Connecting the dots: Musculoskeletal adaptation in cerebral palsy

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Biceps brachii can add to performance of tasks requiring supination in cerebral palsy patients

M de Bruin, HEJ Veeger, M Kreulen, MJC Smeulders, SA Bus

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Abstract
The aim of this study was to assess whether cerebral palsy patients can use biceps brachii for supination during movement tasks requiring supination and pronation. 3D upper extremity kinematic and EMG-data of twelve patients (mean age 13y 8mo ± 36mo) were compared to 10 healthy age-matched controls. Significant difference in biceps brachii activation between maximal isolated pronation and supination in both groups showed that it is possible for CP patients to use biceps brachii for supination. Performance of reach-to-grasp with either pronation or supination showed similar activation patterns as during isolated tasks in both groups, although increased biceps brachii activation likely also hampered performance of reach-to-grasp in the patient group by causing increased, and possibly unwanted elbow flexion. However, the functional effect of this flexion for supination purposes cannot be ruled out. Therefore, one should be cautious with simply weakening biceps brachii when the purpose is to improve functional reach. Ideally treatment might focus more on changing the flexion moment/supination moment ratio of biceps toward a stronger supination function.
Introduction

Cerebral palsy (CP) is known as a non-progressive neurological disorder, which is caused by damage to the brain during fetal development, birth, or in the first year of life (Bax et al., 2005). Of all children with CP, 70% suffer from some form of spasticity of the forearm muscles (Wichers et al., 2005). These patients typically present with awkward movement patterns that highly affect arm-hand function during functional tasks (Donkervoort et al., 2007; Livingston et al., 2011). Patients for instance perform grasping of objects with increased elbow flexion, pronation of the forearm, extreme flexion and ulnar deviation of the wrist, and endorotation of the shoulder (Steenbergen & Gordon, 2006; Kreulen et al., 2007). Consequently, they tend to compensate for lack of supination and increased elbow flexion with extrinsic forearm rotation (Kreulen et al., 2007) and forward flexion of the trunk (i.e., Kreulen et al., 2007; Jaspers et al., 2012).

The biceps brachii muscle is a powerful supinator with an overall larger supination moment than the supinator muscle (Veeger et al., 2004). Because active supination of the forearm combined with extension of the elbow is often required in functional reaching tasks, the biceps brachii could be more active to overcome the pronation moments of the spastic pronator quadratus and pronator teres muscles. Increased elbow flexion may then be a secondary effect of this increased activity of the biceps brachii. If the biceps brachii is indeed task-specifically activated to a larger extent, primary treatment should be focused on enforcing forearm supination function instead of weakening of the elbow flexors.

For this purpose, we wanted to answer the question: Does the biceps brachii contribute similarly to the performance of reach-to-grasp tasks in CP patients and healthy subjects? To answer this question we tested the following hypotheses: (1) the biceps brachii is minimally active at maximal active extension of the elbow; (2) maximal isolated forearm supination results in higher biceps brachii activity than maximal isolated pronation in both patients and controls; (3) a reach-to-grasp task requiring supination results in higher biceps brachii activity compared to a reach-to-grasp task requiring pronation in both patients and controls. Testing these hypotheses is expected to clarify movement strategies of CP patients during reach-to-grasp tasks.
Methods

Participants

Twelve patients with CP (6 male, mean ± SD age 13y 8mo ± 36mo) who were planned for upper extremity surgery to improve upper extremity function were included in this study. All patients could be described as hemiplegic and had a Zancolli IIa or IIb grasp and release pattern, which means active finger extension is accompanied by a wrist flexion angle greater than 20° (Zancolli et al., 1987). Two patients had functional use of the upper extremity at level II and ten patients at level III on the Manual Ability Classification Scale (MACS; Eliasson et al., 2006). Exclusion criteria were biceps spasticity score Ashworth 2 or higher, inability to understand and/or perform the tasks (MACS level IV or higher), botuline toxin injections in the upper extremity within 6 months before measurements or previous upper extremity surgery. Ten age-matched healthy children (3 male, mean ± SD age 14y 8mo ± 15mo) were recruited as control group. Exclusion criteria for the control group were inability to understand and/or perform the tasks and any neurological pathology. Depending on age, all subjects and/or their parents gave written informed consent before the start of the study, which was approved by the local Medical Ethics Committee.

