Foot control in incomplete SCI: distinction between paresis and
dexterity

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Foot control in incomplete SCI: distinction between paresis and dexterity

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Objective: To complement the clinical assessment of motor impairment after incomplete spinal cord injury (iSCI) by introducing a test that reliably distinguishes between muscle weakness (paresis) and impairment of dexterity in a simple foot motor task. Methods: Auditory-paced ankle dorsi- and plantarflexion, in a supine position, was studied in 30 controls (to establish control values and to test reliability) and in 16 iSCI patients (test validation). The subjects were instructed to initiate dorsi- and plantarflexion as accurately in timing and within the largest range of motion (ROM) possible. For each frequency, accuracy of timing, ROM, peak velocity of dorsi- and plantarflexion and a time quotient for changing from dorsi- to plantarflexion and vice versa were determined. In iSCI subjects, these parameters were related to clinical measures of paresis, spasticity and proprioception.

Results: The test parameters showed good to very good reliability. The iSCI subjects were able to follow the target frequency with high accuracy, while ROM and peak velocity for dorsi- and plantarflexion were significantly reduced. Furthermore, there was a strong correlation between ROM/peak velocities and motor scores within the iSCI patients.

Discussion: Repetitive foot dorsi- and plantarflexion enables a distinction to be made between muscle weakness and reduced dexterity as the underlying cause of affected foot control. This distinction between and quantification of these two movement components complements the existing clinical examination, and in follow-up works, the recovery of these components may provide further insight into the mechanisms underlying motor function improvement after iSCI.

Keywords: Dexterity; motor control; paresis; incomplete spinal cord injury

INTRODUCTION

Clinical recovery after a lesion of the central nervous system (CNS) is a multidimensional process that is based on neuronal changes (regeneration of damaged neuropathways and plasticity within preserved neuronal structures) and functional (non-neuronal) compensation, e.g. training effects in preserved physical resources1-3. In CNS lesions, movement performance is limited by muscle weakness (paresis) as well as by deficits in movement dexterity that are not attributable to motor weakness4,5.

However, the clinical scoring of strength, such as proposed by the American Spinal Injury Association (ASIA), primarily addresses force generation, which is only one of the components involved in the recovery of motor function after spinal cord injury (SCI)1,2,6-8. Assessing the recovery of walking function (timed and qualitative walking tests) in patients with incomplete spinal cord injury (iSCI)9,10 indicates a complex outcome measure, which does not allow for a conclusion to be made regarding specific changes within the nervous system11-13. To assess recovery of motor performance after iSCI, two important aspects should be addressed by a clinical test: (1) the assessments should be applicable soon after the initial injury, i.e. when patients are not (yet) capable of walking; (2) the test should be able to distinguish between recovery of motor strength and improved movement dexterity. The latter can be defined as the ability to coordinate muscle activity to meet environmental demands5, i.e. optimized timing of muscle activation. As locomotion is a key function of the lower limbs, the focus of such an evaluation should be on functions that are relevant to gait. Ankle dorsiflexion was shown to be a critical component of the gait cycle in stroke and iSCI patients and was proposed as a potential marker for gains in motor control of the lower limb during rehabilitation14.

Therefore, the present study assessed the ability of iSCI patients to switch the foot repeatedly from dorsi- to plantarflexion and vice versa, in a supine position. The aim was to provide a sensitive, simple motor task that can be used as a clinical test for evaluating impaired motor performance in iSCI and reliably distinguishes between paresis and deficits in dexterity.
MATERIAL AND METHODS

All procedures were in accordance with the standards of the local ethics committee and with the Declaration of Helsinki. The subjects gave written consent to participate in this study.

Two works were performed: (1) to establish control values and to examine test reliability, 30 healthy volunteers were tested twice; (2) for feasibility and validation in iSCI, a cross-sectional study with iSCI patients and controls (matched for gender and age) was carried out.

