Changes in soleus H-reflex modulation after treadmill training in children with cerebral palsy

Maike Hodapp,1 Julia Vry,2 Volker Mall2 and Michael Faist1

1 Department of Neurology and Clinical Neurophysiology, University Hospital Freiburg, Breisacher Strasse 64, 79106 Freiburg, Germany
2 Department of Neuropediatrics and Muscular Disorders, Children’s University Hospital, University of Freiburg, Mathildenstraße 1, 79106 Freiburg, Germany

Correspondence to: Michael Faist,
Department of Neurology and Clinical Neurophysiology,
University Hospital Freiburg, Breisacher Strasse 64,
79106 Freiburg, Germany
E-mail: michael.faist@uniklinik-freiburg.de

In healthy children, short latency leg muscle reflexes are profoundly modulated throughout the step cycle in a functionally meaningful way and contribute to the electromyographic (EMG) pattern observed during gait. With maturation of the corticospinal tract, the reflex amplitudes are depressed via supraspinal inhibitory mechanisms. In the soleus muscle the rhythmic part of the modulation pattern is present in children with cerebral palsy (CP), but the development of tonic depression with increasing age, as seen in healthy children, is disturbed. Treadmill training clinically improves the walking pattern in children with CP. Presuming that short latency reflexes contribute significantly to the walking pattern, a change in the modulation may occur after training. The aim of this study was to assess whether treadmill training also improves the soleus reflex modulation during gait in children with CP. Seven children with CP underwent brief treadmill training for 10 min a day over 10 consecutive days; all of them were functional walkers. Soleus Hoffmann (H-) reflexes were investigated during walking on a treadmill before the first, and one day after the last, training session. Treadmill training led to a considerable clinical improvement in gait velocity. After 10 days of training, soleus H-reflexes during gait were almost completely depressed during the swing phase. The complete suppression of the soleus H-reflex during the swing phase, which is also exhibited by healthy subjects, could reflect an improvement towards a functionally more useful pattern. In conclusion, treadmill training can induce changes in the modulation of short latency reflexes during gait.

Keywords: cerebral palsy; child; H-reflex; gait; training
Abbreviations: CP = cerebral palsy; EMG = electromyographic; GMFCS = Gross Motor Classification System; SCI = spinal cord injury

Introduction

Treadmill training can clinically improve gait parameters in patients with spasticity. In children with cerebral palsy (CP), improvements in walking speed and, to a lesser extent, walking endurance, are evident after (partial body weight) treadmill training of varying durations (Schindl et al., 2000; Day et al., 2004; Dodd and Foley, 2007; Provost et al., 2007; Cherng et al., 2007). Moreover, a combination of traditional physical therapy and partial body weight treadmill training is shown to improve motor skills in children with CP (Begnoche and Pitetti, 2007). In adults suffering from incomplete spinal cord injury (SCI), treadmill training was shown to be beneficial for recovery (Dietz et al., 1994; Wernig et al., 1999; Phadke et al., 2007). Although some individual studies about treadmill training on adult stroke patients demonstrated an improvement in gait ability and velocity (Hesse et al., 1995), a Cochrane analysis revealed no overall statistical effect of treadmill training in these patients (Moseley et al., 2005). The underlying neuronal mechanisms responsible for the beneficial effects of treadmill training are still poorly understood.
In healthy subjects, the electromyographic (EMG) pattern is rhythmically modulated during gait. Paraplegic patients show a less dynamic mode of EMG activation pattern in the soleus muscle, and an inappropriate tibialis anterior activation compared to healthy subjects. After treadmill training the amplitude of the soleus-EMG during the stance phase increases while the activation of tibialis anterior decreases (Dietz et al., 1995).

