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Wearable textile EMG recordings during daily life activities in children with cerebral palsy and typically developed children – a feasibility study

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ABSTRACT

Aim: To test whether wearable textile EMG recording systems (wtEMGrs) may detect differences in muscle activity levels during daily activities between children with Cerebral Palsy (CP) and age-matched typically developing (TD) children.

Method: wtEMGrs were used to obtain leg muscle activity in 10 children with spastic CP (mean age 9.6±2.3 years, 4 girls, GMFCS I–II) and 11 TD children (mean age 9.9±1.9 years, 4 girls) at rest and while performing seven daily activities.

Results: Children with CP showed significantly lower absolute EMG levels during maximal voluntary contractions (MVC) of muscles on the most affected (MA) side as compared to the least affected side (LA) and to TD children. None of the TD or CP children showed detectable EMG activity in resting situations. EMG activity relative to MVC was greater in children with CP during walking, jumping and kicking on the MA side as compared to the LA side and to TD children.

Interpretations: wtEMGrs may be used to determine differences in muscle activity during daily activities in children with CP. Children with CP showed reduced muscle activity during daily activities compared to their peers, but used a significantly larger part of their maximal voluntary muscle strength to perform these activities.

What this paper adds:

- Wearable textile EMG systems are feasible for measurement of daily muscle activity in children with CP
- Children with CP showed reduced EMG levels during maximal-voluntary-contractions
- Neither TD or children with CP showed EMG activity in resting situations
- Children with CP used a larger part of their voluntary muscle strength during daily activities

Daily physical activity of moderate to vigorous intensity lasting at least 60 minutes is recommended world wide for children in the age group 5-17 years to improve cardiorespiratory and muscular fitness, bone health, and cardiovascular and metabolic health biomarkers[1-3].

Many children fall short of these recommendations and there is therefore an increasing threat of a world wide epidemic of cardiovascular and metabolic disorders caused by sedentary life-styles established already in early childhood[1]. Children with disabilities such as cerebral palsy (CP) have particular difficulties in meeting the recommendations[4,5] and have been found to be much less active than their typically developing (TD) peers [6,4,7,8]. Not surprisingly, this depends on the severity of the disability, but even high functioning children with CP have been found to be almost 50 % less active than TD children[7,6,8].

To efficiently help high functioning CP children to become more active, it is important that we understand the exact causes of their functional limitations in daily life. In this respect it is a problem that studies on daily activity levels in children with CP have been based on questionnaires, step counters or accelerometer data [8,7,6]. Such studies do not provide any information about movement limitations in specific joints, increased involuntary muscle activity (spasticity) or muscle paresis and muscle weakness. As such, our knowledge of whether functional impairments that have been found in a clinical setting (e.g. gait lab or outpatient clinic) pose real functional problems that limit daily life activities is sparse. This may result in treatment of symptoms that are not fundamental problems in daily life and do not limit the daily activities and participation of the child. One example is spasticity which may not have the functional significance that was once assumed[9-11]

Recently, wearable textile EMG recording systems (wtEMGrs) that allow several hours of recording of muscle activity during daily life activities outside the laboratory or clinic have become available [12-14]. These systems have been found to be valid and reliable in adults during everyday life [14,15], but have not yet been tested in children with disabilities.

The aim of the present study was to test whether wtEMGrs may be used for detection of differences in muscle activity levels during daily life activities between children with CP and age-matched TD children. We hypothesized that children with CP would show reduced or similar EMG levels in affected muscles during daily life activities compared to TD children.

Methods

PARTICIPANTS

Ten children with Cerebral Palsy (CP; 6 boys; mean age 9 yr 6 months (range: 6 to 13) and eleven typically-developed (TD) children (7 boys, mean age 9 yr 9 months (range: 7 to 12) participated in the study (Table 1). All procedures were conducted according to the Helsinki Declaration and the study was approved by the local ethics committee (H-15011260). Prior to testing, both children and their parents received written and verbal information about the test procedures and parents gave written consent to the study.

The children with CP were all diagnosed as spastic and belonged to GMFCS level I (n=5) or level II (n=5; Gross Motor Function Classification Scale (GMFCS; Palisano et al. 1997 [16]). Six children were hemiplegic and 4 were diplegic. The most affected leg (MA) was identified by reduced strength in plantar- and dorsi flexor muscles measured by MRC Scale for Muscle Strength (Medical Research Council, 1976)[17]. In two cases where equal MRC scores were found the MAS; Bohannon & Smith, 1987) [18] scores were used for the identification. All children with CP showed asymmetric distribution of weakness or spasticity with a most affected (MA) and a least affected (LA) leg. In 6 children the right leg was the MA limb. Children who had received botulinum toxin injection or surgery within the previous 3 months were excluded from the study. Five children had undergone surgery and seven had received botulinum toxin injections more than one year before the study (Table I). None of the children used other muscle tone changing treatments during the project period.

