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Movement patterns of the upper extremity and trunk before and after corrective surgery of impaired forearm rotation in patients with cerebral palsy

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The effect of surgical correction of impaired forearm rotation on associated body movement patterns was studied prospectively by comparison of preoperative and postoperative three-dimensional video analysis of the upper extremity and trunk in eight male and two female patients with hemiplegic cerebral palsy (CP; mean age 16y 2mo [SD 4y 11mo]; range 11–27y). A customized parameter, 'extrinsic forearm rotation', was used to quantify associated movements supplementing forearm rotation. After surgical correction of the pronation deformity, active forearm supination during a functional reaching task had improved by a mean of 37° in combination with significantly decreased extrinsic forearm rotation by a mean of 13°. In addition, an average loss of 16° of active pronation in combination with increased extrinsic forearm rotation (mean 8°) was observed. On the basis of these results we conclude that successful surgical correction of a pronation deformity in patients with CP directly affects related movement patterns of the upper extremity and trunk.

The affected upper extremity of patients with hemiplegic cerebral palsy (CP) moves in complex patterns during functional activities. Additional joint movements are recruited to compensate for insufficient range of motion of the upper extremity joints (Cirstea and Levin 2000, Steenbergen et al. 2000), or when the effort of bringing the required range of motion into action exceeds the effort of recruitment of the trunk (Michaelsen et al. 2001). Hence, surgical correction of a pronation deformity in patients with CP is hypothesized to affect not only forearm rotation but also these associated movements. The effect of a change in forearm range of motion by corrective surgery on the movement patterns of the upper extremity and trunk has not previously been investigated. For this purpose, we customized a parameter called 'extrinsic forearm rotation' to quantify the collective result of all body movements that rotate the hand except forearm rotation. Thus, 'extrinsic forearm rotation' supplements or counteracts the effect of forearm rotation on the rotational position of the hand in space.

Here we present the outcome of a prospective study investigating changes in movement patterns by comparison of the values for extrinsic forearm rotation before, and 1 year after, surgical correction of the pronation deformity in 10 patients with CP. We test the hypothesis that movement patterns of the upper extremity and trunk are affected by the surgical correction of a pronation deformity of the forearm. If this is true, such an effect on the movement pattern should be anticipated in the planning of multiple procedures because these might involve deformities that are affected by the correction of others.

Method

PATIENTS

Ten patients with hemiplegic CP (mean age 16y 2mo [SD 4y 11mo]; range 11–27y) underwent surgical correction of their pronation deformity of the affected forearm. The surgical procedures performed in these eight male and two female patients were aimed at functional improvement of the upper extremity (Table I). Correction of the pronation deformity was achieved by pronator teres release, pronator teres rerouting, and/or flexor carpi ulnaris transfer. The study protocol was approved by the Medical Ethics Committee of the Academic Medical Centre in Amsterdam. Informed consent was obtained from all patients included in the study.

PREOPERATIVE AND POSTOPERATIVE THREE-DIMENSIONAL VIDEO REGISTRATION AND DATA ANALYSIS

Three-dimensional (3D) video analysis of the movement patterns was performed 1 day preoperatively and 1 year postoperatively by the same two examiners (MK and MJCS) in accordance with previously reported methods (Kreulen et al. 2004) and in conformity with recommendations for standardization (Anglin and Wyss 2000, Van Thiel and Steenbergen 2001). The participant was seated on a stool without arm or back support and with both feet on the ground; ample time was allowed to familiarize the participant with the experimental set-up. Two synchronized S-VHS video cameras registered the following tasks: (1) maximal active supination of both forearms; (2) picking up a drinking glass from a table top using a cylinder grip and holding it steady in a vertical position, requiring a neutral position of the forearm; (3) maximal active pronation of both forearms; and (4) picking up a wooden disk 8cm in diameter and 1cm in height that had been placed flat on the table top, requiring full pronation of the forearm. Special care was taken to standardize preoperative and postoperative table-top height and target distance for each patient.

Five images from both video recordings and of each session were selected for 3D analysis of the upper extremity and trunk position (Fig. 1): (1) while sitting on the stool just before performing the tasks; (2) at the moment of maximal active supination; (3) at the moment of grasping the glass and stabilizing it in vertical position; (4) at the moment of maximal active pronation; and (5) at the moment of grasping the wooden disk.

Local coordinate systems relative to anatomical landmarks on the patient were defined, permitting the calculation of the 3D positions of the trunk, upper arm, and forearm on the selected images (see Appendix I). In this way, the movement pattern could be expressed as a collection of eight parameters: (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. Parameters 4, 5, and 6 together constitute an interdependent sequence of angles expressing the position of the upper arm relative to the trunk as longitudes and latitudes of a globe projected around the shoulder (Pearl et al. 1992).

