On tendon transfer surgery of the upper extremity in cerebral palsy
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CHAPTER 5

Movement patterns of the upper extremity and trunk associated with impaired forearm rotation in patients with cerebral palsy

Part I: a comparison to healthy controls

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Abstract

The aim of this study was to assess the relation between impaired forearm rotation and concomitant movement patterns of the upper arm and trunk in patients with cerebral palsy. For this purpose, 'extrinsic forearm rotation' is introduced as a parameter to quantify the cumulative result of all movements that supplement forearm rotation. The results of three-dimensional video analysis of the upper extremity and trunk in different reaching tasks in eight male and two female patients (mean age, 16 years and 2 months) are compared to those of ten case-matched controls. The active forearm rotation impairment in the patient group as compared to the controls was combined with a significantly higher value for extrinsic forearm rotation. Based on this observation, we conclude that impaired forearm rotation is associated with movement patterns that externally supplement forearm rotation and advocate to assess the overall movement strategy rather than just the forearm deformities in patients with cerebral palsy.

Submitted for publication

Introduction

As a result of disturbed inter-joint coordination⁸, ⁷³ and limited available range of motion of the joints⁷³, ⁸², the affected upper extremity of patients with hemiplegic cerebral palsy moves in complex patterns during functional activities. To compensate for the lack of available range of motion of the affected joints, additional degrees of freedom are integrated in the movement strategy to complete a task⁸, ⁷³. Compensatory trunk movements are recruited when the range of motion of the upper extremity joints is insufficient, or when the effort of bringing the required range of motion into action exceeds the effort of recruitment of the trunk⁴⁹.
This study was set up to objectify whether, and how, the upper arm and trunk are recruited for compensation of impaired forearm rotation in surgically untreated patients with cerebral palsy. For this purpose, we introduced a parameter called 'extrinsic forearm rotation' that quantifies the collective result of all body movements that rotate the hand except forearm rotation. As such, 'extrinsic forearm rotation' supplements or counteracts the effect of forearm rotation on the rotational position of the hand in space. Patients with impaired forearm rotation were expected to have higher values for extrinsic forearm rotation compared to subjects without impairment. If this proved true, the recruited degrees of freedom that constitute this increased extrinsic forearm rotation may be considered as pathological movements directly associated with impaired forearm rotation. The linking of associated movements to a specific joint deformity implies that treatment aiming at the correction of that single impairment will have effect on all degrees of freedom involved in these associated movements.

In this paper we present the results of three-dimensional analysis of forearm rotation, its concomitant recruitment of the upper arm and trunk, and the extrinsic forearm rotation in ten patients with cerebral palsy and compare them to those in ten case-matched controls.

**Methods**

*Patients and age-matched controls*

Eight male and two female patients (mean age, 16 years and 2 months; range, 11 - 27 years) were included in the study. Inclusion criteria were: 1) hemiplegic cerebral palsy, 2) impaired active supination of the forearm, 3) the ability to initiate voluntary use of the upper extremity, 4) no prescription medicine known to affect the musculoskeletal system, and no history of trauma or surgery of the upper extremities or trunk, and 5) the ability to independently sit on a stool, as this was a prerequisite for the three-dimensional movement analysis. Patients who were not able to perform the measurement protocol using the required grips were excluded from the study.

Inclusion criteria for the ten age- and sex-matched healthy controls (mean age, 16 years and 5 months; range, 11 - 27 years) were: 1) unrestricted forearm rotation, and 2) no history of trauma, surgery, disease or prescription medicine known to affect the musculoskeletal system. In the control group, movement patterns of the non-dominant upper extremity were examined for this study.

