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

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Abstract
It is still widely believed that exaggerated stretch reflex activity and the resulting 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. Here we investigated the contribution of sensory feedback mechanisms to ankle plantar flexor muscle activity during treadmill walking in 20 children with cerebral palsy (9.68 +/- 2.3 years; 7 females) and 41 control children (9.77 +/- 2.5 years, 19 females).

Stretch responses in plantar flexor muscles evoked late in stance by dorsiflexion perturbations (8 deg, 300deg/sec) showed an age-related decline in control children but not in children with CP. In late swing the responses were abolished in the control children, but significant responses were observed in 14 of the children with CP. This was related to reduced activation of the Tibialis anterior muscle in late swing (i.e. foot drop). Removal of sensory feedback to the active soleus muscle late in stance by shortening the plantar flexors produced a drop in soleus EMG activity of a similar size and latency in control children and children with CP. Soleus EMG activity was observed in late swing in a similar proportion of control children and children with CP. Shortening of the plantar flexors late in swing caused a larger drop in the Soleus EMG in the control children than in the children with CP.

The lack of the normal age related decline in stretch reflexes in the stance phase and the inability to suppress the reflex in the swing phase is likely related to lack of maturation of descending corticospinal control in children with CP. However, since they did not show soleus EMG activity to a larger extent than control children late in swing and since sensory afferent feedback did not contribute more to their soleus EMG activity, spasticity in ankle plantar flexors 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 (including contractures) are the main causes of foot droop and toe walking.

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The majority of children with cerebral palsy (CP) have gait problems, which impact their quality of life (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 their peers (Hullin et al 1996, Parkes et al 2010). In some cases pareses or paralysis of ankle dorsi flexors are responsible, whereas contractures and reduced range of movement are involved in other cases. In addition it is generally believed that hyper excitable stretch reflexes (spasticity according to the definition by Lance 1980) in ankle plantar flexors play a major role in creating premature over-activity 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 hyper activity 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 & Sinkjaer 2007, Sinkjaer & Magnussen 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 years) reflexes were similar to age matched controls, but in older children (15-16 years) with CP reflexes were significantly larger during stance possible reflecting their spasticity. In both young and old 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 by passes 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 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 & Berger 1983, Leonard et al 1991). There is, however, no direct evidence that this is the case. Crenna (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 of a larger muscle activity to overcome increased muscle and joint stiffness in the children. Dietz and Berger (Dietz & 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 & Sinkjaer 2007, Ibrahim et al
A number of studies have demonstrated that hyperexcitable stretch reflexes in spastic patients are not manifest during voluntary movement including gait (Dietz & 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 that 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 (Sinkjaer et al 1996). They demonstrated that it is possible to elicit stretch reflexes in ankle muscles during gait in adults using 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 (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 the EMG activity. This drop in the 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. 20 children with cerebral palsy (CP)(Table 1; age 9.68 ±2.29 years, range 4-14; 13 boys, 7 girls; weight 32.25±9.44kg; height 138.68±11.76cm) were recruited through the Danish cerebral palsy organisation. The children had all been diagnosed as spastic through clinical examination by a neurologist prior to recruitment. All children were hemiplegic (7 children: right hemiplegia and 13 subjects: left hemiplegia), had foot drop and were toe walkers to varying extent as their major gait impairment. The children had no or only minor reduction in passive and active ROM in the order of 5-10 degrees. They were all able to stand flat on their foot. In all children the brain injury happened during pregnancy or during birth. Children were excluded if there was any evidence of dystonia or if surgery or any orthopaedic operation had taken place.
less than six month prior to testing. As a control group 41 age matched children without CP were recruited (Table 1; age 9.80±2.26 years, range 4-14; 22 boys, 19 girls; weight 35.73±12.88kg; height 143.29±13.59cm).

