, tonic stretch reflexes to passive movement[1] and has been used to describe a number of signs and symptoms that together contribute to the syndrome.[2] Cutaneous reflex (CR) dysfunction has also been regarded as an additional sign of the spasticity syndrome following spinal cord injury (SCI),[3–9] especially when detected in subjects with hypertonia and increased tonic stretch reflexes.[10–12] In addition, abnormal flexor reflex excitability is present during subacute[4,13] and chronic SCI,[14,15] impacts on residual gait function after SCI[16] and interferes with daily activities.[17]

Lower limb CR activity in humans is modulated by several segmental and descending control mechanisms,[18–21] and the loss of descending modulatory mechanisms may contribute to the SCI spasticity syndrome. Tibialis Anterior (TA) muscle reflex activity evoked following cutaneous stimulation of the plantar surface (Pl-TA CR)[22–24] has been used as a test to assess the integrity of segmental and descending motor control mechanisms in healthy subjects with physiological reflex modulation during the step-cycle in healthy subjects.[3] Typically, the TA CR is strongly inhibited during the stance phase,[25] whereas this inhibition is reduced naturally during the swing phase of gait.[3,11,26,27] Following incomplete SCI, inhibitory modulation of CR activity during gait is partially lost in subjects diagnosed with the SCI spasticity syndrome,[11] although this observation was not controlled by comparison with a SCI group without spasticity. In contrast, abnormal CR activity observed during rhythmic ankle joint displacement in subjects with spasticity[3,10] strongly supports systematic flexor reflex testing during rest and controlled plantarflexion.[28] The hypothesis of this study, therefore, is that testing for abnormal CR function during both rest and controlled ramp and hold phases of controlled plantarflexion after incomplete SCI would demonstrate better loss of physiological inhibitory control, specifically in subjects with the spasticity syndrome, including any potential negative impact on muscle paresis.[29–31]

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The objective of this study was to characterise abnormal TA CR activity measured during controlled plantarflexion in subjects with and without the spasticity syndrome. In this study, we show that abnormal CR activity measured during controlled ramp and hold plantarflexion in subjects with the SCI spasticity syndrome suggests damage to the descending modulatory mechanisms and that this activity may develop during subacute and chronic phase of injury.[4]

MATERIALS AND METHODS

Subjects and general procedures

The experimental protocol was approved by the Hospital's Clinical Research Ethics Committee, and signed consent was obtained from the subjects in accordance with the Helsinki Declaration of 1975. Sixteen non-injured subjects (10 women and 6 men) with no central or peripheral neurological deficit and 19 individuals with SCI were recruited. The inclusion criteria for individuals with SCI were as follows: age range 18–65 years; motor incomplete SCI, diagnosed as grade C or D using the ASIA Impairment Scale (AIS);[32] a neurological level of SCI between C4 and Th10; SCI greater than 3 months time post injury; and preservation of muscle function for both the TA and Triceps Surae (TS) scored with at least 3 on the International Muscle Grading Scale.[33] The exclusion criteria included the following: peripheral nerve injury (that is, no denervation), which may have influenced reflex function in subjects with lower thoracic SCI or neurotrauma at the supraspinal level corroborated with a neurological examination; a clinical history of epilepsy; pregnancy; lower limb joint and/or muscle injuries; and failure to elicit reflex responses in the TA muscle following non-noxious electrical stimulation of the plantar pad at sensory threshold for observable CR activity applied at a tolerable intensity (see below).

For the study purposes, SCI spasticity syndrome was defined by the presence of spastic hypertonia assessed using the modified Ashworth scale[34] and involuntary muscle activity assessed with the Penn spasm frequency scale.[35] Following evaluation, subjects were assigned to the SCI spasticity group ($n=9$) when the lower limb modified Ashworth scale scored higher than 1 and/or a Penn spasm score was rated higher than 0. As considered in previous studies, slight muscle hypertonia (1 in the modified Ashworth scale) without the presence of spasms (0 in the Penn scale) was operationally defined as not characteristic of the spasticity syndrome.[16,36,37] Ten subjects with SCI were recruited without the spasticity syndrome. All clinical evaluations were assessed by a physiotherapist working at the hospital who was blinded to the experimental design of the study. Patients followed their standard treatment for spasticity, which included in some cases oral baclofen.

