Sensory feedback to ankle plantar flexors is not exaggerated during gait in spastic hemiplegic children with cerebral palsy

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Willerslev-Olsen M, Andersen JB, Sinkjaer T, Nielsen JB. Sensory feedback to ankle plantar flexors is not exaggerated during gait in spastic hemiplegic children with cerebral palsy. J Neurophysiol. 2014. First published November 13, 2013; doi:10.1152/jn.00372.2013.—It is still widely believed that exaggerated stretch reflexes and increased muscle tone in ankle plantar flexors contribute to reduced ankle joint movement during gait in children with cerebral palsy (CP). However, no study has directly measured stretch reflex activity during gait in these children. We investigated sensory feedback mechanisms during walking in 20 CP children and 41 control children. Stretch responses in plantar flexor muscles evoked in stance showed an age-related decline in control but not CP children. In swing the responses were abolished in control children, but significant responses were observed in 14 CP children. This was related to reduced activation of dorsiflexors in swing. Removal of sensory feedback in stance produced a drop in soleus activity of a similar size in control and CP children. Soleus activity was observed in swing to the same extent in control and CP children. Removal of sensory feedback in swing caused a larger drop in soleus activity in control children than in CP children. The lack of age-related decline in stretch reflexes and the inability to suppress reflexes in swing is likely related to lack of maturation of corticospinal control in CP children. Since soleus activity was not seen more frequently than in control children in swing and since sensory feedback did not contribute more to their soleus activity, spasticity is unlikely to contribute to foot drop and toe walking. We propose that altered central drive to the ankle muscles and increased passive muscle stiffness are the main causes of foot drop and toe walking.

age-dependent changes; stretch reflex; biomechanical evaluation; cerebral palsy; electrophysiology; spasticity

THE MAJORITY OF CHILDREN with cerebral palsy (CP) have gait problems, which impact their quality of life (af Klint et al. 2010; Hullin et al. 1996; Parkes et al. 2010; Shikako-Thomas et al. 2012).

Foot drop and toe walking are especially common in hemiplegic CP and are often perceived as important impediments for full integration in social activities with peers (Hullin et al. 1996; Parkes et al. 2010). In some cases pareses or paralysis of ankle dorsiflexors is responsible, whereas contractures and reduced range of movement are involved in other cases. In addition, it is generally believed that hyperexcitable stretch reflexes (spasticity according to the definition by Lance 1980) in ankle plantar flexors play a major role in creating premature overactivity in plantar flexors prior to heel strike (Winters et al. 1987). As a consequence, antispastic treatment such as botulinum toxin A (Btx) is frequently administered in an effort to reduce plantar flexor hyperactivity and facilitate heel strike (Criswell et al. 2006). However, in the last two decades several studies have questioned the functional significance of exaggerated stretch reflexes (Dietz et al. 1981; Dietz and Sinkjaer 2007; Sinkjaer and Magnusson 1994). There is in fact little evidence available regarding the role of stretch reflex activity during gait in children with CP. Hodapp and colleagues (Hodapp et al. 2007b) found impaired age-related tonic inhibition of the soleus H reflex in the stance phase in children with CP. In young children (5–11 yr) reflexes were similar to age-matched control children, but in older children (15–16 yr) with CP reflexes were significantly larger during stance, possibly reflecting their spasticity. In both young and older children with CP, reflexes were normally modulated during the gait cycle and thus depressed throughout swing phase including just prior to foot fall and foot contact. However, H reflexes are elicited by a brief synchronous electrical stimulus, which bypasses muscle spindles, and are therefore not equivalent to natural stretch reflexes (Burke et al. 1984; Enriquez-Denton et al. 2002; Morita et al. 1998). It has been reported that large electromyographic (EMG) potentials are evoked in the plantar flexor muscles soon after foot contact in children with CP, and these have been suggested to be caused by hyperexcitable stretch reflexes (Dietz and Berger 1983; Leonard et al. 1991). There is, however, no direct evidence that this is the case.

Crenna (1998) found abnormal EMG activity when muscles were lengthened during gait in children with CP and argued that this reflected increased stretch reflex activity. However, as the author also discussed, it is not possible to dissociate descending motor commands and sensory feedback mechanisms when measuring overall EMG activity. The increased EMG activity may simply reflect the necessity for a larger muscle activity to overcome increased muscle and joint stiffness in the children. Dietz and Berger (1983), indeed, found pronounced increased mechanical muscle stiffness during gait in children with CP. From experiments in adults there is also reason to question the functional significance of increased stretch reflex activity measures at rest in spastic patients (Dietz and Sinkjaer 2007; Ibrahim et al. 1993). A number of studies have demonstrated that hyperexcitable stretch reflexes in spastic patients are not manifest during voluntary movement including gait (Dietz and Sinkjaer 2007; Schindler-Ivens et al. 2008; Sinkjaer et al. 1996). Most recently, Marsden and colleagues (Marsden et al. 2012) argued that muscle paresis and...
passive stiffness, rather than spasticity, are the main determinants of impaired movement in the knee joint during gait in patients with spastic paraparesis.