All children were classified according to the Gross Motor 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 (JBN, co-author). Although all had been diagnosed as spastic prior to recruitment four scored zero on the Modified Ashworth scale and in only five a spastic catch was noticed. In order to objectively assess the passive and reflex mediated stiffness components of the ankle plantar flexors biomechanical and electrophysiological evaluation was performed according to Lorentzen (Lorentzen et al 2010) and Willerslev-Olsen (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 (Brüel & Kjaer; model 2708) and could deliver maintained torques up to 80 Nm and peak torques up to 120 Nm. An electro-goniometer, connected to the foot plate, measured the angle of the ankle joint and a torque meter measured the torque exerted on the foot plate prior to and during the stretch perturbations. The hip joint was positioned in 100º flexion, the knee in 130º flexion and the ankle joint in 100º flexion. The perturbations consisted of ramp and hold dorsiflexion with amplitude of 6º at 17 different velocities between 5 and 220º/s; hold time 460ms. Perturbations were delivered every second in a random order until ten 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 were tested on the right and 13 children on the left side. 9 children without cerebral palsy were tested on the right side and 32 children were tested on the left side).

Experimental set up

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 (fig.1). The joint comprised two coaxial actuators that were aligned on a fixed axle with six independent slide bearings. The first joint was attached to the foot and the calf and acted about the ankle joint. The second joint was connected to the Bowden mechanism and also acted about the ankle joint, but with a slip of ±3.5 deg. 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 approximately 1 Kg. (details in (Andersen & Sinkjaer 2003)). 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 in

Leg casts were made in polypropylene to give a formfitting 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 five years 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 five years 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 2.6km/h with a range of 1.5-4km/h, whereas children with CP walked at an average
speed of 2.2km/h with a range of 1-3km/h. After an adaptation period of 5min 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 50-100ms prior to the maximal soleus EMG, whereas it was applied 50-
100ms prior to heel strike late in swing. These timings corresponded to 350-450 ms and 1100-1200ms after
the previous heel strike, depending on the gait velocity and individual gait pattern of the child. The
amplitude of the perturbation was 8º and the velocity was 280º/s with a hold time of 100ms. Perturbations
were randomly assigned with an interval of 4-6 steps and collected for each specific time until 20 trials
were obtained. Steps with and without perturbation were collected in a randomised order to prevent the
child from predicting in which step the perturbation would occur. Following some familiarisation all
children felt comfortable with the perturbations and walked relaxed on the treadmill without paying any
special attention to the perturbation.
**Data Collection**

*Electromyographic (EMG) recording*

EMG activity was recorded by bipolar electrodes (Ambu Blue sensor N,N-10-A/25. Ambu A/S Ballerup, Recording area 0.5 cm² inter-electrode distance, 2 cm) placed over the soleus muscle below the gastrocnemii muscles and from the Tibialis Anterior muscle. The skin was brushed softly with sandpaper (3M red dot; 3M, Glostrup, Denmark). A ground electrode was placed under the knee. EMG signals were filtered (band-pass, 25 Hz–1 kHz), amplified (2000x), 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.

To be qualified as a stretch reflex, EMG activity in a window 22-100ms after onset of perturbation had to be more than 10µV above the background EMG. The window 22-100ms was chosen since the onset latency of the short-latency reflex is around 40 ms in adults and the voluntary reaction time is around 100ms. The area of the reflex was calculated from the onset of reflex to the end of the reflex or to 20ms 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 requirements for an unload response was to match the EMG activity from the control steps until around 50ms 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 110ms post perturbation if the response was longer lasting. This area was subtracted from the background EMG activity during the same time period in unperturbed steps. Presence of soleus EMG activity in the swing phase was determined from visual inspection of individual averaged traces and a threshold value of 2µV was set to distinguish actual EMG activity from noise.

In order to determine if modulation of responses to ankle joint perturbation were related to activation of the ankle dorsi flexors in the swing phase, the TA EMG activity in the children was quantified. This was done
by measuring the peak TA EMG activity within a window of 200ms 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 TA EMG burst within the first 200ms 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 figure 1. When dorsi flexion perturbation was applied late in stance (550ms after heel strike) a reflex response was observed with an onset latency of 30ms and a peak at 41ms (Fig. 1B). Subsequent peaks were observed at 66ms and 92ms. 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. The average latency of the response was 39.2ms and 41.0ms for the two populations respectively (table.1). For the whole population of children no difference was found in the area of the response (control children; 448µVms stdv: 505µVms, CP; 580µVms stdv: 646µVms, P=0.14). 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; 3140µVms, stdv. 11870µVms, CP; 525µVms, stdv. 561µVms 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). 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 and CP; P=0.8).