Subjects

In the first study, 30 healthy controls (11 females and 19 males) were tested. All age groups were deliberately chosen for this study (range: 18–74 years). The mean age of the females was 39 ± 16.8 years and that of the males was 43.3 ± 16.8 years. For the second study, 16 iSCI subjects (five females and 11 males), mainly ASIA C and D (one patient with ASIA E) (mean age: 53.6 ± 17.0 years), were recruited at the SCI center in Zurich, Switzerland. The participants did not suffer from any neurological diseases, apart from iSCI. The data of 16 of the 30 healthy control subjects (mean age: 51.9 ± 14.4 years) were matched for gender and age to the iSCI subjects. For more detailed characteristics about the patients, see Table 1.

Experimental procedure

The subjects were tested in a supine position. Their dominant leg, except for the heel, was placed lengthwise on a pillow, and the knee slightly flexed (10–20°), in order to allow free dorsi- and plantarflexion movements. Foot dominance was determined by self-reporting which foot would be selected for kicking a ball, which is regarded as the predominant test for this. The patients were able to visually control the placement of their foot to compensate for impaired proprioception, but the subjects were not explicitly asked to visually monitor their foot movements. Muscle strength was determined according to the six level scale of ASIA standards. Spasticity was assessed by a modified Ashworth test, and perception of vibration was assessed by a tuning fork at both the malleolus medialis and carpometacarpal joint of the first toe (64 Hz, 8/8 scale). Active and passive range of motion (ROM) was determined using an electric goniometer (Biometrics Ltd, Gwent, UK), with the sampling rate set at 1000 Hz. Computer-generated metronome sounds were presented to the subjects in blocks of different frequencies (0.8–3.2 Hz at intervals of 0.4 Hz) with breaks of ~30 seconds in between. The acoustic signal consisted of two sinusoidal beeps of 0.05 seconds each: a high-pitched tone with a frequency of 1400 Hz and a low-pitched one of 700 Hz. The subjects were instructed to perform alternate dorsi- and plantarflexions as accurately as possible by changing the movement direction at the metronome sounds and to do so with the largest ROM possible. Whether the high- or low-pitched tone indicated dorsi- or plantarflexion was not determined. For each frequency, the subjects had to perform 20 dorsi- and plantarflexion repetitions.

Data analysis

The goniometer signals were analysed using SOLEASY software (ALEA solutions GmbH, Zurich, Switzerland) and Matlab 6.5 (The MathWorks, Natick, MA, USA).

Data from the first five movement cycles were not included in the analysis since a minimum of 3–5 signals had previously been reported to be required for picking up the beat. From the remaining 15 ankle dorsiflexions and 15 plantarflexions, accuracy of timing, ROM, peak velocity for both types of flexion and the time