The study protocol was approved by the Medical Ethical Committee of the Academic Medical Centre in Amsterdam. Informed consent was obtained from all included patients and controls.
3D video registration

To allow for unrestricted movements in order to explore the full adaptive capacity of the disordered movement system\(^2\), we used three-dimensional video analysis of range of motion as an accurate technique of non-contact posture measurement of the forearm, upper arm, and trunk. The method we used has previously been used and reported\(^3\) and adheres to recommendations for standardisation\(^2,82\). In short, the subject was seated on a stool without arm or back support with both feet on the ground. Ink markings were placed on the skin over the manubrium sterni, the xiphoid process, the acromion of both shoulders, the medial and lateral epicondyles of the humerus, and the ulnar and radial styloid processes on the affected arm (figure 1). The skin markings in all patients were made by the

Figure 1
Illustration of the anatomical markings on the patient and the orientation of the global and local coordinate systems. Legend: Xg, Yg and Zg: x-, y- and z-axes of the global coordinate system; Xt, Yt and Zt: x-, y- and z-axes of the local coordinate system for the trunk; Xu, YU and ZU: x-, y- and z-axes of the local coordinate system for the upper extremity.
same two examiners (MK & MJCS). Two synchronised S-VHS video cameras were positioned in front of the subject at an angle of 60 degrees. Prior to video registration, the field of view was calibrated and set to match the borders of a 60 x 60 x 60 centimetres calibration frame, after which the position and settings of the cameras were not changed. The patients were allowed ample time to familiarise with the experimental set-up. After a demonstration by the examiner and a trial session by both the examiner and the subject, each of the following four tasks were performed twice. First, the subject was asked to maximally supinate both forearms. Then, a table was placed directly in front of the subject with its surface at elbow height. A drinking glass was placed on the table within reach of the affected arm. The subject was asked to pick up the glass using a cylinder grip and to steadily hold it as vertical as possible (as if to avoid spilling the beverage) requiring a neutral position of the forearm. After that, the subject was asked to maximally pronate both forearms. Subsequently, a wooden disk of 8 centimetres diameter and 1 centimetre height was placed flat on the table for the fourth and last task. The subject was asked to pick up the wooden disk by placing the thumb and fingers around it in a spherical grasp requiring forearm pronation.

**Data analysis**

An S-VHS videocassette recorder (Panasonic AG-7130, Matsushita Electric Industrial Co., Osaka, Japan) was connected to a Macintosh Quadra 650 computer (Apple Computer Inc., Cupertino, CA, USA). Five images from both video recordings and of each session were selected for further analysis of upper extremity and trunk position (figure 2): the subject 1) while sitting on the stool in a resting position just before performing the tasks, 2) at the moment of maximal active supination, 3) at the moment of grasping the glass and stabilising it in vertical position, 4) at the moment of maximal active pronation, and 5) at the moment of grasping the wooden disk. The recorded markers of the calibration frame (i.e. a global coordinate system) and those on the subjects in all selected images were identified and digitized. Identification was repeated five times for each marker to increase accuracy. A set of average values of the digitized data of each marker was used for further calculations. From the two sets of digitized video coordinates (one set for each camera), the three-dimensional positions of the anatomical landmarks relative to the global coordinate system were reconstructed using the Direct Linear Transformation method. Overall precision of static and dynamic error of the 3D coordinates was estimated to be within 5 millimetres or 0.3% of the field of view. This way, the positions of the forearm, upper arm, and trunk in the five selected images could be calculated using the 3D coordinates of the anatomical landmarks.
Figure 2
Illustrations of the five selected images from the video recordings. Legend: Image #1 = resting position; Image #2 = maximal supination; Image #3 = grasping the glass in supination; Image #4 = maximal pronation; Image #5 = grasping the disk in pronation.