STUDY DESIGN

All measurements were performed in the same environment and setting at the Elsass center. Care was taken to ensure that the environment resembled a traditional home of Danish children as much as possible. The children were asked to perform motor activities under standardized conditions that resembled daily life activities. During these activities all children wore specially designed pants with electromyography (EMG) electrodes woven into the fabric (see picture in supplementary material 1). All children wore their own clothes and sport shoes with neither shoe inserts nor braces during all motor tasks. During measurements of maximum voluntary isometric contraction (MVC) and in resting situations, the shoes were taken off.

Neurological examination

All experimental sessions started with a neurological examination performed by a physioterapist (JL) or a physician (MCL) while the children sat comfortably and relaxed on a couch. Passive range of movement (ROM) was determined for ankle and knee joints using manual goniometer. Muscle resistance was estimated using the modified Ashworth scale (MAS)[18] and muscle strength was assessed using the MRC Scale for Muscle Strength[17] (table 1).

EMG recordings

Muscle activity from quadriceps, hamstrings, tibialis anterior and gastrocnemius muscles bilaterally were measured using wearable leggings with embedded textile EMG electrodes (Myontec Ltd, Kuopio, Finland). Conductive textile electrodes and wires are integrated and sewn into the fabric. Rectangular bipolar electrode pairs are placed symmetrically on each side spanning 9x2.5 cm for quadriceps muscles, 6.5x2,5 cm for hamstrings muscles, 5.5x2.5 cm for tibialis anterior muscles and 7x2,5 cm for gastrocnemius muscles. The reference electrodes lie laterally within longitudinal rectangles spanning 11x2.5 cm covering the most proximal part of tractus iliotibialis.

Validity and reliability of such wearable electrodes have been previously tested by Finni et al.[14] and Tikkanen et al.[15] While these textile electrodes with large conductive area provide lower EMG amplitude than traditional bipolar surface electrodes, they respond well to the intensity level and show excellent reliability during a day[15] and from day-to-day[14]. When putting on the leggings, care was taken that the child's underwear would not block skin contact from the reference electrodes. All electrodes were moisturized with neutral lotion (Irmas Tusindfryd Bodylotion, Coop Danmark A/S, Denmark). Apart from improving signal conduction, the moisture also provided friction, thus decreasing the risk of electrode displacement and thereby movement artefacts. The size of the leggings (120, 130 or 140 cm) were chosen to be tightly fitted but in case the leggings were loose around thighs or calves, tape (3M Micropore, 3M, Maplewood, Minnesota, USA) was wrapped around the leg to ensure proper placement of the electrodes. The waist had strings that could be tightened, and size 140 cm had an additional zipper in the back of the waist allowing extra flexibility.

The recording module was fixed to the front of the waist where it incorporated signal amplifiers, microprocessor with firmware, data memory and PC interface (Myontec Ltd, Kuopio, Finland). Before initiating a new test session the recording module was synchronized with the timer on a mobile phone enabling us to log initiation and end of each of the tasks.

After each test, the leggings were hand washed according to the manufacturer's instructions.

EXPERIMENTAL PROTOCOL

The test battery consisted of seven motor tasks (MVC, walking, running, jumping, walking on stairs, kicking) and three resting situations (standing, lying, watching cartoons in seated position; Fig. 1). Each child performed the tasks in the same order (MVC, walking, running, jumping, standing, kicking, stair walking, supine resting, and watching cartoon (resting in seated position). The resting situations were placed after physically demanding motor tasks.

Verbal encouragement was given by experimenters and parents during measurements to help children to maintain focus and accomplish the tasks as quickly and correctly as possible.

Each test session lasted around 3 hours (including verbal information, neurological examination, putting on the leggings, and 30 minutes of rest in the end).

Maximal isometric voluntary contraction (MVC)

MVCs were performed unilaterally on both legs for knee extension, knee flexion, plantar flexion and dorsi flexion and were used to standardize EMG amplitudes for corresponding muscles during activities. Each MVC was repeated three times with a break in between lasting one minute. During the MVC test the experimenter (MCL opposed the leg movement for either knee extension, knee flexion, plantar flexion or dorsi flexion while the child attempted to make a maximal contraction. We ensured that the position was the same for all subjects during the tests (for details about this method please see supplementary material 2).

