Quadriceps Femoris Muscle Voluntary Force and Relaxation Capacity in Children With Spastic Diplegic Cerebral Palsy

Karin Tammik, Mariann Matlep, Jaan Ereline, Helena Gapeyeva, and Mati Pääsuke

Isometric voluntary force production and relaxation capacity of the quadriceps femoris (QF) muscle was compared between 12 children with spastic diplegic cerebral palsy (CP) and healthy controls, age 10–11 years. Children with CP had less ($p < .05$) maximal voluntary-contraction force, voluntary activation, and rate of force development than controls. Visual reaction to contraction did not differ significantly in measured groups, whereas the reaction time to relaxation and half-relaxation time were longer ($p < .05$) in children with CP. The authors concluded that in children with CP, the capacity for rapid voluntary force production and relaxation is reduced to a greater extent than isometric maximal force.

Cerebral palsy (CP) is an umbrella term for a group of frequent disorders of motor function caused by a nonprogressive lesion of the developing brain. Many subtypes of CP have been defined, with spastic diplegia and hemiplegia being the most prevalent. A significant weakness of the muscles of lower limbs has been suggested in children with spastic diplegic CP (8,22,26,30), which can be associated with difficulties performing everyday functional activities. Most studies assessing muscle weakness in children with spastic CP have indicated a markedly reduced isometric maximal voluntary contraction (MVC) force (3,8,26,30) or isokinetic peak torque (5,9) of different muscle groups than in age- and gender-matched healthy children. Reduced force production in children with CP has been attributed to either incomplete recruitment or decreased motor-unit discharge rates during MVC (5,30). An increased muscle cocontraction as the simultaneous activation of agonist and antagonist muscle groups is an important factor of neuromuscular impairment in CP (7,8,12). Knowledge of mechanisms underlying muscle weakness in lower extremities in children with spastic diplegic CP is necessary to develop more effective interventions for increasing force production in such children.

A significantly reduced isometric MVC force of the quadriceps femoris (QF) muscle has been observed in children with spastic diplegic CP as compared with age- and gender-matched healthy children (3,6,26). A reduced force production of the knee extensor muscles has been shown to be related to diminished functional capacity in children with CP, as evidenced by lower scores on the gross motor
function measure and increased energy expenditure during gait in the weaker children (15). The weakness of the QF muscles in children with spastic diplegic CP can in part be attributed to a central activation failure, that is, the inability of the central nervous system to fully recruit and optimally activate available motor units. The ability to achieve complete activation of the QF muscle in healthy and clinical populations is commonly assessed by twitch interpolation (14,20) and burst superimposition (17,26), both with superimposing the supramaximal electrical stimulus while a participant performs an isometric MVC. Any increment in force from the stimulus suggests incomplete activation of the muscle. It is assumed that the superimposed stimulation will recruit muscle fibers that are not activated by voluntary effort and thereby will produce an extra force that is superimposed on the voluntary force. Only one previous study, however (26), has compared voluntary activation (VA) of the QF muscle in children with and without spastic diplegic CP, indicating a significantly lowered VA in children with CP. Little attention has been paid to investigating the capacity for rapid voluntary force production and relaxation of the QF muscle in children with spastic diplegic CP, which is an important indicator of neuromuscular performance and movement control.

The purpose of this study therefore was to compare voluntary force production and relaxation capacity of the QF muscle in prepubertal children with spastic diplegic CP and age- and gender-matched healthy controls. The QF muscle plays an important role in many movement activities, including gait. This muscle group has a great importance in the function and stability of the knee joint, as well as prevention of knee injuries. We hypothesized that the children with spastic diplegic CP would exhibit a reduced isometric MVC force and VA and impaired capacity for rapid voluntary isometric force production and relaxation of the QF muscle, whereas the capacity for rapid isometric force production and relaxation in children with CP would be reduced to a greater extent than isometric MVC force.