There is consequently a need for an evaluation of reflex activity and the functional contribution of sensory feedback mechanisms during gait in children with CP. This was the purpose of the present study using the technique developed by Sinkjaer et al. (1996). They demonstrated that it is possible to elicit stretch reflexes in ankle muscles during gait in adults with a portable stretching device and that adults with spasticity have increased EMG stretch-mediated reflex activity in the stance phase of walking (Mazzaro et al. 2007; Sinkjaer et al. 1996). Eliciting stretch reflex activity by an external perturbation in this way does not provide evidence of the ongoing sensory feedback contribution to the EMG activity and thus the functional contribution of the stretch reflex circuitry to the muscle activity. However, Sinkjaer et al. (2000) demonstrated that a brief shortening of active plantar flexor muscles in the stance phase of walking may cause decreased activity in the length- and load-sensitive sensory afferents and a pronounced drop in EMG activity. This drop in EMG activity reflects the contribution of the sensory afferent feedback to the muscle activation and thus provides a measure of the ongoing functional contribution of activity in the stretch reflex circuitry. In the present study we therefore investigated responses to both lengthening and shortening of ankle plantar flexor muscles during gait in children with CP.

METHODS

Participants

The study was approved by the local ethics committee (H-B-2009-017), and all procedures were conducted within the standards of the Helsinki Declaration. Prior to experiments parents and children received written and verbal information, and consent for participation was obtained.

Twenty children with CP (Table 1; age 9.68 ± 2.29 yr, range 4–14 yr; 13 boys, 7 girls; weight 32.25 ± 9.44 kg; height 138.68 ± 11.76 cm) were recruited through the Danish cerebral palsy organization. The children had all been diagnosed as spastic through clinical examinations by a neurologist prior to recruitment. All children were classified according to the Gross Motor Function Classification System (GMFCS; Palisano et al. 1997). The neurological examinations were performed by a medical doctor with 20 years of experience in assessment of contractures and spasticity (J. B. Nielsen). Although all had been diagnosed as spastic prior to recruitment, four scored 0 on the Modified Ashworth Scale and in only five was a spastic catch noted. To objectively assess the passive and reflex-mediated stiffness components of the ankle plantar flexors, biomechanical and electrophysiological evaluation was performed according to Lorentzen et al. (2010) and Willerslev-Olsen et al. (2013). Briefly, children were seated in a reclining armchair with the examined foot attached to a footplate, which could be rotated by a motor (CEM model 26). The motor was driven by a DC power amplifier (Briel & Kjaer model 2708) and could deliver maintained torques up to 80 Nm and peak torques up to 120 Nm. An electrogoniometer, connected to the footplate, measured the angle of the ankle joint, and a torque meter measured the torque exerted on the footplate prior to and during the stretch perturbations. The hip joint was positioned in 100° flexion, the knee in 130° flexion, and the ankle joint in 100° flexion. The perturbations consisted of ramp and hold dorsiflexion with amplitude of 6° at 17 different velocities between 5 and 220°/s, with hold time of 460 ms. Perturbations were delivered every second in a random order until 10 trials per velocity were collected. Passive stiffness was calculated from the torque response at low velocities without stretch responses, whereas reflex stiffness was calculated from the torque response to the fastest perturbation (see Willerslev-Olsen et al. 2013). The more spastic ankle joint was subsequently selected for further testing (7 children with CP were tested on the right and 13 on the left side; 9 children without CP were tested on the right and 32 on the left side).

Experimental Setup

A portable stretch device capable of rotating the ankle joint during walking on a treadmill was used to elicit perturbations of the ankle joint. The system consisted of a mechanical joint mounted coaxially with the ankle joint. The mechanical joint was connected to a powerful actuator system by means of two flexible Bowden cables.

