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Contractile behavior of the medial gastrocnemius in children with bilateral spastic cerebral palsy during forward, uphill and backward-downhill gait

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ABSTRACT

Background: Plantarflexor tightness due to muscle degenerations has been frequently documented in children with spastic cerebral palsy but the contractile behavior of muscles during ambulation is largely unclear. Especially the adaptability of gastrocnemius muscle contraction on sloped surface could be relevant during therapy.

Methods: Medial gastrocnemius contractions were measured during flat-forward, uphill (+12% incline) and backward-downhill (−12% decline) treadmill gait in 15 children with bilateral cerebral palsy, walking in crouch, and 17 typically developing controls (age: 7–16 years) by means of ultrasound and motion analysis. Tracked fascicle and calculated series elastic element length during gait were normalized on seated rest length. Additionally electromyography of the medial gastrocnemius, soleus and tibialis anterior was collected.

Findings: During forward gait spastic gastrocnemii reached 10% shorter relative fascicle length, 5% shorter series elastic element length and showed 37% less concentric fascicle excursion than controls. No difference in eccentric fascicle excursion existed. Uphill gait increased concentric fascicle excursion in children with cerebral palsy and controls (by 23% and 41%) and tibialis anterior activity during swing (by 33% and 48%). Backward downhill gait more than doubled (+112%) eccentric fascicle excursion in cerebral palsy patients.

Interpretation: Apart from having innately shorter fascicles at rest, flat-forward walking showed that spastic gastrocnemius fascicles work at shorter relative length than those of controls. Uphill gait may be useful to concentrically train push-off skills and foot lift. During backward-downhill gait the gastrocnemius functions as a brake and displays more eccentric excursion which could potentially stimulate sarcomere-genesis in series with repeated training.

1. Introduction

Weak (Barber et al., 2012; Dallmeijer et al., 2011) and less extensible plantarflexors (Barber et al., 2011) are major constraints in spastic cerebral palsy (SCP). Both can have neural origins since impaired voluntary drive reduces active strength (Stackhouse et al., 2005) and involuntary, velocity or posture dependent muscle activity increases passive stretch resistance (Bar-On et al., 2014). Apart from that, structural degenerations could have a negative impact because the triceps-surae shows large volumetric loss and increased intramuscular connective tissue (Noble et al., 2014; Pitcher et al., 2015). While gastrocnemius fascicles (bundles of fibers) seem to be shorter in SCP-patients than in typically developing (TD) (Hösl et al., 2015; Matthiasdottir et al., 2014; Barber et al., 2011), biopsies revealed longer sarcomeres (Mathewson et al., 2014). The shorter fascicles hence contain less sarcomeres in series and this may contribute to reduced passive fascicle extensibility (Hösl et al., 2015; Barber et al., 2011) and a smaller range for active force exertion (Barber et al., 2012).

The relationship between muscle structure and ambulatory dysfunction in SCP are still largely unknown. Typically plantarflexor weakness is associated with less propulsion during gait (Dallmeijer et al., 2011). Concerning fascicles, less sarcomeres in series could compromise shortening excursion and velocity (Butterfield, 2010) and active force exertion may be shifted towards plantarflexion. As a consequence, short gastrocnemii may force to walk in equinus. However, the bi-articular gastrocnemii can also promote crouch gait (Maas et al., 2015). Besides it had been speculated that the spastic gastrocnemius was unable to resist tensile forces and experiences increased eccentric

Abbreviations: SCP, spastic cerebral palsy; TD, typically developing; SEE, series elastic element.

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loadings (Fry et al., 2006). These loadings were vaguely supposed to harm fiber growth (Gough and Shortland, 2012) or promote fibrosis (Pitcher et al., 2015).

Insights might be gained by monitoring gastrocnemius contractions during gait. So far, such approaches are based on simulations (Steele et al., 2013; Neptune et al., 2007) or on TD mimicking spastic gait (Fry et al., 2006). In toe-walking, the gastrocnemius seems to work isometrically to concentrically and operates on short-length (Fry et al., 2006; Neptune et al., 2007). Brightness-mode ultrasonography has been used as an acceptable methodology to directly assess the contractile behavior of the muscle–tendon unit (Aggeloussis et al., 2010), for example in adults (Ishikawa and Komi, 2008; Cronin and Finni, 2013), in children (Fry et al., 2006) or in elderly (Mian et al., 2007). It has been found that gastrocnemius' fascicles and muscle–tendon unit do not necessarily lengthen or shorten simultaneously (Ishikawa and Komi, 2008). Consequently, inference about fascicle action from muscle–tendon unit length calculations appears inconclusive. Fascicle contraction changes in elderly (Mian et al., 2007), during running (Ishikawa and Komi, 2008) and is modified on inclines or declines (Lichtwark and Wilson, 2006; Hoffman et al., 2014). So contractile behavior depends on the investigated subgroup and is generally modifiable.

Such information could aid to understand pathological gait patterns in SCP. In addition, it might help to develop exercises against gastrocnemius deficits since different types of dynamic muscle contraction can cause particular muscle adaptations. In TD, eccentric training might be favorable to induce longitudinal growth of fascicles (Franchi et al., 2014). Treadmills are often used to practice level walking in SCP but modifications, e.g. concerning the slope or walking direction, may modulate the type and extent of the contractile activity and thereby target the muscular deficit: forward-uphill training reduces passive stiffness of spastic plantarflexors (Willerslev-Olsen et al., 2014, 2015) but the mechanisms remain somewhat unclear while backward-downhill may provide eccentric calf loadings, as shown in TD (Hoffman et al., 2014; Hoang et al., 2007a). Investigating SCP-patients during these two tasks hence could be relevant for promoting non-invasive therapies.

