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Pathological and physiological muscle co-activation during active elbow extension in children with unilateral cerebral palsy

A. Sarcher^{a,e,*}, M. Raison^b, F. Leboeuf^{a,c}, B. Perrouin-Verbe^a, S. Brochard^{d,e}, R. Gross^{a,e}

^a Motion Analysis Laboratory, Physical Medicine and Rehabilitation, Saint Jacques Hospital, University Hospital of Nantes, Nantes, France

^b Rehabilitation Engineering Chair Applied to Pediatrics (RECAP), Sainte-Justine University Hospital and Ecole Polytechnique de Montréal, 5200 rue Bélanger Est, Montréal, Québec, Canada

^c College of Health and Social Care, University of Salford, Frederick Road Campus, Salford, United Kingdom

^d Physical Medicine and Rehabilitation Department, University Hospital of Brest, Brest, France

^e Laboratory of Medical Information Processing (LaTIM), INSERM UMR 1101, Brest, France

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HIGHLIGHTS

- Muscle co-activation in children with cerebral palsy was pathological and physiological.
- Pathological co-activation increased with elbow extension speed.
- Pathological co-activation was more pronounced in brachioradialis than biceps brachii.

ABSTRACT

Objective: To address the roles and mechanisms of co-activation in two flexor/extensor pairs during elbow extension in children with cerebral palsy (CP).

Methods: 13 Typically Developing (TD) and 13 children with unilateral spastic CP performed elbow extension/flexion at different speeds. Elbow angle and velocity were recorded using a 3D motion analysis system. The acceleration and deceleration phases of extension were analyzed. Co-activation of the brachioradialis/triceps and biceps/triceps pairs was computed for each phase from surface electromyographic signals. Statistical analysis involved linear mixed effects models and Spearman rank correlations.

Results: During the acceleration phase, there was strong co-activation in both muscle pairs in the children with CP, which increased with speed. Co-activation was weak in the TD children and it was not speed-dependent. During the deceleration phase, co-activation was strong and increased with speed in both groups; co-activation of brachioradialis/triceps was stronger in children with CP, and was negatively correlated with extension range and positively correlated with flexor spasticity.

Conclusions: Abnormal patterns of co-activation in children with CP were found throughout the entire movement. Co-activation was specific to the movement phase and to each flexor muscle.

Significance: Co-activation in children with CP is both physiological and pathological.

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1. Introduction

Cerebral palsy (CP) is a neurological pathology caused by a defect or lesion of the immature brain, which leads to disorders of movement and posture. CP is characterized by a combination of motor impairments, including spasticity, hyper-reflexia, muscle weakness, loss of selective motor control and excessive muscle co-activation (CA). These motor impairments can severely limit activities of daily living (O'Shea, 2008).

Abbreviations: AROM, active range of motion; CA, co-activation; CP, cerebral palsy; EAccP, extension acceleration phase; EDecP, extension deceleration phase; EF, extension/flexion; EMG, electromyography; IUL, involved upper limb; MACS, Manual Ability Classification System; MAS, Modified Ashworth Scale; PPV, Percentage to Peak Velocity; SUCP, Spastic Unilateral Cerebral Palsy; TD, Typically Developing.

* Corresponding author at: Motion Analysis Laboratory, Physical Medicine and Rehabilitation, Saint Jacques Hospital, University Hospital of Nantes, Nantes, France.

E-mail address: aurelie.sarcher@gmail.com (A. Sarcher).

Muscle CA is the simultaneous activation of an agonist muscle, which causes movement at a joint in a particular direction, and an antagonist muscle, which opposes the movement (Ikeda et al., 1998). Physiologically, muscle CA induces mechanical co-contraction of muscles, the role of which is to regulate joint stiffness (Bullock and Grossberg, 1991). Appropriate levels of co-contraction are required during sudden changes in the direction of joint motion, fine motor activities, and to stabilize loaded joints (Humphrey and Reed, 1983; Johansson and Westling, 1988; Valero-Cuevas, 2005). Any alteration in the capacity to regulate the level of co-contraction has a direct impact on movement.

It is well established that children with CP often have excessive CA of the muscles of both lower limbs (Leonard et al., 1991; Unnithan et al., 1996; Ikeda et al., 1998; Prosser et al., 2010; Gross et al., 2013, 2015) and both upper limbs (Feltham et al., 2010; Braendvik and Roeleveld, 2012; Sarcher et al., 2015; Xu et al., 2015). Specifically, active elbow extension of the involved upper limb (IUL) in children with spastic unilateral CP (SUCP) induces excessive CA (Van Thiel et al., 2000; Volman et al., 2002; Sarcher et al., 2015) because of excessive activation of the flexor muscles, which are spastic (Sarcher et al., 2015).

However, it is not yet clear whether the effect of this excessive CA is actually negative, i.e. if it restricts movement (henceforth termed pathological CA), or if it also serves to increase joint stability in patients who also have muscle weakness (henceforth termed physiological CA). Some studies have suggested that there is a relationship between excessive CA and reduced peak elbow velocity (Van Thiel et al., 2000; Rameckers et al., 2010), and between excessive CA and restricted elbow active range of motion (AROM) (Levin et al., 2000; Sarcher et al., 2015). However, there are discrepancies in the literature regarding the effect of reducing muscle hyperactivity, including CA, on motor capacity, by the use of intramuscular injections of botulinum toxin type A. Some studies have found improvements in motor capacity after botulinum toxin A injections in the upper limbs (Lee et al., 2013; Ferrari et al., 2014; Sakzewski et al., 2014; Lidman et al., 2015) while others have found little or no improvement due to the concomitant reduction in strength and loss of necessary, functional CA (Fehlings et al., 2000; Rameckers et al., 2007, 2009; Hoare et al., 2010; Olesch et al., 2010; Speth et al., 2015).