### Table 1. Average information about all children enrolled in the study

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>Sex (MF)</th>
<th>Age, yr, mo</th>
<th>Weight, kg</th>
<th>GMFCS</th>
<th>MAS</th>
<th>DF/PF</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP children</td>
<td>20</td>
<td>13:7</td>
<td>9.8 (2, 4)</td>
<td>32.25 (9.44)</td>
<td>GMFCS I:13</td>
<td>1.3 (0.8)</td>
<td>4.5/2.7</td>
</tr>
<tr>
<td>Control children</td>
<td>41</td>
<td>22:19</td>
<td>9.9 (2, 4)</td>
<td>35.73 (12.88)</td>
<td>GMFCS II:7</td>
<td>36.87 (22.64)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>M1 Area Stance, μV·ms</th>
<th>Unload Area Stance, μV·ms</th>
<th>M1 Area Swing, μV·ms</th>
<th>Unload Area Swing, μV·ms</th>
<th>Reflex Stiffness Rest, %Tmetry</th>
<th>Passive Stiffness Rest, %Tmetry</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP children</td>
<td>580 (646)</td>
<td>1,050 (1,130)</td>
<td>560 (554)</td>
<td>520 (13.2)</td>
<td>35.54 (32.66)</td>
<td>36.87 (22.64)</td>
</tr>
<tr>
<td>Control children</td>
<td>448 (505)</td>
<td>1,430 (1,680)</td>
<td>346 (409)</td>
<td>355 (288)</td>
<td>8.46 (7.80)</td>
<td>16.64 (4.71)</td>
</tr>
</tbody>
</table>

Values are averages (SD in parentheses). CP, cerebral palsy; GMFCS, Gross Motor Function Classification System; DF, dorsiflexors; PF, plantar flexors; MAS, Modified Ashworth Scale; Tmetry, maximal torque response measured by a supramaximal stimulation of n. tibialis at popliteal fossa. Muscle power in DF and PF was evaluated according to the UK Medical Research Council rating scale: 0, no contraction; 1, trace of contraction; 2, active movement through full range of motion with gravity eliminated; 3, active movement through range of motion against gravity; 4, active movement through range of motion against resistance (but weak); 5, normal.
perturbations of the ankle joint. Flexion directions were made during gait. A portable stretch device capable of velocity while perturbation in the dorsal flexion direction and the plantar from a single subject. Part of the stretch device was about the ankle joint, but with a slip of 3.5°. The slip was imposed to compensate for the elasticity of the Bowden wires and to give the motor controller a proper input to act upon. The weight of the portable part of the stretch device was ~1 kg (see Andersen and Sinkjaer 2003 for details). When a position feedback from the joint was used, the motor was regulated in such a way that it followed the movement of the ankle joint without influencing the pattern of gait. A detailed description of the technique and the device has been given by Andersen and Sinkjaer (2003).

Leg casts were made in polypropylene to give a form-fitting interface from the mechanical joint to the child’s ankle. Different sizes of leg casts were made in order to fit the age range and the variability of leg size. The mechanical joint was strapped to the child’s leg and around the shoe. Under the heel of the cast, a heel contact was placed. Pilot experiments demonstrated that children older than 5 yr were able to walk with the equipment without any measurable differences in leg muscle EMG activity and ankle joint movements. Younger children generally found the equipment too heavy and were quickly exhausted, resulting in major changes in gait pattern. Only children older than 5 yr were therefore included in this study.

All children were told to choose a gait velocity resembling their natural cadence. Control children walked at an average speed of 2.6 km/h with a range of 1.5–4 km/h, whereas children with CP walked at an average speed of 2.2 km/h with a range of 1–3 km/h. After an adaptation period of 5 min an averaged EMG profile, triggered from heel contact, was obtained from the soleus and tibialis anterior muscles.

Heel contact was determined from a pressure-sensitive resistance placed under the investigated foot of the child. Care was taken to position the resistance so that a trigger signal would be elicited with the very first contact of the foot with the ground. In children with severe foot drop or toe walking this usually required placement of the resistance just anterior to the heel. Stretch of the soleus muscle or tibialis anterior muscle was made late in stance and late in swing at various delays in relation to the trigger signal from the resistance. The time of perturbation was adjusted to the individual gait pattern. For perturbations in late stance the stretch was applied 50–100 ms prior to the maximal soleus EMG, whereas it was applied 50–100 ms prior to heel strike late in swing. These timings corresponded to 350–450 ms and 1,100–1,200 ms after the previous heel strike, depending on the gait velocity and individual gait pattern of the child. The amplitude of the perturbation was 8°, and the velocity was 280°/s with a hold time of 100 ms. Perturbations were randomly assigned with an interval of four to six steps and collected for each specific time until 20 trials were obtained. Steps with and without perturbation were collected in a randomized order to prevent the child from predicting in which step the perturbation would occur. After some familiarization, all children felt comfortable with the perturbations and walked relaxed on the treadmill without paying any special attention to the perturbation.