The main purpose of this study was to analyze the contraction of the medial gastrocnemius in SCP-patients and TD during level, uphill and backward-downhill gait with ultrasound, motion analysis and EMG. Due to the shortened fascicles and the findings from mimicry and simulation studies, we expected that the spastic gastrocnemii show less fascicle lengthening than TD and that fascicles reach shorter length during level gait. Due to reports in healthy adults, we anticipated that uphill gait induces larger fascicle operating length and more concentric fascicle shortening in TD and SCP while backward-downhill gait causes larger eccentric fascicle lengthening and a shift of the fascicle operating regions towards shorter length.

2. Methods

2.1. Participants

Children with SCP had to be classified as GMFCS-Level I or II (Palisano et al., 1997) and display bilateral involvement. Exclusion criteria were any leg surgeries at all or botulinum toxin injections within 12 months. Only data of the more involved side (less passive dorsiflexion) was included. 15 children with SCP (4 females) and 17 TD (8 females) between 7 and 16 years took part. 11 SCP children were classified as GMFCS I, 4 as GMFCS II. For TD the right leg was analyzed. Experiments received medical ethics approval by the Technische Universität München and informed written consent was obtained.

2.2. Protocol

Participants were physically examined and performed a 3D gait analysis on a treadmill (Atlantis, Heinz Kettler, Ense-Parsit, Germany). Subjects wore a harness (h/p/cosmos, Nussdorf-Traunstein, Germany) without weight support which was connected to a safety frame (Mobil Konzept Loadmaster 80, RMT RehaMed Technology, Dietzenbach, Germany). All trials were done barefoot on even surface (flat-forward), on +12% inclined surface (uphill) and on −12% declined surface (backward-downhill) (Fig. 1B–D). This protocol was applied twice because probe fixation did not allow for simultaneous measurements of ultrasound and EMG. The order of the slopes was randomized and half of the participants started with EMG. During each condition data was captured during 10 s., starting when the subjects felt comfortable. Prior to walking, a 5 s. long seated rest measurement was done, with knees 90° flexed and ankles in neutral (Fig. 1A). On the treadmill, 5–10 min habituation time was provided during which preferred forward speed was determined with the subject blinded to the panel (Dal et al., 2010). The investigator increased the speed in 0.1 km/h increments until the subject reported to walk comfortable. Then, 1–1.5 km/h was added, followed by a stepwise decrease of 0.1 km/h to re-establish comfortable walking. This procedure was repeated three times and speeds were averaged. The uphill and backward-downhill speed was reduced to 85% and 50% of flat-forward speed to provide settings that should be also applicable for prolonged exercise. Values were chosen after studying the literature (Willerslev-Olsen et al., 2014; Joseph et al., 2016) and pilot testing. Since some SCP-patients were not able to walk without handrail, all participants were constrained to touch a lateral rail. During backward-downhill walking subjects grasped a rail at chest height.

2.3. Physical exam

Passive range-of-motion for knee extension, dorsiflexion and popliteal angle was measured using ruler-based goniometry. Plantarflexor tone was graded on modified Ashworth Scale (Bohannon and Smith, 1987). Peak isometric plantarflexor force (N/kg bodyweight) was assessed by handheld dynamometry using an uniaxial Force sensor (Mobi, Sakaimed, Tokyo, Japan) during 5 MVCs (3 s. contraction, 1 min rest). Subjects were seated (hips semi-flexed, knees extended). After discarding the lowest and highest value, 3 trials were averaged.

2.4. Gait analysis

A Nexus system (Vicon Inc., Oxford, UK) with 8 MX-Cameras was used to capture lower limb kinematics using a modified Plug-In gait Model (Stief et al., 2013) at 200 Hz. One additional marker was placed at the medial calcaneus, leveled with the heel marker. Gait events were derived as described by Zeni et al. (2008). All subsequent analysis was done in MatLab (MathWorks, Natick, USA). Non-dimensional walking speed was calculated (Hof, 1996) and sagittal joint angles were determined. Ankle angles were calculated using the foot markers without the toe to avoid bias by midfoot-bending. Peak values for dorsi-, knee- and hip flexion in stance and swing were calculated. Furthermore the sole angle (foot to belt) and knee flexion at initial contact were extracted.

2.5. Electromyography

Activity of the medial gastrocnemius, soleus and tibialis anterior was captured wireless with a DTS System (Noraxon, Scottsdale, USA). Surface electrodes (Blue Sensor N, Ambu, Ballerup, Denmark) were placed on the muscle bellies and signals were sampled at 1000 Hz. All strides during the 10 s. were analyzed separately. Signals were off-line filtered as described by Panizzolo et al. (2013) and mean rest activity was subtracted from walking signals before normalizing each signal on max. activity of all forward trials. For the medial gastrocnemius and soleus, mean activity during stance and for the tibialis anterior, mean activity from end of single stance to touch-down was calculated.