1. Calculation of forearm position

The forearm was represented by the markers of the medial and lateral epicondyles combined with those of the radial and ulnar styloid processes. Forearm rotation and elbow flexion were determined relative to the upper arm\textsuperscript{32, 84}. For this, a local coordinate system for the upper arm was constructed using the markers of the
medial and lateral epicondyles and the acromion (figure 1). The axes of forearm rotation and of elbow flexion-extension were based on the average actual rotation axes relative to anatomical landmarks. This method ensured a value for a rotational angle around actual anatomical axes that was corrected for the use of skin markers and was not influenced by possible carrying angles. The zero position (0 degrees flexion, 0 degrees rotation) was defined as the virtual position of the arm in which the ulnar and radial styloid processes were in one plane with the medial and lateral epicondyles and the acromion. The degree of forearm motion was calculated by first mathematically rotating the 3D coordinates of the ulnar styloid process from the zero position around the anatomical elbow flexion-extension axis, until its position fitted the actual position of the ulnar styloid process of the patient. Second, the coordinates of the radial styloid process were mathematically rotated around the anatomical forearm rotation axis until its calculated position fitted the position of the marker of the radial styloid process on the patient. Finally, the angle of rotation around the anatomical forearm axis was expressed as forearm pronation-supination with 0 degrees rotation from the zero position equalling 90 degrees of supination and 180 degrees rotation from the zero position equalling -90 degrees (i.e. 90 degrees pronation). Elbow flexion angles were expressed in positive values equalling the degree of flexion relative to the zero position, whereas elbow extension angles were expressed in negative values.

2. Calculation of extrinsic forearm rotation

Thus, forearm rotation is determined relative to the local coordinate system of the upper arm. Although the hand is rotated by the forearm, it is also rotated by movements of the rest of the body, supplementing or countering the effect of forearm rotation on the position of the hand in space. Any movement of the body outside the forearm that rotates the hand is reflected by rotation of the upper arm coordinate system. Hence, we introduced the 'extrinsic forearm rotation' parameter as the rotation of the upper arm coordinate system in a vertical plane through its x-axis (the line through the medial and lateral epicondyle). The degree of this rotation can be recognised as the angle of the upper arm y-axis with a vertical plane that both includes the acromion and the ulnar styloid process, as that is the plane perpendicular to the plane of rotation (figure 3). This extrinsic forearm rotation was expressed as a positive value if it supplemented forearm supination, and as a negative value if it supplemented pronation.
Figure 3
Illustration of the extrinsic forearm rotation parameter.
Legend: Extrinsic forearm rotation, i.e. rotation of the upper arm coordinate system x-axis (Xu) in its vertical plane, is recognised as the angle (α) of the upper arm y-axis (Yu) with the vertical plane through both the acromion (ac) and the ulnar styloid process (us). This angle quantifies the result of all movements except for forearm rotation that rotate the hand in a vertical plane in space.

3. Calculation of upper arm position

The position of the upper arm was calculated from its local coordinate system relative to the global coordinate system after mathematically rotating the trunk back to its resting position. For this, the trunk was represented by the markings of the contralateral acromion, the manubrium sterni, and the xiphoid process. From these markings, a local coordinate system for the trunk was constructed centred over the manubrium sterni (figure 1). The position of the upper arm relative to the
trunk could then be expressed by three angles in the following sequence: the plane of upper arm elevation, the angle of elevation, and the angle of upper arm rotation\textsuperscript{11,58}. This way, the upper arm position could be interpreted as longitudes and latitudes of a globe projected around the shoulder (figure 4a). The plane of elevation is not necessarily the plane in which the action is taking place as it, rather, is only a mathematical rotation around an axis parallel to the trunk through the acromion needed to define a particular static position\textsuperscript{7}. As such, it was indicated in degrees relative to the coronal plane (figure 4b). The plane of elevation corresponds with the longitudes in the globe system, and the angle of elevation corresponds with the latitudes (figure 4c). The zero position for upper arm elevation was defined as the position at which the upper arm axis between the acromion and the middle of both epicondyles was parallel to the y-axis of the global coordinate system. The angle of upper arm rotation was defined by the angle of the z-axis of the upper arm coordinate system and a line perpendicular to the plane of elevation\textsuperscript{58}. From the position of 0 degrees rotation (upper arm z-axis perpendicular to the plane of elevation), exorotation was expressed as positive values and endorotation as negative values (figure 4d).

4. Calculation of trunk position

The orientation of the trunk in resting position (image #1) relative to the global coordinate system was used to adjust the local coordinate system of the trunk to the anatomical planes. Starting from that position, trunk recruitment in the four tasks was determined by the displacement of its local coordinate system. The angles of forward trunk flexion were expressed in degrees as positive values. Likewise, lateral flexion angles were expressed as positive values in the direction of the affected extremity, and axial rotation angles were expressed as positive values in the direction moving the affected extremity posteriorly.