Walking and running on the floor

On a plane surface of a hallway the children were asked to walk back and forth consecutively for two minutes between two cones placed 25 m apart from each other. In a first test, the child was asked to walk as naturally as possible i.e. a constant pace which they would choose when not in a hurry. After a small break the child was asked to walk as fast as possible ”as if in a hurry” without running or risk falling. Finally, the child was asked to run at a self-chosen pace. This last test was performed only for one minute due to fatigue.

Jumping

The children were instructed to perform three jumps as high as possible. Each of the three jumps was initiated on the verbal command ”go” after a countdown from three. The children were instructed to bend their legs a little and pull the hands in the air during the jump. Approximately 30 seconds break between the jumps was allowed.

Standing

The children were asked to stand in upright position with both of their hands resting on an elevated medical bench for two minutes. The children were told to try distributing their weight equally on both legs.

Kicking a football

The children were asked to kick a leather football with their dominant foot. The football was placed on a plane surface, which allowed them to run 3 meters before kicking. It was emphasized that they should do it in the way that they would normally kick a football.

The children kicked the football at the verbal command ”go” and repeated this three times with 30 seconds in between.

Climbing stairs

The stair used for this task spanned two floors. The children were to choose a pace similar to how they would normally climb a stair. They were told to keep a constant pace both upstairs and downstairs as they would only get a small break of approximately 20 seconds every time they reached either of them. All children were to climb the two consecutive floors both ways twice. All children were asked to hold onto the railing with one hand to ensure comparability between the children.

The breaks served as an opportunity for the children to recover their breath. Also, it was a way of standardising this task, since climbing stairs without a break would exhaust most children and decrease their pace.

Resting situations

In the first task, the children lay supine on a bench with both legs straight and relaxed. The children were asked to lay down and keeping their legs as calm as possible. Information about the time elapsed was given for every 30 seconds. The lying task was performed for two consecutive minutes

The final resting situation also ended the entire test battery. During 30 minutes the children were to stay seated in a couch with their back supported by a large pillow and with both legs straight resting their feet on a pillow. However, contrary to the other resting situations, this time they were not asked to keep their legs as calm as possible. Rather, they were instructed to relax as they would at home in a similar situation. During this time the children were either watching a movie or entertaining themselves with a tablet. This situation provided the possibility to assess EMG during normal sedentary behavior.

EMG ANALYSIS

All EMG signals were sampled at a sampling frequency of 1000 Hz and 2nd order band-pass filtered at 50–200 Hz, before being full-wave rectified. The memory of the module stored the averaged data until downloaded to a PC using the MegaWin software (Mega Electronics Ltd., Kuopio, Finland).

Periods with obvious artefacts (recording exceeding EMG activity by several magnitudes) were removed leaving periods of equal duration for analysis. Data sets were imported into MATLAB (version R2016a) for further analysis. A customized MATLAB script calculated muscle activity for the four different muscle groups.

MVC was calclulated as the peak EMG activity in the agonist muscle during the three tests for knee extension, knee flexion, plantar flexion and dorsiflexion, respectively. For all other tasks, EMG activity was quantified as the Root Mean Square (RMS) value for the respective muscles during the recorded time period. It was ensured that a similar recording time was used for all children.

STATISTICAL ANALYSIS

SigmaPlot statistical software version 12.5 (Systat Software, San Jose, CA) was used in all statistical analysis. For all tests the significance level was set to $P<0.05$. The Shapiro-Wilk test was used to check whether data were normally distributed. Unpaired t-test was used to compare height, weight and age between TD children and children with CP, two-way (group x muscle) ANOVA was used to test for statistically significant differences between the children with CP and TD children and different muscles. In cases with significant group effects, the Student-Newman-Keuls (SNK) post hoc test was used to locate the differences. A separate analysis was made for each task (MVC, walking, running, stair walking, standing, jumping, kicking, lying supine and watching cartoons). Since this study is a feasibility study no power analysis was made.

RESULTS

Unpaired t-test revealed no statistically significant between-group differences with respect to age (10y 1month+/-22month (CP), 9y 9 month+/- 24 (TD); P=0.7), height 141.6+/-13.8 cm (CP), 140.6+/- 12.8 cm (TD); P= 0.75) or weight (36.7+/-10.4 kg (CP), 33.7+/-8.8kg (TD); P=0.84).