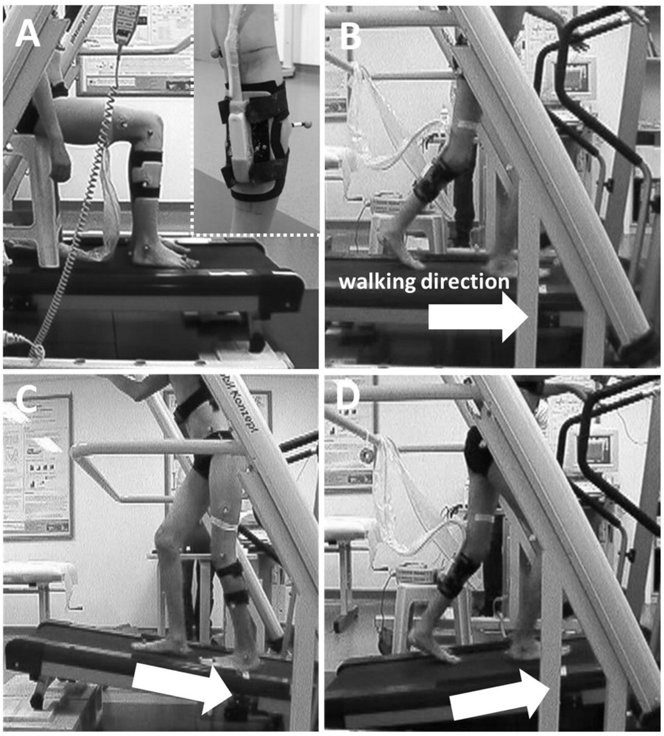

Fig. 1. Test conditions: A) seated rest measurement and ultrasound probe placement, B–D) treadmill walking for B) flat-forward, C) −12% backward-downhill slope and D) +12% uphill slope.

2.6. Ultrasound

An Echoblaster 128 ultrasound (Telemed, Vilnius, Lithuania) was used to image medial gastrocnemius fascicles at 60 Hz with a linear probe at 8 MHz and a field of view of 60 mm. The probe was held in place with a plastic cast covered with neoprene (Fig. 1A). Measurements of fascicle length were made at a mid-belly position (half-way between muscle–tendon-junction and popliteal crease) and the scanner was aligned according to Benard et al. (2009). The ultrasound was synchronized with the motion capture data via a pulse that was fed to the EMG System. Ultrasound videos of 6 strides were analyzed separately during gait and static measurements were performed during seated rest. Fascicle length was measured with a tracking algorithm (Gillett et al., 2013) and subsequent manual frame-wise inspection. Pennation angle (α) was determined with respect to the deep aponeurosis (Mian et al., 2007) and muscle–tendon unit (MTU) length was calculated from knee and ankle angles (Orendurff et al., 2002). The length of the series elastic element (SEE) was determined by $L_{SEE} = L_{MTU} - L_{FASCICLE} * \cos\alpha$ (Fukunaga et al., 2001). Thickness of the muscle belly during rest was measured, too (Hösl et al., 2015). During gait, all morphometric variables were normalized on resting length and all rest values were normalized on shank length. Gait data were interpolated to 100 points across each stride and an average for each participant and condition was determined. Outcome parameters were max. values during stance as well as the amount of lengthening (throughout loading response and single stance) and shortening excursions (throughout single stance and push-off) of fascicles and SEE.

2.7. Statistics

Participant characteristics, physical exam results and morphometrics during rest were compared with unpaired t-tests. Using the Shapiro–Wilk test, requirements for normality in some walking data sets were not achieved. So differences between conditions (flat-forward vs. uphill vs. backward-downhill) were tested separately for SCP-children and TD with repeated measure or Friedman ANOVAs where indicated. Paired t- or Wilcoxon tests were used for post-hoc comparisons. Differences between groups (SCP vs. TD) on flat-forward walking were tested directly with unpaired t- or Mann–Whitney U test where appropriate. Alpha-level was set to 0.05 and effect sizes were expressed as Cohen's *d* for significant results.

3. Results

3.1. Anthropometrics and physical exam

There were no significant differences in age between groups (Table 1), but SCP-patients were 8% smaller in height, 18% lighter and had 10% and 8% shorter legs and shanks (all $P \leq 0.031$). They displayed significant reductions in passive dorsiflexion (−14°), as well as 23° of popliteal angle restrictions. Max. isometric plantarflexor force was 28% less in children with SCP (all $P \leq 0.003$).

3.2. Morphometrics during rest

During rest children with SCP had 17% shorter fascicles, 19% thinner muscle bellies (both $P \leq 0.014$, $d \geq 0.9$) and tended to have a 1.5% longer SEE ($P = 0.081$).

3.3. Walking speed

Absolut flat-forward speed was lower in SCP-patients, 1.07 (0.16) m/s vs. 1.23 (0.08) m/s ($P < 0.001$, $d = 1.2$). Non-dimensional speed was also lower: 0.40 (0.06) in SCP vs. 0.44 (0.03) in TD, but differences were not significant ($P = 0.071$). SCP children took shorter steps 0.53 (0.08) m vs. 0.65 (0.05) m ($P < 0.001$, $d = 1.8$) at a higher cadence 2.03 (0.18) steps/s vs. 1.89 (0.15) steps/s ($P = 0.031$, $d = 0.8$). Belt speed on slopes were preset but 2 (of 15) SCP-patients only managed to walk backward-downhill at 34% and 38% of flat-forward speed.

3.4. Joint kinematics

Group means (1 standard deviation) for all conditions are shown in Fig. 2. Raw values can be found in the supplements. For TD the ANOVA indicated significant differences between conditions for all parameters ($P < 0.001$). For children with SCP significant main effects were found concerning the sole angle, dorsiflexion in stance, knee flexion at initial contact and hip flexion in stance and swing ($P \leq 0.007$).