**Material and Methods**

**Participants**

Twelve prepubertal children age 10–11 years (6 girls and 6 boys) with spastic diplegic CP and 12 age- and gender-matched children without disabilities (also 6 girls and 6 boys) as controls participated in this study (Table 1). Inclusion criteria for children with CP were diagnosis of spastic diplegia, presence of spasticity with a rating of 2 or 3 on the modified Ashworth scale (1), ability to ambulate at least 10 m without stopping, and no fixed contractures or previous surgery on the lower limb. The children with spastic diplegic CP were also classified according to the gross motor function classification system (21). Accordingly, 2 were on Level I, 8 on Level II, and 2 on Level III. All children were able to follow instructions. None of the children had impaired visual, somatosensory, hearing, or vestibular function. Pubertal stage was determined according to the criteria of Tanner (27) by a pediatrician of the same gender as the participant. The children were classified as prepubertal if pubic hair and genital development for boys and breast development and pubic hair for girls were both scored as Stage 1. All children (CP and controls) and parents and guardians were informed of the purpose and experimental methods and gave written and verbal consent to be participants. The study was approved by the university ethics committee.
Apparatus and Experimental Protocol

During measurement, the participants sat in a custom-made dynamometric chair with the knee and hip angles equal to 90° and 110°, respectively. The body position of the subjects was secured by three Velcro belts placed over the chest, hip, and thigh. The unilateral knee extension force was recorded by a chair-fixed standard strain-gauge transducer (DST 1778, Russia) connected with the plate by a rigid bar. The strain-gauge transducer pad was placed approximately 3 cm above the apex of the lateral malleolus on the anterior aspect of the leg. Signals from the strain-gauge transducer were linear from 0 to 2500 N. The force signals were sampled at the frequency of 1 kHz and stored on the hard disk of a computer using WSportLab software (Urania, Estonia).

During the testing of isometric MVC force of the QF muscle, participants were asked to exert knee extension against the pad of the strain-gauge system as forcefully as possible. The maximal contraction effort was held for approximately 3 s. Three maximal attempts were recorded, and the best result was taken for further analysis. Strong verbal encouragement and visual online feedback were used to motivate the participants. A rest period of 2 min was allowed between the attempts. Isometric MVC force relative to body mass was calculated.

During testing of the isometric force–time and relaxation–time characteristics of the QF muscle, the participants were instructed to react to visual stimuli (lighting of the signal lamp, placed 1.5 m from the subject) as quickly and forcefully as possible by extending the leg against a cuff fixed to a strain-gauge system, to maintain the maximal effort as long as the signal was on (2 s) and to relax the muscles suddenly after the disappearance of the signal. Three attempts were carried out, and the trial with highest isometric MVC force was used for further analysis. A rest period of 2 min was allowed between the attempts. The following characteristics were calculated: latency of contraction (LATc)—the time delay between the visual signal and the onset of force production, rate of isometric force development (RFD50)—the first derivate of force development (dF/dt) at the level of 50% of MVC, latency of relaxation (LATr)—the time delay between the visual signal stopping and onset of quick decline in force production during relaxation, and half-relaxation time (HRT)—the time of half of the decline in force during relaxation.

During testing of VA of the QF muscle, transcutaneous electrical stimulation with supramaximal square wave pulses of 1-ms duration was applied using an