Statistical analysis

For each of the selected images the average values for all parameters were collected: 1) trunk flexion, 2) lateral trunk flexion, 3) trunk rotation, 4) plane of upper arm elevation, 5) upper arm elevation, 6) upper arm rotation, 7) elbow flexion, and 8) forearm rotation. Extrinsic forearm rotation was calculated only for images #3 and #5. Comparison of these parameters between the patient group and the control group was performed by a two-tailed Student’s \( t \)-test for paired observations. The correlation between impaired forearm rotation and increased extrinsic forearm rotation as compared to the matched controls was verified using two-tailed Spearman’s rho correlation coefficient. For all analyses, an alpha level of \( p < 0.05 \) was used for determining statistical significance.
Figure 4
Illustration of the 'globe system' that expresses the position of the upper arm relative to the trunk by three angles.
Legend:
A: longitudes and latitudes of a globe;
B: the plane of upper arm elevation is the angle of the upper arm relative to the coronal axis in the transverse plane (longitudes);
C: upper arm elevation is expressed as the angle of the upper arm with the vertical axis in the coronal plane (latitudes);
D: upper arm rotation can be visualised with the elbow in 90° flexion by the angle (α) of the forearm and a horizontal line perpendicular to the plane of elevation.
Results

Control group

Task 1. All controls were able to supinate their forearm well beyond the neutral position (mean, +91°; SD, 23.3), and this was achieved without any significant trunk motion (table 1). Upper arm elevation was small (mean, 11°; SD, 6.3), and thus approached a gimbal lock position where the axes of humeral rotation and plane of elevation coincide. This means that differentiation between the humeral rotation and plane of elevation angles is frustrated. These angles were, therefore, not used in further analysis of this task.

Task 2. Grasping the drinking glass required elbow extension as well as forearm supination towards zero degrees (table 1). The movement pattern for this task in all our control individuals included upper arm elevation not directed in a straight line towards the glass, but in a plane of elevation below 90°, i.e. containing upper arm abduction (mean, +68°; SD, 20.7). Subsequently, endorotation of the upper arm (mean, -52°; SD, 21.1) directed the forearm back to the glass, bringing the hand in position to grasp it. This movement pattern resulted in a marked negative extrinsic forearm rotation (mean, -11°; SD, 3.0) (table 3).

Task 3. Like active forearm supination, maximal active forearm pronation (mean, -87°; SD, 10.4), did not induce marked recruitment of trunk movement.

Task 4. Reaching for the wooden disk with the forearm in pronation (mean, -59°; SD, 7.7) resulted in a movement pattern similar to grasping the drinking glass. Marked upper arm elevation (mean elevation, 34°; SD, 6.6) was now even less directed towards the target (mean plane of elevation, +62°; SD, 10.6) resulting

Table 1
Averaged data on the control group (in degrees)

<table>
<thead>
<tr>
<th>Task</th>
<th>Trunk</th>
<th>Upper Arm</th>
<th>Forearm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lateral flexion</td>
<td>Flexion</td>
<td>Rotation</td>
</tr>
<tr>
<td></td>
<td>ave. (sd)</td>
<td>ave. (sd)</td>
<td>ave. (sd)</td>
</tr>
<tr>
<td>#1: sup.</td>
<td>-3 (4.7)</td>
<td>1 (4.2)</td>
<td>0 (5.3)</td>
</tr>
<tr>
<td>#2: glass</td>
<td>-2 (3.5)</td>
<td>-3 (2.0)</td>
<td>5 (3.0)</td>
</tr>
<tr>
<td>#3: pron.</td>
<td>-3 (4.4)</td>
<td>1 (4.2)</td>
<td>-1 (5.3)</td>
</tr>
<tr>
<td>#4: disk</td>
<td>-1 (2.4)</td>
<td>-6 (5.3)</td>
<td>7 (4.9)</td>
</tr>
</tbody>
</table>
in more negative values for extrinsic forearm rotation (mean, -18°; SD, 4.7), supplementing forearm pronation.