Children with CP have lower EMG activity during MVC

Figure 2 shows the mean absolute EMG activity for all muscles and tasks in TD children (Fig. 2A) and children with CP (Fig. 2B). Fig. 2C shows the ratio between the EMG activities in the two populations. The ratios were close to 100% for most of the tasks, except during MVC where the EMG activity levels were lower in the TD children compared to the children with CP. For the MVC tests, ANOVA revealed a significant interaction between muscle and group (TD vs CP) (DF= 7; F= 3.84; p<0.001). The post hoc test showed a significant difference in MVC between TD and CP for all muscle groups in the MA leg and for TA and Q also in the LA leg (p<0.05). In contrast to this, no significant difference in absolute EMG activity was observed between CP and TD for any other tasks (ANOVA; F<2; p>0.1). It is noteworthy that all the children showed no or very low EMG levels (below 5 μV) in the resting situations (standing, supine, cartoon watching).

Children with CP use a proportionally larger part of their maximal effort during daily life activities

As a consequence of the lower MVC in children with CP on the MA side without differences in EMG in any of the other tasks, it follows that children with CP must activate their muscles on the MA side to a higher extent relative to MVC than TD children. This is illustrated in Fig. 3 where the muscle activities during the different tasks has been expressed relative to the EMG activity recorded during MVC in TD children (Fig. 3A) and children with CP (Fig. 3B). Fig. 3 C shows the relation between the two populations to illustrate the larger relative muscle activation on the MA side in children with CP. Significant interaction between muscle activity and population group was found for all active tasks (gait (F=3.9; p<0.001), running (F=3.7; p<0.001), stair walking (F=4.2; p<0.001), jumping (F=3.7; p<0.001 and kicking (F=3.5; p=0.002), but not for any of the resting situations (p>0.3). The post hoc tests revealed that muscle activity relative to MVC was significantly higher for all muscles on the MA side than on the LA side in CP children for all active tasks (p<0.01). There were no significant differences in muscle activity between the left and the right side in TD children for any of the tasks (p>0.3).

Discussion

We found no sign of excessive muscle activity in the children with CP, when compared to their peers - neither at rest nor during movement. However, children with CP used a much larger proportion of their maximal voluntary effort during daily life activities than TD children. This is likely contributing to explain why children with CP report fatigue as a major limitation for participation in sports and other activities[16,19].

Children with CP show less EMG activity in the MA leg during MVC.

Although muscle weakness and altered muscle properties contribute to reduced muscle strength and power in children and adults with CP, reduced neural drive is the primary and dominating cause[20-22]. The lower absolute EMG activity in children with CP during MVC supports this observation. However, interpretation of absolute EMG should be taken with some caution, although the absolute amplitude has been previously shown to correlate with strength[14].

The amplitude of EMG signals depends on the thickness of the subcutaneous tissue layer, the distance from the source to the electrodes, characteristics of the muscles, the location of the electrodes, and the contact between the electrode and skin[23]. This may introduce considerable variability and uncertainty in the absolute EMG values reported for the individual children. It is in particular a problem that children with CP generally have smaller muscles on the most affected side with a relative increase in fat tissue[24]. As a consequence they had a smaller circumference of both thighs and calves, which made it difficult to fit the electrodes in the pants so that they were as tightly connected to the skin of the legs as in TD children.

Given that there were approximately equal number of participants in the TD and CP groups, and that same electrode size was used in both groups the lower absolute amplitudes found in CP were therefore likely related to their lower strength level.

Children with CP show more EMG activity relative to MVC during tasks that resemble daily life activities

When the RMS EMG was normalized to peak MVC, children with CP were seen to use a larger muscle activity during daily life activities, such as walking and climbing stairs relative to their maximal voluntary effort. This is consistent with Berger et *al.* (1982)[25], who found that children with CP used twice as much EMG relative to their maximal EMG during gait than TD children.

The RMS EMG activity during gait, running, jumping and kicking often exceeded 100 % of the peak EMG activity during MVC. This is most likely explained by more efficient temporal summation of the EMG activity during these dynamic tasks than during the MVC task. The children were not instructed to perform the MVC as quickly as possible, but only to produce as much force as possible and the MVC contractions were therefore generally performed slower than the contractions during walking, running, kicking and jumping.

The larger relative EMG activity in children with CP indicates that they have to make a considerable larger relative effort during daily activities than their peers. This may contribute to the experience of fatigue in children and adults with CP[27,28,16].