Controlled isometric ramp and hold plantarflexion torque

Subjects were seated with their hip, knee and ankle joints set at an angle of 90° and their foot placed on a custom-built dynamometer (Figure 1a) that offered visual feedback for plantarflexion torque (Figure 1b).[37] The foot was secured in place with Velcro straps immediately following placement of the plantar electrode. The entire dynamometer platform acted to measure plantarflexion torque (Figures 1a and c). The task was performed with the dominant leg in the case of the non-injured control subjects or with the limb with the higher muscle score for the SCI subjects.[33] Maximum voluntary torque (MVT) was recorded in all participants during isometric plantarflexion hold and was calculated as the average of three maximum 5-s contractions separated by 20-s intervals. Subjects were instructed to follow a visual feedback-guided plantarflexion pattern that included ramp and hold isometric contractions (Figure 1b). Subjects were familiarised with the task at least one time before recording. The target template was programmed to present 10 plantarflexion ramp and hold targets on a monitor, which the subject was asked to match by performing controlled ramp and hold isometric activation of the TS muscle at 50% MVT. The template provided an audible warning if the plantarflexion torque recorded during either the ramp or the hold phase deviated more than 10% from the target torque. The initial 3-s rest period of the template was set at 5% maximum isometric plantarflexion torque value, which was equivalent to the weight of the foot on the dynamometer without evident background electromyographic (EMG) activity from the TS. The motor task was initiated with 4-s isometric ramp phase, to reach the 50% MVT, and a 4 -s isometric hold phase, keeping the 50% MVT of plantarflexion, followed by a 4-s relaxation period. Plantarflexion torque and Pl-TA CR activity data were collected during the controlled motor task, converted to digital form and analysed using custom-built software (LabView Version 7, MicroPlus 1401 and Signal version 2.14).

Pl-TA CR activity measured during ramp and hold plantarflexion torque

The plantarflexion protocol was first performed without evoked CR activity to record EMG that coincided with the same period of reflex analysis performed during controlled plantarflexion. Pl-TA CR activity was then evoked during the rest, ramp and hold phases of the controlled isometric plantarflexion (Figure 1b, 10 trials for each TS contraction). Pl-TA CR activity was evoked 2 s into the rest, ramp and hold phases of controlled plantarflexion torque. The anode (8×10 cm) was placed on the dorsal surface of the foot and the cathode (4×6 cm) was positioned on the plantar sole between the first and the second metatarsal to permit localised cutaneous stimulation. Testing within the laboratory confirmed that this form of reflex stimulation was comfortable when compared with electrical stimulation applied to the skin overlying the sural or tibial nerve.

Special care was also taken to apply stimuli that were not noxious, at an intensity close to reflex threshold, and that were perceived within the plantar sole following incomplete SCI. Reflex activity was evoked with a constant current stimulator (DS7A, Digitimer Ltd., Welwyn Garden City, Hertfordshire, UK), which applied electrical stimulation delivered as five rectangular pulses (1 ms duration with a 5-ms interval).[38] TA CR threshold was defined during the rest period (Figure 1a) as the non-painful stimulus intensity sufficient to elicit an observable Pl-TA CR response. The TA CR threshold was identified with test stimuli applied every 20 s. Thereafter, the plantar stimulus intensity was set as a 1.2 multiple of the individual Pl-TA reflex threshold.

CR measurement and analysis

Background signal and CR EMG activity were measured from the TA, in addition to non-reflex activity recorded from the Gastrocnemius Medialis muscle, with bipolar silver chloride electrodes ($1000\times$ amplification) with a built-in 20–450 Hz bandpass filter (Signal Conditioning Electrodes version 2.3). EMG activity was sampled at 10 KHz (MicroPlus 1401), whereupon reflex activity was full-wave rectified (Signal version 2.14). Integration of total reflex activity (50–300 ms) was performed as the primary outcome measure in subjects with SCI with ($n=9$) or without the spasticity syndrome ($n=10$, Figure 1c), which was consistent with previous studies.[11,38] However, specific CR activity was also calculated for short (50–100 ms), medium (100–200 ms) and long latency (200–300 ms) in Table 2, to broadly differentiate long-latency reflex activity.[14] Inclusion of the SCI group without diagnosis of the spasticity syndrome was performed to incorporate an appropriate control group for comparison of CR activity. Pl-TA reflex examples were presented following a 3-point smoothing function for clarity in Figure 1c.

Integrated Pl-TA reflex activity was normalised with respect to the rest period using a technique adopted in other reflex studies.[11,38,39] First, background EMG signal activity was subtracted from evoked TA reflex activity. Second, reflex activity ratios were calculated between the ramp or hold phases of plantarflexion and activity measured during the rest period. Finally, the value of 1 was subtracted from the ratio to obtain normalised values of reflex modulation during movement. Hence, CR activity measured during the rest phase was expressed as a zero score, in contrast to negative values calculated during controlled plantarflexion, which represented reflex inhibition.