The discrepancies between the results of studies investigating the effect of chemodenervation on upper limb movements are likely related to two issues: On one hand, there is a lack of understanding of the CA mechanisms in the IUL of children with SUCP. Van Thiel et al. (2000) hypothesized that excessive CA in the IUL occurs particularly at the end of the extension movement, when the need for joint stability is the greatest. It is thus necessary to carry out separate analyses of CA during the acceleration and deceleration phases of the movement, in order to determine at which point of the movement the pathological CA occurs. To our knowledge, this has not yet been done. Moreover, movement speed has been shown to increase muscle activation and CA levels during gait, more significantly in the lower limb of children with CP than in the lower limb of Typically Developing (TD) children (Gross et al., 2013). Although some studies of upper limb movements have included the notion of speed (Van Thiel et al., 2000; Rameckers et al., 2010) by analyzing “fast” movements, presumably to induce higher levels of CA, to our knowledge the effect of movement speed on CA in the IUL of children with SUCP has never been quantified. A thorough analysis of the movement conditions under which CA in the IUL of children with SUCP differs from CA in the upper limbs of TD children may provide insights into the different roles of CA, both for diagnostic purposes and to optimize treatment effectiveness.

On the other hand, there is little evidence regarding which muscles should be targeted by chemodenervation treatments, such as botulinum type A injections. Indeed, it remains unclear whether

spastic muscle overactivity differs between different muscles that produce similar movements, and the extent to which it interferes with these movements. In order to determine the muscles which are the most affected, it is necessary to analyze the activation of individual elbow flexor muscles during elbow movement. This would enable the development of appropriate guidelines for treatment by botulinum toxin type A injection.

Therefore, the primary aim of this study was to highlight the different roles of CA in the IUL of children with SUCP. We studied the extent of flexor/extensor CA induced at different velocities of active elbow extension in the IUL of children with SUCP and in the upper limbs of TD children. We developed an approach based on methods that split the movement into the phases of acceleration and deceleration and hypothesized that CA would differ depending on the movement phase. We also expected to find increases in CA with increasing movement speed during active elbow extensions of the IUL.

The second aim was to compare the patterns of activation of the biceps and the brachioradialis muscles during active elbow extension movements.

2. Methods

2.1. Experimentation

2.1.1. Participants

Thirteen children with SUCP (seven males, mean age = 9.1 years, Standard Deviation (SD) = 2.0, range 6.2–12.5) took part in the experiment. Exclusion criteria for the SUCP participants were: botulinum toxin injections within the previous six months or previous surgery of the upper limbs, inability to fully understand or perform the tasks. Table 1 lists the demographic and clinical data for the children with SUCP (Bohannon and Smith, 1987; Eliasson et al., 2006).

Thirteen TD children (eight males, mean age = 9.5 years, SD = 1.9, range 6.3–12.9) were recruited as a control group. The exclusion criterion for the TD children was previous surgery of the upper limbs. The Research Ethics Board of Sainte-Justine Hospital approved the study and the children’s parents or guardians gave informed consent.

2.1.2. Experimental set-up

Kinematics: Upper limb kinematics were assessed using an optoelectronic motion analysis system equipped with twelve infra-

Table 1

Demographic and clinical data for the children with SUCP. The Modified Ashworth Scale (MAS) was used to evaluate spasticity [0: none, 4: severe] (Bohannon and Smith, 1987) and the Manual Ability Classification System (MACS) was used to evaluate upper limb function (1: quite good, 5: very impaired) (Eliasson et al., 2006). *Abbreviations:* F-female. IUL-involved upper limb. M-Male. MACS-Manual Ability Classification System. MAS-Modified Ashworth Scale. SUCP-Spastic Unilateral Cerebral Palsy.

Children with SUCP	Age (years)	Gender	MAS for the IUL Flexors	MACS score
1	8.3	F	2	2
2	6.8	M	0	1
3	7.5	M	1+	2
4	9.1	F	1	1
5	9.3	M	1+	2
6	11.3	M	1	1
7	8.9	M	1+	3
8	6.2	F	0	1
9	8.2	M	1+	3
10	10.8	F	1	2
11	12	F	0	2
12	7.8	F	1	2
13	12.5	M	1	2

red cameras (T40S, VICON, Oxford) operating at 100 Hz. The upper limb marker set from [Laitenberg et al. \(2015\)](#) was used in this study: twenty-nine retro-reflective markers were positioned on anatomical landmarks of the thorax, shoulder, arm, forearm, and hand of one side of the body.

Electromyography: Electromyographic signals of the triceps brachii longus (elbow extensor muscle), the biceps brachii brevis (flexor muscle) and the brachioradialis (flexor muscle) ([Basmajian, 1982](#)) were measured using a wireless surface EMG FreeEMG300 system (BTS, Milan, Italy) (see [Sarcher et al. \(2015\)](#) for electrode placement). Self-adhesive pairs of disposable Ag/AgCl surface electrodes with a recording diameter of 10 mm (Covidien, Mansfield, MA, USA) were placed according to the SENIAM (Surface Electromyography for Non-Invasive Assessment of Muscles) guidelines ([Hermens et al., 1999](#)).

2.1.3. Participant instructions and measurements

Markers were positioned on the dominant upper limbs of the TD children and on the IUL of the children with SUCP. The participants were seated on a bench with the height adjusted so that both feet were flat on the floor and the knees were bent to 90°. A baseline signal was recorded from the EMG electrodes while the participants were at rest. Consecutive cycles of active EF in the sagittal plane, with no elevation of the shoulder were then recorded at three different movement frequencies. The participants were instructed to cover their maximal EF AROM and to keep the shoulder, wrist and finger joints as still as possible during each trial. They were asked to keep their forearm in neutral pronation/supination as much as possible.

The children were instructed to time their maximal extension and maximal flexion with the “bleep” of an auditory metronome. The frequencies for a full EF cycle were 0.35 Hz, 0.50 Hz and 0.65 Hz, meaning that the children had to perform the extension movement in 1.43 s, 1 s and 0.77 s respectively. Standardization of the experimental conditions using externally paced movement allows comparison between the AROM and muscle activation between participants ([van Roon et al., 2005](#)). Moreover, it has been shown that the motor responses of adults with SUCP are improved by externally paced movements compared to internally paced movements ([Van Thiel et al., 2000](#)). AROM and movement smoothness of children with SUCP is improved by the execution of functional, relevant tasks compared to abstract movements ([van der Weel et al., 1991](#); [Wu et al., 2000](#); [Volman et al., 2002](#); [Steenbergen et al., 2004](#)). However, we chose this extension movement for three reasons: 1. It is a simple upper limb movement, which could be performed by all the children included. 2. It is a single degree of freedom movement, minimizing the risk of crosstalk from the forearm, particularly the wrist and finger muscles. 3. The movement is not demanding in terms of precision, thus the role of any physiological CA would simply be to slow down the arm, facilitating interpretation. [Van Roon et al. \(2005\)](#) showed that the need for accuracy increased the strength of CA in adolescents with CP.