Table 1: Characteristics of the iSCI patients

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>Gender</th>
<th>Time interval since SCI (years)</th>
<th>Cause of lesion</th>
<th>Level of lesion</th>
<th>ASIA category</th>
<th>Motor score tibialis anterior</th>
<th>Motor score gastrocnemius medialis</th>
<th>Vibration sense malleolus medialis</th>
<th>Vibration sense toe 1</th>
<th>Spasticity (modified Ashworth)</th>
</tr>
</thead>
<tbody>
<tr>
<td>65 M</td>
<td>&lt;1</td>
<td>Trauma</td>
<td>C6</td>
<td>D</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>45 F</td>
<td>&lt;1</td>
<td>Meningioma</td>
<td>T8</td>
<td>D</td>
<td>5</td>
<td>5</td>
<td>6</td>
<td>8</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>65 M</td>
<td>4</td>
<td>Trauma</td>
<td>C5</td>
<td>C</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>55 M</td>
<td>&lt;1</td>
<td>Myeloma</td>
<td>T8</td>
<td>D</td>
<td>NT</td>
<td>NT</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>59 M</td>
<td>3</td>
<td>Trauma</td>
<td>C3</td>
<td>D</td>
<td>4</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>70 F</td>
<td>1</td>
<td>Stenosis</td>
<td>T12</td>
<td>E</td>
<td>5</td>
<td>5</td>
<td>6</td>
<td>6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>68 M</td>
<td>7</td>
<td>Myelopathy</td>
<td>T9</td>
<td>D</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>46 M</td>
<td>2</td>
<td>Tumor intramedullar</td>
<td>T5</td>
<td>D</td>
<td>2</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>60 F</td>
<td>&lt;1</td>
<td>Myeloma compression</td>
<td>T3</td>
<td>D</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>71 M</td>
<td>&lt;1</td>
<td>Trauma</td>
<td>T11</td>
<td>D</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>68 F</td>
<td>&lt;1</td>
<td>Arteriovenous fistula</td>
<td>L1</td>
<td>C</td>
<td>2</td>
<td>4</td>
<td>8</td>
<td>8</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>75 M</td>
<td>&lt;1</td>
<td>Trauma</td>
<td>L1</td>
<td>D</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>40 F</td>
<td>&lt;1</td>
<td>Trauma</td>
<td>T12</td>
<td>D</td>
<td>5</td>
<td>5</td>
<td>8</td>
<td>8</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>27 M</td>
<td>&lt;1</td>
<td>Trauma</td>
<td>T11</td>
<td>D</td>
<td>5</td>
<td>5</td>
<td>8</td>
<td>8</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>29 M</td>
<td>&lt;1</td>
<td>Ischemia</td>
<td>T6</td>
<td>D</td>
<td>5</td>
<td>4</td>
<td>8</td>
<td>8</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>26 M</td>
<td>&lt;1</td>
<td>Arteriovenous fistula</td>
<td>L1</td>
<td>D</td>
<td>3</td>
<td>3</td>
<td>6</td>
<td>4</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

M=male; F=female; NT=not tested.
quotient for changing movement direction were determined for each frequency.

For the parameter accuracy, the duration of movement cycles was averaged, converted to a frequency and then compared to the target frequency. The standard deviation of accuracy was determined as a measure for intercycle variation. For ROM, the difference between maximal dorsiflexion and plantarflexion for each movement cycle was averaged. Peak velocity was calculated by deriving the data of the goniometer and by then averaging maxima and minima of the movement cycles, respectively. The quotient of the time spent in the upper- and lowermost 10% of the movement was calculated by dividing the time spent in the lowermost 10% of plantarflexion by the time spent in the uppermost 10% of dorsiflexion. This quotient was determined to describe the ability to switch from dorsiflexion to plantarflexion and vice versa. To establish reference values, 95% confidence intervals were calculated from the results of the 30 healthy subjects.

Statistical analysis

The deviations from the performance of the target frequency and from the time quotient for changing movement direction of 1 (equal duration of switch between dorsiflexion and plantarflexion and vice versa) were determined by one sample t-tests. Differences in performance between the groups were analysed using Wilcoxon rank sum tests. Age and gender dependency of the parameters was determined by multiple regression analyses. Reliability of the test was determined by intraclass correlation and Bland–Altman plots. Multiple regression analysis and Spearman correlation were used to examine correlation between the outcome measures. The significance level \( \alpha \) was set at 0.05 for all tests.

RESULTS

Study 1: control subjects

Control values

As the target frequency became higher, the healthy subjects accomplished the task by reducing both accuracy and ROM. They were able to follow the target frequency up to 2.4 Hz (no significant difference between the target frequency and the frequency performed in the test). At 2.8 and 3.2 Hz, the performed frequency differed significantly from the target frequency (\( p=0.015 \) at 2.8 Hz, \( p=0.001 \) at 3.2 Hz) (Figure 1A). The mean of ROM continuously decreased as the target frequency increased. However, the confidence interval for ROM remained approximately stable (Figure 1B). The peak velocities in dorsiflexion and plantarflexion showed significant increases up to a frequency of 2.4 Hz, i.e. for plantarflexion, 0.8–1.2 Hz (\( p<0.001 \)) and 1.2–1.6 Hz (\( p=0.03 \)); for dorsiflexion, 0.8–1.2 Hz (\( p=0.001 \)) and 2.0–2.4 Hz (\( p=0.04 \)) (Figure 1C,D). Peak velocity in plantarflexion was significantly higher than in dorsiflexion at all frequencies (\( p<0.01 \) for all frequencies). The time quotient ranged between 0.90 and 1.12 and was significantly higher than 1 at 0.8 and 1.2 Hz (\( p=0.001 \) and \( p=0.035 \), respectively, Figure 1E).