Statistical analysis

Normality, descriptive and inferential statistical tests were performed with a commercial statistical software package (Prism version 4.0). Normality of the reflex-data distribution was tested with the Kolmogorov–Smirnov procedure using a Lilliefors significance level, and the data were described as non-Gaussian. Hence, non-parametric statistical analysis and data presentation were justified.

Inter-group comparisons were performed using the Kruskall–Wallis test with a *post hoc* Bonferroni correction. Background EMG and evoked CR activity data normalised to the rest period were statistically analysed using the Friedman test

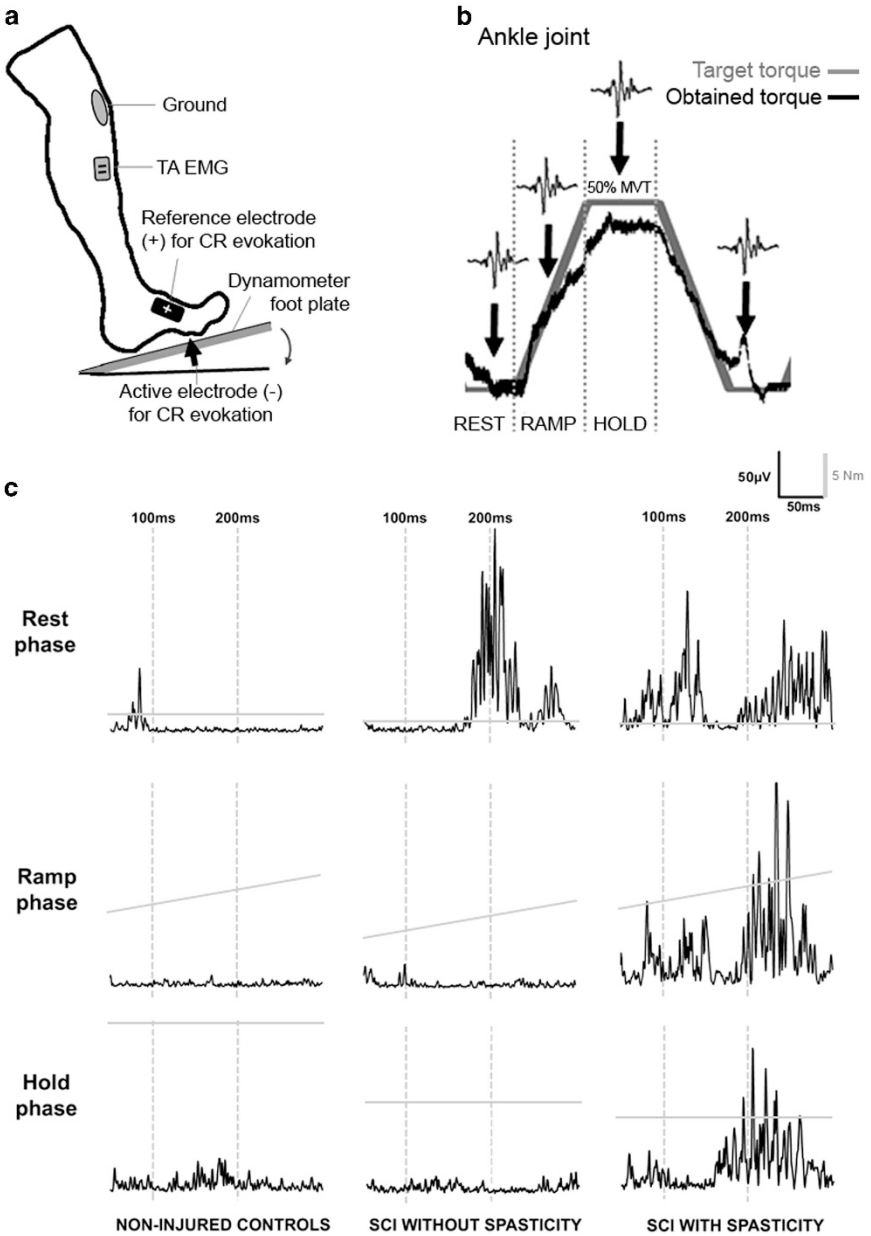

Figure 1 Plantar-TA reflex testing method, motor task template and reflex EMG records recorded during rest and controlled ramp and hold phases of plantarflexion torque. (**a**) Schematic diagram illustrating the placement of the electrical stimulating plantar and TA EMG electrode used to evoke and record CR activity. (**b**) TA CR activity was evoked at rest (5% of MVT recorded with the dynamometer) and during the ramp and hold phase of plantarflexion torque (set at 50% MVT). (**c**) PI-TA CR recorded from a non-injured healthy subject (left column), an individual with SCI without (centre column) and a person diagnosed with the SCI spasticity syndrome (right column), during the rest, ramp and hold phases of plantarflexion. Early (50–100 ms), medium (100–200 ms) and long-latency (200–300 ms) PI-TA CR activity are shown for all rectified EMG records, with the majority of reflex activity measured within the long-latency window for the SCI groups. Note that CR activity up to 50 ms is not presented and that background TA EMG was not significantly different between the experimental groups (see results section).

and *post hoc* Bonferroni correction. Correlation analysis was performed with Spearman's rank test to detect relationships between the CR responses, plantarflexion MVT and standard measures of the spasticity syndrome.[4–8] EMG, CR and functional measures were expressed as the median with the 25th–75th percentile values. The null hypothesis was rejected at $P<0.05$.

RESULTS