Short latency reflexes of the major leg muscles are also profoundly modulated throughout the step cycle in adults. During walking and running, Soleus-Hoffmann (H-) reflexes show a maximum in the stance phase and a minimum in the swing phase (Capaday and Stein, 1986, 1987). In addition to the rhythmic part of the modulation, there is also general reflex depression during locomotion, as compared to free standing or sitting (Morin et al., 1982; Capaday and Stein, 1986; Brooke et al., 1991; Faist et al., 1996). In healthy children the rhythmic part of the modulation is already present at the age of 6, while tonic depression of the reflexes during gait develops up to the age of 13 (Hodapp et al., 2007a). Between the ages of 6 and 13 years H-reflex amplitudes decrease, especially in the stance phase of gait, while H-reflexes during quiet standing remain unchanged (Hodapp et al., 2007a). Children with CP suffering from spastic tetraplegia show the rhythmic reflex modulation but lack the development of the age-dependent tonic depression during gait (Hodapp et al., 2007b), which is suggested to contribute to the impaired gait pattern of these children. In adult spastic patients the modulation of short latency reflexes has been shown to be severely disturbed (Yang et al., 1991b; Sinkjaer et al., 1996; Faist et al., 1999). In healthy adults there is some evidence that training can induce changes in H-reflexes. Reduced gain of H-reflexes was shown after both balancing training (Trimble and Koceja, 1994; Gruber et al., 2007), after a single training session of cycling (Mazzocchio et al., 2006; Meunier et al., 2007), and co-contraction training (Perez et al., 2007), indicating a task-specific functional adaptation. In addition, decreased H-reflex amplitudes during gait were found immediately after a single treadmill training in four patients suffering from SCI (Trimble et al., 2001). Phadke et al. (2007) showed that H/M ratios during midstance and midswing were significantly smaller during treadmill walking with body weight support compared to a single training session of overground walking. The authors therefore suggested that treadmill training may be a more optimal environment in which to promote the normalization of reflex modulation. These studies indicate a functional relevance of reflexes on motor performance.

It is unknown whether treadmill training can induce longer lasting alterations beyond the acute effect in H-reflex modulation during gait. For a single cycling training session of 16 min, an increased homosynaptic depression on soleus H-reflexes could be observed for at least 48 h after training (Meunier et al., 2007), indicating possible longer lasting effects even of short training periods. It has been estimated that reflex pathways contribute substantially (30–60%) to the activation of the soleus muscle particularly during the early part of the stance phase (Yang et al., 1991a). This would mean that they also contribute to the EMG activation pattern during walking. As reflex modulation is disturbed in spastic gait, (Yang et al., 1991b; Sinkjaer et al., 1996; Faist et al., 1999), it may be hypothesized that an improvement in gait in spastic patients may be accompanied by changes in reflex modulation. Soleus H-reflexes are larger during gait in children with bilateral cerebral palsy than those in healthy children. In light of the findings by Meunier et al. (2007), even brief treadmill training might both improve walking ability and induce depression of soleus H-reflexes in these patients.

To test this hypothesis, H-reflexes during gait were investigated in seven children with CP before and after 10 days of treadmill training. Hence, this investigation aims to generate important new information about task-specific plasticity in the central nervous system.

**Methods**

A total of 10 children who were seen with strongly leg-dominated bilateral spastic cerebral palsy and were all functional walkers (at least with device support) were included for the treadmill training protocol. Three of them were unable to complete the H-reflex protocol during walking because of the severe disturbance of their gait pattern. Seven children (mean age, 9.7 years; range, 5–15) finally participated in this study. Severity of motor impairment was classified according to the Gross Motor Classification System (GMFCS) consisting of five levels of impairment (Palsino et al., 1997). GMFCS ranged from one to three out of five (see Table 1 for details). Parents or guardians provided written informed consent on behalf of their children. The study was approved by the ethics committee of the University of Freiburg.

**Table 1 Patient characteristics**

<table>
<thead>
<tr>
<th>Child</th>
<th>Age (years)</th>
<th>GMFCS</th>
<th>Devices</th>
<th>Medication</th>
<th>Ground walking speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Before training (km/h)</td>
</tr>
<tr>
<td>1</td>
<td>5.2</td>
<td>1</td>
<td>No</td>
<td>No</td>
<td>5.4</td>
</tr>
<tr>
<td>2</td>
<td>6.7</td>
<td>2</td>
<td>Dynamic orthosis</td>
<td>No</td>
<td>4.5</td>
</tr>
<tr>
<td>3</td>
<td>9.3</td>
<td>3</td>
<td>Dynamic orthosis; walking sticks</td>
<td>No</td>
<td>1.3</td>
</tr>
<tr>
<td>4</td>
<td>9.3</td>
<td>3</td>
<td>Wheelchair for longer distances; dynamic orthosis</td>
<td>No</td>
<td>4.7</td>
</tr>
<tr>
<td>5</td>
<td>10.9</td>
<td>2</td>
<td>Dynamic orthosis</td>
<td>No</td>
<td>4.0</td>
</tr>
<tr>
<td>6</td>
<td>14.8</td>
<td>3</td>
<td>Wheelchair for longer distances; walking sticks</td>
<td>No</td>
<td>2.5</td>
</tr>
<tr>
<td>7</td>
<td>14.8</td>
<td>2</td>
<td>No</td>
<td>No</td>
<td>4.8</td>
</tr>
</tbody>
</table>
General experimental arrangement