It is well documented that the motor control of arm movements changes considerably around the age of 8 years ([Van Braeckel et al., 2007](#); [Wilson and Hyde, 2013](#)). This has been demonstrated for spatial and temporal accuracy ([Bard et al., 1990](#); [Yan et al., 2003](#)), intralimb coordination ([Thomas et al., 2000](#)), and variability ([King et al., 2009](#)). However, these studies analysed arm movements that required both visual and proprioceptive information to be processed, since they involved pointing or reaching and grasping objects. The motor control of linear movements such as elbow flexion/extension develops well before more complex movements such as the patterns of rotation needed in functional tasks like reaching or pointing. Moreover, elbow flexion/extension is a single-joint task that does not require fine motor skills or strength. Therefore there should be few differences in the motor control of

this movement between children aged 6 and 12.5 years. Moreover, the groups were age-matched so any variability in motor control due to age would be similar in both groups.

In order to help the children to achieve the desired frequencies, an occupational therapist stood next to them and mimed the movements. If necessary, prior to data collection, she also guided the movement. Two minutes of rest were allowed between each condition.

2.2. Data processing

Kinematic and EMG data were processed using custom MATLAB® (MathWorks®, Natick (MA), USA) routines and the open-source Biomechanical ToolKit library ([Barre and Armand, 2014](#)).

2.2.1. Kinematic and kinetic processing

The kinematics of the elbow, specifically the relative EF angles, were obtained using the upper limb model proposed by [Laitenberg et al. \(2015\)](#). This subject-specific upper limb model with twenty degrees of freedom includes a closed-loop forearm model which separates the radius and ulna ([Laitenberg et al., 2015](#)). The joint kinematics are obtained from the 3D positions of the markers, using an inverse kinematic process coupled with a global optimization procedure ([Lu and O'Connor, 1999](#)). EF velocity was then obtained by differentiating the relative EF angle.

2.2.2. EMG processing

EMG signals were band-pass filtered (10–450 Hz, Butterworth zero-lag 4th order), full-wave rectified, and smoothed with a low-pass filter (50 Hz, Butterworth zero-lag 2nd order) ([Hodges and Bui, 1996](#)). A 300 ms window with the smallest standard deviation (σ [V]) was located in each EMG signal recorded in the relaxed state (baseline) ([Tedroff et al., 2006](#)), and its mean value (μ [V]) was calculated. An activation threshold T_m [V] was then calculated for each of the three recorded muscles $m = 1 \dots 3$ using Eq. (1).

$$T_m = \mu_m + k\sigma_m, \quad (1)$$

The variable k was set to 3, following the recommendations of [Hodges and Bui \(1996\)](#).

Then, for all trials, the onset time of each muscle, t_{ONm} [s] was determined as the instant at which the processed EMG signal of muscle m exceeded its threshold T_m for at least the following 25 consecutive samples ([Hodges and Bui, 1996](#)). Offset times, t_{OFFm} [s], were similarly considered as the instant at which the signal dropped below the threshold T_m for at least the following 25 consecutive samples.

Finally, the T_m value of each muscle was subtracted from the smoothed EMG signals between t_{ONm} and t_{OFFm} ([Roberts and Gabaldón, 2008](#)). Outside of those bands, the value of the smoothed EMG signal was subtracted from itself in order to obtain a signal of zero ([Ghosh and Haggard, 2014](#)).

This was done to keep only the real activation periods of the smoothed EMG signals and to ignore the baseline noise which differed according to the recorded muscle and to the participant.

EMG processing steps are depicted in [Fig. 1](#).

2.2.3. Extension movement decomposition

Elbow extension was defined as movement between the instant of maximal flexion and the instant of maximal extension. Processed EMG, kinematic and kinetic signals were temporally normalized by the duration of the extension movement. The extension movement was then decomposed into its extension acceleration phase (EAccP), from the instant of maximal flexion to the instant of maximal extension velocity, and its extension

deceleration phase (EDecP), from the instant of maximal extension velocity to the instant of maximal extension (Fig. 2). The Percentage to Peak Velocity (PPV) [%] was defined as the percentage of the extension movement between the EAccP and the EDecP.

2.2.4. Co-activation index (CAI)

Children with spastic CP are unable to perform maximum voluntary contractions due to spasticity and weakness (Damiano et al., 2000). Therefore, the post processed EMG signals of each participant's muscles were divided by their peak value, obtained from the entire EF cycle, not only during the extension movements, to include agonist activations of the flexor muscles (Burden, 2010; Gross et al., 2013). This was the only step in which the flexion movement was considered. The activation area of a muscle was defined as the area under the normalized values of its EMG signal.

Fig. 3 shows the normalized post-processed EMG signals for biceps, brachioradialis and triceps for the mean EF cycle at 0.35 Hz and 0.65 Hz of a TD child and an SUCP child (subject 13 in Table 1).

Co-activation index: as presented in Eq. (2), the co-activation index CAI [%] was based on Falconer and Winter (1985).

$$CAI = 2 \cdot \frac{\int (Ag, Antag)}{\int Ag + \int Antag} \cdot 100, \quad (2)$$

where $\int (Ag, Antag)$ represents the common activation area between agonist and antagonist muscles (coloured area in Fig. 3); $\int Ag$ and $\int Antag$ represent the activation areas of agonist and antagonist muscles respectively.