3.4.1. Flat-forward

During flat-forward gait, SCP-patients showed 10° more hip flexion in stance and swing ($d = 1.5$ and 1.3) and more knee flexion in stance (12° concerning min. knee flexion, $d = 1.9$). They also landed with 17° flatter sole angle ($d = 2.8$). All corresponding tests showed $P \leq 0.001$. No group differences in dorsiflexion were noted in stance and swing ($P \geq 0.518$) or in knee flexion in swing ($P = 0.078$).

3.4.2. Uphill

With respect to flat-forward gait, both SCP and TD-children landed with 2° and 5° flatter sole angles ($P = 0.019$, $d = 0.6$ for SCP and $P < 0.001$, $d = 1.6$ for TD) and with 5° and 9° more knee flexion (both $P < 0.001$. $d = 1.1$ for SCP and $d = 1.0$ for TD). The following tests remained at $P \leq 0.001$: both groups increased their dorsiflexion in stance (3°, $d = 1.4$ and 4°, $d = 2.0$) while TD also increased dorsiflexion in swing (2°, $d = 1.0$). The hip of SCP and TD-children was more flexed in stance (3°, $d = 1.2$ and 5°, $d = 1.6$) and in swing (5°, $d = 1.5$ and 9°, $d = 2.2$). Only in TD, more knee flexion in stance (4°, $d = 1.4$) and less knee flexion in swing (3°, $d = 1.6$) was noted.

Table 1
Anthropometrics, physical exam and muscle morphometrics during rest.

	SCP (n = 15)		TD (n = 17)		*P*	ES
	Mean	(SD)	Mean	(SD)		
Anthropometrics						
Age [years]	11.0	(2.8)	12.2	(2.3)	0.219	0.4
Height [cm]	142.6	(14.5)	154.6	(11.9)	0.016	0.9
Mass [kg]	35.8	(8.6)	43.9	(9.9)	0.019	0.9
BMI [kgm^{-2}]	17.4	(2.1)	18.1	(2.0)	0.289	0.4
Leg length [cm]	73.7	(9.0)	81.8	(7.4)	0.009	1.0
Shank length [cm]	32.7	(3.9)	35.6	(3.4)	0.031	0.8
Physical exam						
Passive knee extension [°]	4	(5)	6	(3)	0.077	0.6
Popliteal angle [°] – (opposite hip 90° flexed)	34	(10)	11	(12)	<0.001	2.1
Passive dorsiflexion [°] – (0° knee flexion)	1	(8)	15	(4)	<0.001	2.1
Passive dorsiflexion [°] – (90° knee flexion)	17	(11)	27	(5)	0.001	1.3
Instrumented plantarflexor force [N/kg]	3.9	(1.4)	5.4	(1.1)	0.003	1.2
Plantarflexor tone [MAS] – (0° knees flexion)	2.2	(0.8)	0.0	(0.0)	<0.001	4.0
Medial gastrocnemius morphometrics (seated rest)						
Fascicle length [mm]	27.4	(9.4)	36.8	(5.2)	0.001	1.3
Fascicle length [% shank length]	8.5	(2.8)	10.3	(1.1)	0.014	0.9
Series elastic element length [% shank length]	89.1	(2.8)	87.8	(1.2)	0.081	0.6
Pennation angle [°]	26.0	(5.7)	24.9	(3.4)	0.504	0.2
Thickness [% shank length]	3.5	(0.9)	4.3	(0.5)	0.003	1.1

MAS: Modified Asworth Scale [1–4], SD: Standard Deviation, ES: Effect Size (Cohen's *d*). TD (typically developing) and children with SCP (spastic cerebral palsy).

3.4.3. Backward-downhill

Both groups landed with toes first. With respect to uphill gait they further increased knee flexion at ground contact (10° in SCP and 15° in TD), as well as hip flexion in stance (16° in SCP and 11° in TD). The Cohen's d was 0.8–2.0 (all $P \leq 0.011$). Only TD further increased dorsiflexion in swing (2° from uphill, $P = 0.003$, $d = 0.9$) while knee flexion in swing further decreased (12° from uphill, $P < 0.001$, $d = 2.0$). Similar to uphill walking, TD showed more knee flexion in stance than forward ($P < 0.001$, $d = 1.2$). But dorsiflexion of TD in stance decreased ($P = 0.003$, $d = 0.9$) and was similar to forward gait.

3.5. Electromyography

Fig. 3 shows the traces of muscle activity and morphometrics and Fig. 4 visualizes the outcome parameters. For TD the ANOVA indicated significant differences between conditions for all muscles (all $P \leq 0.007$). For SCP-children significant main effects were found for soleus and medial gastrocnemius activity (both $P < 0.001$).

3.5.1. Flat-forward

During flat-forward gait, activity of the medial gastrocnemius (+31%), soleus (+32%) and tibialis anterior (+58%) was larger in SCP-children than in TD (all $P \leq 0.031$, $d = 0.9$–1.3).

3.5.2. Uphill

Only in TD-children, medial gastrocnemius (+23%, $d = 1.2$) and soleus activity (+29%, $d = 0.8$) was significantly increased (both $P < 0.001$), while in SCP-patients rather similar medial gastrocnemius and soleus activity was noted with respect to flat-forward gait ($P > 0.855$). Tibialis anterior activity increased by 48% in TD ($P = 0.001$, $d = 0.9$) with respect to flat-forward gait. Despite the absent main effect, also 33% more tibialis anterior activity in SCP had been found with respect to flat-forward walking ($P = 0.048$, $d = 0.5$).