Kinematic model

An upper limb marker set was developed consisting of marker clusters of 3 or 4 markers (each 9 mm diameter) that were affixed to the sternum and acromion, upper arm, forearm, and metacarpals of both limbs (Figure 6.1). With static trials of 32 anatomical landmarks using a 3-marker pointer, marker cluster positions were linked to local anatomical coordinate systems (Van Andel et al., 2008). The glenohumeral rotation center of both left and right humerus was estimated by calculating the pivot point of instantaneous helical axes from dynamic abduction, anterior flexion, and rotation of the humerus with respect to the thorax (Woltring, 1990; Veeger, 2000). Local coordinate systems and segment rotations were defined according to the ISB standard proposal for the upper extremity (Wu et al., 2005; Van
Andel et al., 2008). For the definition of the humerus coordinate system, we used the second option in the ISB proposal using anatomical landmarks of humerus and forearm (Wu et al., 2005).

**Figure 6.1. Patient with marker clusters and EMG-electrodes.**

**Instrumentation**

Subjects were tested in a laboratory setting using an 8-camera VICON MX1.3 3D movement analysis system (sample frequency: 100 Hz) driven by Nexus software (VICON, Oxford, UK). Electromyographic signals (sample frequency: 1000 Hz) of the biceps brachii muscle and the long head of the triceps brachii muscle of the affected arm in CP patients and the preferred arm in control subjects were measured using a TeleMyo 2400R 16 channel telemetric EMG system (Noraxon, US). Electrode placement was performed according to SENIAM guidelines (Hermens et al., 1999). The muscles underneath biceps brachii and triceps brachii do not have supination moment. As such, the possibility of EMG cross talk of these muscles was considered of minimal influence (Blanc & Dimanico, 2010). Kinematic and electromyographic data were synchronized during data collection by operating both data through the VICON system.
Measurement procedure

Subjects performed a series of isometric maximum voluntary contractions (MVCs) of the biceps brachii and triceps brachii to allow for normalization of EMG measurements. MVC measurements of both muscles were alternated and both performed three times. The highest MVC measured was used for normalization of the EMG signals. Maximal elbow flexion and extension force was measured at the distal end of the forearm during MVC with a hand-held dynamometer. These moments were multiplied by forearm length to compare flexion and extension moment (Nm) generated during the biceps brachii and triceps brachii MVC, respectively.

Subjects were seated on a height adjustable stool at a standardized height with a 90° knee flexion angle and with the hands positioned on a height adjustable table that was placed within one forearm's length in front of the subject and set at a height giving 100° elbow flexion when the subject was sitting upright and with upper arms hanging down alongside the body and the hands placed flat on the table. Tasks started and ended in this position to guarantee marker visibility for the model. Subjects performed isolated movement tasks as well as reach-to-grasp tasks. Isolated movement consisted of three cycles of maximum active elbow flexion and extension and three cycles of maximum active forearm pronation and supination. During the pro-supination task, subjects were asked to keep the elbow in a 90°-flexion angle. Reach-to-grasp tasks provoked elbow extension and included picking up a disk (requiring forearm pronation) and picking up a glass and moving it to the mouth (requiring forearm supination). Objects were placed at 1.5 forearm’s length (measured from processus xiphoideus) in front of the shoulder of the arm that was used for performing the task. After demonstrating the task, subjects were given one practice trial. Subsequently, each task was performed once and in a non-randomized sequence. In case of failure of the trial (for instance when a subject dropped the object before finishing the trial), subjects were given a second try.

Post-processing

Relevant gaps in the marker trajectories during motion capture were filled using interpolation based on the position data of at least two other markers in the
marker–cluster (Nexus for Vicon). EMG signals were preamplified, band-pass filtered (from 10 to 400 Hz), and smoothed with a low-pass filter (5 Hz) using custom-written MATLAB® (Mathworks, Natick, MA) routines. EMG signals of the biceps and triceps brachii muscles were normalized to MVC.