The CAI was calculated for both the EAccP and the EDecP, according to the following Eqs. (3) and (4), and so that Eq. (5) was verified.

$$CAI_{[EAccP]} = 2 \cdot \frac{\int_{EAccP} (Ag, Antag)}{\int_{EAccP+EDecP} (Ag) + \int_{EAccP+EDecP} (Antag)} \cdot 100, \quad (3)$$

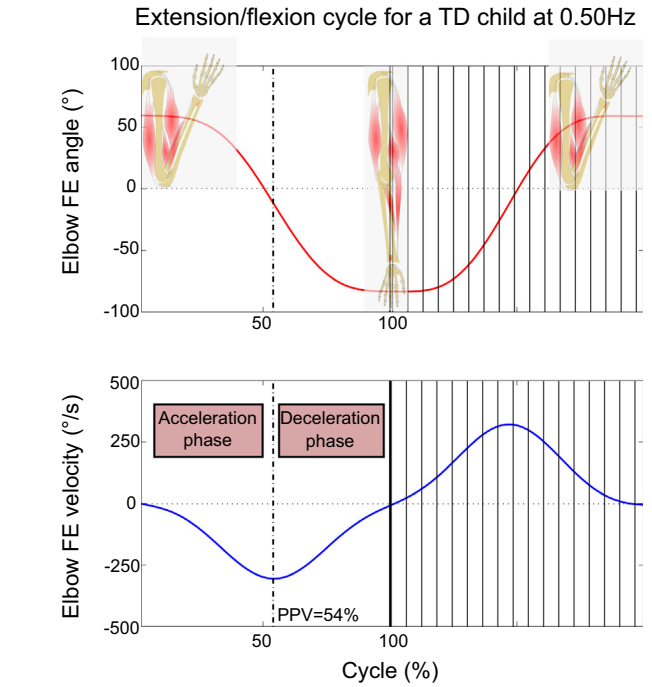


Fig. 2. Elbow EF angle (°) and velocity (°/s) temporally normalized as a function of extension movement time, for a TD child performing an EF trial at 0.50 Hz. Since only the extension movement was analyzed in this study, the flexion movement appears hatched in the figure. The dashed line indicates the instant of maximal extension velocity, or Percentage to Peak Velocity (PPV) which separates the extension acceleration and deceleration phases. Abbreviations: EF-extension/flexion. TD-Typically Developing.

$$CAI_{[EDecP]} = 2 \cdot \frac{\int_{EDecP} (Ag, Antag)}{\int_{EAccP+EDecP} (Ag) + \int_{EAccP+EDecP} (Antag)} \cdot 100, \quad (4)$$

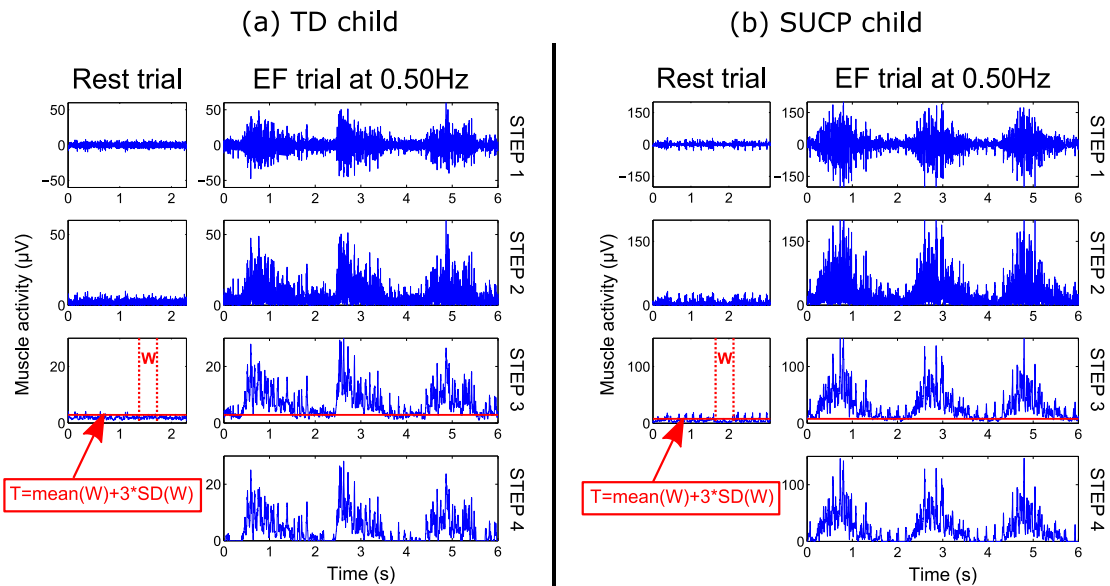


Fig. 1. EMG signals (μV) from the biceps brachii muscle as a function of time (s) shown for 4 different steps of post-processing for a) a TD child during the “rest” trial (left) and during an EF trial at 0.50 Hz (right) and b) a SUCP child (subject 13 in Table 1) during the “rest” trial (left) and during an EF trial at 0.50 Hz (right). Step 1: Band-pass filtered (10–450 Hz, Butterworth zero-lag 4th order) EMG signals. Step 2: Full wave rectified EMG signals. Step 3: EMG signals smoothed with a low-pass filter (50 Hz, Butterworth zero-lag 2nd order). A 300 ms window “W” with the smallest SD was located in the EMG signal of the “rest” trial (Tedroff et al., 2006), and its mean value was calculated. An activation threshold T was then calculated following the equation on the Figure (Hodges and Bui, 1996). Step 4: Smoothed EMG signal with the T value subtracted. The muscle was considered active only if its signal was positive for at least 25 ms. For intervals of less than 25 ms, the value of the smoothed EMG signal was subtracted from itself in order to obtain a signal of zero (Ghosh and Haggard, 2014). Abbreviations: EF-extension/flexion, EMG-electromyography, SD-Standard Deviation, SUCP-Spastic Unilateral Cerebral Palsy, TD-Typically Developing.