3.5.3. Backward-downhill

The soleus and medial gastrocnemius activity dropped by 37% and 44% in SCP-children (both $P < 0.001$, $d = 1.1$ and 1.5) and by 31% ($P = 0.003$, $d = 1.0$) and 23% ($P = 0.038$, $d = 0.8$) in TD with respect to flat-forward gait. Consequently, plantarflexor muscle activity was also significantly less than uphill. Tibialis anterior activity was not different from flat-forward or uphill in both groups (all $P \geq 0.080$).

3.6. Morphometrics during gait

In TD-children the ANOVA indicated significant differences between conditions for all parameters (all $P < 0.001$) despite fascicle lengthening ($P = 0.351$). For SCP-children, significant differences between conditions were found for fascicle lengthening ($P = 0.041$), SEE lengthening and shortening ($P = 0.008$ and $P < 0.001$) and for max. SEE length ($P = 0.028$).

3.6.1. Flat-forward

There was 37% less concentric fascicle ($P = 0.001$, $d = 1.4$) and 24% less concentric SEE excursion ($P = 0.002$, $d = 1.1$) in SCP-patients with respect to TD. Spastic fascicles (−10%, $P = 0.038$, $d = 0.9$) and SEE (−5%, $P = 0.004$, $d = 1.3$) also reached significantly shorter max. length. No significant group differences in eccentric fascicle ($P = 0.571$) or SEE excursion ($P = 0.345$) were found.

3.6.2. Uphill

During uphill walking significantly more concentric fascicle excursion than during flat-forward gait was noted in TD (+40%, $P < 0.001$, $d = 1.2$). Also in SCP-children an increase of 23% ($P = 0.034$, $d = 0.6$) occurred but the ANOVA failed to indicate a significant main effect. Only in SCP-children, this was accompanied by 19% increase in eccentric SEE excursion ($P = 0.001$, $d = 1.0$). The SEE reached significantly shorter max. length than in flat-forward gait in SCP-children (−1%, $P = 0.048$, $d = 0.6$) and in TD (−2%, $P = 0.038$, $d = 0.5$).

3.6.3. Backward-downhill

Only in SCP-children, eccentric fascicle contraction increased with respect to flat-forward and uphill walking (+112% and +132%, both $P \leq 0.017$, $d = 0.7$–0.9). In TD, fascicle shortening was significantly reduced with respect to flat-forward (−41%, $P = 0.002$, $d = 0.9$) and thus also from uphill gait. In TD max. fascicle length was shorter than forward (−5%, $P = 0.002$, $d = 0.9$) and uphill (−6%, $P = 0.001$, $d = 1.0$). In both groups this was accompanied by larger lengthening excursions of the SEE with respect to the flat-forward condition, +42% in SCP ($P = 0.010$, $d = 0.7$) and +28% in TD-children ($P = 0.001$, $d = 1.0$). Only in TD this SEE lengthening was significantly larger than uphill (+18%, $P = 0.006$, $d = 0.8$). At the end of stance, SEE shortening was diminished in both groups with respect to the other conditions (Fig. 4). The max. SEE length in SCP-children was 3% shorter than forward ($P = 0.030$, $d = 0.6$). The reductions with respect to uphill-gait were not significant ($P = 0.156$). In TD the max. SEE length was 3% shorter than uphill ($P < 0.001$, $d = 1.2$) and thus also shorter than forward.

4. Discussion

We analyzed SCP-children and TD with specific focus on adaptations of the medial gastrocnemius contractile behavior during flat-forward, uphill and backward-downhill gait. Apart from having innately shorter fascicles at rest, SCP-children also reached shorter relative fascicle length than TD during flat-forward walking and showed less concentric excursion during push-off. Uphill gait increased concentric excursion of the fascicles in both groups while backward-downhill gait induced larger eccentric fascicle excursions in SCP-children.

During flat-forward gait, participants with SCP walked with considerably flexed knees which is inefficient and puts great burden on knee