**Data Collection**

*Electromyographic recording.* EMG activity was recorded by bipolar electrodes (Ambu Blue sensor N,N-10-A/25, Ambu, Ballerup, Denmark; recording area 0.5 cm², interelectrode distance 2 cm) placed over the soleus muscle below the gastrocnemius muscles and from the tibialis anterior muscle. The skin was brushed softly with sandpaper (3M red dot; 3M, Glostrup, Denmark) and polar electrodes (Ambu Blue sensor N,N-10-A/25, Ambu, Ballerup, Denmark; recording area 0.5 cm², interelectrode distance 2 cm) placed under the knee. EMG signals were filtered (band pass, 25 Hz–1 kHz), amplified (2,000×), sampled at 2 kHz, and stored on a PC for off-line analysis.

*Off-line analysis.* Signal processing and analysis was carried out off-line. The EMG records were rectified and low-pass filtered at 40 Hz (first-order Butterworth). All trials were manually examined, and any trials where the ankle angle of the perturbation showed an overshoot or where the EMG response contained excessive noise were excluded from further analysis. The remaining trials were then ensemble-averaged to produce a single record for all situations. The averaged EMG recordings and ankle angles from control steps were superimposed on the averaged recordings with perturbations. The exact onset of perturbation was manually determined from the averaged ankle angles. Subsequently, the latency of the EMG responses to both stretch of the soleus muscle and stretch of the tibialis anterior muscle could be measured.

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Fig. 1. Experimental setup and example of perturbations and EMG responses from a single subject. A: experimental setup. Children walked at their preferred velocity while perturbation in the dorsal flexion direction and the plantar flexion direction were made during gait. A portable stretch device capable of rotating the ankle joint during walking on a treadmill was used to elicit perturbations of the ankle joint. B and C: averaged responses of a single subject to perturbations. B: position of the ankle joint in the stance phase. The red line is an average of 20 individual steps with an 8° dorsiflexion (stretch of the soleus muscle), the blue line shows an average of 20 individual steps with an 8° plantar flexion (unload of the soleus muscle), and the black line indicates the ankle angle when no perturbation was applied (an average of 20 individual steps). C: EMG response in the soleus muscle in late stance. The response late in the stance phase when a plantar flexion perturbation is applied (unload). The black soleus EMG response demonstrates EMG activity when no perturbation is applied. The vertical dotted line indicates the onset of perturbation.
To be qualified as a stretch reflex, EMG activity in a window 22–100 ms after onset of perturbation had to be >10 μV above the background EMG. The window of 22–100 ms was chosen since the onset latency of the short-latency reflex is ~40 ms in adults and the voluntary reaction time is ~100 ms. The area of the reflex was calculated from the onset of reflex to the end of the reflex or to 20 ms from onset if the reflex was wider. The EMG activity in the exact same area from the unperturbed steps was subtracted from the calculation. The stretch of tibialis anterior caused a reduction in the soleus EMG (Sinkjaer et al. 2000), an unload response. The requirement for an unload response was to match the EMG activity from the control steps until ~50 ms from perturbation onset, where a marked decrease in the soleus EMG was present (Fig. 1). The area of this unload response was measured from the onset to the end of the response or to 110 ms after perturbation if the response was longer lasting. This area was subtracted from the background EMG activity during the same time period in unperturbed steps. The presence of soleus EMG activity in the swing phase was determined from visual inspection of individual averaged traces, and a threshold value of 2 μV was set to distinguish actual EMG activity from noise.

To determine whether modulation of responses to ankle joint perturbation were related to activation of the ankle dorsiflexors in the swing phase, the tibialis anterior EMG activity in the children was quantified. This was done by measuring the peak tibialis anterior EMG activity within a window of 200 ms prior to heel strike in each individual child. Since the size of the EMG activity is influenced by electrode placement and local skin resistance, the peak EMG activity was expressed as a percentage of the peak amplitude of the first tibialis anterior EMG burst within the first 200 ms after onset of the swing phase.

Data Analysis

Sigma Plot statistical software version 11.0 was used for all statistical analysis. Pearson correlation was used for all correlations, whereas Student’s t-test was applied for all comparisons between children with CP and control children.