In general, similar demographic, clinical or functional characteristics were observed between the SCI groups with and without spasticity (Table 1). The age of the SCI groups was also similar (Table 1), although a significant difference was identified for the younger university students (23.6 ± 6.8, mean $\pm$ s.e.) enroled in the non-injured group compared with all subjects with SCI (44.5 ± 14.6, $P<0.01$, Mann–Whitney test). No differences in gender were identified between non-injured controls and subjects with SCI.

Pl-TA CR modulation during controlled isometric plantarflexion

Typical individual Pl-TA CR reflex records are presented in Figure 1c for both non-injured subjects (left column) and SCI subjects without (middle column) and with spasticity (right column) during the rest

period and both the ramp and hold phases of controlled isometric plantarflexion. Pl-TA CR latency and duration time for the SCI group without spasticity syndrome were 173 ± 12 ms and 74 ± 13 ms, compared with 154 ± 19 ms and 138 ± 20 ms ($P<0.05$) for the group with spasticity. The majority of the total Pl-TA CR activity was detected from 100 ms for both the SCI groups (Figure 1c). Closer examination of the CR records indicated the inhibition of total Pl-TA reflex during the ramp and hold phases of plantarflexion torque in the non-injured and SCI subject without the spasticity syndrome. In contrast, no inhibition of Pl-TA CR activity was observed during plantarflexion torque in the subject diagnosed with the SCI spasticity syndrome (Figure 1c).

Table 1 Demographic and neurological characteristics of subjects with SCI spasticity

	SCI without spasticity (n = 10)	*SCI without spasticity (n = 9)*
Age (years)	51 ± 12	37 ± 14
Gender	8 Male	8 Male
Aetiology	9 Trauma/1 Medical	7 Trauma/2 Medical
AIS score (A, B, C, D)	4C/6D	7C/2D
Neur. level SCI	9 C/1 Th	6 C/3 Th
Time from SCI (months)	7 ± 4	6 ± 2
TA muscle score (0–5)	4 (3–4)	4 (3–4)
TS muscle score (0–5)	4 (4–4)	4 (4–4)
Max. vol. Pl. Tor. (Nm)	21 ± 8	19 ± 8
Modified Ashworth score (0–4)	0 (0.0–0.0)	**2.0 (1.0–3.0)**[a]
PENN score (0–4)	0 (0.0–0.0)	**2.0 (1.8–2.0)**[a]

Abbreviations: AIS, ASIA impairment scale; C, cervical; Neur. Level, neurological level; Max. Pl. Tor., maximum plantarflexion torque; SCI, spinal cord injury; TA, Tibialis Anterior; Th, Thoracic; TS, Triceps Surae. All values presented as mean ± s.e., except muscle score, modified Ashworth scale and Penn scores, which are presented as median values with 25th–75th percentile range. [a]Significant difference ($P<0.001$) when compared with the group without spasticity (Mann–Whitney Test). Statistical significant data are represented in bold.