No sign of overactive muscles at rest in children with CP

The observation of similar activity levels at rest in children with CP and TD children (supine, watching cartoons) is consistent with a recent study[29], in which no difference in muscle activity between spastic patients and healthy controls was observed at rest (sitting and lying). This indicates that none of the children in our study presented involuntary sustained muscle activity (i.e. dystonia or spastic dystonia), which could potentially contribute to development of contractures and abnormal joint positions. The children were all in GMFCS group I-II and showed only little signs of spasticity (Table I). It is likely that children who are more severely affected and with more pronounced spasticity or dystonia would have shown more involuntary resting EMG activity than what we observed here. However, since our primary goal was to investigate EMG activity during daily motor activities, only ambulatory children who were able to perform the motor tasks were included.

Strengths and weaknesses

Wearable EMG textiles provide information about magnitude and patterns of muscle activity during daily activities that cannot be achieved through conventional accelerometer activity monitoring. This allows more exact monitoring of the relation between daily exercise patterns and health issues and it opens the possibility of detecting and diagnosing movement abnormalities during daily living. This may be of importance in the early detection of movement abnormalities in infants with neurodevelopmental disorders such as cerebral palsy. Although the wearable technology is easier to use than conventional EMG recording, it still requires considerable technical expertise and careful positioning of electrodes and preparation of skin. At present successful recordings the presence of trained personnel with considerable expertise in EMG recording is therefore required. The cost of wearable EMG systems is at present also several magnitudes higher than conventional accelerometer and EMG recording systems.

Conclusion

No sign of excessive muscle activity was seen at rest or during motor activities designed to reflect activities of daily living in children with CP. This study thus does not support that excessive muscle activity during daily life is a major problem in children with CP in GMFCS groups I-II and with only mild spasticity. The results suggest that impaired ability to provide sufficient neural drive to the muscles is a more important impairment for these children in their daily life.

Our findings further indicate that children with CP use a higher percentage of the maximal muscle strength in order to accomplish activities of daily living, which could explain why these children are less physically active than their peers.

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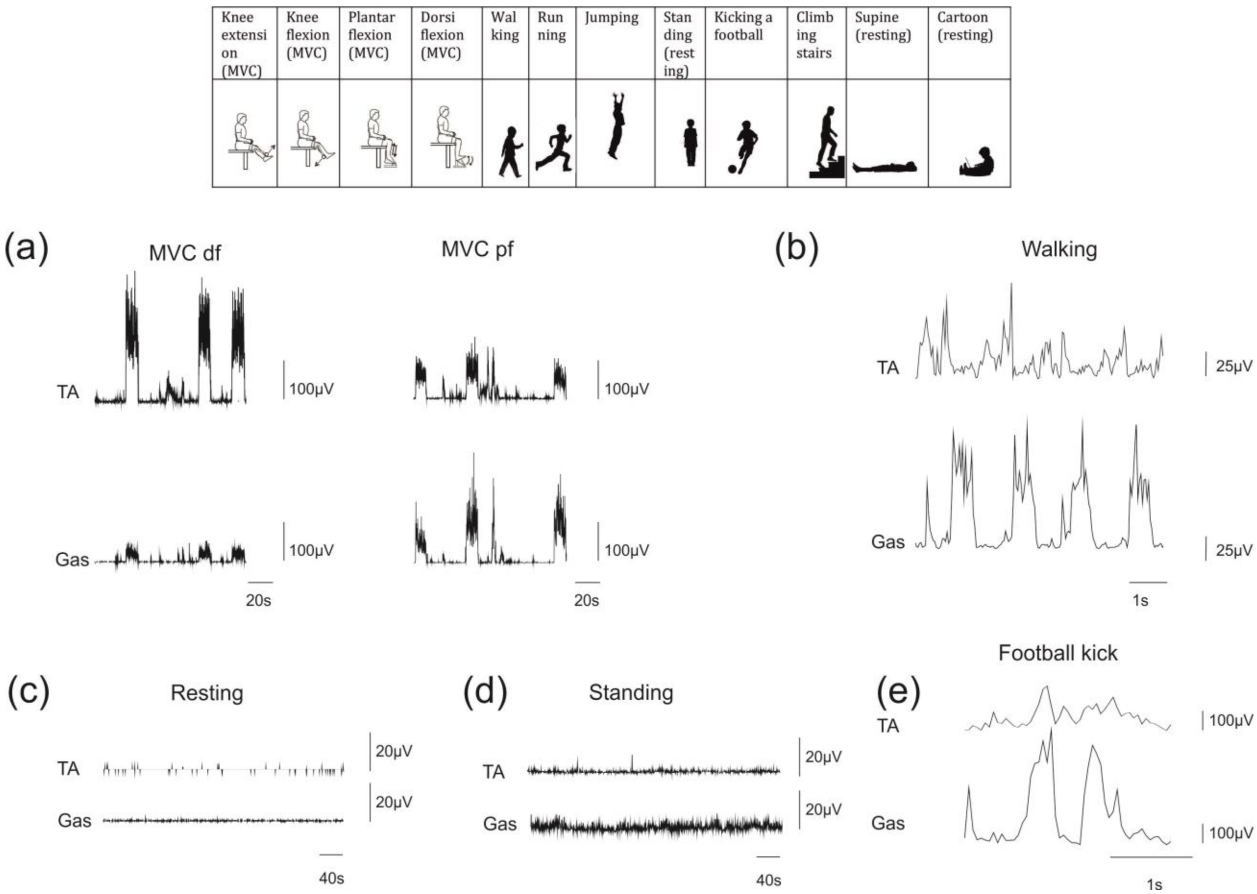
Figures and legends