<table>
<thead>
<tr>
<th>Variable</th>
<th>Children With CP (n = 12)</th>
<th>Controls (n = 12)</th>
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</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>11.2 ± 0.7</td>
<td>11.2 ± 0.7</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>136.8 ± 7.6</td>
<td>138.9 ± 7.6</td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>33.0 ± 11.4</td>
<td>33.7 ± 10.0</td>
</tr>
<tr>
<td>Body mass index (kg × m²)</td>
<td>17.4 ± 4.2</td>
<td>17.3 ± 3.5</td>
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Note. CP = cerebral palsy. Variables are expressed as mean ± SD. No significant differences (p > .05) were noted among groups.
isolated voltage stimulator (Medicor MG-440, Hungary) and two self-adhesive surface electrodes (5 × 10 cm, Medicompex SA, Ecublens, Switzerland) placed transversely on the proximal (cathode) and distal (anode) third of the anterior thigh. Skin preparation for each electrode included shaving and light abrasion of the skin followed by cleaning with isopropyl alcohol. Voluntary activation of the QF muscle was estimated by twitch-interpolated technique (14). Participants were asked to reach their maximal force level in approximately 3 s and to maintain it after the supramaximal stimulus was delivered and until they were told to relax. The total duration of this contraction was approximately 5 s. Visual feedback was provided by the display of the strain-gauge amplifier. In fully activated QF muscle, no additional force is generated by the muscle as a result of superimposed electrical twitches. If VA of the QF muscle is reduced, additional force can be generated by superimposed twitches (20). This indicates additional activity from motor units not fully activated at the time of stimulus. The intensity for supramaximal stimuli was assessed during a familiarization session and corresponded to 10% of the level required to evoke a resting maximal twitch contraction (19). Three trials were performed with an interval of 2 min, and the trial with the greatest prestimulus voluntary force was taken for further analysis. The VA of the QF muscle was calculated from force-time curve by the formula:

\[ VA = \left( \frac{F_v}{F_{ES}} \right) \times 100 \% \]

in which \( F_v \) is the voluntary isometric force produced immediately before the electrical stimulus and \( F_{ES} \) is the peak force produced by the electrical stimulus superimposed on the voluntary effort. VA ≥95% was used as the operational definition of full activation of the QF (19,20).

Participants were given instructions 24–48 hr before data collection, and the testing of isometric MVC force, force–time, and relaxation–time characteristics of the QF muscle and electrical-stimulation procedures were demonstrated. This was followed by a practice session to familiarize the participants with the procedures. The participant’s dominant leg was determined based on kicking preference. During the testing, recording of isometric MVC force of the QF muscle followed with assessment of isometric force–time and relaxation–time characteristics. After a 5-min rest period, VA of the QF muscle was recorded. The same researcher with long-term experience in this kind of testing procedure tested all participants between 11 a.m. and 3 p.m.

Statistics

Data are means and standard errors of mean (±SE). One-way analysis of variance (ANOVA) followed by Scheffé post hoc comparisons was used to test for differences between groups. A level of \( p < .05 \) was selected to indicate statistical significance. Main differences in three primary measures in the current study (MVC force, RFD_{50}, and VA) between children with CP and controls were tested for statistical significance (alpha = .05). Statistical power analysis demonstrated that 12 children in each group is a sufficient number to detect a significant difference (\( \beta < 0.080 \)) in MVC force (\( \beta = 0.99 \)), RFD_{50} (\( \beta = 0.98 \)), and VA (\( \beta = 0.99 \)).
Results
As shown in Figure 1, prepubertal children with spastic diplegic CP had a significantly lower \( (p < 0.05) \) isometric MVC force, isometric MVC force:BM ratio, and isometric \( \text{RFD}_{50} \) of the QF muscle than the age- and gender-matched healthy controls. In children with spastic diplegic CP, HRT was significantly longer \( (p < .05) \) than in controls (Figure 2[a]). When compared with controls, VA of the QF muscle in children with spastic diplegic CP was significantly lower \( (p < .05; \text{Figure 2[b]}) \). There were no significant differences \((> .05)\) in \( \text{LAT}_C \) between the measured groups of children in the current study (Figure 3[a]). Children with spastic diplegic CP, however, had a significantly longer \((p < .05)\) \( \text{LAT}_R \) than controls (Figure 3[b]).