Data analysis

Kinematic data were processed using custom-written MATLAB® routines. For analysis, the endpoints of maximal range of motion and reach-to-grasp were selected (Schot et al., 2010). For the reach-to-grasp tasks, trunk motion was analyzed to be able to describe compensation for suspected decreased ability to reach forward in the patient group.

Normalized EMG signals were used for calculation of coactivation measures of the biceps and triceps brachii. Coactivation ratio was calculated as the activation of antagonist divided by the activation of agonist. In all trials except those for maximal elbow extension, the triceps brachii was defined as antagonist and the biceps brachii as agonist.

Statistical analysis

Independent t-tests were used to compare EMG activation and forces at MVC between groups and to compare maximal passive and active elbow extension in the patient group. To investigate possible negative influence of biceps activation on elbow extension (hypothesis 1), biceps activation and elbow angle at maximal isolated elbow extension were compared between groups using a one-way ANOVA with group as between factor. To test hypotheses 2 and 3, differences between tasks on kinematic (elbow flexion angle, forearm rotation angle, trunk anteflexion) and EMG-data (biceps and triceps brachii activation and coactivation) were compared between groups with separate mixed model ANOVAs for each factor, including group (patient vs. control) as between factor and task (requiring pronation vs. requiring supination) and muscle (biceps vs. triceps) as within factors, respectively. The interaction of task * group and task * muscle * group were used to determine differences between groups in movement strategy on the different movement tasks.
Because patients had difficulty holding the elbow in 90°-flexion angle during maximal pronation and supination condition, actual elbow flexion angle during this task was added as covariate to this analysis. The association between muscle activation and ROM measures and between maximal supination ROM and associated elbow movements were evaluated with linear regression analysis. Significance was set at $P = 0.05$, all statistical analyses were performed using PASW Statistics 18.0 (SPSS, Chicago, IL, USA).

Results

Participants

The EMG-data of one control subject were excluded from analysis due to hardware failure. In two other control subjects, EMG-data at maximal active isolated elbow extension were not measured. There was no significant age-difference between groups ($t = 1.01$, $P > 0.05$). Biceps brachii activity at MVC was significantly lower in the patient group (0.59 µV ± 0.45) compared to controls (2.13 µV ± 1.10; $t = 4.47$, $P < 0.05$). Triceps activity at MVC was not significantly different between groups ($t = 1.87$, $P > 0.05$). Both maximal elbow flexion (patients 22.2 Nm ± 9.7; controls 41.6 Nm ± 12.1) and extension moment (patients 16.3 Nm ± 6.0; controls 24.2 ± 6.4) were significantly lower in the patient group compared to controls ($t = 3.99$, $P < 0.05$ and $t = 2.80$, $P < 0.05$, respectively).

Isolated extension of the elbow

Results are shown in Table 6.1. Patients showed significantly more passive than active isolated elbow extension ($t = 7.35$, $P < 0.05$). Controls could actively extend their elbow significantly further than patients ($F(1,21) = 17.99$, $P < 0.05$). Overall, patients showed significantly higher average activation of both biceps brachii and triceps brachii at maximal extension than controls ($F(1,18) = 15.71$, $P < 0.05$; Figure 6.2). However, within the patient group, elbow extension angle was not significantly related to biceps brachii activation ($R = 0.09$; $P > 0.05$).
Table 6.1. Mean (SD) values of kinematic data (measured in 3D and with goniometry) and EMG-data during maximal elbow extension.

<table>
<thead>
<tr>
<th>Task</th>
<th>Max elbow extension</th>
<th>3D-active</th>
<th>Patient</th>
<th>Goniometry</th>
<th>Goniometry</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control</td>
<td>Patient</td>
<td>Patient</td>
<td>Patient</td>
<td>Patient</td>
</tr>
<tr>
<td>Elbow angle (°)</td>
<td>22.1 (7.9)</td>
<td>39.1 (12.9)</td>
<td>14.6 (13.8)</td>
<td>15.8 (13.5)</td>
<td></td>
</tr>
<tr>
<td>Spontaneous forearm rotation (°)</td>
<td>169.3 (36.3)</td>
<td>177.3 (16.3)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biceps activation (%MVC)</td>
<td>5.7 (3.1)</td>
<td>20.3 (10.9)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Triceps activation (%MVC)</td>
<td>21.2 (16.0)</td>
<td>40.6 (16.4)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coactivation-ratio (biceps/triceps)</td>
<td>0.47 (0.58)</td>
<td>0.62 (0.45)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 6.2. Biceps activation expressed as a function of maximal elbow extension angle. Overall patients show higher normalized biceps activation at maximal elbow extension than controls. Patients are less able to actively extend the elbow than controls.