H-reflexes, gait velocity, step length and step frequency were investigated during walking without body weight support on a split-belt treadmill (Woodway®, type 56) one day before and one day after a 10 days period of training. Force-measuring platforms (quartz-crystal, Kistler®, type 9041) placed under each belt allowed for the assessment of both the time course of the stance and the swing phase of gait. EMG activity of the soleus muscle was recorded with pairs of surface silver/silver chloride electrodes (Hellige®, diameter 0.9 cm) placed in a longitudinal direction above the belly of the muscle (inter-electrode distance 2 cm). H-reflex and EMG data were processed using customized software programmed into LabView®. All children were investigated at a walking velocity at which they felt comfortable (before training: mean, 1.7 km/h; range, 1.2–2.0 km/h; after training mean, 2.5 km/h; range, 2.0–3.0 km/h). At the beginning of the experiment, they were asked to walk on the treadmill while the velocity was increased step-wise. When the children reported a convenient velocity at which they believed they were able to walk for a few minutes, this velocity was then chosen for the experiment. To ensure that differences in reflex modulation are not simply an effect of walking velocity, the experiment was repeated on three children who walked at the same velocity as that set before training. Ground walking velocity before and after training was assessed as the fastest attainable velocity within 6 min, and was performed with the aid of any devices which the children normally used for walking.

Treadmill training

Treadmill training was carried out with the assistance of two trained therapists (one for each leg), albeit without body weight support or any type of orthosis. Each training session lasted 10 min, and was performed over 10 consecutive days. Walking speed was serially increased so that the patients always felt comfortable during the training. Mean walking speed was increased from 1.90 (±0.60) km/h in the first training session to 3.10 (±0.50) km/h in the last training session. The relatively slow walking velocity during training was chosen to generate a regular gait pattern, and the children were therefore instructed to walk with a constant step length. Time endurance of the training session was kept constant to investigate possible effects of even a brief treadmill training. The reason for not using body-weight support was to carry out a type of training that could easily be incorporated into daily life. Children did not receive any additional therapy during the training period and had neither botulinum toxin injections nor new orthosis in the 6 months preceding the study.

H-reflexes

Soleus H-reflexes were elicited by placing the cathode in the popliteal fossa and stimulating N. tibialis. At the beginning and end of each experimental session, stimulus thresholds and maximal amplitudes of H- (= H\text{max}) and M-responses (= M\text{max}) were assessed during free standing, with the weight distributed equally on both legs. The stimulus intensity at which H\text{max} was obtained during standing was used as the reference for the stimulus intensity chosen for eliciting H-reflexes during gait. To ensure the H-reflexes were on the ascending part of the H-reflex recruitment curve (cf. Crone et al., 1990), the stimulus intensity applied to elicit H-reflexes during gait was chosen to be just below, i.e. at 0.9 times of the stimulus intensity required to elicit H\text{max} during standing (cf. Hodapp et al. 2007a, b). Choosing the stimulus intensity with reference to H\text{max} allows for inter-individual comparison of the reflex size during gait. This chosen stimulus intensity was sufficient to elicit an M response in all subjects. The effective stimulus intensity applied at the tibial nerve during gait was determined by this M response during the gait condition. The amplitude of the M response was maintained to ensure that the effective stimulus intensity applied at the nerve remained constant throughout the gait experiments. Reflexes were obtained during eight different phases of the step cycle. At least 12 reflexes, with an interstimulus interval of at least 4 s, were elicited in a randomized sequence during each phase (for details see Faist et al., 1996). The size of each H-reflex was measured as the peak-to-peak-amplitude of the non-rectified EMG trace, and the mean H-reflex was calculated for each of the eight phases of the step cycle investigated. To allow for inter-individual comparison, H-reflex size was normalized by expressing it as a percentage of the amplitude of M\text{max}.