Discussion
The current study indicated a marked isometric voluntary force deficit in the QF muscle in prepubertal children with spastic diplegic CP. Children with CP produced 38% less isometric MVC force and 37% less MVC force relative to body mass than the age- and gender-matched healthy controls. Damiano et al. (7) reported an isometric voluntary force deficit of 31% in the QF muscle for children with spastic diplegic CP at the same knee joint angle (90°) during testing as in the current study, whereas Stackhouse et al. (26) demonstrated an isometric force deficit of 56% in the QF muscle for these children at the knee joint angle of 60°. In the current study, children with CP had 64% less isometric \( \text{RFD}_{50} \) of the QF muscle during fast MVC than controls. This fact supports our hypothesis of a relatively greater deficiency in the capacity for rapid voluntary force production than in isometric MVC force of the QF muscle in children with spastic diplegic CP. Routine measurements of isometric MVC force include many potential sources of error, the most important of which is a possible lack of central drive to the muscles (19). The degree of VA is rarely taken into consideration when assessing maximal isometric force in a clinical contingent. VA refers to the level of neural drive to the muscle during MVC. Most VA studies using twitch-interpolation technique during isometric MVC have concluded that adult young healthy subjects can completely or nearly completely \((VA > 95\%)\) activate the QF muscle (19,20). In the current study, the mean VA percentages of the QF muscles for control children and children with spastic diplegic CP were 94% and 74%, respectively. Our results indicated that normal prepubertal children had nearly complete activation of the QF muscle, whereas children with CP demonstrated incomplete activation. Ramsay et al. (22), however, demonstrated incomplete activation of the QF muscle also in healthy prepubertal boys age 9–11 years using twitch-interpolation technique. This incomplete activation might represent maturational differences in the recruitment of motor units between children and adults. Only Stackhouse et al. (26) measured previous VA of the QF muscles in children with spastic diplegic CP by burst-superimposition technique, suggesting a 33% VA deficit in boys with CP (with mean age of 10.5 years) compared with age-matched healthy boys. The current study indicated a 21% VA deficit in children with spastic diplegic CP of similar age, whereas differences between two studies can in part be attributed to the different methods of measuring VA.
Figure 1 — Mean (± SE) (a) isometric maximal voluntary contraction (MVC) force, (b) MVC force relative to body mass (MVC:BM), and (c) rate of isometric force development at level of 50% of MVC (RFD₅₀) of the quadriceps femoris muscle in children with cerebral palsy (CP) and controls. ** p < .01; *** p < .001.
The reduced voluntary isometric force-generation capacity of the skeletal muscles in children with CP could be partly attributable to a reduced ability to recruit higher threshold (fast) motor units or to drive lower threshold (slow) motor units to higher firing rates (24). The current results indicated that children with spastic diplegic CP were more deficient in the capacity for rapid isometric force production than in maximal isometric force during slower voluntary effort, supporting the notion of an inability to adequately recruit fast motor units. Increased antagonist coactivation could also contribute to measured deficits in voluntary muscle force production in CP (7,8,12). It has been observed that children with spastic CP had significantly higher cocontraction ratio of QF and hamstrings muscles than normal children during knee extension (12). Cocontraction increases joint stiffness, which
makes movement more laborious. Damiano et al. (7) suggested that the cocontraction ratio of QF and hamstrings muscles during testing of isometric knee extension maximal isometric force correlated directly with those during gait. A reduced isometric MVC force and rate of force development of the QF muscle in children with CP can be also attributed in part to peripheral factors. An increased incidence of muscle-fiber atrophy, increased intramuscular fat and connective tissue in the most involved muscle groups, and increased percent of slow-twitch (type I) muscle fibers (13,23) have been demonstrated in CP. Histological and histochemical studies also have shown mild myopathic changes in muscles and atrophy of Type I and Type II muscle fibers in children with CP (23). Ito et al. (13) reported a selective atrophy of Type II muscle fibers during the development of CP. An abnormal variation in the size of muscle fibers and myosin heavy-chain expression (23) has been found in children with spastic CP. It has been suggested that muscle cells in patients with spasticity are shorter and stiffer than normal muscle cells (10).
The movement preparation process can be assessed by reaction time to visual or auditory stimuli. Our data indicated no significant differences in the indicator of visual reaction (LAT\textsubscript{C}) during unilateral MVC of the QF muscle between the groups of children with and without spastic diplegic CP. These results indicated that the reaction time of isometric muscle contraction was not significantly prolonged in children with CP, suggesting that movement preparation was not affected.