Median integrated Pl-TA CR activity was similar between the experimental groups when analysed within the early (50–100 ms) or medium (100–200 ms) latency window during the rest period or ramp and hold phases of controlled isometric plantarflexion (Table 2). Long-latency Pl-TA CR activity was higher for the SCI spasticity syndrome group when compared with the early reflex response in the non-injured control group during rest (Table 2). Furthermore, during controlled isometric plantarflexion, the 200–300 ms Pl-TA CR activity was higher in the SCI spasticity group compared with the SCI group without spasticity (Table 2). Reflex stimulation intensities were similar when compared between non-injured subjects 29 (25–45) mA, the group without SCI spasticity 38 (34–55) mA and the group with SCI spasticity 40 (28–50) mA ($P=0.30$).

Pl-TA reflex activity measured during the rest period and during either the ramp or hold phase of plantarflexion torque is presented in Table 3. Subjects with SCI spasticity syndrome showed higher activity during both the ramp and hold phases of plantarflexion but not during rest.

Pl-TA CR activity analysed following the subtraction of background EMG activity and normalised to the rest period is shown in Table 4. As shown previously, the normalised reflex data demonstrated that both the non-injured controls and SCI group without the spasticity syndrome revealed Pl-TA CR inhibition during plantarflexion. In contrast, a loss of physiological inhibition of reflex function during controlled isometric plantarflexion was observed in the SCI group diagnosed with the spasticity syndrome (Table 4).

Pl-TA CR activity, plantarflexor torque and spasticity measures

Pl-TA CR amplitude correlated negatively with residual plantarflexion torque during ramp plantarflexion ($\rho=-0.75$, $P=0.016$, Figure 2a) in the SCI spasticity syndrome group, although this was not evident in either the the rest period ($\rho=-0.28$, $P=0.43$) or isometric hold phase of plantarflexion torque ($\rho=-0.54$, $P=0.11$). The possibility that increased TA muscle activation contributed to plantarflexor weakness in the SCI spasticity group was controlled following identification that

Table 2 Short, medium and long-latency integrated Pl-TA CR activity measured from non-injured individuals and from subjects with spinal cord injury with and without spasticity

	50–100 ms Pl-TA CR activity (mV.s)	*100–200 ms Pl-TA CR activity (mV.s)*	*200–300 ms Pl-TA CR activity (mV.s)*
Rest			
Non-injured controls	0.06 (0.04–0.07)	0.08 (0.04–0.10)	0.09 (0.04–0.12)
SCI without spasticity	0.02 (0.02–0.07)	0.10 (0.04–0.22)	**0.30 (0.14–0.36)#**
SCI with spasticity	0.05 (0.02–0.09)	0.20 (0.08–0.36)	**0.24 (0.20–0.39)*##**
Ramp			
Non-injured controls	0.04 (0.02–0.079)	0.07 (0.05–0.07)	0.05 (0.04–0.11)
SCI without spasticity	0.02 (0.02–0.03)	0.05 (0.04–0.07)	0.04 (0.04–0.08)
SCI with spasticity	0.08 (0.03–0.14)	0.12 (0.07–0.31)	**0.17 (0.14–0.36)#**
Hold			
Non-injured controls	0.03 (0.02–0.04)	0.05 (0.04–0.07)	0.06 (0.04–0.08)
SCI without spasticity	0.03 (0.02–0.04)	0.05 (0.03–0.07)	0.05 (0.04–0.13)
SCI with spasticity	0.04 (0.03–0.14)	0.13 (0.05–0.33)	**0.23 (0.13–0.28)#**

Abbreviations: Pl-TA CR, Tibialis Anterior (TA) muscle reflex activity evoked following cutaneous stimulation of the plantar surface; SCI, spinal cord injury. *$P<0.05$ compared with the non-injured control group using the Kruskall–Wallis and the Bonferroni post-test. # $P<0.05$ ## $P<0.01$ compared with early latency reflex activity using the Friedman test and the Bonferroni post-test. Statistical significant data are represented in bold.

Table 3 Median Pl-TA CR activity during rest, ramp and hold phases of controlled plantarflexion

Pl-TA CR activity (mV.s)	*Rest*	*Ramp*	*Hold*
Non-injured controls	0.15 (0.12, 0.29)	0.14 (0.10, 0.26)	0.13 (0.10, 0.17)
SCI without spasticity	0.41 (0.26, 0.79)	0.11 (0.10, 0.17)	0.12 (0.09, 0.35)
SCI with spasticity	0.45 (0.31, 1.05)	**0.43 (0.21, 0.94)*#**	**0.36 (0.22, 0.82)*#**

Abbreviations: Pl-TA CR, Tibialis Anterior (TA) muscle reflex activity evoked following cutaneous stimulation of the plantar surface; SCI, spinal cord injury. Data are expressed as median values (25th–75th percentiles). *$P<0.05$ compared with SCI without spasticity; #$P<0.05$ compared with non-injured controls (Kruskall–Wallis test with the Bonferroni *post hoc* correction). Statistical significant data are represented in bold.