Soleus background EMG during gait

The amplitude of the H-reflex is essentially dependent on the EMG-activity of the same muscle. Furthermore, the EMG-activity during locomotion depends on the walking velocity. For each of the eight-step phases, the background EMG-activity of the soleus muscle was assessed by the rectified and averaged EMG. The mean background EMG activity of each of the eight step phases was expressed as a percentage of the mean EMG activity during the whole step cycle before training. This normalization allows for inter-individual comparison of the background EMG modulation during the step cycle, and between the two walking velocities before and after training.

Statistical analysis

First, the mean values (n = 12) of reflex size and background EMG for each of the eight gait phases (each phase corresponds to 12.5% of the step cycle) were calculated for each individual subject. Second, the mean reflex size and mean background EMG of all the eight phases were calculated. To test for changes in reflex size in stance versus swing phase, mean stance- and mean swing-phase reflex sizes were calculated for each subject during each session. Step phases at the beginning of stance (Phase 1) and at the transition from stance to swing (Phase 5) were not considered for this part of the analysis. Accordingly, the mean stance phase reflex size was calculated from the reflexes obtained during Phases 2, 3 and 4, and the mean swing phase reflex size from reflexes obtained during Phases 6, 7 and 8.

To illustrate changes before and after training, mean values ± standard error of the mean (SEM) for reflex size background EMG, corresponding to the before- and after-periods of training, were calculated for all the seven children. To test for statistically significant differences between mean values before and after training, a non-parametric Wilcoxon test was performed using statistical software (StatView®). To test for age-dependent differences or effects of body mass, a regression analysis was carried out. P-values < 0.05 were considered to be significant.

Results

H-reflexes during standing and stimulus intensities

For all the seven children investigated, no significant differences were found before and after training, neither for the mean size of the maximal soleus H-reflex amplitude (H\text{max}) obtained during
quiet standing without support, nor for the mean stimulus intensity applied during gait (Table 2).

**Gait parameters**

Ground walking velocity ($P<0.05$), as well as walking velocity on the treadmill, increased significantly after training ($P<0.05$). Ground walking velocity was assessed as the fastest reachable velocity. Duration of swing phase increased significantly ($P<0.05$), whereas duration of stance phase and both double stance phases decreased significantly ($P<0.05$) (Table 2).

**Reflex modulation during gait**

Figure 1 shows a typical example of a reflex modulation and M-waves in a single child. Figure 2A illustrates the mean H-reflex amplitudes obtained during gait in the children with CP both before and after training (walking velocity before training: mean, 1.7 km/h; range, 1.2–2.0 km/h; after training, mean 2.5 km/h; range, 2.0–3.0 km/h). Both before and after training, children with CP showed a rhythmic modulation during the step cycle which was maximal in mid-stance. When calculated separately, a significant decrease in the reflex amplitude was found during step Phases 1, 5, 6, 7 and 8 ($P<0.05$). The mean H-reflex size over the entire step cycle decreased significantly after training ($30.9 \pm 1.79\%$ versus $16.8 \pm 1.2\%$ of $M_{max}$, $P<0.05$). No statistically significant differences were apparent if the stance phase was calculated separately ($45.5 \pm 7.3\%$ versus $32.5 \pm 2.9\%$ of $M_{max}$, $P=0.40$). Mean reflex amplitudes in the swing phase showed significant differences ($17.2 \pm 1.3\%$ versus $5.4 \pm 0.8\%$ of $M_{max}$, $P<0.05$; Fig. 2B, Table 3). H-reflexes during the whole step cycle decreased in six subjects with CP, and remained unchanged in one child. A regression analysis revealed no effects of age ($R^2=0.11$) or body mass index ($R^2=0.12$) on the reflex depression after training. No significant differences were found in the absolute values of the background EMG during gait ($0.34 \pm 0.12$ mV versus $0.31 \pm 0.14$ mV; $P=0.50$). Soleus EMG-activity underwent a similar pattern of modulation throughout the step cycle (Fig. 2C).