RESULTS

Stretch Responses Late in Stance

An example of soleus EMG activity and ankle joint movement during a gait cycle in one of the control children is shown in Fig. 1. When dorsiflexion perturbation was applied late in stance (550 ms after heel strike), a reflex response was observed with an onset latency of 30 ms and a peak at 41 ms (Fig. 1B). Subsequent peaks were observed at 66 ms and 92 ms. These peaks likely correspond to the M1, M2, and M3 reflex responses described in adult subjects (Sinkjaer et al. 1996; Toft et al. 1991). The M1 response was observed in 33 of the control children (80.5%) and in all of the children with CP (Fig. 2). The average latency of the response was 39.2 ms and 41.0 ms for the two populations, respectively. For the whole population of children no difference was found in the area of the response (Table 1, control children: 448 μV·ms, SD 505 μV·ms; CP: 580 μV·ms, SD 646 μV·ms, P = 0.14) (Fig. 2C). However, the area of the soleus background EMG in unperturbed steps was larger in the control children than in the children with CP (absolute values: control children: 3,140 μV·ms, SD 11,870 μV·ms; CP: 525 μV·ms, SD 561 μV·ms; P = 0.04). When taking this difference into account by expressing the size of M1 as a percentage of the background EMG activity, a significantly larger M1 was found in the children with CP (P = 0.02).

The area of the M1 response was negatively correlated to age in control children (absolute values P = 0.002) (Fig. 2C). No correlation was found in children with CP. The area of the background EMG was unrelated to age in both groups (control children, P = 0.17; CP, P = 0.8).

For children older than 8 yr a significantly larger reflex was observed in the children with CP (P = 0.003), despite a significantly smaller background EMG activity (P = 0.02). Younger children with CP had reflexes and background EMG activity comparable to age-matched control children (P = 0.25 and P = 0.33, respectively). Although all children with CP had been found to be spastic by clinical examination, only three of them were found to have increased reflex stiffness at rest (Table 1; see Willerslev-Olsen et al. 2013). These three children were not among the children who showed exaggerated reflexes during stance. There was no correlation between reflex stiffness at rest and the size of the M1 reflex during gait (P = 0.7).

The M2 and M3 responses were highly variable between subjects and often difficult to discern from the background EMG and/or the preceding M1 response. Further quantification of these responses was therefore not attempted.

Unload Responses Late in Stance

Plantar flexion perturbation at the same time in stance produced a significant drop in soleus EMG activity at an onset latency of 40 ms and a duration of 75 ms in the control child used for the illustration in Fig. 1. A similar unload effect was
observed in all control children and all but three children with CP. The average onset latency was similar in the two groups (control: 62.1 ms, CP: 56.9 ms; \( P = 0.2 \)). The size of the unload effect was unrelated to age (Fig. 3), with no statistically significant differences between the two groups in the area (\( P = 0.2 \)). This was also the case when the size was expressed as a percentage of background EMG activity. The size of the unload effect increased with the size of background EMG activity in control children (\( P = 0.01 \)) but not in children with CP (\( P = 0.38 \)).

**Stretch Responses Late in Swing**

In control children no or only very small soleus reflex responses were evoked late in swing by ankle dorsiflexion perturbation. In contrast, large responses were evoked in 14 of the children with CP. When the two populations were compared, significantly larger responses were found in the children with CP (Fig. 4A; Table 1, control children: 346 \( \mu \)V·ms, SD 409 \( \mu \)V·ms; CP: 560 \( \mu \)V·ms, SD 554 \( \mu \)V·ms; \( P = 0.017 \)). When stance and swing were compared, a suppression of the responses in swing was observed in the control children, whereas the reflex responses were of similar size in swing and stance in the children with CP (control children: \( P = 0.04 \), CP: \( P = 0.55 \)). Lack of suppression of M1 was unrelated to the presence of soleus EMG activity, which was observed in a roughly similar proportion of control children and children with CP (24 control children (59%) and 15 children with CP (75%)). There were also no quantitative differences in the size of the background soleus EMG in the two populations (control children: 227 \( \mu \)V·ms, SD 266 \( \mu \)V·ms; CP: 248 \( \mu \)V·ms, SD 218 \( \mu \)V·ms; \( P = 0.77 \)). This was also the case when the EMG activity was normalized by expressing it as a percentage of the EMG activity in the stance phase (\( P = 0.99 \)). The presence and size of the M1 response were also unrelated to age and gait velocity (all \( P > 0.15 \)). However, the children with CP who showed a M1 response in swing also showed significantly smaller tibialis anterior EMG activity (normalized to the first tibialis anterior EMG burst) at the time of the stretch of the plantar flexors (\( P = 0.002 \), suggesting that inability to activate the ankle dorsiflexors was responsible for the lack of suppression of M1.