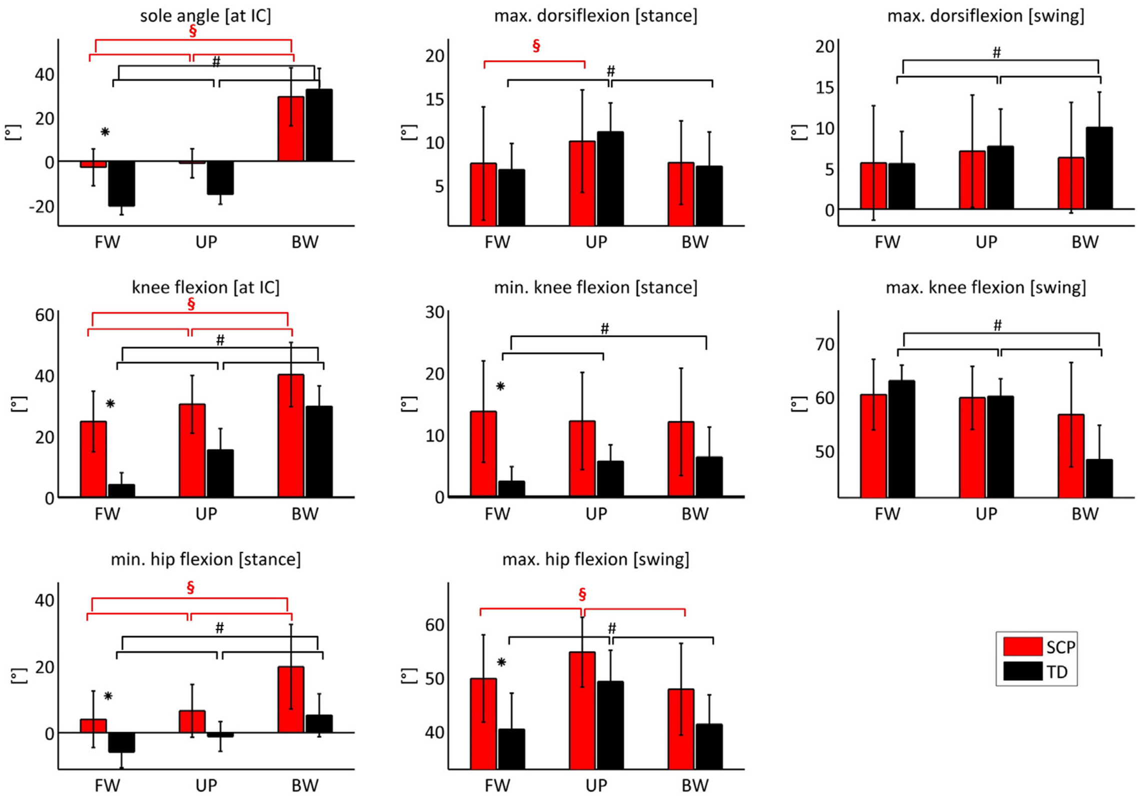

Fig. 2. Sagittal joint kinematics of the foot, ankle, knee and hip. FW: flat-forward; UP: uphill, BW: backward-downhill, IC: Initial contact. * significant differences between TD (typically developing) and children with SCP (spastic cerebral palsy) during FW; § significant differences between conditions for SCP; # significant differences between conditions for TD, $P < 0.05$.

extensors. Deterioration of passive dorsiflexion (assessed with extended knees) is a negative factor for such a crouch gait pattern (Maas et al., 2015). On the one hand, short and inextensible gastrocnemius fascicles could constrain knee extension to permit similar dorsiflexion during gait. When comparing the fascicle operating regions (Fig. 5), the spastic fascicles only somewhat reached the regions of healthy fascicles. On the other hand, healthy gastrocnemius fascicles usually work near the descending limb of their length-tension curve during gait (Hoffman et al., 2014) and since spastic fascicles worked at shorter length, they may be used more towards the ascending limb. In this region, fascicles are ordinarily able to produce less active force. So, limited relative fascicle length during gait may be a pathological sign. This assumption relies on a fascicle force length relationship that assumes equal inherent sarcomere length between groups. However, due to findings of much longer sarcomeres in spastic muscles (Mathewson et al., 2014), contractile filament overlap within sarcomeres may worsen at more extended fascicle length. Hence, limited relative fascicle length could be an adjustment in SCP to use sarcomeres in a configuration where they are able to produce enough active forces, otherwise contractile filaments could be stretched apart beyond overlap.

The observed lack of concentric fascicle shortening could be affected by less sarcomeres in series and may contribute to the typical reductions in ankle joint power (Dallmeijer et al., 2011). Reduced pull from muscle shortening contraction could in turn be the reason why the SEE reached shorter relative length in SCP-children. In addition, no difference in eccentric fascicle excursion between SCP-patients and TD existed. Although such loads may not be responsible for the genesis of contracture or fibrosis (Pitcher et al., 2015), SCP-children with less isometric plantarflexor force experienced more fascicle lengthening excursion (Pearson's $r = -0.57$, $P = 0.026$) and therefore the gastrocnemius fascicles may indeed face difficulties to resist tensile forces (Fry et al., 2006).

Since muscles can adapt to altered use, it appeared interesting to modulate the gastrocnemius contractile behavior with sloped treadmill walking. In general, gait adaptations concerning joint angles and muscle activity appeared to be more diverse and more pronounced in TD. This could be due to coordinative or musculoskeletal restrictions in SCP-children. Nevertheless, uphill gait increased concentric excursion of the medial gastrocnemius fascicles but no significant change in max. fascicle length or eccentric fascicle excursion occurred. Decreased passive stiffness of spastic plantarflexors after uphill training (Willerslev-Olsen et al., 2015) could accordingly be a response to increased concentric loads. Interestingly, uphill training also strengthens dorsiflexors and increases toe-clearance during flat-forward gait (Willerslev-Olsen et al., 2014). Even though tibialis anterior activity increased in our sample of SCP-children, the clearest kinematic adaptations during uphill walking happened in hip flexion (Fig. 2) and SCP-children faced difficulties to increase dorsiflexion in swing. This was possibly constrained by less voluntary tibialis anterior recruitment (~smaller EMG increase than in TD) or impeded by the plantarflexor contractures. Likewise the plantarflexor EMG in SCP-children did not increase in stance. Altogether SCP-patients may substantially rely on hipflexors during uphill training.

Walking backward-downhill forced to strike the ground with the toes which appears counterintuitive in SCP-children. However, it couples knee extension with dorsiflexion motion during weight acceptance and thereby induced larger medial gastrocnemius fascicle lengthening excursions in SCP. This was not the case for TD who might have been able to provide more isometric force to withstand lengthening. Besides the eccentric excursion values were rather variable in TD. Although all subjects had experience in treadmill walking, backward-downhill gait may be less variable and stabilize with further training.

Backward-flat gait has been successfully applied for coordinative gait training in SCP-children (Kim et al., 2013) but no effects of backward-downhill training on calf muscle pathology have been reported. Generally, effects of eccentric plantarflexor training appear to be promising: for TD-adults, eccentric training can increase passive ankle joint flexibility, plantarflexor strength (Mahieu et al., 2008), medial gastrocnemius fascicle length and tendon stiffness (Duclay et al., 2009).