Figure 3A illustrates the mean H-reflex amplitudes which were recorded both before and after training during gait in three children with CP walking at a velocity which was faster or the same as that endured before training (walking velocity before training: mean, 1.6 km/h; range, 1.2–2.0 km/h; after training, mean 2.6 km/h; range, 2.4–3.0 km/h). Before and after training children with CP who walked at faster and with the same velocity as before training showed a rhythmic modulation during the step cycle with the maximum in mid-stance. The mean H-reflex size over the entire step cycle ($20.8 \pm 0.85\%$ versus $16.9 \pm 1.6\%$ of $M_{max}$) between the two velocities remained almost the same. This was also true if the stance phase ($34.0 \pm 2.2\%$ versus $27.0 \pm 0.9\%$ of $M_{max}$) or the swing phase was calculated separately ($9.4 \pm 2.2\%$ versus $8.6 \pm 2.4\%$ of $M_{max}$; Fig. 3B, Table 3).

**Discussion**

This study has demonstrated that children with CP who undergo even brief treadmill training have further depression of soleus

---

**Table 2** H/M ratio, stimulus intensity and gait parameters

<table>
<thead>
<tr>
<th></th>
<th>Before training</th>
<th>After training</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H/M$ ratio ($\pm SE$) during standing</td>
<td>65.0 ($\pm 17.3%$) of $M_{max}$</td>
<td>63.6 ($\pm 19.4%$) of $M_{max}$</td>
<td>NS</td>
</tr>
<tr>
<td>$M_{max}$ ($\pm SE$) during standing</td>
<td>6.60 ($\pm 3.3$) mV</td>
<td>6.57 ($\pm 1.1$) mV</td>
<td>NS</td>
</tr>
<tr>
<td>Mean stimulus intensity ($\pm SE$)</td>
<td>0.86 ($\pm 0.07$) $\times H_{max}$ stimulus intensity</td>
<td>0.85 ($\pm 0.14$) $\times H_{max}$ stimulus intensity</td>
<td>NS</td>
</tr>
<tr>
<td>Treadmill walking velocity ($\pm SE$)</td>
<td>1.67 ($\pm 0.43$) km/h</td>
<td>2.53 ($\pm 0.34$) km/h</td>
<td>$P&lt;0.05$</td>
</tr>
<tr>
<td>Ground walking velocity ($\pm SE$)</td>
<td>3.89 ($\pm 0.55$) km/h</td>
<td>4.24 ($\pm 0.60$) km/h</td>
<td>$P&lt;0.05$</td>
</tr>
<tr>
<td>Duration of swing phase ($\pm SE$)</td>
<td>35.8 ($\pm 3.4$) % of step duration</td>
<td>38.3 ($\pm 2.9$) % of step duration</td>
<td>$P&lt;0.05$</td>
</tr>
<tr>
<td>Duration of stance phase ($\pm SE$)</td>
<td>64.1 ($\pm 3.4$) % of step duration</td>
<td>61.8 ($\pm 2.9$) % of step duration</td>
<td>$P&lt;0.05$</td>
</tr>
<tr>
<td>Duration of double stance Phase I ($\pm SE$)</td>
<td>12.8 ($\pm 2.1$) % of step duration</td>
<td>11.3 ($\pm 2.5$) % of step duration</td>
<td>$P&lt;0.05$</td>
</tr>
<tr>
<td>Duration of double stance Phase II ($\pm SE$)</td>
<td>14.4 ($\pm 3.4$) % of step duration</td>
<td>11.0 ($\pm 1.8$) % of step duration</td>
<td>$P&lt;0.05$</td>
</tr>
</tbody>
</table>
H-reflexes, at least in the swing phase of gait. This data therefore show that treadmill training can induce changes in the modulation of short latency reflexes during gait. These changes in reflex modulation were associated with an improvement in overground and treadmill gait velocity.