	Characteristics of children with CP (n = 10)									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Age (year)	9 yr	10 yr	13 yr	7 yr	12 y	9 y	12 y	10 y	7 yr	7 yr
Sex	F	F	M	M	F	M	M	F	M	M
Most affected side (and type of CP)	**Left** (hemiplegia)	Primary **Right** side(diplegia)	**Right** (hemiplegia)	**Right** (hemiplegia)	Primarily **right** side (diplegia)	Primarily **left** side (diplegia)	**Left** (hemiplegia)	**Right** (hemiplegia)	**Right** (hemiplegia)	Primarily **left** side (diplegia)
MRC plantar/dorsi flexion For left (L) and right (R) leg	5/0 (L) 5/5 (R)	3/3 (R) 4/4 (L)	5/4+ (R) 5/5 (L)	4/3 (R) 5/5 (L)	4+/5 (R) 5//5 (L)	3/3 (R) 4/4 (L)	5/4+ (L) 5/5 (R)	5/3–4 (R) 5/5 (L)	5/5 (R) 5/5 (L)	5/5 (L) 5/(5 (R)
ROM* plantar/dorsi flexion	Full / 10 deg. reduced dorsi flexion	Full / 20 deg. reduced dorsi flexion	Full / 5 deg. reduced dorsi flexion	Full / Full	Full / 10 deg. reduced dorsi flexion	Full / Full	10 deg. reduced plantar flexion / 10 deg. reduced dorsi flexion	Full / Full	Full / 10 deg. reduced dorsi flexion	Full / Full
MAS* ankle spasticity (plantarflexors)	0	2	1	N/A	1+	1+	N/A	2	3	1+
GMFCS level	II	II	I	II	I	II	I	II	I	I
Botulinum toxin injections	Yes (>1 year ago)	Yes (>6 years ago)	Yes (> 1 year ago)	Yes (>2 years ago)	Yes (>5 years ago)	no	no	yes (>1 yeear ago)	no	Yes (>two years ago)
Ankle surgery	Yes (> one year ago)	Yes (> 1 year ago)	Yes (>3 years ago)	Yes (>3 years ago)	Yes (> 4 years ago)	no	no	no	no	no

Table 1. Characteristics of the 10 children diagnosed with spastic CP. * Only the most affected side is reported. Medical Research Council (MRC) Scale for Muscle Strength. Range of Motion (ROM). The Modified Ashworth scale (MAS). Information not available (N/A).

Figure 1. Example of EMG data patterns. Example of raw (EMG data from the left gastrocnemious and tibialis anterior muscle from one TD subject during various activities. A: MVC during dorsiflexion (df) and plantarflexion (pf) ; B: Treadmill walking ; C: Resting ; D: Standing: E: Football kick.