Table 4 Median integrated Pl-TA CR activity without background EMG activity analysed during ramp and hold phases of controlled plantarflexion and normalised to the rest period

Pl-TA CR activity ((ramp or hold phase/rest phase)-1)	*Ramp*	*Hold*
Non-inj. contr.	**−0.67 (−2.05, −0.12)***	**−0.80 (−1.83, −0.54)****
SCI without sp.	−0.86 (−0.98, −0.68)	**−0.90 (−0.99, −0.37)***
SCI with sp.	−0.16 (−0.69, +1.19)	−0.33 (−0.79, +0.83)

Abbreviations: Non-Inj., non-injured; Pl-TA CR, Tibialis Anterior (TA) muscle reflex activity evoked following cutaneous stimulation of the plantar surface; SCI, spinal cord injury; Sp, spasticity syndrome. Median (25th percentile 75th percentile). Negative values correspond to CR inhibition. *$P<0.05$ and **$P<0.01$ when compared with the rest period (Friedman test with the Bonferroni *post hoc* correction). Statistical significant data are represented in bold.

TA EMG was statistically similar during either the ramp or hold phases of plantarflexion in subjects with (ramp: 0.11, 0.08–0.13 mV.s, hold: 0.11, 0.11–0.16 mV.s) or without this syndrome (ramp: 0.09, 0.07–0.12 mV.s, hold: 0.09, 0.06–0.09 mV.s). The inverse relationship between Pl-TA CR activity and plantarflexion torque was not identified in either the non-injured control group or in the SCI group without the spasticity syndrome.

In the group diagnosed with the spasticity syndrome, significant correlations were identified between time after injury and Pl-TA CR activity measured either during the ramp ($\rho=0.72$, $P=0.02$, Figure 2b) or the hold phase of plantarflexion torque ($\rho=0.66$, $P=0.04$). Analysis of the normalised Pl-TA CR amplitude (Figure 2c) indicated a reversal from reflex inhibition to facilitation during plantarflexion at approximately 5–6 months after injury, assessed either during the ramp ($\rho=0.79$, $P=0.01$, Figure 2c) or the hold ($\rho=0.66$, $P=0.04$) phases of plantarflexion. In contrast, no relationship was identified between time after injury and Pl-TA CR amplitude in the SCI group without the spasticity syndrome (rest $\rho=0.15$, $P=0.72$; ramp $\rho=0.63$, $P=0.10$; hold $\rho=0.26$, $P=0.54$).

Spearman's correlational analysis failed to reveal a clear relationship between Pl-TA CR activity and either the modified Ashworth scale or Penn spasm scores during the rest period or during the ramp and hold phases of plantarflexion torque.

DISCUSSION

This study is novel in characterising the loss of Pl-TA CR modulation during controlled isometric plantarflexion in subjects with SCI spasticity syndrome and supports a previous study that also identified the loss of medium latency reflex function during gait.[11] Measurement of Pl-TA reflex activity also provides information regarding the temporal development of CR dysfunction from 5 to 6 months after SCI. At the experimental level, we expect that this method of quantifying loss of physiological inhibition of CR activity during controlled muscle activation after early SCI will add to other reflex diagnostic methods[40,41] and together will serve to develop antispastic and/or neurorehabilitatory techniques that will better treat the SCI spasticity syndrome,[42] while maintaining residual motor function.[41]

Loss of segmental and descending Pl-TA CR modulation after SCI

Several candidate pathophysiological mechanisms could mediate the loss of physiological inhibition of the Pl-TA CR observed during controlled isometric plantarflexion in subjects with the SCI spasticity syndrome.[43] At the spinal level, dysfunction of spinal inhibitory mechanisms mediated by gamma-aminobutyric acid is related to cutaneous hyperreflexia after SCI,[44,45] whereas other structural spinal changes are associated with reflex dysfunction as a consequence of the loss of supraspinal descending control mechanisms.[21] Damage to descending supraspinal pathways,[20,46] including the corticospinal[47,48] or extrapyramidal control systems,[19,46,49] also may contribute specifically to the change in CR modulation observed during controlled plantarflexion. Indeed, higher long-latency (200–300 ms) reflex activity observed in the SCI spasticity group during controlled plantarflexion suggests in part that a loss of supraspinal modulation may be implicated as an underlying mechanism.[48] Nevertheless, another recent study has shown long-latency CR activity in subjects with both complete and incomplete SCI, suggesting that the pathophysiological mechanism mediating this effect could be organised in part at the spinal level.[14,50]