Table 3 Raw data for H-reflex and M-wave

<table>
<thead>
<tr>
<th></th>
<th>Before training</th>
<th>After training</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H-reflex</td>
<td>M-wave</td>
</tr>
<tr>
<td></td>
<td>(±SEM)</td>
<td>(±SEM)</td>
</tr>
<tr>
<td>Different velocities (n=7)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phase 1</td>
<td>1.98±0.19</td>
<td>0.60±0.07</td>
</tr>
<tr>
<td>Phase 2</td>
<td>2.84±0.29</td>
<td>0.64±0.16</td>
</tr>
<tr>
<td>Phase 3</td>
<td>3.05±0.32</td>
<td>0.63±0.08</td>
</tr>
<tr>
<td>Phase 4</td>
<td>3.15±0.34</td>
<td>0.69±0.15</td>
</tr>
<tr>
<td>Phase 5</td>
<td>1.83±0.19</td>
<td>0.72±0.15</td>
</tr>
<tr>
<td>Phase 6</td>
<td>0.78±0.15</td>
<td>0.57±0.08</td>
</tr>
<tr>
<td>Phase 7</td>
<td>0.46±0.05</td>
<td>0.57±0.06</td>
</tr>
<tr>
<td>Phase 8</td>
<td>1.78±0.21</td>
<td>0.52±0.02</td>
</tr>
<tr>
<td>Same velocity (n=3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phase 1</td>
<td>1.64±0.62</td>
<td>0.43±0.07</td>
</tr>
<tr>
<td>Phase 2</td>
<td>2.19±0.99</td>
<td>0.35±0.05</td>
</tr>
<tr>
<td>Phase 3</td>
<td>2.33±0.93</td>
<td>0.44±0.01</td>
</tr>
<tr>
<td>Phase 4</td>
<td>2.22±0.92</td>
<td>0.39±0.02</td>
</tr>
<tr>
<td>Phase 5</td>
<td>0.64±0.06</td>
<td>0.44±0.01</td>
</tr>
<tr>
<td>Phase 6</td>
<td>0.47±0.02</td>
<td>0.45±0.02</td>
</tr>
<tr>
<td>Phase 7</td>
<td>0.39±0.03</td>
<td>0.50±0.05</td>
</tr>
<tr>
<td>Phase 8</td>
<td>0.87±0.17</td>
<td>0.50±0.03</td>
</tr>
</tbody>
</table>

Fig. 2 (A) Reflex amplitudes (in percentage of $M_{max}$) during the step cycle in all seven children before (at 1.7±0.4 km/h) and after (at 2.5±0.3 km/h) training aged 5–16 years. (B) Mean amplitudes (in percentage of $M_{max}$) of overall step cycle (Phases 1–8, corresponding to 0–100% step cycle), stance phase (Phases 2–4, corresponding to 20–45% step cycle) and swing phase (Phases 6–8, corresponding to 60–85% step cycle) before and after training. (C) Background-EMGs before and after training at 1.7 and 1.2 km/h in % of mean EMG during gait before training. Vertical bars indicate SEM; *P<0.05.

These findings are in line with results found in adult SCI patients immediately after a single treadmill training session, where a significant reduction in H-reflex amplitudes during stance- and swing phase was observed with increasing walking speed (Trimble et al., 2001). Similarly, a brief period of cycling training in healthy adults led to a persistent decrease in H-reflex amplitude, correlated with skill acquisition (Mazzochio et al., 2006).

In spastic patients with severe gait disturbance soleus H-reflex modulation is disturbed showing a lack of depression compared to healthy subjects, especially in the swing phase. This was observed in patients with incomplete SCI (Yang et al., 1991b), CP-children (Hodapp et al., 2007b), and hemiplegic patients after stroke (Faist et al., unpublished data). Petersen et al. (1999) showed in healthy subjects that disynaptic reciprocal Ia-inhibition between ankle extensors and flexors is strongly modulated and thereby contributes to reflex depression during swing, avoiding co-contraction which would otherwise interfere with the walking pattern. The reflex depression during the swing phase of gait could be of functional relevance since soleus reflexes would counteract dorsiflexion of the foot during swing and thus disturb foot clearance while during the stance phase soleus reflexes have been estimated to contribute to the soleus activation in a functionally useful way (Yang et al., 1991a). Therefore, the observed reduction in soleus H-reflexes during the swing phase in this study may be functionally important since large soleus reflex amplitudes during the swing phase might impair dorsiflexion of the foot, especially in spastic gait with reduced foot clearance (Yang et al., 1991a, Faist et al., 1999).

In contrast to the above-mentioned studies (Trimble et al., 2001; Mazzochio et al., 2006), which only performed measurements...
immediately after the training sessions, this study shows that the described changes in H-reflexes persist for at least 24 h after the last training session. This points to presynaptic mechanisms as likely candidates in view of the finding by Meunier et al. (2007) who showed a long-lasting increase (>24 h) in homosynaptic depression after a single cycling session. It has also been proposed that some parts of reciprocal inhibition between tibialis anterior and soleus act presynaptically (Edamura et al., 1991).