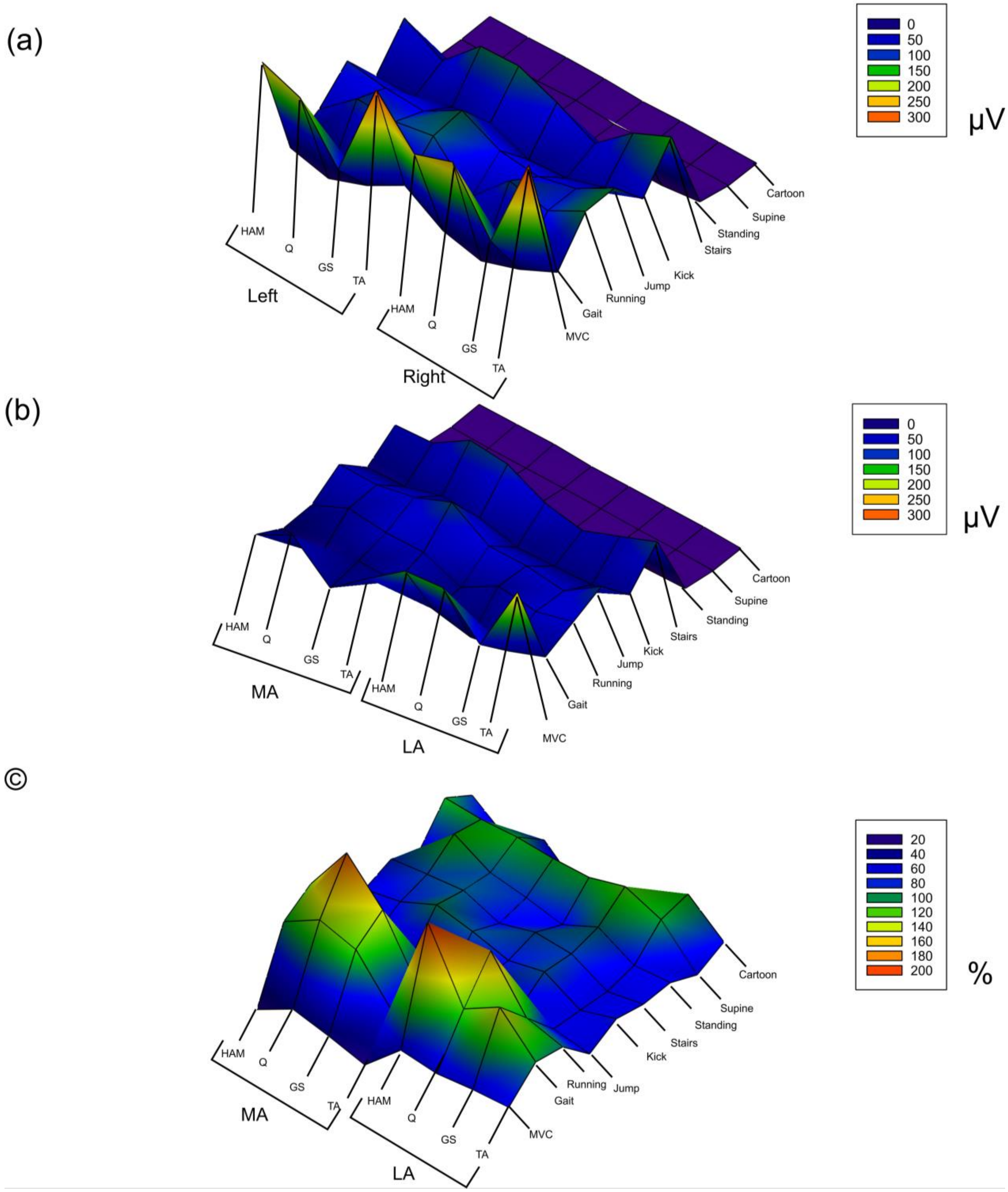


Fig. 2. Heat maps of the absolute amount of EMG activity in TD children (A) and children with CP (B) in all 8 recorded muscles and during all 9 tasks. The data was averaged from all 11 TD children and 10 children with CP. The amount of EMG activity in the individual muscles in the different tasks is given in µV and colour coded according to the bar presented to the right in each

graph. C gives the relative amount of EMG activity in the children with CP relative to the corresponding measurements in TD children expressed in % and colour coded according to the scaling bar presented to the right of the graph. In this comparison the least affected leg in children with CP was related to the right leg in TD children and similar for the most affected and left legs. TA: Tibialis anterior; GS: Gastrocnemius-Soleus. Q: Quadriceps; Ham: Hamstrings. LA: Least affected leg in children with CP; MA: Most affected leg in children with CP.