**Patient group**

**Task 1.** Compared to the control subjects, all patients had impaired maximal active forearm supination (mean, -25°; SD, 37.1; \( p < 0.0001 \)) that coincided with a significantly marked trunk lateral flexion (mean, 14°; SD, 11.3; \( p < 0.005 \)), endorotation of the upper arm (mean, -61°; SD, 43.7; \( p < 0.0001 \)), and elbow flexion (mean, 129°; SD, 16.1; \( p < 0.0005 \)) (table 2).

**Task 2.** Subsequent reaching for the drinking glass was reflected by increased upper arm elevation in an increased plane of elevation, and elbow extension. In addition, the already marked trunk lateral flexion was supplemented by a significantly increased trunk flexion (mean, 12°; SD, 10.4; \( p < 0.005 \)) and rotation (mean, 10°; SD, 14.7; \( p < 0.01 \)), although the drinking glass was within reach of the affected arm. Significantly less active supination was used to grasp the glass compared to the maximal available supination in the first task (mean, -55°; SD, 20.9; \( p < 0.05 \)). Extrinsic forearm rotation in this movement pattern supplemented forearm supination significantly more than observed in the controls (mean increase, +13°; \( p < 0.05 \)) (table 3). The extent of variation of the extrinsic forearm rotation data was considerable within the patient group, but the data correlated reasonably well with the extent of forearm rotation impairment as compared to the controls (Spearman's rho correlation coefficient, 0.73; \( p < 0.05 \)).

**Task 3.** Active forearm pronation was not impaired (mean, -80°; SD, 8.9) and did not induce obvious trunk recruitment.

**Table 2**
Averaged data on the patient group (in degrees)

<table>
<thead>
<tr>
<th>Task</th>
<th>Trunk</th>
<th>Upper Arm</th>
<th>Forearm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>lateral flexion</td>
<td>rotation</td>
<td>plane of elevation</td>
</tr>
<tr>
<td></td>
<td>ave. (sd)</td>
<td>ave. (sd)</td>
<td>ave. (sd)</td>
</tr>
<tr>
<td>#1: sup.</td>
<td>0 (6.5)</td>
<td>14 (11.3)</td>
<td>1 (7.4)</td>
</tr>
<tr>
<td>#2: glass</td>
<td>12 (10.4)</td>
<td>14 (10.7)</td>
<td>10 (14.7)</td>
</tr>
<tr>
<td>#3: pron.</td>
<td>2 (5.4)</td>
<td>5 (5.6)</td>
<td>3 (7.9)</td>
</tr>
<tr>
<td>#4: disk</td>
<td>14 (10.2)</td>
<td>3 (7.5)</td>
<td>2 (11.0)</td>
</tr>
</tbody>
</table>
Task 4. As active forearm pronation was comparable between patients and controls, extrinsic forearm rotation did not differ significantly at subsequent reaching for the wooden disk (table 3). However, forward flexion of the trunk did increase significantly (mean, 14°; SD, 10.2; p < 0.01). Again, data on extrinsic forearm rotation correlated well with active forearm pronation data (Spearman's rho correlation coefficient, -0.76; p < 0.05).

Table 3
Data on extrinsic forearm rotation

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Task 2</th>
<th>Task 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>the drinking glass</td>
<td>the wooden disk</td>
</tr>
<tr>
<td></td>
<td>(image #3)</td>
<td>(image #5)</td>
</tr>
<tr>
<td>No.</td>
<td>controls (degrees)</td>
<td>patients (degrees)</td>
</tr>
<tr>
<td>#1</td>
<td>-9</td>
<td>-37</td>
</tr>
<tr>
<td>#2</td>
<td>-5</td>
<td>1</td>
</tr>
<tr>
<td>#3</td>
<td>-14</td>
<td>20</td>
</tr>
<tr>
<td>#4</td>
<td>-13</td>
<td>4</td>
</tr>
<tr>
<td>#5</td>
<td>-10</td>
<td>22</td>
</tr>
<tr>
<td>#6</td>
<td>-11</td>
<td>7</td>
</tr>
<tr>
<td>#7</td>
<td>-8</td>
<td>5</td>
</tr>
<tr>
<td>#8</td>
<td>-15</td>
<td>1</td>
</tr>
<tr>
<td>#9</td>
<td>-14</td>
<td>11</td>
</tr>
<tr>
<td>#10</td>
<td>-10</td>
<td>-1</td>
</tr>
</tbody>
</table>