*Isolated forearm pronation-supination*

Patients show significantly less forearm supination at maximal supination than controls (Table 6.2), as shown with a significant task*group-interaction for factor forearm rotation (F(1,21) = 20.92, P < 0.05).

Despite a standardized protocol (elbow flexion 90 degrees), patients showed increased actual elbow flexion during isolated maximal supination and increased actual elbow extension during isolated maximal pronation (task * group-interaction; F(1,21) = 36.62, P < 0.05; Figure 6.3) compared to controls. Patients with a lower
ability to supinate did not show significantly more elbow flexion at maximal supination angle \((R = 0.49; P > 0.05)\).

Patients show overall significantly higher activation of biceps and triceps brachii than controls \((F(1,18) = 5.85, P < 0.05)\). Both groups show significantly lower biceps brachii activation during maximal pronation than maximal supination whereas triceps brachii activation was not different between tasks (task * muscle-interaction; \(F(1,18) = 20.83, P < 0.05\)). The latter interaction effect was not different between groups (task * muscle * group-interaction; \(F(1,18) = 0.22, P > 0.05\)).

Table 6.2. Mean (SD) values of kinematic and EMG-data during maximal isolated pro- and supination of the forearm. Bold P-values indicate a significant difference.

<table>
<thead>
<tr>
<th>Task</th>
<th>Max supination</th>
<th>Max pronation</th>
<th>Between groups</th>
<th>Between groups</th>
<th>Within groups</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control</td>
<td>Patient</td>
<td>Control</td>
<td>Patient</td>
<td>Control</td>
</tr>
<tr>
<td>Forearm rotation (°)</td>
<td>37 (15)</td>
<td>70 (24.1)</td>
<td>P&lt;0.05</td>
<td>177 (13)</td>
<td>P&gt;0.05</td>
</tr>
<tr>
<td>Spontaneous elbow angle (°)</td>
<td>90 (16)</td>
<td>108 (19.3)</td>
<td>P&lt;0.05</td>
<td>82 (15)</td>
<td>P&lt;0.05</td>
</tr>
<tr>
<td>Biceps activation (%MVC)</td>
<td>25.7 (24.8)</td>
<td>35.8 (24.8)</td>
<td>P&gt;0.05</td>
<td>2.2 (1.5)</td>
<td>P&lt;0.05</td>
</tr>
<tr>
<td>Triceps activation (%MVC)</td>
<td>8.9 (4.8)</td>
<td>16.3 (11.8)</td>
<td>P&gt;0.05</td>
<td>5.2 (4.1)</td>
<td>P&lt;0.05</td>
</tr>
<tr>
<td>Coactivation-ratio (triceps/biceps)</td>
<td>0.67 (0.7)</td>
<td>0.57 (0.43)</td>
<td>P&gt;0.05</td>
<td>3.83 (5.1)</td>
<td>P&gt;0.05</td>
</tr>
</tbody>
</table>

Figure 6.3. Elbow flexion ROM as a function of maximal pro-supination ROM.Patients with a smaller maximal pro-supination ROM of the forearm show more elbow flexion at maximal supination and more elbow extension at maximal pronation than patients with a high pro-supination ROM.
Reach-to-grasp tasks

Overall, patients showed significantly more flexion of the elbow at endpoint of reach-to-grasp ($F(1,21) = 59.97, P < 0.05$) and more forward flexion of the trunk than controls ($F(1,19) = 6.15, P < 0.05$) in both reach-to-grasp tasks (Table 6.3).