For children older than 8 years 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 aged matched control children (P=0.25, 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. and 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 at significant drop in soleus EMG activity
at an onset latency of 40ms and a duration of 75ms 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 children: 62.1ms, CP: 56.9ms, 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 expressed as a percentage of background EMG
activity. The size of the unload effect increased with the size of background EMG activity 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 dorsi
flexion perturbation. In contrast large responses were evoked in 14 of the children with CP. When
comparing the two populations significantly larger responses were found in the children with CP (Fig.4A.
control children: 346µVms, stdv.409µVms, and CP: 560 μVms, stdv.554 µVms, P=0.017). Comparing stance
and swing 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; 227μVms, stdv.266μVms, CP; 248μVms,
stdv.218μVms, 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 was
also unrelated to age and gait velocity (all P values above 0.15). However, the children with CP who showed
an M1 response in swing also showed significantly smaller TA EMG activity (normalised to the first TA EMG
burst) at the time of the stretch of the plantar flexors (P=0.002) suggesting that inability to activate the
ankle dorsi flexors 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, dorsi 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 dorsi flexion force was correlated to large reflex (P<0.0001), passive stiffness (P<0.001) and low TA 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. Based on these finding we argue that exaggeration of reflex activity is unlikely to contribute to the foot drop and toe walking in the 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 normalising the measurements to maximal M responses as is customary in H-reflex experiments for two reasons; 1) proper normalisation would require elicitation of Mmax at the investigated time of the gait cycle and this was not acceptable for the children. 2) Mmax is several magnitudes larger than the small reflexes and unload responses measured in the present study and small changes in Mmax 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 time 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 max 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 39.2ms, which compares to the 57-62ms observed by Toft (Toft et al 1991) and the 54ms observed by Sinkjaer (Sinkjaer et al 1996) for the M1 response. With an average height of 143.3cm in the children and an average height of 180cm 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 which 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 motor neurons 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 (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 62ms in control children and 56ms 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 (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 (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 afferents pathways from muscle spindles also contribute. 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 years) as compared to older children, which may indicate a more excitable monosynaptic reflex loop early during development. This was similarly observed by Hodapp (Hodapp et al 2007a) for the soleus H-reflex. Hodapp (Hodapp et al 2007a) observed that the soleus H-reflex when measured at rest was unrelated to age and Willerslev-Olsen (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 correlation between age and stretch reflex size in the children with CP. Hodapp (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 suggested by them, 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 (Petersen et al 2013).

**Smaller unload response in children with CP late in stance**

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 neurones that mediate the sensory feedback to the spinal motoneurones in the children with CP, or alternatively by less pronounced activation of sensory receptors in muscles and tendons. Sensory afferents and descending motor fibres converge on common spinal neurones 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 motor neurons 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. It is finally also a possibility that the unloading
had less effect on muscle spindles and other sensory receptors in the children with CP due to changes in
mechanical properties of their muscles.

Lack of suppression of M1 in late swing in children with CP

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 & 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 MS patients also show less reduction of H-reflexes and stretch reflexes in the swing
phase during walking (Sinkjaer et al 1996), but Hodapp (Hodapp et al 2007b) found a normal modulation of
H-reflexes during the gait cycle in children with CP. The difference to 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 (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 (Hodapp et al
2007b). We found that the lack of suppression of M1 in the swing phase was related to reduced dorsi
flexion force and foot drop as measured from a reduction in Tibialis anterior EMG activity late in swing. In
contrast, no correlation was found with the presence or size of background soleus 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 motoneurones (Petersen et al 1999) or presynaptic inhibition of soleus Ia afferents is
involved (Faist et al 1996).

Smaller unload response late in swing in children with CP

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 already mentioned 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 dorsi
flexors 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 neurones as the
descending motor pathways and reduction in corticospinal drive to 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.