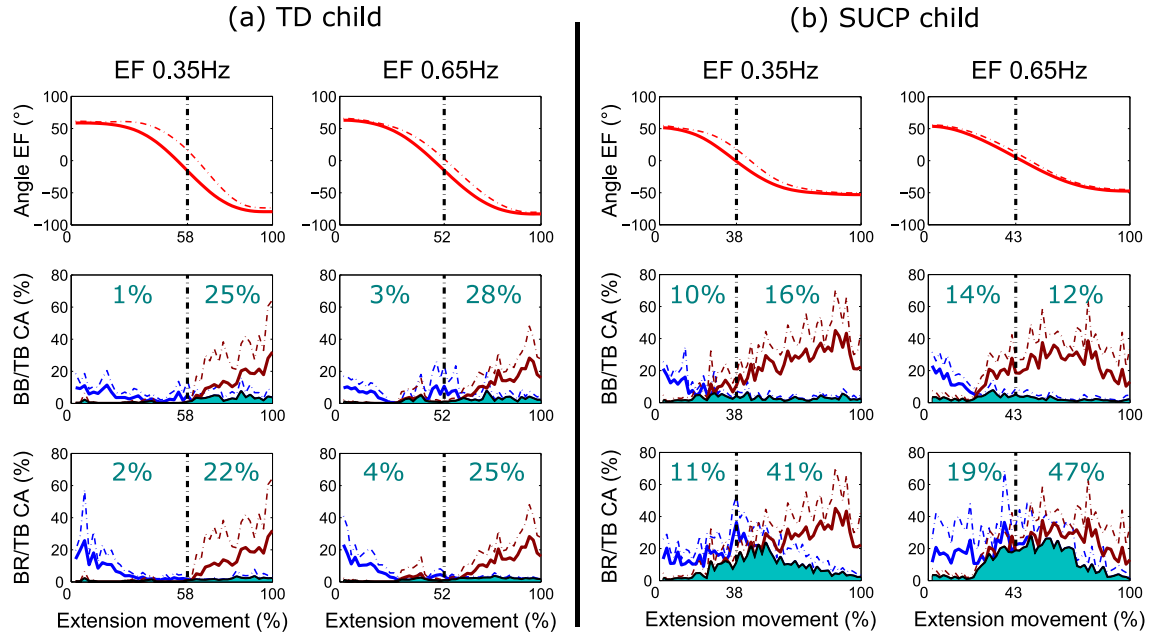


Fig. 3. From top to bottom, temporally normalized as a function of extension movement time: elbow EF angle ($^{\circ}$), normalized EMG signals of the biceps (BB) (blue line)/triceps (TB) (red line) pair, normalized EMG signals of the brachioradialis (BR) (blue line)/triceps (TB) (red line) pair (mean + standard deviation) for a) a TD child performing an EF trial at 0.35 Hz (left) and at 0.65 Hz (right) and b) a SUCP child (subject 13 in Table 1) performing an EF trial at 0.35 Hz (left) and at 0.65 Hz (right). The dotted line indicates the separation between the extension acceleration phase and the extension deceleration phase. For each trial, each antagonist muscle pair, and each movement phase (extension acceleration and extension deceleration), the co-activation index (%), based on the common activation area between the antagonist and the agonist muscles (coloured area) are indicated on the graph. *Abbreviations:* BB-biceps brachii. BR-brachioradialis. TB-triceps brachii. CA-co-activation. EF-extension/flexion. EMG-electromyography. SUCP-Spastic Unilateral Cerebral Palsy. TD-Typically Developing. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$$CAI_{[EAccP]} + CAI_{[EDecP]} = CAI_{[EAccP+EDecP]}, \quad (5)$$

Moreover, since two flexor muscles were recorded, the CAI was calculated for each antagonist pair. Therefore, the CAI was calculated during the extension movement when the action of the two flexors, the biceps brachii and the brachioradialis (antagonist muscles), can oppose the action of the triceps brachii (agonist muscle): 1. for the biceps/triceps brachii pair and 2. for the brachioradialis/triceps brachii pair. Since we considered the EAccP and EDecP, four CAI were calculated for each extension movement. The values of these four CAI for the mean EF cycle at 0.35 Hz and 0.65 Hz of a TD child and an SUCP child (subject 13 in Table 1), are indicated on Fig. 3 to make the link between the post-processed EMG signals and the CAI analysed in this study.

2.2.5. Statistical analysis

An unpaired Student's *t*-test was used to assess inter-group differences in age, height and weight.

Linear mixed effects models were used to test:

- The effect of the group (TD or SUCP) (independent variable) on elbow AROM during the entire extension movement, on PPV, on mean elbow velocity during the extension acceleration phase, and on the four different CAI (dependent variables) of the participant (random variable).
- The effect of movement frequency (independent variable) on the previously cited parameters (dependent variables) of the participant (random variable), for each group.
- The interaction effect between movement frequency and group (independent variables) on the previously cited parameters (dependent variables) of the participant (random variable).

The random variable linked all data obtained within one participant as described in Gross et al. (2013).

In the SUCP group, a Spearman Rank correlation was applied to analyse the correlations between the four different CAI and active elbow extension ROM, PPV, EAccP elbow velocity and the Modified Ashworth Scale (MAS) score for the elbow flexors.

R 2.14 software (R Development Core Team, 2011) was used for the statistical analyses. The 'nlme' package was used to implement the mixed linear models. Significance was set to $P < 0.05$.

3. Results

3.1. Between-group comparison of morphological parameters

There were no significant differences between groups for age, weight or height.

3.2. Kinematic and spatiotemporal data

Elbow AROM during extension was smaller in the SUCP group than in the TD group (data from the 3 movement frequencies pooled) ($P < 0.001$) (Table 2). There was no effect of movement frequency on elbow AROM during extension in any group ($P > 0.05$) (Table 2).

PPV was shorter in the SUCP group than in the TD group (data from the 3 movement frequencies pooled) ($P = 0.009$) (Table 2). For both SUCP and TD groups, the PPV became shorter with increasing movement frequency (respectively $P = 0.002$ and $P < 0.001$) (Table 2).

Mean elbow velocity during the acceleration phase was lower in the SUCP group than in the TD group (data from the 3 movement frequencies pooled) ($P = 0.004$) (Table 2). For both SUCP and TD groups, mean elbow velocity during the acceleration phase was higher with increasing movement frequency ($P < 0.001$), but this effect was smaller in the SUCP group ($P < 0.001$) (Table 2).

3.3. Co-activation index (CAI) analysis

3.3.1. General results

Biceps/triceps CAI and brachioradialis/triceps CAI during the acceleration phase were higher in the SUCP group than in the TD group (data from the 3 movement frequencies pooled) (respectively $P = 0.004$ and $P < 0.001$) (Table 2). Biceps/triceps CAI and brachioradialis/triceps CAI during the acceleration phase only increased with movement frequency in the SUCP group (respectively $P = 0.001$ and $P = 0.021$) (Table 2).

Fig. 4 shows the change in biceps/triceps CAI (Fig. 4a) and brachioradialis/triceps CAI (Fig. 4b) with movement frequency during the acceleration phase for both the TD and SUCP groups.

Brachioradialis/triceps CAI was higher in the SUCP group than in the TD group during the deceleration phase ($P < 0.001$), but not biceps/triceps CAI (data from the 3 movement frequencies pooled) (Table 2). CAI during the deceleration phase increased with movement frequency for both antagonist pairs ($P < 0.001$ for both muscle pairs and for both groups), with no difference between groups ($P > 0.05$ for the interaction group/movement frequency effect) (Table 2).