Forearm supination at endpoint of reach-to-grasp of the glass was similar between groups, but patients showed significantly less forearm pronation at endpoint of reach-to-grasp of the disc than controls (task * group-interaction; $F(1,21) = 15.33, P < 0.05$). Adding biceps brachii activation as covariate to the analysis of forearm pronation at endpoint of reach-to-grasp of the disc, resulted in a non-significant difference between groups ($F(1,21) = 4.36, P > 0.05$; Figure 6.4). Nevertheless, the biceps brachii activation was not significantly related to forearm rotation angle at this endpoint ($R = -0.47; P > 0.05$).

Biceps and triceps brachii activation were significantly increased in patients compared with controls on both reach-to-grasp tasks ($F(1,19) = 17.16, P < 0.05$). Biceps brachii activation in reach-to-grasp of the disc was lower than in reach-to-grasp of the glass; triceps brachii activation was similar between tasks (task * muscle-interaction; $F(1,19) = 4.99, P < 0.05$). This interaction was not different between groups (task * muscle * group-interaction; $F(1,19) = 0.67, P > 0.05$).

Table 6.3. Mean (SD) values for kinematic and EMG data during reach-to-grasp tasks. Bold P-values indicate a significant difference.

<table>
<thead>
<tr>
<th>Task</th>
<th>Glass</th>
<th>Disc</th>
<th>Between groups</th>
<th>Between groups</th>
<th>Within groups</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forearm rotation (°)</td>
<td>Control: 123.0 (12.5)</td>
<td>Patient: 120.7 (13.8)</td>
<td>P&gt;0.05</td>
<td>Control: 161.7 (14.8)</td>
<td>Patient: 137.7 (12.2)</td>
</tr>
<tr>
<td>Elbow angle (°)</td>
<td>Control: 47.5 (6.2)</td>
<td>Patient: 88.2 (17.8)</td>
<td>P&lt;0.05</td>
<td>Control: 48.4 (13.9)</td>
<td>Patient: 85.8 (12.0)</td>
</tr>
<tr>
<td>Trunk anteflexion (°)</td>
<td>Control: 12.9 (7.3)</td>
<td>Patient: 20.6 (12.1)</td>
<td>P&gt;0.05</td>
<td>Control: 11.4 (5.8)</td>
<td>Patient: 22.8 (11.0)</td>
</tr>
<tr>
<td>Trunk lateral flexion (°)</td>
<td>Control: -1.7 (7.0)</td>
<td>Patient: 3.1 (9.5)</td>
<td>P&gt;0.05</td>
<td>Control: -2.7 (8.7)</td>
<td>Patient: 2.6 (7.5)</td>
</tr>
<tr>
<td>Trunk rotation (°)</td>
<td>Control: 3.6 (9.8)</td>
<td>Patient: 3.9 (17.5)</td>
<td>P&gt;0.05</td>
<td>Control: 4.7 (8.7)</td>
<td>Patient: 2.5 (13.8)</td>
</tr>
<tr>
<td>Biceps activation (%MVC)</td>
<td>Control: 7.36 (4.2)</td>
<td>Patient: 26.6 (16.2)</td>
<td>P&lt;0.05</td>
<td>Control: 4.4 (3.7)</td>
<td>Patient: 21.7 (13.0)</td>
</tr>
<tr>
<td>Triceps activation (%MVC)</td>
<td>Control: 5.9 (4.2)</td>
<td>Patient: 20.1 (14.1)</td>
<td>P&lt;0.05</td>
<td>Control: 5.8 (4.0)</td>
<td>Patient: 21.5 (12.2)</td>
</tr>
<tr>
<td>Coactivation-ratio (triceps/biceps)</td>
<td>Control: 1.03 (0.89)</td>
<td>Patient: 0.79 (0.39)</td>
<td>P&gt;0.05</td>
<td>Control: 2.23 (2.52)</td>
<td>Patient: 1.03 (0.54)</td>
</tr>
</tbody>
</table>
Figure 6.4. Biceps activation as a function of forearm rotation angle at endpoint of reach-to-grasp of a disc. Patients that show a decreased forearm rotation angle (°) at endpoint of reach-to-grasp of a disc, show higher biceps activation at this point. Controls show low biceps activation irrespective of forearm rotation angle at this endpoint.