Ave.       | -11 | 2 | -18 | -19 |
SD         | 3.0 | 15.6 | 4.7 | 11.5 |

p < 0.05 p < 0.360

Discussion
Interest in three dimensional motion analysis of the upper extremity has increased rapidly in recent years \(^8, 32, 35, 49, 82, 85\), but the complexity of upper extremity movements and the lack of standardized functional tasks hinders the establishment of a universal standard in upper extremity motion analysis \(^2, 61\). For this study, we adopted recommendations from reports on this topic to design a method for three-dimensional assessment that meets our purpose \(^2, 14, 58, 82, 84\). Our method is suitable for an accurate three-dimensional posture assessment of the upper extrem-
ity and trunk in patients with cerebral palsy, but it has its limitations. As such, it analyses the end result of a movement pattern, but it does not address the velocity of movement or the timing and sequencing of degrees of freedom. Moreover, table height, target distance, and type of grasp will greatly influence the movement strategy of the upper extremity and trunk. Thus, even though we strived for three-dimensional positional analysis under optimally standardized circumstances, it is safest to view the studied movement patterns as significant tendencies in the observed direction rather than as the actual quantification of it.

The 'globe system' for describing the position of the upper arm relative to the trunk provides an unambiguous definition of rotation axes that is easy to visualise. It is preferred over the use of the clinically familiar angles of flexion in the sagittal plane and abduction in the coronal plane because there is no anatomical description in-between these planes. It should be noted, however, that a system describing the position of the upper arm relative to the trunk disregards rotations of the scapula and clavicle. Like any Euler description system, the 'globe system' also harbours gimbal lock positions where the axes of humeral rotation and plane of elevation coincide, causing their values to be sensitive to measurement errors. In this convention, the arm is either not, or fully elevated in gimbal lock position. Since elevation close to zero degrees occurred in some of our tasks, and 'humeral rotation' and 'plane of elevation' are hardly relevant for this particular position, these parameters were not used for those tasks.

The musculoskeletal system is considered abundant, since it potentially has a larger number of ways to combine individual joint movements than necessary to complete one specific task. This permits the body to adapt to different environmental conditions or to compensate for functional deficits. We have introduced the 'extrinsic forearm rotation' as a parameter to objectify that part of the movement strategy outside the forearm itself that is supplementary to (impaired) forearm rotation. As yet, we can not state that supplementation is the same as compensation because we do not know what part of this extrinsic forearm rotation is compensatory strategy for impaired forearm rotation and what part is the consequence of other task specific movement strategies that rotate the forearm. For example, our controls used a movement pattern for the 'supinative' task of grasping the drinking glass that resulted in negative values for extrinsic forearm rotation correlated with 'pronative' movement. This negative extrinsic forearm rotation is part of the movement pattern for that specific task and not a compensation for impaired rotation. In fact, the movement pattern put the forearm in a pronated position in space, opposite to the unimpaired forearm supination itself. This is in agreement with
earlier reports on upper extremity movement patterns during reaching tasks in healthy subjects.\textsuperscript{5, 10, 63}