Influence of age, gender and target frequency

All test parameters were significantly influenced by the target frequency, while age influenced ROM and peak velocities. Gender showed no significant influence on the test parameters.

The regression equation for the deviation of the performed frequency from target frequency (as dependent variable) and age, gender and target frequency as independent variables was:

\[
\text{Deviation from target frequency} = 0.09 - 0.03 \times \text{gender} (p=0.09) + 0.09 \times \text{target frequency} (p<0.001)(R^2_{adj} = 0.299)
\]

The parameter age was removed from the regression model.

The same analysis with ROM as dependent variable resulted in the regression equation:

\[
\text{ROM} = 61.39 - 0.14 \times \text{age} (p<0.001) - 7.04 \times \text{target frequency} (p<0.001) (R^2_{adj} = 0.379)
\]

The parameter gender was removed from the model. The regression equations for the peak velocities in plantar- and dorsiflexion were:

Peak velocity in plantarflexion:

\[
367.08 - 1.10 \times \text{age} (p=0.004) + 17.94 \times \text{target frequency} (p=0.020) (R^2_{adj} = 0.063)
\]

Peak velocity in dorsiflexion:

\[
329.73 - 1.57 \times \text{age} (p<0.001) + 21.33 \times \text{target frequency} (p<0.001) (R^2_{adj} = 0.211)
\]

The time quotient showed dependency on neither age nor gender:

\[
\text{Time quotient} = 1.18 - 0.090 \times \text{target frequency} (p<0.001) (R^2_{adj} = 0.055)
\]

Reliability

Test-retest reliability was determined in 31 healthy subjects and in six iSCI patients. In general, the second assessment was carried out within 1 week and in some cases within 2 weeks, of the initial test. The intraclass correlation coefficients (ICC) are shown in Table 2. For the parameter accuracy, ICC could not be calculated for 0.8 and 1.2 Hz due to the low variation in the data. Instead, a Bland–Altman plot illustrated the low variability of the data and a paired samples t-test showed that the difference between the data of test 1 and 2 did not significantly differ from 0 (\( p=0.88 \) for 0.8 Hz, \( p=0.09 \) for 1.2 Hz) (Figure 2A,B). From 1.6 to 3.2 Hz, the ICC for accuracy were very good (>0.75).
Figure 1: Control values (95% confidence intervals) for 30 healthy subjects for the measurements of accuracy (A), range of motion (ROM) (B) and the time quotient of movement alteration (C), peak velocity in dorsiflexion (D), peak velocity in plantarflexion (E) measured at all target frequencies (0.8–3.2 Hz). *p<0.05; **p<0.01; ***p<0.001
of the ASIA motor score for the tibialis anterior and the gastrocnemius medialis muscle was 4 (data ranged from 2 to 5 for the tibialis anterior and from 3 to 5 for the gastrocnemius medialis muscle). The median of vibration sense was 5/8 at the malleolus medialis and 4/8 at the carpotacarpal joint of the first toe. Spasticity ranged between 0 and 1 (median of 0) for the modified Ashworth test.

Test results: comparison of groups

The performance of the two groups differed in all outcome parameters, but most noticeably in ROM and peak velocity. The accuracy of the 16 healthy volunteers differed significantly from the target frequency at 2.8 (p=0.04) and 3.2 Hz (p=0.02). In the iSCI subjects, accuracy deviated from the target frequency at 2.0 Hz and upwards (2.0 Hz: p=0.03; 2.4 Hz: p=0.03; 2.8 Hz: p=0.004; 3.2 Hz: p<0.001, Figure 3A). Yet, the difference in accuracy between the two subject groups was not significant prior to 3.2 Hz (p=0.023). The standard deviation of accuracy, which quantifies the intercycle variation, differed significantly between the two groups from 2.0 Hz and upwards (p<0.05, Figure 3B).