'Extrinsic forearm rotation' was defined as a specific parameter for this study to identify movement patterns directly related to impaired forearm rotation on images 3 and 5 (Appendix I). Thus, any change in compensatory movement strategy related to a change in impairment of forearm rotation can be identified by calculating the difference between postoperative and preoperative values for extrinsic forearm rotation.

STATISTICAL ANALYSIS

Statistical preoperative and postoperative comparison of the average values for all parameters was performed with a

Table I: Patient characteristics and data on forearm rotation

Patient no.	*Sex*	*Age, y*	*Preoperative forearm rotation, degrees*		*Surgical procedures*	*Postoperative forearm rotation, degrees*	
			Pronation (negative)	*Supination (positive)*		*Pronation (negative)*	*Supination (positive)*
1	M	11	–85	–40	PT-r, FCU-t, TIP	–81	5
2	F	11	–75	–23	PT-t, FCU-t, FDS/P-fr, TIP	–43	29
3	M	11	–77	61	PT-t, FCU-t, TIP	–56	61
4	M	13	–88	–59	PT-r, FCU-ECRB, TIP	–49	29
5	M	14	–81	–46	PT-r, FCU-ECRB, FDS/P-fr, TIP	–72	–11
6	M	17	–94	–67	PT-r, FCU-ECRB, TIP	–95	–24
7	M	19	–88	–13	PT-r, Apon, FCU-EDC, TIP	–60	68
8	M	19	–67	–14	PT-r, FCU-EDC	–67	–2
9	M	19	–65	–58	PT-r, Apon, FCU-ECRB, TIP	–52	14
10	F	27	–75	13	PT-r, FCU-EDC, TIP	–54	47
Mean (SD)	–	16.1 (4.9)	–80 (8.9)	–25 (37.1)	–	–63 (15.2)	22 (29.1)
p	–	0.013	0.030	–	–	<0.005	<0.005

PT-r, pronator teres rerouting; FCU-t, flexor carpi ulnaris -tenotomy; TIP, correction of thumb-in-palm deformity; FDS/P-fr, fractional lengthening of flexor digitorum sublimis and profundis tendons; Apon, aponeurectomy of the flexor/pronator muscle group; ECRB, extensor carpi radialis brevis; EDC, extensor digitorum communis.

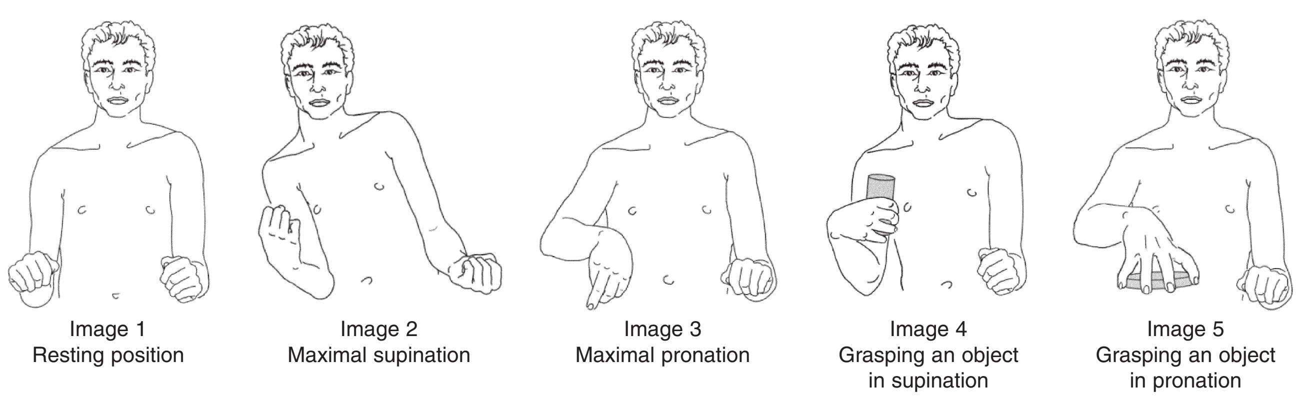

Figure 1: *Illustrations of the five selected images from the video recordings. Image 1, resting position; image 2, maximal supination; image 3, maximal pronation; image 4, grasping the glass in supination; image 5, grasping the disk in pronation.*

two-tailed Student's *t*-test for paired observations. For all analyses, an alpha level of $p<0.05$ was used for determining statistical significance.