Abnormal Pl-TA CR activity as a sign of the SCI spasticity syndrome

The SCI spasticity syndrome continues to be defined[1] and diagnosed on the basis of the detection of muscle hypertonia using the Ashworth scale.[34] However, this sign represents only one aspect of this motor disorder.[2] Furthermore, although exaggerated stretch and H reflex activity have been detected in the clinic and in an animal model of the spasticity syndrome,[6,51] these signs are not thought to contribute significantly to movement disorder after SCI.[52]

Lower limb flexor CR excitability has often been reported to increase after SCI measured during passive[4,10,15,29,53] or active movement.[3,11,26,54] Furthermore, CR is actively modulated during passive movement,[55] balance[56] and gait.[26,39,56] As such, it is surprising that only one study has observed abnormal CR activity in subjects with the spasticity syndrome during gait after incomplete SCI.[11]

Higher Pl-TA CR activity in subjects diagnosed specifically with the SCI spasticity syndrome, detected without a change in background TA EMG activity during controlled ramp and hold phases of plantarflexion, supports further characterisation of cutaneous hyperreflexia as a test of spasticity for this pathology. Furthermore, the correlation of Pl-TA CR activity with time during subacute and chronic SCI based on the small number of subjects recruited in this study, documented in previous studies,[4,14,57] also suggests that further characterisation of this reflex measure will provide further information regarding loss of segmental or descending modulatory mechanisms during the late subacute and chronic SCI.

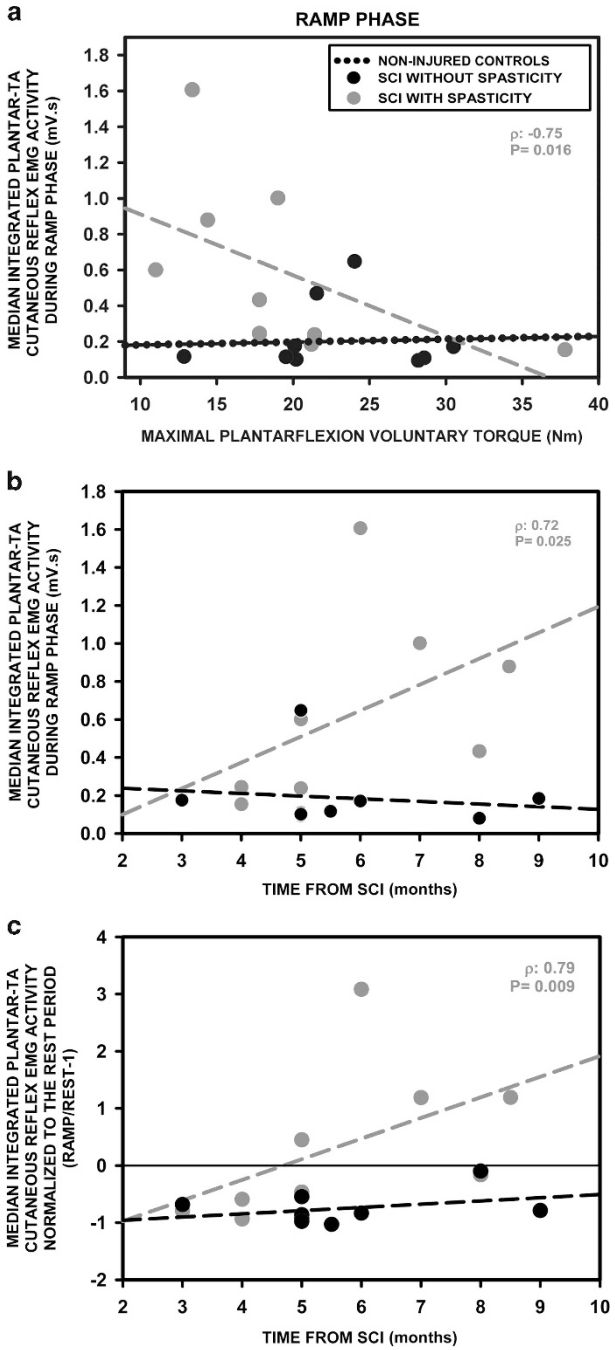

Figure 2 Relationship between plantar-TA reflex activity, maximal TS torque during plantarflexion and time after SCI. Pl-TA CR activity evoked following cutaneous electrical stimulation of the plantar sole during controlled plantarflexion in subjects diagnosed with (broken grey lines) or without lower limb spasticity syndrome (broken black lines), plotted against (**a**) maximal plantarflexion torque and (**b** and **c**) time after SCI. The horizontal dotted line represents the median Pl-TA CR activity recorded in the non-injured healthy group.