ROM and peak velocity in dorsi- and plantarflexion differed significantly between control and patient and groups at all frequencies (ROM: p<0.001 for all frequencies; peak velocities: p<0.01 for all frequencies for both dorsi- and plantarflexion, Figure 3C–E). At all frequencies, the iSCI patients spent more time in plantarflexion (range of the time quotient: 1.14–1.43 in the iSCI group and 0.92–1.11 in the control group, respectively). However, the time quotient significantly differed only at a frequency of 1.6 Hz between the groups (p=0.04, Figure 3F).

Test validation: correlation between outcome parameters

Muscle strength (ASIA motor scores) correlated well with the parameters of ROM and peak velocity (rS: 0.71–0.83 and 0.72–0.86, respectively). Target frequency, peak velocity, proprioception and spasticity were used to explain the variation between the iSCI subjects in the parameters accuracy (deviation from target frequency), ROM and the time quotient. The regression model with the deviation from target frequency as dependent variable and standardized regression coefficients was

Study 2: healthy versus iSCI subjects

Characteristics of the iSCI patients

Muscle strength, sense of vibration and spasticity of the iSCI patients were as follows (Table 1): The median

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>0.8</th>
<th>1.2</th>
<th>1.6</th>
<th>2.0</th>
<th>2.4</th>
<th>2.8</th>
<th>3.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>0.80</td>
<td>0.78</td>
<td>0.71</td>
<td>0.72</td>
<td>0.65</td>
<td>0.69</td>
<td>0.7</td>
</tr>
<tr>
<td>ROM</td>
<td>Bland–Altman (Figure 2)</td>
<td>Bland–Altman (Figure 2)</td>
<td>0.88</td>
<td>0.55</td>
<td>0.75</td>
<td>0.81</td>
<td>0.69</td>
</tr>
<tr>
<td>Peak velocity in dorsiexion (degrees/s)</td>
<td>0.80</td>
<td>0.71</td>
<td>0.60</td>
<td>0.61</td>
<td>0.70</td>
<td>−0.24</td>
<td></td>
</tr>
<tr>
<td>Peak velocity in plantarflexion (degrees/s)</td>
<td>0.84</td>
<td>0.82</td>
<td>0.67</td>
<td>0.65</td>
<td>0.68</td>
<td>0.69</td>
<td>−0.34</td>
</tr>
<tr>
<td>Time quotient of movement alteration</td>
<td>0.80</td>
<td>0.60</td>
<td>0.60</td>
<td>0.60</td>
<td>0.81</td>
<td>0.83</td>
<td>0.76</td>
</tr>
</tbody>
</table>
Figure 3: Results of the cross-sectional study. The results of the iSCI patients and the healthy subjects for accuracy (A), the standard deviation of accuracy (B), range of motion (ROM) (C), peak velocity in plantarflexion (D), peak velocity in dorsiflexion (E) and the time quotient of movement alteration (F). Please note that the differences were calculated from target values (A) and between the groups (B–F). *p<0.05; **p<0.01; ***p<0.001
Deviation from target frequency =
0.043 + 0.567 \times \text{target frequency} (p < 0.001) -
0.163 \times \text{spasticity} (p = 0.049) - 0.501 \times
\text{sum peak velocity in dorsiflexion} (p < 0.001)

This model accounted for 42.9% of the variation in accuracy between the subjects ($R^2_{\text{adj}} = 0.429$). The same regression analysis, using peak velocity in dorsiflexion, instead of the sum of the peak velocities for both dorsiflexion and plantarflexion, resulted in

Deviation from target frequency =
0.044 + 0.577 \times \text{target frequency} (p < 0.001) -
0.441 \times \text{peak velocity in dorsiflexion} (p < 0.001)

($R^2_{\text{adj}} = 0.409$)

The multiple regression model to explain the variation in the parameter ROM (standardized regression coefficients) was

ROM = 0.009 - 0.384 \times \text{target frequency} (p < 0.001) +
0.908 \times \text{sum peak velocity in dorsiflexion} (p < 0.001)

($R^2_{\text{adj}} = 0.920$)