**Unload Responses Late in Swing**

For the 24 control children and 15 children with CP in whom soleus EMG activity was observed late in swing, ankle plantar flexion perturbation evoked a drop in EMG activity in 6 of the control children (25%) and in 3 of the children with CP (20%) (Fig. 4B). The unload effect was of similar size in the two populations (\( P = 0.19 \)).

**Correlation with Clinical Measures**

There was no correlation between the size of the stretch reflex in stance or swing and ankle plantar flexor force, dorsiflexion perturbation evoked a drop in EMG activity in 6 of the control children (25%) and in 3 of the children with CP (20%) (Fig. 4B). The unload effect was of similar size in the two populations (\( P = 0.19 \)).

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Fig. 3. Unload response during stance phase. A and B: relationship between the onset latency of the unload response and age (A) and height (B). C: relationship between age and the area of the unload response. ●, Control children; ○, children with CP. Solid black line indicates linear regression for control children; dashed line is linear regression line for children with CP.

Fig. 4. M1 reflex response and unload response during swing phase: relationship between age and M1 reflex area (A) and unload area (B). ●, Control children; ○, children with CP. Solid black line indicates linear regression for control children; dashed line is linear regression line for children with CP.
flexor force, or MAS score. There was also no correlation between MAS and the size of EMG suppression following plantar flexion perturbation in stance or swing. Low dorsiflexion force was correlated to large reflex (P < 0.0001), passive stiffness (P < 0.001), and low tibialis anterior EMG activity late in swing (P = 0.03).

DISCUSSION

The present study has shown that soleus stretch reflexes in the stance phase of gait decline with age in control children and are effectively suppressed in the swing phase, whereas this is not the case in children with CP. Despite relative exaggeration of reflexes in these two phases of gait, unloading of the active plantar flexors produced a similar or in some cases a smaller drop in soleus EMG activity in the children with CP. This indicates that sensory feedback mechanisms if anything contribute less to the soleus EMG activity in children with CP than in control children. On the basis of these finding we argue that exaggeration of reflex activity is unlikely to contribute to the foot drop and toe walking in children with CP.

Methodological Considerations

All measurements in this study are based on absolute EMG values, which are difficult to compare between subjects. We refrained from normalizing the measurements to maximal M (M_max) responses, as is customary in H reflex experiments, for two reasons: 1) Proper normalization would require elicitation of M_max at the investigated time of the gait cycle, and this was not acceptable for the children. 2) M_max is several magnitudes larger than the small reflexes and unload responses measured in the present study, and small changes in M_max would therefore have a disproportionately large influence on the results.

We instead chose to relate all reflex and unload measurements to the background EMG activity measured at the time of perturbation in control steps, similar to what has been done in previous studies (Hodapp et al. 2007a; Sinkjaer et al. 1996).

Control children walked at a slightly higher speed than children with CP, and it may be speculated that this could explain some of the differences in the stretch and unload responses between the two populations. However, the times of perturbations were adjusted individually in the children according to their gait velocity and gait pattern in order to ensure that responses were measured at the same time relative to maximal soleus EMG in the stance phase and the end of swing phase.

What Are the Mechanisms of Stretch and Unload Responses?

To our knowledge this is the first study to investigate stretch reflex activity during gait in children. The observed pattern of EMG responses to both stretch and shortening of the ankle plantar flexors in the gait cycle closely resembles the responses observed in adults (Sinkjaer et al. 1996; Toft et al. 1991). The initial response to stretch was seen at a peak latency of 39.2 ms, which compares to the 57–62 ms observed by Toft et al. (1991) and the 54 ms observed by Sinkjaer et al. (1996) for the M1 response. With an average height of 143.3 cm in the children and an average height of 180 cm in adult Danish men, this latency difference is accounted for by the shorter conduction path in the children. As in adults, the initial stretch response is thus in all likelihood mediated by the Ia monosynaptic stretch reflex pathway (Sinkjaer et al. 1996; Toft et al. 1991). We did observe subsequent reflex responses that may be equivalent to M2 and M3 responses described in adults, but since these responses were greatly variable and were not observed in all children, we did not attempt a more detailed analysis.