Fig. 5 shows changes in biceps/triceps CAI (Fig. 5a) and brachioradialis/triceps CAI (Fig. 5b) with movement frequency during the deceleration phase for both TD and SUCP groups.

3.3.2. Sub-groups according to the severity of impairment

Due to the heterogeneity of impairments in the children in the SUCP group, this group was divided into 2 sub-groups according to the Manual Ability Classification System scores (Eliasson et al., 2006): SUCP_1: children with a MACS score I ($n = 4$), and SUCP_2-3: children with a MACS score of II or III. See the Supplement for results.

Fig. 3 presents an example of data from one child with SUCP (subject 13, MACS score II) and one TD child. Similarly to the SUCP group results, SUCP subject 13 had increasing EAccP biceps/triceps

CAI (from 10% to 14%), EAccP brachioradialis/triceps CAI (from 11% to 19%), and EDecP brachioradialis/triceps CAI (from 41% to 47%) with increasing movement frequency. Moreover, these 3 CAI were larger than for the TD child. However, his EDecP biceps/triceps CAI was lower than the TD child and decreased with movement frequency (from 16% to 12%).

3.4. Relationship between CA and clinical and kinematic parameters

In the SUCP group, the Spearman Rank test showed significant moderate to strong correlations ($|r| > 0.5$) (Table 3):

- Between the brachioradialis/triceps CAI during the deceleration phase and the elbow AROM during extension ($r = -0.50$; $P < 0.001$).
- Between the brachioradialis/triceps CAI during the deceleration phase and the PPV ($r = -0.57$; $P < 0.001$).
- Between the brachioradialis/triceps CAI during the deceleration phase and the MAS score of the flexors ($r = 0.56$; $P < 0.001$).

4. Discussion

The objectives of this study were to highlight the different roles of CA during active elbow extensions of the IUL of children with SUCP and to determine whether elbow flexors were similarly affected by pathological CA. We found abnormal patterns of co-activation in children with SUCP that were specific to the movement phase and to the antagonist flexor muscle. Table 4 summarizes the differences between both populations.

4.1. CA in Typically Developing children

In the TD children, CA during the acceleration phase of the elbow extension movement was weak and was not speed-dependent. CA during the deceleration phase was stronger (150%

Table 2

Mean (SD) values for kinematic, spatiotemporal and CAI data, differences between groups, movement frequency effects and between-group and movement frequency interactions, tested with linear mixed effects models. Abbreviations: *-Significant. AROM-active range of motion. CAI-Co-activation index. EAccP-extension acceleration phase. EDecP-extension deceleration phase. PPV-Percentage to Peak Velocity. NS-non significant. SD-Standard deviation. SUCP-Spastic Unilateral Cerebral Palsy. TD-Typically Developing. Bold P -values indicate a significant difference.

Kinematic, spatiotemporal and CAI data (units)	Mean (SD)		Between groups: Parameter estimate (Std.Error) F-value (dof) (P-value)	Movement frequency effect: Parameter estimate (Std.Error) F-value (dof) (P-value)		Group/movement frequency interaction: Parameter estimate (Std.Error) F-value (dof) (P-value)
	SUCP	TD		SUCP	TD	
Kinematic and spatiotemporal data						
Elbow AROM during extension (°)	106.19 (22.82)	138.61 (11.85)	36.57 (7.87) F = 21.59 (1,24) (<0.001*)	1.64 (1.66) F = 0.98 (1,516) NS	3.42 (1.79) F = 3.66 (1,516) NS	1.77 (2.44) F = 0.53 (1,516) NS
PPV (%)	51.25 (8.07)	55.70 (6.78)	4.97 (1.73) F = 8.20 (1,24) (0.009*)	-4.29 (1.36) F = 9.89 (1,516) (0.002*)	-7.94 (1.46) F = 29.41 (1,516) (<0.001*)	-3.65 (2.00) F = 3.32 (1,516) NS
EAccP Elbow velocity (°/s)	124.02 (39.38)	149.83 (37.28)	30.46 (9.67) F = 9.91 (1,24) (0.004*)	88.51 (3.41) F = 672.25 (1,516) (<0.001*)	119.02 (3.67) F = 1053.66 (1,516) (<0.001*)	30.51 (5.01) F = 37.09 (1,516) (<0.001*)
<i>CAI data</i>						
EAccP Biceps/triceps CAI (%)	16.49 (11.01)	7.64 (7.11)	-9.37 (2.89) F = 10.50 (1,24) (0.004*)	4.38 (1.34) F = 10.69 (1,516) (0.001*)	-1.96 (1.44) F = 1.85 (1,516) NS	-6.34 (1.97) F = 10.38 (1,516) (0.001*)
EAccP Brachioradialis/triceps CAI (%)	17.49 (10.43)	7.56 (6.46)	-10.16 (2.69) F = 14.32 (1,24) (<0.001*)	2.91 (2.38) F = 5.36 (1,516) (0.021*)	-1.60 (1.35) F = 1.41 (1,516) NS	-4.51 (1.84) F = 5.99 (1,516) (0.015*)
EDecP Biceps/triceps CAI (%)	22.00 (12.40)	18.72 (11.03)	-3.81 (3.50) F = 1.19 (1,24) NS	7.89 (1.72) F = 20.95 (1,516) (<0.001*)	10.79 (1.85) F = 34.00 (1,516) (<0.001*)	2.90 (2.53) F = 1.32 (1,516) NS
EDecP Brachioradialis/triceps CAI (%)	30.04 (16.20)	15.32 (8.95)	-15.69 (4.15) F = 14.28 (1,24) (<0.001*)	9.64 (1.77) F = 29.56 (1,516) (<0.001*)	8.77 (1.91) F = 51.12 (1,516) (<0.001*)	-0.88 (2.60) F = 0.11 (1,516) NS