Replacing the sum of peak velocities by peak velocity in dorsiflexion resulted in

$\text{ROM} = 0.010 - 0.424 \times \text{target frequency} (p < 0.001) +
0.883 \times \text{peak velocity in dorsiflexion} (p < 0.001)$

($R^2_{\text{adj}} = 0.869$)

The same procedure for the time quotient as dependent variable resulted in (standardized regression coefficients)

Time quotient = 0.011 - 0.471 \times
\text{spasticity} (p < 0.001) - 0.566 \times
\text{sum peak velocity in dorsiflexion} -
\text{and plantarflexion} (p < 0.001) ($R^2_{\text{adj}} = 0.347$) and

Time quotient = -0.010 - 0.431 \times
\text{spasticity} (p < 0.001) - 0.542 \times
\text{peak velocity in dorsiflexion} (p < 0.001) ($R^2_{\text{adj}} = 0.335$)

Furthermore, a Spearman correlation between ROM and peak velocity showed high correlation for both movement directions ($r_s$ for dorsiflexion: 0.82–0.97 and for plantarflexion: 0.77–0.96).

**DISCUSSION**

**Summary of main findings**

The purpose of the presented test was to distinguish between changes in muscle strength and dexterity of foot movements in iSCI subjects. The analysis of alternating foot dorsi- and plantarflexions showed that dexterity was only slightly reduced after iSCI, whereas foot movements were severely affected by the reduced muscle strength. In addition, the transition from plantarflexion to dorsiflexion was prolonged in iSCI patients, regardless of movement frequency. As the derived parameters showed high reliability, follow-up measures during the course of iSCI will allow for quantifying changes in paresis and dexterity and for assessing their contribution to functional recovery.

**Foot control in healthy subjects**

The present study showed that healthy subjects were able to accurately follow the target frequency with high accuracy up to 2.4 Hz. When the target frequency increased, ROM decreased, while the peak velocities in dorsi- and plantarflexion remained approximately constant. Only the muscle strength related measures ROM and peak velocities showed age dependency, which confirms the finding that older subjects favor accuracy over speed as has previously been reported in reciprocal hand tapping tasks.

**Reliability of alternating foot dorsi- and plantarflexion**

Retest measurements showed a high reliability for all test parameters. The transient reduction of repeatability in accuracy at 2.0 Hz (ICC = 0.55) might reflect a change in the mode of motor control. A change from a closed loop (continuous integration of sensory input into appropriate motor output) to an open loop strategy (intrinsic pattern of feed forward control) of motor control has also been reported in hand writing at 2.0 Hz. Since the test performed in our study is newly developed, no reference values are available in literature. Foot tapping tests have currently been used in various fields of neurology, i.e. cerebral palsy and Alzheimer’s disease, to study the impairment of motor control. In these tests, a sitting subject is asked to perform as many taps of the forefoot as possible in a given time period while the heel remains on the floor. However, such tests do not allow for a distinction to be made between foot dexterity and paresis. Furthermore, only limited data exist with regard to reliability. In children, values ranged between 0.15 and 0.82 (Spearman correlation coefficients) while no values are currently available for adults. Because these reliability values have been retrieved only by counting foot taps, the present parameters based on the more exact method of electrogoniometry show a very good reliability. The ICC for the isolated measurement of ROM of 0.85 confirms the previous finding that electrogoniometry is a reliable method for the measurement of ROM in the ankle joint.