Results

TASK 1

Maximal active forearm supination was preoperatively impaired in all patients (Table I) but increased significantly after surgical correction (mean increase +46°; $p<0.005$). The trunk lateral flexion, upper arm internal rotation, and elbow flexion, observed to occur preoperatively in our patients upon active forearm supination (Table II), had subsided postoperatively (Tables III and IV).

TASK 2

In comparison with the preoperative situation, more active forearm supination was used postoperatively to grasp the drinking glass (mean –19° [SD 30.9]; $p<0.05$). However, it was less than the postoperatively maximal available supination in the first task ($p<0.01$; Table III). The increased postoperative forearm supination while grasping the glass occurred in combination with a decrease in extrinsic forearm rotation to a mean of –13° (SD 12.5; $p<0.01$; Table V). This is reflected by a decreased need for trunk lateral flexion ($p<0.005$), a decrease in internal rotation of the upper arm ($p<0.01$) and a decrease in elbow flexion ($p<0.05$; Table IV). The plane of elevation also decreased, indicating that less adduction of the upper arm was used to grasp the drinking glass. However, this decrease was not statistically significant (mean decrease of 16°; $p=0.079$).

TASK 3

Surgical correction of the pronation deformity also resulted in a loss of maximal active pronation (mean loss of 17°; $p<0.005$). An associated decrease in elbow flexion (mean decrease of 14°; $p<0.05$) and upper arm internal rotation (mean decrease of 28°; $p<0.05$) was seen during the attempt to pronate the forearm maximally (Table IV).

TASK 4

The same loss of forearm pronation was seen while grasping the wooden disk (Tables III and IV). This induced the need for new compensatory strategies, reflected by a significant postoperative change in extrinsic forearm rotation in the same direction as forearm pronation itself (mean –8° [SD 10.6]; $p<0.05$; Table V). The movement strategy selected to compensate for this loss of pronation differed between patients. Trunk

Table II: Preoperative data

Task	*Trunk*			*Upper arm*			*Forearm*	
	Flexion	*Lateral flexion*	*Rotation*	*Plane of elevation*	*Elevation*	*Rotation*	*Elbow flexion*	*Forearm rotation*
1	0 (6.5)	14 (11.3)	1 (7.4)	54 (37.9)	20 (9.7)	–61 (43.7)	129 (16.1)	–25 (37.1)
2	12 (10.4)	14 (10.7)	10 (14.7)	80 (20.0)	36 (15.6)	–73 (20.7)	107 (28.6)	–55 (20.9)
3	2 (5.4)	5 (5.6)	3 (7.9)	41 (43.9)	21 (10.3)	–46 (44.0)	99 (21.8)	–80 (8.9)
4	14 (10.2)	3 (7.5)	2 (11.0)	55 (23.5)	47 (14.4)	–36 (26.9)	110 (18.1)	–68 (19.4)

Results are in degrees and are shown as means (SD).

Table III: Postoperative data

Task	*Trunk*			*Upper arm*			*Forearm*	
	Flexion	*Lateral flexion*	*Rotation*	*Plane of elevation*	*Elevation*	*Rotation*	*Elbow flexion*	*Forearm rotation*
1	1 (6.0)	8 (4.8)	–5 (5.8)	34 (73.6)	16 (6.2)	–25 (82.5)	111 (16.8)	22 (29.1)
2	7 (8.5)	6 (5.5)	4 (7.9)	64 (28.4)	36 (16.1)	–48 (37.0)	95 (21.6)	–19 (30.9)
3	3 (4.9)	1 (6.5)	–2 (7.0)	50 (23.6)	25 (9.9)	–18 (24.3)	85 (27.3)	–63 (15.2)
4	12 (9.6)	–3 (7.4)	4 (9.5)	45 (18.6)	47 (18.9)	–18 (17.2)	97 (20.1)	–51 (17.9)

Results are in degrees and are shown as means (SD).

Table IV: Differences between postoperative and preoperative data

Task	*Trunk*			*Upper arm*			*Forearm*	
	Flexion	*Lateral flexion*	*Rotation*	*Plane of elevation*	*Elevation*	*Rotation*	*Elbow flexion*	*Forearm rotation*
1	+1	–6[a]	–6[a]	–19	–4	+36	–18[a]	+46[d]
2	–5	–9[c]	–6	–16	0	+25[b]	–13[a]	+37[a]
3	+2	–3	–5	+9	+4	+28[a]	–14[a]	+17[c]
4	–3	–6	+2	–10	0	+17[a]	–13[c]	+16[a]

Results are in degrees. [a]$p<0.05$; [b]$p<0.01$; [c]$p<0.005$; [d]$p<0.001$.

lateral flexion in the opposite direction and a decreased plane of elevation of the upper arm towards more abduction contributed to directing the extrinsic forearm rotation towards pronation, but these were not both recruited by all patients. As a result, these changes were not significant (Tables III and IV). As in maximal active pronation, upper arm internal rotation and elbow flexion both decreased significantly in comparison with the preoperative movement pattern while grasping the disk (Table IV).