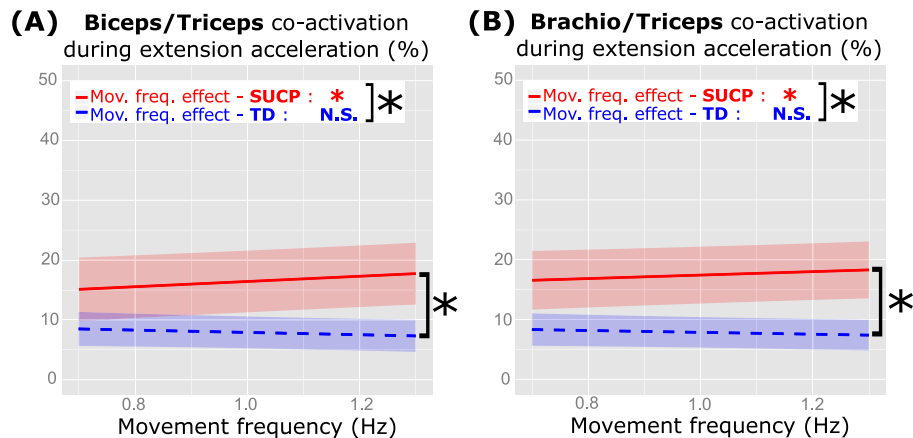


Fig. 4. Change in a. EAccP biceps/triceps CAI (%) and b. EAccP brachioradialis/triceps CAI (%), as a function of movement frequency (Hz) for both TD (blue dashed line) and SUCP (red solid line) groups. The standard deviation of the predictions for each linear mixed effects model is represented by a shaded area. The statistical significance of between-groups effects is directly indicated on the graphs. Movement frequency effects and group/movement frequency interactions are indicated in the white frame. *Abbreviations:* *-Significant. CAI-co-activation index. EAccP-extension acceleration phase. Mov. freq.-movement frequency. NS-non significant. SUCP-Spastic Unilateral Cerebral Palsy. TD-Typically Developing. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

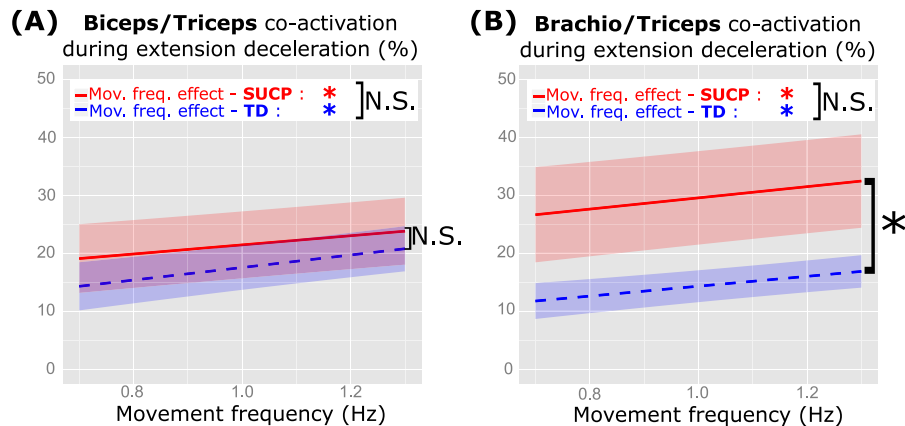


Fig. 5. Change in a. EDecP biceps/triceps CAI (%) and b. EDecP brachioradialis/triceps CAI (%), as a function of movement frequency (Hz) for both TD (blue dashed line) and SUCP (red solid line) groups. The standard deviation of the predictions for each linear mixed effects model is represented by a shaded area. The statistical significance of between-groups effects is directly indicated on the graphs. Movement frequency effects and group/movement frequency interactions are indicated in the white frame. *Abbreviations:* *-Significant. CAI-co-activation index. EDecP-extension deceleration phase. Mov. freq.-movement frequency. NS-non significant. SUCP-Spastic Unilateral Cerebral Palsy. TD-Typically Developing. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Spearman Rank correlations in the Spastic Unilateral Cerebral Palsy (SUCP) group for kinematic, spatiotemporal and CAI data. For each variable, upper line = Spearman test rho value; lower line = P-value. *Abbreviations:* *-Significant. AROM-active range of motion. CAI-co-activation index. EAccP-extension acceleration phase. EDecP-extension deceleration phase. IUL-involved upper limb. MAS-Modified Ashworth Scale. PPV-Percentage to Peak Velocity. NS-non significant. SUCP-Spastic Unilateral Cerebral Palsy. Bold P-values indicate a significant difference.

	EAccP Biceps/triceps CAI	EAccP Brachioradialis/triceps CAI	EDecP Biceps/triceps CAI	EDecP Brachioradialis/triceps CAI
Elbow AROM during extension	-0.12 NS	-0.03 NS	-0.13 (0.033*)	-0.50 (<0.001*)
PPV	-0.12 NS	-0.03 NS	-0.30 (<0.001*)	-0.57 (<0.001*)
EAccP Elbow Velocity	0.00 NS	0.07 NS	0.00 NS	-0.18 (0.003*)
MAS for the IUL flexors	0.32 (<0.001*)	0.22 (<0.001*)	0.34 (<0.001*)	0.56 (<0.001*)

of CA during the acceleration phase), and increased with movement speed. These results are in accordance with previous studies which suggest that the role of CA is to slow down and stabilize the joint at the end of the movement (Humphrey and Reed, 1983; Johansson and Westling, 1988; Valero-Cuevas, 2005). We hypothesize that the purpose of CA in this case may also be to prepare the arm for a sudden change of direction, since the tasks involved cyclical EF movements (Rouard and Clarys, 1995). In contrast, CA must be weak at the beginning of the movement to allow the agonist muscle to initiate the movement. It is important to highlight that for the TD children, the level of CA was similar for both muscle pairs.

4.2. CA in children with Spastic Unilateral Cerebral Palsy

The patterns of CA in the children with SUCP were pathological from the beginning to the end of the movement, compared with the TD children. The patterns were specific to the movement phase and to the flexor/extensor muscle pair. During the acceleration phase, CA differed in both muscle pairs of the children with SUCP compared with the TD children in two aspects: first the level, since CA was stronger in the children with SUCP than in the TD children, and secondly in speed-dependence, since CA increased with speed in the children with SUCP whereas it did not change with speed in the TD children. During the deceleration phase, only CA of the bra-

Table 4

Summary of the differences in CA between the TD and the SUCP groups. In the "SUCP group" column, conclusions regarding pathological CA are indicated in bold type.