Discussion

In the present study we showed that patients are able to use the biceps brachii for supination of the forearm, which resembles use of the muscle in healthy controls. Biceps brachii activation was demonstrated to be lower in tasks requiring pronation of the forearm compared to tasks requiring supination in both groups (Table 6.2 and 6.3). However, biceps brachii activity also comprised an overactivity component affecting elbow and forearm movements in functional reach-to-grasp tasks. This was demonstrated in the maximal elbow extension task, where the decreased ability of patients to extend the elbow coincided with increased biceps brachii activity (Figure 6.2). Furthermore, the patient group showed significantly higher biceps brachii activation on all tasks compared to control, which likely caused the increased elbow flexion angle at endpoint of reach-to-grasp of both tasks (Figure 6.4).

Previously, studies that described quality of movement (i.e. Jaspers et al., 2011; Butler & Rose, 2012) and muscle activation (Braendvik & Roeleveld, 2011) during reaching in CP have always focused on the impairment that is caused by spastic control. The combined findings of increased elbow flexion and anteflexion of the trunk and increased activation of biceps brachii and triceps brachii found in those studies have been confirmed by the present study. However, from simply describing impairment one does not learn much about the remaining function of the upper extremity. By combining results of joint kinematics during movement tasks
with elbow flexor and extensor activation data, we can learn about movement strategies and we might ultimately be able to tailor treatment to functional needs.

Muscle activation and movement strategies in CP

Functional use of muscles during reaching tasks in CP patients has scarcely been described. Whereas (Gribble et al., 2003) reported increased coactivation at the elbow in response to increased accuracy, (Van Roon et al., 2005) could not prove “functional coactivation” of biceps brachii and triceps brachii in tasks that demanded increased accuracy. A reason for this could be that the task in the latter study was too difficult for CP patients to find differences between accuracy conditions. The patients in our study however did not show an increase in coactivation on reach-to-grasp tasks compared to the maximal isolated pronation and supination tasks. This in itself does not mean that functional coactivation does not exist. Judging by the supination angle at endpoint of reach-to-grasp of the glass (121° in the patient group compared to 123° in the control group), the tasks in our study could have been too easy to impose functional coactivation to increase accuracy. Besides, the present study attempted to show the functional use of biceps brachii beyond the coactivation. Furthermore, we aimed to relate the functional use to joint kinematics to find out if biceps brachii is impairing or facilitating forearm function in CP.

The role of biceps brachii during forearm rotation in CP patients

In both groups, biceps brachii activity increased when a subject had to supinate the forearm compared to a pronation task, whereas triceps brachii activity did not change between tasks. In patients with CP, biceps brachii is thought to have both an enforcing and an impairing role. Whereas overactivity of the muscle is impairing extension of the elbow, the muscle has to enforce supination of the forearm, as the supinator muscle is not strong enough to overcome pronation forces. At 90° elbow flexion biceps brachii has a flexion moment arm that is six times the supination moment arm of the same muscle (Ettema et al., 1998). Supination moment arm of biceps brachii is on average approximately 1.5 times the supination moment of the supinator muscle (Veeger et al., 2004). Furthermore, supination
moment of biceps brachii was reported to have its optimum around 90°-elbow flexion (Bechtel & Caldwell, 1994; Veeger et al., 2004). Both at maximal supination angle and at endpoint of reach-to-grasp of the glass, biceps brachii seems to pull the joint in a position that is ideal for the muscle to supinate. Nevertheless, when asked to perform the same task but with forearm in pronation, patients showed the same trunk and elbow angles. Moreover, biceps brachii was active enough to force the forearm into supination during this task (Figure 6.4). It is therefore difficult, if not impossible, to split the two roles and determine when biceps brachii is actually facilitating or impairing reach-to-grasp function. Based on our results, biceps brachii seems to predominantly impair function during reach-to-grasp because flexion moment is simply too large compared to supination moment of the muscle, but the fact that supination moment has an optimum around 90° elbow flexion could be an indication of biceps brachii activity being part of a functional strategy to maximize the muscles’ supination moment.