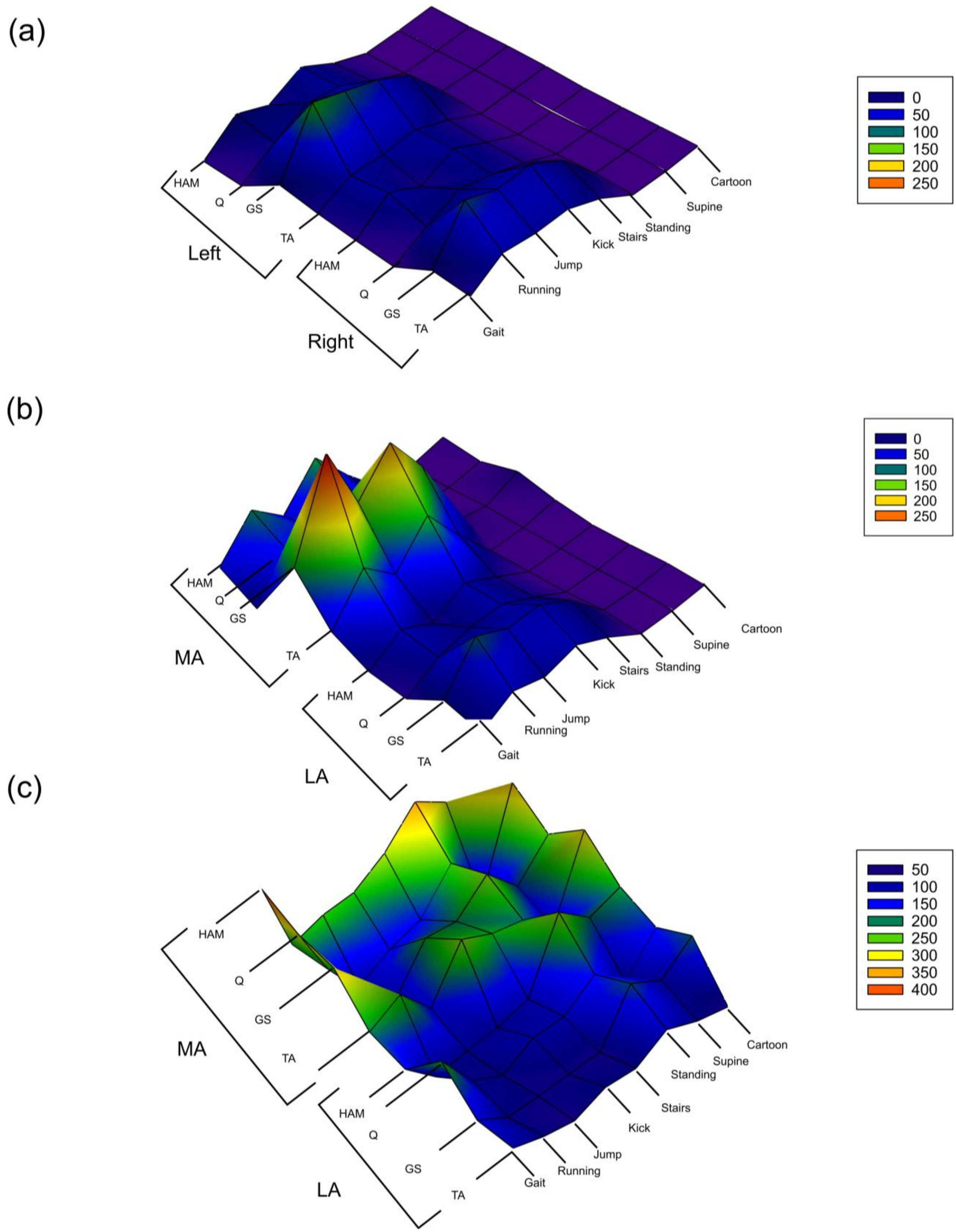


Fig. 3. Heat maps of the amount of EMG activity in TD children (A) and children with CP (B) in

all 8 recorded muscles relative to measurements during MVC in 8 differentand tasks resembling daily activities. The data were averaged from all 11 TD children and 10 children with CP. The amount of EMG activity in the individual muscles in the different tasks is given in % of the amount of EMG activity during MVC and colour coded according to the bar presented to the right in each graph. C gives the relative amount of EMG activity in the children with CP relative to the corresponding measurements in TD children expressed in % and colour coded according to the scaling bar presented to the right of the graph. In this comparison the least affected leg in children with CP was related to the right leg in TD children and similar for the most affected and left legs. TA: Tibialis anterior; GS: Gastrocnemius-Soleus. Q: Quadriceps; Ham: Hamstrings. LA: Least affected leg in children with CP; MA: Most affected leg in children with CP.