Abnormal Pl-TA CR and lower limb muscle function after SCI

A recent study suggests that the development of CR activity following SCI is characteristic of the loss of muscle function during training,[14] which is tentatively supported by the observation of TS paresis in subjects diagnosed with greater Pl-TA CR activity. Moreover, we have recently demonstrated low intramuscular TA muscle coherence in subjects with the SCI spasticity syndrome, suggesting that this motor disorder is related to a dysfunction of descending motor drive.[36] We have also shown that exaggerated lower limb flexor reflex activity evoked in patients with incomplete SCI correlates with poor residual gait function.[16] However, it is also possible that abnormal CR activity after SCI may be associated with recovery of motor or locomotor function after injury.[58–60] The relationship between the grade of abnormal CR activity as a factor that either promotes or impedes residual motor function during SCI rehabilitation needs to be addressed in relation to the spasticity syndrome.

Pharmacological treatment for the SCI spasticity syndrome is also known to affect residual motor function after SCI.[41,61–63] Specifically, the alpha-2 adrenoceptor agonist clonidine has been shown not only to restore inhibition of CR activity after SCI but also to facilitate TA muscle activation during gait,[64] supporting the hypothesis that adequate CR control improves residual motor function. We believe that careful CR testing should be used to benchmark standard and new pharmacological strategies for the control of the SCI spasticity syndrome,[63,65,66] while examining the wider effect of these therapies on residual muscle function after SCI[40,41]

Limitations and future studies

No correlation was identified between Pl-TA CR activity and the grade of hypertonia or spasm frequency, perhaps reflecting the poor sensitivity of the modified Ashworth and Penn scales to detect flexor reflex activity. Measurement of spasm activity in clinical studies is usually performed with the Penn scale,[35] but this scale often fails to correlate with the underlying pathophysiological mechanisms of SCI spasticity syndrome during movement,[7] or indeed with CR activity in general.[29,31] Adoption of clinically relevant outcome measures, such as the Spinal Cord Assessment Tool for Spastic reflexes (SCATS), which provides a better evaluation of evoked flexor reflex activity, should also be evaluated.[16,36,67]

Several experimental aspects of the reflex testing technique remain to be addressed, such as identifying correctly CR thresholds and normalising EMG data across experimental groups. We defined TA CR reflex threshold in part on the subjective assessment of the stimulus being innocuous. We recommend the use of a systematic method to identify reflex threshold such as the method of limits. However, perception of the stimulus may be affected in those subjects with greater SCI severity and would therefore require reflex threshold identification based on the TA reflex response alone. It is important to note that the reflex threshold method used in this study demonstrated no significant differences between experimental groups. With respect to normalising EMG data across experimental groups, the TA CR response was normalised for all subjects by recording activity measured during rest and at 50% maximal voluntary torque. This sub-maximal isometric normalisation method has been used in other biomechanical studies and provides good reliability,[68,69] and this may be optimal for subjects who are not able to generate high maximal contractions.

Finally, the contribution of TA muscle coactivation during TS muscle contraction should be assessed, as this may account for the correlation between plantarflexor weakness identified in those subjects with Pl-TA hyperreflexia. However, in a previous study, we demonstrated that TA EMG activity measured during ramp plantarflexion was the same in subjects with or without SCI spasticity syndrome.[37] Examination of TA, Soleus and Gastrocnemius muscle activity during controlled plantarflexion will be instrumental in assessing the role of abnormal CR activity in TS muscle weakness, by controlling for possible lower limb muscle coactivation.

CONCLUSION

This study not only adds to the previous observation of loss of CR inhibition during gait in subjects with SCI[11] but also demonstrates that measurement of the loss of physiological inhibition of CR activity during controlled isometric plantarflexion is characteristic of the SCI spasticity syndrome. The reflex testing procedure developed here provides a useful technique to differentiate abnormal CR activity in subjects with clinical signs of SCI spasticity and could be used to benchmark novel pharmacological or sensorimotor rehabilitation techniques designed to re-establish appropriate inhibitory modulation of CR function, thereby contributing to the better management of SCI spasticity.[40,42,66,70]

DATA ARCHIVING

There were no data to deposit.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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