**Foot control in iSCI subjects: distinction between paresis and dexterity**

Subjects with an iSCI were able to maintain a high dexterity, i.e. accuracy of timing was reduced only at
high frequencies with increased intercycle variation, while ROM and peak velocity of the foot movement were significantly reduced at all frequencies. It could be shown that ROM and peak velocity were closely related to reduced motor scores and can be used to quantify paresis. The accuracy of timing was less influenced by motor weakness and was impaired only at higher levels of paresis. Therefore, parameters of paresis and dexterity are differently affected in iSCI and can be distinguished. The finding of reduced movement speed confirms the results of a study in patients with brain injuries, which reported slowness of speed in the foot tapping test to be very sensitive to CNS lesions, and it has been proposed that foot tapping should be included in the standard neurological examination. However, reduced speed in foot tapping tests can be influenced by both muscle strength and movement control (i.e. dexterity), two components that have been demonstrated to be independently impaired in upper limb movements in stroke patients. Spasticity, another feature of CNS lesions, influenced the parameter accuracy only marginally in this sample of patients, which is in accordance with a finding in stroke patients that spasticity does not contribute greatly to motor dysfunction. Nevertheless, all patients in this study had only limited spasticity (modified Ashworth test results of 0 or 1), and testing patients with greater degrees of spasticity would be expected to affect accuracy more significantly. Impaired proprioception was not found to influence accuracy. This is probably due to the fact that subjects could visually control their foot movements, as well as the implementation of an intrinsically patterned open loop movement strategy at higher speeds.

The iSCI patients in this study spent, compared to the healthy subjects, slightly more time changing from plantarflexion to dorsiflexion than vice versa. The statistical analysis showed that spasticity and the strength-related parameter peak velocity in dorsiflexion were mainly responsible for this finding. This is in line with works in patients with stroke and cerebral palsy, which reported plantarflexor stiffness and dorsiflexor paresis to be possible mechanisms for the failure to produce adequate dorsiflexion movements. However, the statistical model only accounts for about a third of the observed variation in the data. This suggests that other mechanisms also contribute to the finding of impaired initiation of dorsiflexion and the prevalence of plantarflexor muscles. In gait, corticospinal input has been shown to have predominant input on the tibialis anterior, muscle compared to the gastrocnemius muscle; thus corticospinal damage may result in a predominant use of the gastrocnemius muscle (in preference to the tibialis anterior muscle).

The measures ROM and peak velocity in dorsiflexion were highly intercorrelated, which may indicate redundancy. It is therefore likely that they develop in parallel during recovery of iSCI. However, gait analysis had previously shown no difference in ankle excursion between healthy and iSCI subjects, but did reveal significantly reduced ankle peak velocity in thoracic and lumbar iSCI patients.

Relationship of paresis and dexterity to function
Ankle dorsiflexion is a crucial part of locomotion and its accurate timing is highly important in initiating the swing phase. An impaired ankle dorsiflexion was shown to be a particular problem in stroke patients and a delayed initiation of dorsiflexion in the swing phase is a predictor of falls in elderly people. With a view to rehabilitation, ankle dorsiflexion has been proposed as a potential marker for gains in motor control of the lower extremity and as a substitute for multi joint walking movements of the affected leg in patients with stroke and SCI.

The parameter peak velocity in dorsiflexion has been shown to be a very sensitive measure in the present foot motor task, because it was significantly reduced at all frequencies. According to the finding that slowness of speed of foot tapping is a characteristic finding in upper motor neuron lesions, this parameter might be a reliable clinical indicator of corticospinal damage. However, the ability to perform a voluntary movement in a supine or sitting position can only be indirectly related to walking ability. The basic locomotor rhythm in unobstructed locomotion is thought to be supported by spinal circuits and to be adapted by afferent feedback that is less dependent on voluntary activation. In monkeys, damage to the corticospinal tract was mainly indicated by the absence of proper initiation of the swing phase (dragging the hind paw in swing phase), an increase in cycle duration and an alteration in the relationship between stance and swing phase. A possible correlation of some outcome measures, particularly of the parameter peak velocity in dorsiflexion, of this simple auditory-paced dorsi- and plantarflexion task and gait parameters, and hence the possible predictive value of this task for walking ability, will be the subject of investigation in future works.

CONCLUSION
This simple, auditory-paced ankle dorsi- and plantarflexion task allows for a distinction to be made between motor strength and dexterity. In iSCI patients, mainly muscle strength was impaired, while dexterity was less affected. These findings, based on measurements in the supine position, will improve the clinical testing of motor impairment in iSCI by providing quantifiable measures of these two components. In longitudinal works, changes in these parameters during the course of rehabilitation might provide further insight into the mechanisms underlying the improvement of motor function after iSCI.

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REFERENCES