**Effect of velocity**

In this study H-reflexes were reduced after treadmill training. Since gait velocity increased after training, an effect of velocity on the H-reflex amplitude could not be excluded. To address this possibility, three children were further investigated at the same velocity as that used before training. The further suppression of H-reflexes in the swing phase after training was present at both velocities and is therefore likely to be the sole effect of training. Reflex amplitudes during the stance phase tended to be smaller at higher velocities after training. In a previous study we could demonstrate in healthy children that H-reflex amplitudes were higher during the stance phase when velocity was increased (Hodapp et al., 2007a). This finding suggests that a training effect also underlies the changes observed during the stance phase.

**Mechanisms contributing to H-reflex depression**

Presynaptic inhibition is responsible for tonic depression during gait and has been shown to be disturbed in children with CP (Hodapp et al., 2007b). Presynaptic inhibition is the most likely mechanism contributing to the further suppression of H-reflexes after training, as discussed later in the text. The lack of further suppression of reflexes during gait with increasing age can at least be partly compensated by training.

In healthy adults who were instructed to step over an obstacle with reduced vision, increased H-reflexes were observed in the stance phase during the first obstacle run (Hess et al., 2003). H-reflexes decreased to their previous values in the subsequent runs. These changes in H-reflexes during motor learning have been ascribed to supraspinal alterations (Hess et al., 2003). After a long-lasting (3–5 months) treadmill training in adult SCI patients, there was a significant enhancement in MEP amplitudes elicited by TMS during rest, thus indicating an increase in corticospinal tract connectivity (Thomas and Gorassini, 2005). There was also a strong relationship between the percentage of increase in maximum MEP amplitude (corticospinal connectivity) and the improvement in walking function, as assessed by a clinical score, the distance a subject could walk in 6 min and the amplitude of the locomotor EMG activity. It was therefore suggested that recovery of walking is in part mediated by the corticospinal tract (Thomas and Gorassini, 2005).

After 2 weeks of training in children with CP, walking speed was increased while enhanced cortical activation during ankle dorsiflexion was visualized by functional magnetic resonance tomography; thus indicating training-induced cortical plasticity (Phillips et al., 2007).

Motor skill training (performing voluntary ankle dorsiflexion and plantarflexion during a computer-based learning program) has been shown to alter the excitability of the leg cortical area in healthy adults, as revealed by TMS (Perez et al., 2004). When repetitive TMS (rTMS) is applied over the leg motor cortex area, MEPs to the soleus and tibialis anterior are facilitated, but the soleus H-reflex is depressed (Perez et al., 2005). rTMS increased the size of long-latency depression of the soleus H-reflex evoked by common peroneal nerve stimulation and decreased the femoral nerve facilitation of the soleus H-reflex. These results indicate that rTMS can induce depression of soleus H-reflex through its effect on the corticospinal pathway by an increased presynaptic inhibition of soleus la afferents, whereas no effect on disynaptic reciprocal (Ia) inhibition can be seen (Perez et al., 2005). It was suggested that rTMS may modulate transmission in specific spinal circuits and this may be of relevance for future therapeutic strategies in patients with spasticity (Perez et al., 2005). In healthy volunteers, 30 min of co-contraction training resulted in decreased H-reflex size, and this correlated with an improvement in motor performance (Perez et al., 2007). This has been ascribed to increased presynaptic inhibition, with prolonged changes in reflex and corticospinal excitability likely resulting after co-contraction training (Perez et al., 2007). Locomotor training leads to repetitive stretch shortening of the soleus muscle, causing...
repetitive firing of the muscle spindles. Thus, the training method itself may have induced reflex changes (Phadke et al., 2007). In healthy adults, a single cycling session improved performance and led to increased homosynaptic depression, which is ascribed to a presynaptic mechanism (Meunier et al., 2007). In this study, the decreased H-reflex amplitudes during gait may also reflect changes in presynaptic inhibition induced by training. Norton and Gorassini (2006) suggested that the improvement in locomotor function in patients with incomplete SCI is in part mediated by increased drive of corticospinal input to leg muscles. The age of the patients could also be a factor, whereby it is possible that younger children show more plasticity than older children or adults. To further investigate these effects, a study including a higher number of subjects would be required.