		Coactivation	
		TD group CA (Physiological CA)	SUCP group CA (Both physiological and pathological CA)
Extension acceleration <i>biceps brachii</i>	Level	Weak (8%)	Strong (16%)
	Speed dependency	↔	↑
	Role	None	Limits movement, increases with speed
Extension acceleration <i>brachioradialis</i>	Level	Weak (8%)	Strong (17%)
	Speed dependency	↔	↑
	Role	None	Limits movement, increases with speed
Extension deceleration <i>biceps brachii</i>	Level	Strong (19%)	Strong (22%)
	Speed dependency	↑	↑
	Role	Slows down and stabilizes joint	Slows down and stabilizes joint
Extension deceleration <i>brachioradialis</i>	Level	Strong (15%)	Strong (30%)
	Speed dependency	↑	↑
	Role	Slows down and stabilizes joint	-Slows down and stabilizes joint -Limits movement, correlated (negatively) with elbow AROM

Abbreviations: ↔ -Not speed dependent, ↑ -Increases with speed, CA-co-activation, SUCP-Spastic Unilateral Cerebral Palsy, TD-Typically Developing.

chioradialis/triceps pair differed between groups, it was stronger in the SUCP group.

These abnormal patterns are suggestive of pathological CA. Firstly, the regulation of CA was impaired throughout the entire extension movement. Excessive CA in one or several flexor/extensor muscle pairs likely restricts movement. This is supported by the fact that movement speed and range of motion were reduced and the acceleration phase was shorter in the SUCP group. Secondly, the excessive CA was speed-dependent in both flexors, from the instant of movement initiation.

However, physiological patterns of CA were also found in the SUCP group (i.e. similar patterns to the TD children). CA was speed-dependent in both muscle pairs during the deceleration phase, and the level of biceps/triceps CA during the deceleration phase was similar in both groups. This suggests that CA in children with SUCP is regulated by both intact physiological mechanisms which stabilize the joint, and pathological mechanisms resulting from the cerebral lesions.

Unlike in the TD group, the behavior of each flexor muscle differed in the SUCP group. The level of brachioradialis/triceps CA during the deceleration phase was about twice that of the TD children, whereas the level of biceps/triceps CA during the deceleration phase was similar to that of the TD children. This suggests that the regulation of CA differs between agonist muscles, which may thus be more or less affected by motor impairments. Electromyographic evaluations of voluntary upper limb movements provide an insight into the nature of the movement disorder and are therefore useful for diagnosis as well as to guide treatment. It has been suggested that co-contraction is primarily triggered by supraspinal drive, and therefore that it increases with the intensity of the motor task (Gracies et al., 2010). This is fully in accordance with our results that showed a speed-dependence of co-activation. In order to better understand the mechanisms of co-activation, neurophysiological investigations of segmental (medullary) and long loop reflexes should be performed, and confronted with investigations of the descending motor drive from the pyramidal tract.

We made the assumption that the pathological CA during the acceleration phase affected the movement kinematics of the children with SUCP. However, CA of the brachioradialis/triceps and biceps/triceps pairs was not correlated with PPV or mean elbow velocity during this phase. It is well known that movement speed is reduced in children with SUCP, however this restriction is difficult to quantify as their AROM is also restricted. In our study, the children with SUCP successfully performed EF movements at higher movement frequencies, with no loss of their extension AROM. We suggest that this was partly due to the fact that the

movement was gravity-assisted, thus the children could take advantage of the inertial forces which increased with movement velocity. Since pathological CA increased with movement frequency during the acceleration phase, we assume that for higher movement frequencies, at some point the force produced by flexors would overcome the inertial forces, resulting in a decrease in AROM. This is in accordance with Rameckers et al. (2010) who showed that reducing antagonist elbow flexor activity helped children with SUCP to perform fast alternating shift tasks with an increase in elbow velocity.

The excessive CA of brachioradialis/triceps during the deceleration phase in the SUCP group was most correlated (negatively) with elbow AROM during extension and with PPV, suggesting a relationship between the level of brachioradialis/triceps CA during the deceleration phase and motor impairment. This was confirmed by the positive correlation between brachioradialis/triceps CA during the deceleration phase and flexor spasticity (MAS).

4.3. Limitations of the study

The study may be insufficiently statistically-powered because of the small number of subjects included. Non-significant results should therefore be interpreted with caution. Moreover, the distribution of spasticity in the children with SUCP was variable, leading to heterogeneous results. However, this also made the sample representative of children with unilateral spastic cerebral palsy.

4.4. Clinical significance

Impaired regulation of CA was found throughout the entire extension movement in the children with SUCP. CA was pathological for both biceps and brachioradialis during the acceleration phase, but only for brachioradialis during the deceleration phase. These results suggest that the elbow flexors are differently affected by spastic muscle overactivity. However, the results varied between the children because they had each had SUCP of differing severity. Indeed, the results presented in the Supplement show that the CA of brachioradialis and biceps was similarly high in the children with the most severe SUCP (MACS score II and III). On the other hand, it seemed quite obvious looking at subject 13, who had a MACS score of II (Fig. 3), that his brachioradialis was more affected by muscle overactivity than his biceps. We thus suggest that individual analyses of voluntary upper limb movements, including EMG of individual elbow flexor muscles, might be carried out (Van Thiel et al., 2000) in order to determine the specific mechanisms of movement limitations in each child and to provide an appropriate treatment plan.

This could highlight more appropriate muscles than the biceps brachii as targets to treatment. Currently, the biceps brachii is the most common muscle to be injected with botulinum toxin type-A (Gracies, 2005; Nalysnyk et al., 2013), mostly for practical reasons since the muscle is superficial and easy to inject (Ismail et al., 2015). Moreover, maintaining some or all of the biceps muscle activation, when justified, would preserve its powerful supination action, especially as children with SUCP frequently have limited supination AROM (de Bruin et al., 2013; Ismail et al., 2015; Sarcher et al., 2015).

5. Conclusion

This study provided an insight into co-activation during active elbow extension of the involved upper limb of children with Spastic Unilateral Cerebral Palsy. Both pathological and physiological co-activation was found. Excessive, speed-dependent co-activation was found during the acceleration phase of extension, for both brachioradialis/triceps and biceps/triceps muscle pairs, and excessive brachioradialis/triceps co-activation was found during the deceleration phase. Moreover, the brachioradialis/triceps co-activation during the deceleration phase was negatively correlated with active range of extension. Our methodology could be used to evaluate the effectiveness of treatments (for example constraint-induced movement therapy) through pre- and post-treatment evaluations of voluntary upper limb movements with quantification of changes in kinematics and muscle co-activation.

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