The results from the present study show that 1 year after surgical correction of a pronation deformity, active forearm supination increased in combination with a decreased use of movement strategies that supplement forearm supination in 9 out of 10 patients. However, the use of movement strategies to compensate for the observed loss of pronation increased.

Discussion

Many surgical procedures have been described for the correction of a pronation deformity of the forearm (Strecker et al. 1988, Enriquez de Salmanca 1993, Tonkin 2000, Gschwind 2003, Kreulen et al. 2004). Today, the choice between these available procedures depends on the extent of the deformity of the patient and the preference of the surgeon. Surgical treatment of the upper extremity in our series typically consisted of a combination of multiple procedures. Each focused on the increase in available range of motion of a joint. Surgical procedures other than those aimed directly at the correction of the pronation deformity might well have had their effect on forearm rotation as well. However, our study was not an evaluation of the clinical outcome of a surgical procedure. Rather, we set out to study whether a postoperative change in rotational range of motion of the forearm also affected associated movements outside the forearm. Similarly, the timing and sequencing of these movements were not the subject of our study. Instead, positional analysis of the end result of movement patterns during a reaching task was used to observe objectively whether the use of compensatory strategies was reduced by an improvement of forearm rotation.

Obviously, even a follow-up of 1 year may be relatively short for evaluation of the results of treatment in patients with CP, and the long-term development of movement patterns in a maturing musculoskeletal system requires further study.

Change in extrinsic forearm rotation was the parameter used to quantify for each patient the surgery-induced change in associated compensatory movement strategies. Thus, a decreased extrinsic forearm rotation implied that movements associated with the originally impaired forearm supination had subsided. Extrinsic forearm rotation decreased in 9 out of 10 patients performing a reaching task that required forearm supination. The one patient with an increased extrinsic forearm rotation had only a slight postoperative improvement of maximal active supination by 12°. However, he did not recruit this potential advantage at all during the functional task and actually invested more effort in compensation, possibly encouraged by an improved wrist position and grip function.

Surgical correction of a pronation deformity significantly improved the ability of active forearm supination, but it also resulted in a loss of maximal active pronation in 8 out of 10 patients. This is in agreement with previously reported observations in a comparable group of patients (Kreulen et al. 2004). The loss of active forearm pronation resulted in the recruitment of additional joint movements to compensate for this loss during the functional reaching task in our study.

Table V: Difference between postoperative and preoperative extrinsic forearm rotation

Patient	*Task 2 (image 3)*	*Task 4 (image 5)*
1	–2	–7
2	–13	13
3	–35	1
4	–13	–8
5	–16	–19
6	–28	–15
7	–4	–9
8	11	–8
9	–19	–27
10	–13	–2
Mean (SD)	–13 (12.5)	–8 (10.6)
p	<0.01	<0.05

Results (other than *p*) are in degrees.

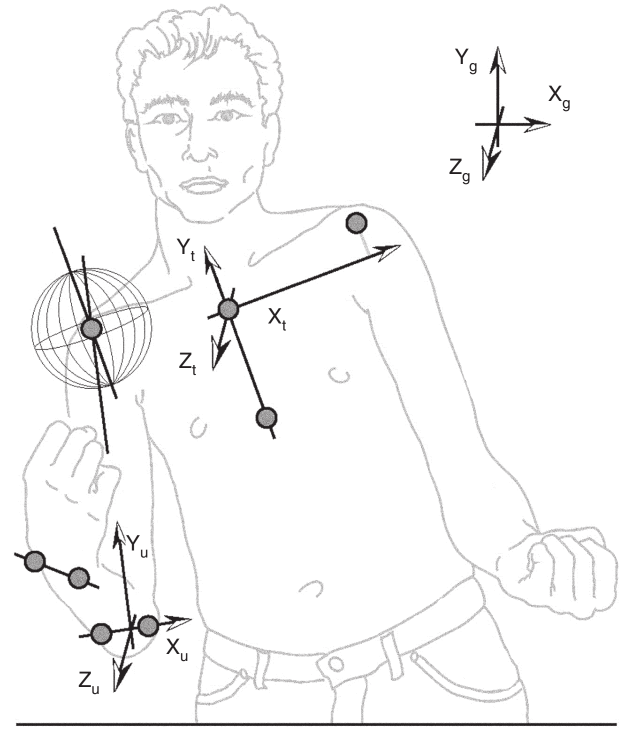

Figure 2: *Illustration of anatomical markings on patient and orientation of global and local coordinate systems.* X_g, Y_g, *and* Z_g *are x-, y-, and z-axes of global coordinate system;* X_t, Y_t, *and* Z_t *are x-, y-, and z-axes of local coordinate system for trunk; and* X_u, Y_u, *and* Z_u *are x-, y-, and z-axes of local coordinate system for upper extremity.*