Possible limitations

One may argue that the number of children with CP in this study is low. However, the experimental procedure was set up to investigate a neurophysiological question that could be answered with a relatively small number of subjects. Many of the previous studies, which have investigated the neurophysiological effects of treadmill training in spastic patients, have similarly recruited a limited number of patients: Dietz et al. (1994) included five subjects in their investigation of EMG pattern after treadmill training in paraplegic patients. Trimble et al. (2001) investigated H-reflexes after a single treadmill training in four patients; Thomas and Gorassini (2005) investigated changes in corticospinal tract function after treadmill training in eight patients with SCI. Moreover, clinical studies in children with CP have only recruited a limited number of 1–10 patients (Schindl et al., 2000; Day et al., 2004; Cherng et al., 2007; Provost et al., 2007), except Dodd and Foley (2007) who recruited 14 patients.

A second limitation may be the clinical significance of results. Although changes in overground walking velocity after training were statistically significant in this study and the 6-min gait test has been shown to be a reliable and valid test (Dean et al., 2001), these changes in most children were only slight in absolute values; only one child improved essentially in ground walking speed. It should be noted that treadmill training was undertaken without orthosis at a velocity with which children felt comfortable, while overground walking velocity was assessed with orthosis. This means that children were trained at velocities lower than those at which they were able to walk overground, at least for a short period of time. It is possible that training at higher, more challenging velocities or longer lasting training sessions might have led to a greater improvement in overground velocity. However, one has to keep in mind that five out of seven children showed overground walking velocities, which were close to what may be considered normal, despite the fact that clinically they showed a clear spastic gait. Although the objective increase in overground gait velocity was comparably small, all children and their parents reported a subjective improvement in gait.

A further limitation may be that most related studies were carried out using body-weight supported treadmill training, whereas this study did not use body-weight support. In stroke patients, body-weight supported treadmill training resulted in better walking and postural abilities compared to motor training without BWS (Barbeau and Visentin, 2003). Finally, the effects of training may depend on age or on the severity of gait disturbance. It is likely that younger children respond more favourably to training because of the higher degree of corticospinal tract plasticity corresponding to that observed in healthy children of younger ages (Hodapp et al., 2007a). However, no real further development was seen in children with CP, which could support age-dependent differences (Hodapp et al., 2007b). The role of age in the effects of training could only be addressed in a study with a higher number of children.

Despite these limitations, it must be noted that even a short training period of 10 days, produced a robust improvement in the reflex modulation. These results indicate promising potential, especially if these children were trained longer or if children with more severe impairment were trained.

Clinical implications

In the line with previous studies (Schindl et al., 2000; Day et al., 2004; Dodd and Foley, 2007; Provost et al., 2007; Cherng et al., 2007), treadmill training in children with CP led to improvements in ground walking and treadmill velocities, as well as in stance and swing phase duration. All studies were carried out in a low number of children; however, to ensure that treadmill training really is an effective therapy in CP children, in contrast to adults after stroke (Moseley et al., 2005), a clinical study with a higher number of children is required. The restricted availability of resources presents as a major limitation for therapy. Longer training periods and technical equipment such as body weight support systems may not be available to most children. In this study we demonstrated that treadmill training sessions as short as 10 min set in a simple environment of a treadmill and two physiotherapists were indeed effective and sufficient to induce neurophysiological changes. Such a therapeutic setting is more likely to be accessible by children with CP than the more complex systems.

In conclusion, treadmill training induced changes in the modulation of short latency reflexes during gait, which could reflect task-specific plasticity of the central nervous system. The complete suppression of the soleus H-reflex during the swing phase, which is similar to that observed in healthy subjects, could reflect an advancement towards a functionally more useful pattern, given that large reflex amplitudes in the soleus during the swing phase may impair dorsiflexion of the foot during gait. For future studies, measurements of reciprocal Ia- or presynaptic inhibition would help to improve our understanding of the role of spinal interneurons in training-induced reflex changes.

Acknowledgements

The authors wish to express their gratitude to all children for participating in this study, to Dr Sandra Dieni for scrutinizing the English, and to Dr Florian Amtage for statistical support.
References