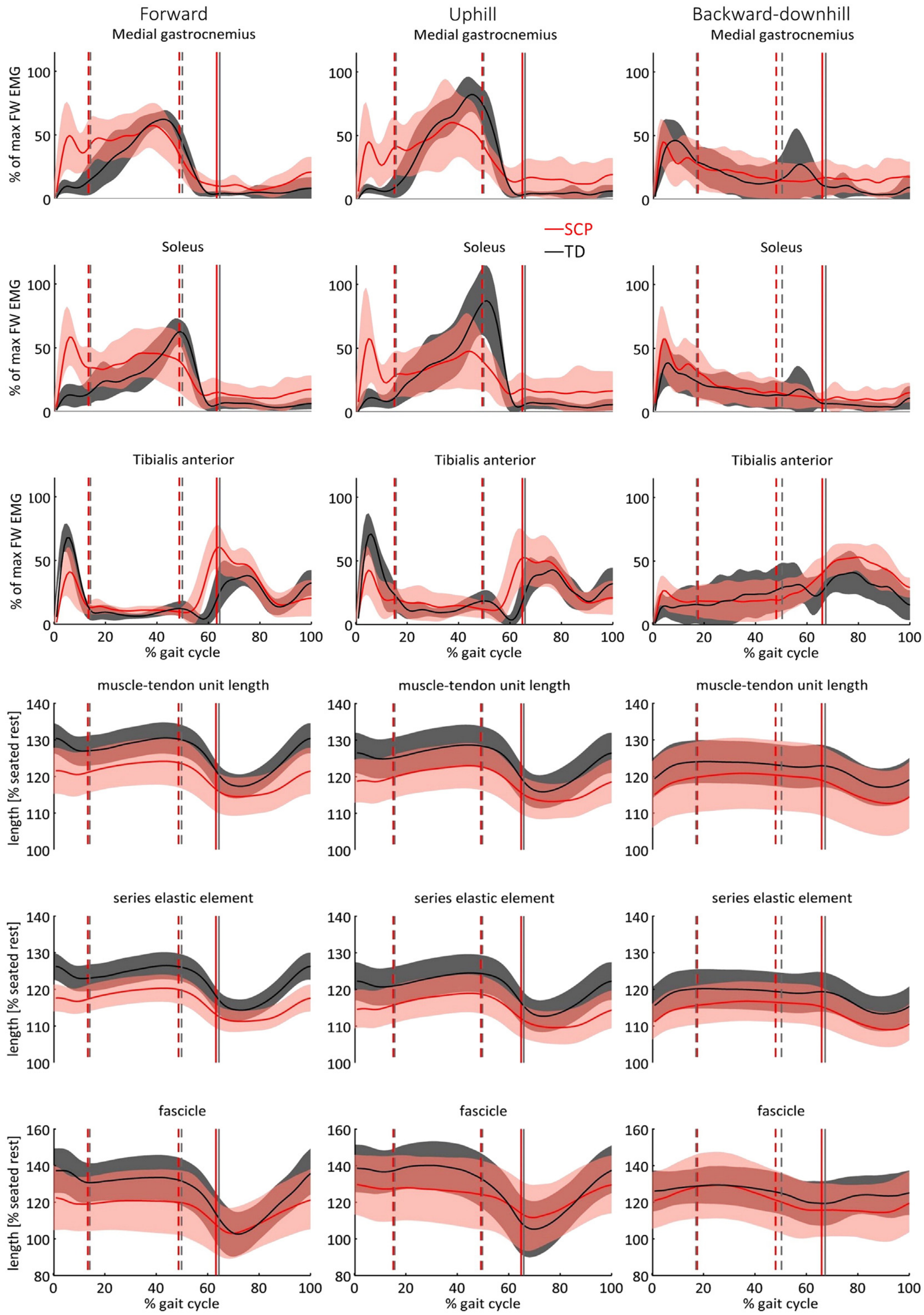

Fig. 3. Group average traces for shank muscle activity and medial gastrocnemius morphometrics across the gait cycle. Vertical dashed lines separate double from single support and vertical solid lines stance from swing. Shaded bands show group means ± 1 standard deviation.

These benefits apparently contrast conceptions about the harmfulness of eccentric loads in SCP (Fry et al., 2006; Pitcher et al., 2015; Gough and Shortland, 2012). When using backward-downhill gait during therapy, the medial gastrocnemius fascicles in SCP are unlikely to sustain macroscopic damage since they seem to be trained at moderate length (not significantly different from forward or uphill) and their eccentric excursion seems to be of low amplitude. As a precaution, such training should be gradually adjusted.

It is difficult to deduce something about tendinous loads but neither backward-downhill, nor uphill gait induced larger max. SEE length in any group (Fig. 4). Taking into account that large contraction induced deformation is necessary for improving tendinous stiffness (Bohm