The novel aspect of the current study was to compare the capacity for rapid voluntary relaxation of the QF muscle following maximal unilateral effort in children with and without CP. The measured time-course characteristics of the voluntary muscle relaxation, LAT\textsubscript{R} and HRT, were both 69\% longer in children with CP as than in controls. The voluntary muscle relaxation, that is, termination of an ongoing muscle contraction, has an important role in the execution of complex movement in humans, particularly during rapid sequence of movements when activation must switch between different sets of contracting muscles (2). The neurophysiological mechanisms underlying voluntary muscle relaxation in humans are not well understood (2). A reduction of cortical motor output can be achieved by the activation of inhibitory cortical areas, and both primary and supplementary motor areas might be activated during voluntary muscle relaxation (28). Using transcranial magnetic stimulation to investigate the paradigm of transcallosal inhibition, Heinen et al. (11) indicated a lack of inhibitory control of the motor cortex by this inhibitory mechanism in adolescent children with diplegic CP. Inhibitory mechanisms can be activated at the spinal level by a pathway descending to the spinal cord. A neuronal population within the motor cortex can cause spinal presynaptic inhibition by activating inhibitory interneurons in the spinal cord (25). A defect of these mechanisms might contribute to the impairment of voluntary relaxation of the QF muscle in children with spastic diplegic CP. Increased antagonist coactivation, typically observed in CP (4,8,12), increases joint stiffness and could contribute to the measured deficits in voluntary muscle relaxation. It has been suggested that abnormal reflexes can restrict the execution of voluntary movement in patients with spasticity (18). The prolongation of HRT observed in the current study can also be influenced by peripheral factors. It has been observed that the duration and rate of muscle relaxation depend on sarcoplasmic reticulum Ca\textsuperscript{2+} uptake and rate of cross-bridge kinetics (29). These intramuscular processes can be affected by muscle fiber atrophy and myopathic changes in muscles in CP.

It has been indicated that maximal voluntary muscle force production capacity of the QF muscle (4,7) and some aspects of movement function (gait, sit-to-stand, jumping performance) (16) in children with mild to moderate CP can be improved by strength-training programs. Results of our study suggest that improvement of capacity for rapid voluntary contraction and relaxation of the QF muscle should be considered when designing strengthening exercise protocols for children with spastic diplegic CP. A limitation of this study was a relatively small number of children (6 girls and 6 boys) in both groups, and, therefore, the gender differences were not analyzed. More research is needed on the pathophysiologic basis of impaired capacity for rapid voluntary muscle force production and relaxation in spastic diplegic CP, the effect of therapeutic intervention, and the functional benefit of reducing this impairment in participants with CP.
In conclusion, the current study indicated a markedly reduced isometric MVC force and voluntary activation, impaired capacity for rapid voluntary isometric force production, and impaired relaxation of the QF muscle in children with spastic diplegic CP. The rate of isometric force development in children with spastic diplegic CP was reduced to a greater extent than isometric MVC force, supporting the notion of a reduced ability to adequately recruit higher threshold motor units. The impaired capacity for rapid voluntary relaxation of the QF muscle following a short-time maximal effort depends both on delayed reaction and on slowing of the muscle force-relaxation process. No significant impairment in movement preparation during rapid MVC of the QF muscle was observed in children with spastic diplegic CP, assessed by visual reaction time.

Acknowledgments

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References