Naito et al. (2002) reported that maximal supination with maintenance of 90° elbow flexion was achieved by electrically stimulating biceps brachii and simultaneously decreasing stimulation of brachioradialis muscle in healthy subjects. In addition, previously described shifts in flexion load toward biceps brachii in tasks requiring flexion and supination in contrast to shifts toward the brachioradialis for tasks requiring flexion and pronation have indicated dynamic flexion load sharing of biceps brachii and brachioradialis (Cnockaert et al., 1975; Jamison & Caldwell, 1993). As was illustrated in Figure 6.3, the smaller the maximal pro-supination ROM is, the more patients seemingly simultaneously flex and extend the elbow during maximal supination and maximal pronation respectively. Measuring EMG of brachioradialis did not fit into the scope of this study, but it would be interesting to see if a lack of reciprocal inhibition to brachioradialis causes both elbow flexors to activate and pull the elbow into flexion on a maximal supination task. On the other hand, elbow extension in patients at maximal effort to pronate may result from a decrease in biceps brachii activity at constant triceps brachii activity, rather than from increased triceps brachii coactivation as would have been expected from the theory of impaired reciprocal inhibition (Leonard et al., 1990).
In addition to joint angles at endpoints of movements, it would be interesting to determine the actual movement trajectory during reach-to-grasp in these patients. Induced acceleration analysis for instance, could tell us more about the dynamic coupling of the different joints within the system. Furthermore, it would be interesting to evaluate EMG-data of more arm muscles during these tasks. These data could also be used in an inverse model aimed to predict the pathological movement patterns in CP.

**Study limitations**

Anxiety and emotional state of the patient has been suggested to influence muscle tone (Sanger et al., 2003). To minimize anxiety in the patients, we wanted to let them perform different reach-to-grasp and isolated maximal ROM tasks as unconstrained as possible. For the maximal isolated pronation and supination this resulted considerable elbow flexion and extension in the patient group despite the encouragements to keep the elbow in 90° flexion. For some patients, it is hard to determine if they could not keep the elbow in this position because the task was too complex to comprehend or whether they simply were not able to reach the same maximum with the elbow in the same position. This could have resulted in an overestimation of the unwanted effect of biceps brachii resulting in compensating movements of the elbow during maximal pronation and supination. Besides, asking patients to perform relatively complex movements could also increase anxiety levels and with that muscle tone. This was illustrated by the decreased ability to actively extend the elbow compared to passive elbow extension measured with goniometry (Table 6.1). The active task was part of an alternating flexion–extension movement of the elbow in free space, whereas the passive extension was focused on solely extending the elbow.

Furthermore, both groups performed forearm rotation at endpoint of reach-to-grasp of the glass with similar angles. Apparently this task was not provocative enough to reach supination of the forearm. Nevertheless, both groups showed a relative decrease of biceps brachii activity in the task that required forearm pronation (disc) compared to the task that required forearm supination (glass). However, the difference between tasks was not significant within the patient group.
A reach–to–grasp task that would have provoked more forearm supination could probably have made the influence of biceps brachii in these tasks more evident. Still, we can conclude that biceps brachii seems to be contributing to the forearm rotation.

*Consequences for treatment*

As was shown in our different isolated and reach-to-grasp tasks, biceps brachii still has a supination function in patients with CP. Besides, biceps brachii activity and consequent elbow flexion could be part of a functional strategy rather than sole result of pathological overactivity. Treatment of the spastic arm often aims at decreasing elbow flexion deformity and forearm pronation deformity. In CP patients, pronator teres and pronator quadratus are considered to be too strong compared with the weakened supinator muscle in the forearm. Weakening biceps brachii would not only affect elbow flexion, but would also decrease supination ability of the forearm. Therefore, one should be cautious with simply weakening biceps brachii when the purpose is to improve functional reach. Then, ideally treatment might focus more on changing the flexion moment/supination moment ratio of biceps toward a stronger supination function.

*Overall conclusion*

Both maximal isolated ROM tasks and reach-to-grasp tasks have shown that it is possible for CP patients to functionally use biceps brachii for supination. However, the high activation level of biceps brachii also hampers performance of reach-to-grasp tasks by causing increased, and possibly unwanted elbow flexion, although the functional effect of this flexion for supination purposes cannot be ruled out.