The stretch reflex is a measure of how easily spinal motoneurons may be excited by an externally evoked volley of activity in Ia afferents. However, this does not necessarily also reflect the contribution of afferent activity to the ongoing muscle activity. Sinkjaer et al. (2000) demonstrated that a sudden plantar flexion perturbation in the stance phase of gait may cause a transient decline in length- and load-sensitive afferent activity from the active plantar flexor muscles. This decline in afferent activity was shown to produce a drop in the soleus EMG activity, which may be taken as a measure of the contribution of afferent activity to the ongoing muscle activity. In the present study plantar flexion perturbation caused a drop in the soleus EMG activity late in stance similar to what has been observed in adults. The latency of this unload effect was 62 ms in control children and 56 ms in children with CP, which compares to the average latency of 64 ms observed in adults (Sinkjaer et al. 2000). It should be noted that the longer latency of the unload effect than the M1 reflex likely reflects that monosynaptic Ia afferent activity does not contribute significantly to the soleus muscle activity in the stance phase during gait. This is also the case in the children with CP, despite the fact that they had all been found to be spastic clinically. In the study by Sinkjaer et al. (2000) evidence that the unload response is not mediated by Ia afferents was provided by the observation that ischemic block of transmission in Ia afferents did not affect the size of the unload effect. It has still not been fully clarified which afferent fibers and central mechanisms are responsible for the unload effect, but af Klint et al. (2010) have provided strong evidence that load-sensitive group I afferents from Golgi tendon organs are involved. However, it cannot be fully excluded that transmission in group II afferent pathways from muscle spindles also contributes. In any case, our data suggest that children already at a young age integrate this afferent feedback into the central motor command during gait and, similar to adults, do not appear to utilize the direct monosynaptic Ia pathway in the activation of plantar flexor muscles during gait. This also appears to apply for children with CP.

Age-Related Decline in M1 Response Late in Stance in Control Children but Not in Children with CP

The M1 response was found to be larger in younger control children (4–8 yr) compared with older children, which may indicate a more excitable monosynaptic reflex loop early during development. This was similarly observed by Hodapp et al. (2007a) for the soleus H reflex. Hodapp et al. (2007a) observed that the soleus H reflex when measured at rest was unrelated to age, and Willerslev-Olsen et al. (2013) observed that reflex stiffness in children at rest was also unrelated to age. This suggests that the age-related decline of the stretch reflex observed in the present study is specific for gait and in all likelihood is related to maturation of the central control of gait. It has indeed recently been demonstrated that maturation of the corticospinal control of gait occurs in this age group (Petersen et al. 2010). In contrast to control children, there was no

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correlation between age and stretch reflex size in the children with CP. Hodapp et al. (2007b) similarly observed that the soleus H reflex evoked in stance during gait did not show an age-related reduction as in control children. As they suggested, this may reflect a lack of maturation of the corticospinal tract in the children with CP. Evidence to support this has also recently been provided by Petersen et al. (2013).

**SmallerUnloadResponseinChildrenwithCPLateinStance**

The size of the unload response late in stance if anything was smaller in the children with CP than in the control children, suggesting that sensory feedback from the active muscles is not exaggerated as could have been expected from the stretch reflex findings. Notably, children with weak ankle plantar flexors and dorsiflexor force had significantly smaller unload effects. This may be explained by impaired descending control of the spinal neurons that mediate the sensory feedback to the spinal motoneurons in the children with CP or, alternatively, by less pronounced activation of sensory receptors in muscles and tendons. Sensory afferents and descending motor fibers converge on common spinal neurons, and reduced descending drive in the children with CP is therefore likely to also affect the contribution from sensory feedback mechanisms to the muscle activity. Changes in the intrinsic membrane properties of the spinal motoneurons such as persistent inward current (Bennett et al. 2001; Eken et al. 1989) could potentially also alter the response of the neurons to the sudden decline in afferent sensory input. Finally, it is also a possibility that the unloading had less effect on muscle spindles and other sensory receptors in the children with CP because of changes in mechanical properties of their muscles.

**LackofSuppressionofM1inLateSwinginChildrenwithCP**

Control children and children with CP showed soleus EMG activity prior to heel strike to the same extent. There was thus no evidence that children with drop foot and/or toe walking showed excessive soleus EMG activity prior to heel strike. Abnormal soleus activation is therefore unlikely to play a significant role in toe walking, at least in this population of children. Although it is commonly assumed that premature activation of plantar flexor muscles contributes to foot drop and toe walking in children with CP (Aiona and Sussman 2004), we have found little actual evidence of this in the literature (Winters et al. 1987).