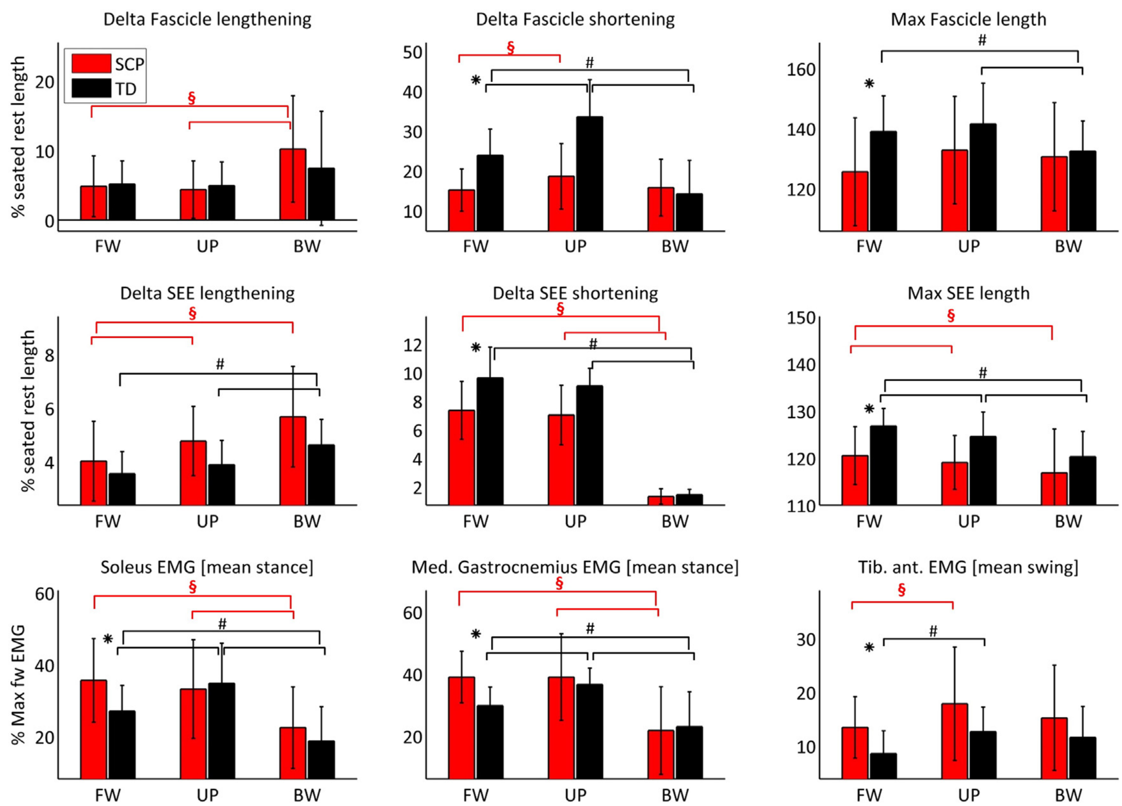

Fig. 4. Fascicle and series-elastic element (SEE) lengthening and shortening excursions and maximal length during stance, as well as shank muscle activity. FW: flat-forward; UP: uphill; BW: backward-downhill. * significant differences between TD (typically developing) and children with SCP (spastic cerebral palsy) during FW; § significant differences between conditions for SCP; # significant differences between conditions for TD, $P < 0.05$.

et al., 2015), the potential benefits of sloped gait modifications may not target the gastrocnemius tendon.

4.1. Limitations

First off, the external validity of treadmill gait has been subject of controversy but no difference in medial gastrocnemius fascicle behavior between treadmill and overground gait had been observed in TD-adults (Cronin and Finni, 2013). Still preferred treadmill speed is slower than overground (Dal et al., 2010; van der Krogt et al., 2015). Additionally, for joint kinetics of SCP-children, a power-shift from the ankle to the hip has been noted on treadmills (van der Krogt et al., 2015). This could explain some general differences in concentric fascicle excursion between SCP-children and TD. Noteworthy, we deliberately reduced the speed on slopes and constrained all subjects to touch handrails since those settings appear realistic during regular treadmill walking therapy (Kim et al., 2013; Willerslev-Olsen et al., 2014; Chrysagis et al., 2012).

Apart from that, a seated position was used for normalization of morphometrics. At this joint configuration, the gastrocnemius muscle has usually fallen slack (Hoang et al., 2007b). Despite the fact that fascicle operating regions of TD-children, expressed with respect to rest length (Fig. 5), appear comparable with data of TD-adults (Hoffman et al., 2014), slack length could be instrumentally assessed when investigating muscle-tendon behavior during gait in future studies.

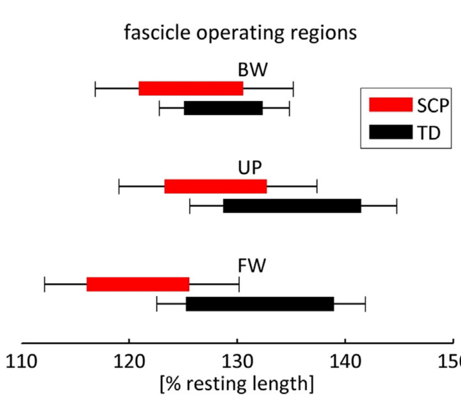

Fig. 5. Fascicle operating regions during stance phase of gait. Error bars indicate the standard error of the group mean minimum or maximum fascicle length. FW: flat-forward; UP: uphill, BW: backward-downhill. Vertical height of the bars is arbitrary. TD (typically developing) and children with SCP (spastic cerebral palsy).

5. Conclusions

Medial gastrocnemius fascicles appear to be used on very short relative length during spastic gait with similar eccentric and less concentric excursion compared to controls. Flexed knees in crouch gait could be related to structural shortness of gastrocnemius fascicles. Uphill gait increases concentric gastrocnemius fascicle action and tibialis anterior activity and may be useful to train push-off and foot lift. During backward-downhill gait, the medial gastrocnemius functioned as a brake and displayed more eccentric excursion in SCP-children which could potentially stimulate sarcomere-genesis in series with repeated training. Both training modes may offer advantages, but none of them may promote tendon stiffness since the SEE was longest during forward gait.

Conflict of interest

None of the authors has any commercial or other interests that create a conflict of interest for the work presented here.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.clinbiomech.2016.05.008.

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