Michaelsen et al.\textsuperscript{49} compared movement patterns during a reaching task between hemiplegic stroke patients and healthy controls. In contrast to healthy controls, trunk restraint altered the pattern of inter-joint coordination and increased the recruited range of motion in the elbow and shoulder in all hemiparetic patients. This may indicate that these hemiparetic patients did not use their potential joint range for free arm movements during a reaching task because this required more effort than compensatory trunk recruitment\textsuperscript{49}. Likewise, maximal recruitment of the available forearm supination in cerebral palsy during reaching might be so labour-intensive, that recruitment of other degrees of freedom is preferred. Accordingly, the insufficient active forearm supination that was recruited during reaching for the drinking glass by the patients in our study was less than the available active forearm supination with the upper arm next to the body. Alternatively, the required forearm rotation might even not have been available during this reaching task that also required elbow extension. Either way, standard assessment of forearm rotation with the upper arm next to the body and the elbow in 90° flexion is not a valid representation of the functionally available forearm rotation to cerebral palsy patients during a reaching task.

For the functional tasks in our study, the patient was not asked to rotate his forearm but to pick up an object, and thus a task-specific movement pattern was composed from all available degrees of freedom. This allows for the study of the recruitment of forearm rotation in cooperation with related degrees of freedom. Active forearm supination in the patient group was always accompanied by active elbow flexion. This is easy to understand when considering that the also spastic biceps brachii muscle is a strong supinator\textsuperscript{56}. Elbow flexion, however, prevents positioning of the hand at table top height in a reaching task. In all patients we observed that less forearm supination was recruited to allow for more elbow extension and the trunk was flexed anteriorly and laterally to bring the supinated hand to the object on the table. Obviously, the trunk contributed to a compensatory strategy for the lack of elbow extension, as well as the lack of forearm supination. In some patients the upper arm was also recruited to supplement forearm supination by elevation in a plane that includes humeral adduction (>90°). In other patients, the trunk lateral flexion used to compensate for the lack of elbow extension even exceeded the required compensation for the limited forearm supination. In those patients, the upper arm was recruited to compensate for the extensive trunk lateral flexion by elevation in a plane of marked abduction (<90°).
The trunk was also recruited in the reaching task with the forearm in pronation. This time, trunk forward flexion compensated for the lack of elbow extension, as trunk lateral flexion would work against forearm pronation.

Comparing values between patients and matched controls performing the same tasks will identify that part of extrinsic forearm rotation related to forearm impairment. The difference in extrinsic forearm rotation has then become a quantitative measure for the compensatory movement strategy directly related to impaired forearm rotation during that specific functional task. This was confirmed in our study by a statistically significant correlation between the difference in extrinsic forearm rotation and the difference in forearm rotation itself. Our observations show that all patients recruited compensatory movement strategies, as was objectified by this difference in extrinsic forearm rotation. However, the involvement of the trunk and upper arm in such a strategy varied between patients and this, we surmise, is explained by the variety of concomitant joint impairments between the patients in our group.

The invariably associated movements of active forearm supination and elbow flexion creates an upper extremity posture unfit for reaching and grasping tasks or bimanual activities that require forearm supination. Many patients with hemiplegic cerebral palsy use the affected extremity mainly as an assisting hand in bimanual activities. It is, therefore, imperative to assess available forearm rotation in concert with elbow extension during the desired functional tasks when considering treatment of a pronation deformity. The movement pattern will be adapted to a new equilibrium, and this may involve alteration of the muscle imbalance around concomitant deformities. Detailed assessment of movement patterns combined with the range of active joint movement used is indispensable in planning therapy for the upper extremity in cerebral palsy. To evaluate the effect of surgical treatment on the movement patterns related to the corrected deformity we compared the postoperative to the preoperative associated movements as presented in this report. The results of this subsequent study are presented in part II of this report.

In conclusion, we compared movement patterns of the upper extremity and trunk in cerebral palsy patients with impaired forearm supination to those in case-matched healthy controls performing the same tasks. Based on the significant difference of extrinsic forearm rotation between these groups, we objectified that the movement strategy in patients with cerebral palsy contains pathological movements that are directly associated with their impaired forearm rotation.
"... Every species of voluntary exercise of the muscles which is calculated to restore power or harmony to the movements of the limbs and trunk, alternately vaunted and decried, will ever hold an important place in the estimation of the orthopaedic practitioner. ..."

WJ Little, 1861