Several of the children with CP were unable to suppress the M1 stretch reflex in the swing phase prior to heel strike. Spastic multiple sclerosis patients also show less reduction of H reflexes and stretch reflexes in the swing phase during walking (Sinkjaer et al. 1996), but Hodapp et al. (2007b) found a normal modulation of H reflexes during the gait cycle in children with CP. The difference from our study may be related to the fact that we specifically focused on children with foot drop and toe walking, which was not the case in the study by Hodapp et al. (2007b). Furthermore, several studies have demonstrated differences in the central processing of H reflexes and stretch reflexes (Burke et al. 1983; Morita et al. 1998). One or more of these differences may explain the discrepancy between our findings and the findings by Hodapp et al. (2007b). We found that the lack of suppression of M1 in the swing phase was related to reduced dorsiflexion force and foot drop as measured from a reduction in tibialis anterior EMG activity. This suggests that the reduced suppression of M1 in swing in the children with CP is related to their reduced central drive to the ankle dorsiflexors rather than to inadvertent co-activation of plantar flexors in the swing phase. In all likelihood, impaired corticospinal drive to inhibitory interneurons mediating reciprocal inhibition of soleus motoneurons (Petersen et al. 1999) or presynaptic inhibition of soleus Ia afferents (Faist et al. 1996) is involved.

**SmallerUnloadResponseLateinSwinginChildrenwithCP**

It could be suggested that the large reflexes in late swing in the children with CP might contribute to their inability to adequately dorsiflex the foot and place the heel on the ground in early stance. Indeed, this is often the reason for injection of botulinum toxin in the plantar flexor muscles of these children (Criswell et al. 2006). However, as mentioned above, the children with CP did not show more soleus EMG activity in the swing phase than the control children and unload of the ankle plantar flexors did not produce any significant suppression of soleus EMG activity in the swing phase in the vast majority of the children. Sensory feedback, therefore, if anything contributed less to the soleus EMG in the swing phase in the children with CP than in control children. This was especially the case in children with reduced EMG activity in the tibialis anterior muscle late in swing. This points to reduced corticospinal drive to the ankle dorsiflexors as the main functional problem for these children. As already mentioned in relation to the findings during stance, sensory feedback from the active muscles converge on the same central neurons as the descending motor pathways and reduction in corticospinal drive in the children with CP (and especially in the children with the least tibialis anterior EMG activity) therefore also results in a reduction of the sensory-mediated contribution to the ongoing EMG.

**ClinicalImplications**

One main reason for performing this study was that treatment of children with CP is based to a large extent on the assumption that spasticity is a major functional impediment for the gait ability of the children. It is therefore assumed that reduction of exaggerated reflex activity in ankle plantar flexors is necessary in order to prevent the plantar flexors from working against the dorsiflexors late in swing (Criswell et al. 2006). Reduction of stretch reflex activity in the plantar flexors is thus assumed to help the child in lifting the foot late in swing and bringing the heel to the ground in early stance. Our data do not support these assumptions. First, we have not found any sign of abnormally increased EMG activity in the plantar flexors prior to heel strike in the children with CP, and, second, sensory feedback if anything contributes less to the plantar flexor muscle activity in children with drop foot and toe walking. The lack of correlation between any of our findings and clinical scores of spasticity further emphasizes that it is...
difficult to make assumptions regarding the functional consequences of increased muscle tone measured clinically in a child at rest.

We consequently propose that the main causes of foot drop and toe walking in children with CP should be attributed to reduced central drive to ankle dorsiflexors and/or altered passive muscle stiffness (including contractures). In cases where premature plantar flexor activity is observed, it is in all likelihood caused by a central adaptation of spinal and/or supraspinal networks secondary to the inability to appropriately lift the toes in late swing and secure an adequate heel strike in early stance. Toe walking may in these cases be seen an adopted strategy by the children in order to maintain functional gait despite insufficient dorsiflexion strength. In addition, changes in other mechanisms such as persistent inward currents in triceps surae motoneurons (Bennett et al. 2001; Eken et al. 1989) may also contribute to premature plantar flexor activity.

Conclusions

These data demonstrate that children with CP do not show the normal age-related decline in stretch reflexes in the stance phase and are unable to suppress the reflex in the swing phase during gait. The findings are likely related to lack of maturation of descending corticospinal control. Despite the exaggerated reflexes, children with CP did not show soleus EMG activity to a larger extent than control children late in swing and sensory afferent feedback did not contribute more to their soleus EMG activity. Spasticity in ankle plantar flexors is therefore unlikely to contribute to foot drop and toe walking in these children. We propose that reduced central drive to ankle dorsiflexors and/or increased passive muscle stiffness are the main causes of foot drop and toe walking in children with CP.

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DISCLOSURES

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AUTHOR CONTRIBUTIONS


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