Clinical implications
One main reason for performing this study was that treatment of children with CP to a large extent is based
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 dorsi flexors 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. Firstly, 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 secondly 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 cerebral palsy
should be attributed to reduced central drive to ankle dorsiflexors and/or altered passive muscle stiffness
(including contractures). In cases where premature plantarflexor 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 as 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 motoneurones (Bennett et al 2001, Eken et al 1989) may also contribute to premature plantar flexor activity.

**Conclusion**

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.
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. The figure illustrates the 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 8º dorsiflexion (stretch of the soleus muscle), the blue line shows an average of 20 individual steps with an 8º 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 dorsiflexion perturbation is applied is red. The blue colour exemplifies 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.

Fig. 2. M1 Reflex response during stance phase. (A) Illustrate the relationship between age and the M1 peak latency during stance, while (B) shows the relation between height and the M1 peak latency. (C) Illustrate the relationship between age and the M1 reflex area during stance. Filled black dots illustrate the control children and the open white circles illustrate the children with cerebral palsy. Solid black line indicates linear regression for control children, while the dotted line is the linear regression line for children with CP.

Fig. 3. Unload response during stance phase. The graphs illustrate the relation between the onset latency of the unload response and age (A) and height (B). The graph in (C) shows the relationship between age and the area of the unload response. Filled black dots illustrate the control children and the open white circles illustrate the children with cerebral palsy. Solid black line indicates linear regression for control children, while the dotted line is the linear regression line for children with CP.

Fig. 4. M1-reflex response and Unload response during swing phase. The figure illustrate the relation between age and the M1 reflex area (A) and the unload area (B). Filled black dots illustrate the control children and the open white circles illustrate the children with cerebral palsy. Solid black line indicates linear regression for control children, while the dotted line is the linear regression line for children with CP.


Lorentzen J, Grey MJ, Crone C, Mazevet D, Biering-Sorensen F, Nielsen JB. 2010. Distinguishing active from passive components of ankle plantar flexor stiffness in stroke, spinal cord injury and


Willerslev-Olsen M, Lorentzen J, Sinkjaer T, Nielsen JB. 2013. Passive muscle properties are altered in children with cerebral palsy before the age of 3 years and are difficult to distinguish clinically from spasticity. Developmental medicine and child neurology

Table I: Average information about all children enrolled in the study

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>Gender (M:F)</th>
<th>Age (y,mo)</th>
<th>Weight (kg)</th>
<th>GMFCS</th>
<th>MAS</th>
<th>DF/PF</th>
<th>M1 area Stance (microV·ms)</th>
<th>Unload area Stance (microV·ms)</th>
<th>M1 area Swing (microV·ms)</th>
<th>Unload area Swing (microV·ms)</th>
<th>Reflex stiffness Rest (%Tmax)</th>
<th>Passive Stiffness Rest (%Tmax)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cp-Children</td>
<td>20</td>
<td>13:7</td>
<td>9,8</td>
<td>32,25</td>
<td>GMFCS I:13</td>
<td>1,3</td>
<td>4,5/2,7</td>
<td>580 (SD:646)</td>
<td>1050 (SD:1130)</td>
<td>560 (SD:554)</td>
<td>52,0 (SD:13,2)</td>
<td>35,54 (SD:32,66)</td>
<td>36,87 (SD:22,64)</td>
</tr>
<tr>
<td>Control-Children</td>
<td>41</td>
<td>22:19</td>
<td>9,9</td>
<td>35.73</td>
<td>GMFCS II:7</td>
<td>-</td>
<td>-</td>
<td>448 (SD:505)</td>
<td>1430 (SD:1680)</td>
<td>346 (SD:409)</td>
<td>355 (SD:288)</td>
<td>8,46 (SD:7,80)</td>
<td>16,64 (SD:4,71)</td>
</tr>
</tbody>
</table>

CP, cerebral palsy; GMFCS, Gross Motor Function Classification System; DF, dorsiflexors; PF, plantar flexors; MAS, Modified Ashworth Scale; NI, not investigated. Muscle power in dorsiflexors and plantar flexors 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. Tmax, maximal torque response measured by a supramaximal stimulation of the n. Tibialis at popliteal fossa.