CLINICAL IMPLICATIONS

A postoperative decrease in compensatory movement patterns may be caused either by an increased range of motion or by facilitation of the already available range of motion. Either way, compensatory movement patterns decrease only when the improved available active supination is actually employed during the functional tasks that the surgery sought to improve. From this perspective, maximal active supination alone may not be a valid parameter for the success of surgical treatment of a pronation deformity. This is in agreement with the observations of Michaelsen et al. (2001) in a study on movement patterns of stroke patients. A limited elbow extension during activities that require some degree of forearm supination, for example, may very well be a movement associated with an impaired forearm supination. In such a case, it will be improved by the correction of the pronation deformity, and may not need a separate surgical correction. Such an associated limitation of elbow extension should be differentiated from true impairment of the elbow joint that is independent of forearm rotation. Furthermore, a changed movement pattern may also indirectly affect manual dexterity. The observed significant postoperative decrease in compensatory movements of the upper arm and trunk alters the positional demands for the hand during functional activities.

Obviously, the movement patterns of the upper extremity in patients with CP remain a complex, task-specific assembly of interacting joint movements that are neurologically impaired. If a pronation deformity is the most prominent feature limiting the functional capacity of the upper extremity, it may be advisable in selected patients to correct only this pronation deformity and to expect a favourable effect on the overall movement pattern and hand function.

Conclusion

On the basis of the results of our study we conclude that a postoperative change in the rotational range of motion of the forearm is coupled directly with a change in the movement pattern that was related to the original pronation deformity. This should be anticipated at the preoperative planning of procedures for multiple deformities, as this change in movement pattern may involve deformities that are also eligible for surgical correction.

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Appendix I

To permit unrestricted movements in exploring the full adaptive capacity of the disordered movement system (Van Thiel and Steenbergen 2001), we used 3D video analysis as an accurate technique of non-contact posture measurement of the forearm, upper arm, and trunk. For this, ink markings were placed on the skin of the patient 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 (Fig. 2). Before video registration, the field of view was calibrated and set to match the borders of a 60cm×60cm×60cm calibration frame, after which the position and settings of the cameras were not changed. The recorded markers of the calibration frame (i.e. a global coordinate system) and those on the participants in all selected images were identified and digitized five times for each marker to increase accuracy. From the two sets of digitized coordinates (one set for each camera), the 3D positions of the anatomical landmarks relative to the global coordinate system were reconstructed with the Direct Linear Transformation method (Miller et al. 1980). In 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.

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 a local coordinate system of the upper arm (Veeger et al. 1997b, Kreulen et al. 2004). The axes of forearm rotation and of elbow flexion–extension were based on the average actual rotation axes relative to anatomical landmarks (Veeger et al. 1997a, b). The zero position (0° flexion, 0° 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 angle of rotation around the anatomical forearm axis was expressed as forearm pronation–supination, with 0° rotation from the zero position equalling 90° of supination, and

180° rotation from the zero position equalling –90° (i.e. 90° 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.

CALCULATION OF EXTRINSIC FOREARM ROTATION

Forearm rotation is determined relative to 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 counteracting the effect of forearm rotation on the position of the hand in space. Thus, any movement of the body outside the forearm that rotates the hand is reflected by rotation of the upper arm coordinate system (Fig. 2). We therefore 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 recognized 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. This extrinsic forearm rotation was expressed as a positive value if it supplemented forearm supination, and as a negative value if it supplemented pronation.

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 a local coordinate system based on the markings of the contralateral acromion, the manubrium sterni, and the xiphoid process (Fig. 2). The position of the upper arm relative to the trunk could then be expressed by a sequence of three angles: the plane of upper arm elevation, the angle of elevation, and the angle of upper arm rotation. In this way the upper arm position could be interpreted as longitudes and latitudes of a globe projected around the shoulder (Pearl et al. 1992, Anglin and Wyss 2000). 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 (Pearl et al. 1992). From the position of 0° rotation (upper arm z-axis perpendicular to the plane of elevation), exorotation was expressed as positive values and internal rotation as negative values.

CALCULATION OF TRUNK POSITION

The orientation of the trunk in resting position 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.