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Precision grip function after free toe transfer in children with hypoplastic digits

Michael Schenker [a,b,c,*], **Mikael Wiberg** [b,c], **Simon P. Kay** [b], **Roland S. Johansson** [a]

[a] *Department of Integrative Medical Biology, Section for Physiology, Umeå University, Sweden*
[b] *Department of Plastic, Reconstructive and Hand Surgery, St. James's University Hospital, Leeds, United Kingdom*
[c] *Department of Hand Surgery, Norrlands University Hospital, Umeå, Sweden*

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Summary Although toe-to-hand transfer has a defined role in the management of congenital hand deformities, it remains unclear how well children integrate the transferred digits into physiological grasping. We analysed fingertip forces in the precision grip of 13 patients when lifting a test object more than three years after free toe transfer for absent or hypoplastic digits. Clinically, most patients showed normal sensibility of transferred digits, but active motion and pinch strength were limited as compared to the normal hand. For the control of fingertip forces, two key features of the normal two-digit opposition grip were seen in all operated hands: adaptation of grip force to object weight and parallel coordination of lift and grip forces. These physiological grasping strategies developed independently of the patients' age at the time of operation, which ranged from one to 13 years. In four patients, we observed increased tangential load forces with the operated hand due to misalignments in the application of fingertips on the grasp surfaces. Such forces lead to increased grip force requirements on both fingers that may overload transferred digits with limited motor function. The need for optimal alignment of the grip axis during toe-transfer surgery is emphasised.

Just over a decade ago, free toe transfer did not have a clearly defined role in the treatment of congenital hand deformities with hypoplastic digits.[1] Following early descriptions,[2,3] Lister's important series of successful microsurgical

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* Corresponding author. Department of Plastic Surgery, Royal Victoria Infirmary, Newcastle Upon Tyne NE1 4LP, UK.
E-mail address: zjc81@dial.pipex.com (M. Schenker).

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second toe transfers for thumb reconstruction[4] encouraged surgeons to extend the indications for this procedure in children. Several clinical series have since demonstrated that free transfers of the second toe have the potential to improve the function of the hand as well as the sense of well-being of these patients.[5–11] The role of this operation in the treatment of congenital hypoplastic digits has now been defined.[12] However, little is known about how well the transferred digits become integrated into the child's physiological grasping behaviour.

The picking up of objects requires moving the hand to the target object, selecting grasp sites on the object, grasping it and applying adequate forces once contacted. In this study, we analysed forces and movements after contact of the digits with the object when the patients carried out a fundamental manipulatory task: lifting a small object using a precision grip between two digits.[13] This task involves the application of coordinated fingertip forces adapted to physical characteristics of the object, such as its surface friction and weight.[14] These fingertip forces are initially generated in anticipation of force requirements but can be corrected during the lift whenever necessary to match the real force demands of the task.[15] A complex system of sensory—motor control is engaged that involves the generation of individual fingertip forces based on memories of previous trials, visual and tactile estimations of object properties and sensory signals from mechanoreceptors during the lift.

We examined 13 patients three years or more following second toe transfer and compared the grasping performance with the thumb and index finger of the normal hand with that of the equivalent reconstructed digits of the hypoplastic hand. Specifically, we aimed to establish if these patients demonstrated physiological coordination of grip and lift forces and how they managed to adapt the forces to changes in object weight when using the transferred digits.

Patients and methods

Patients

For participation in this study, we invited consecutive patients with unilateral symbrachydactyly or transverse absence, who had undergone microvascular transfer of both second toes at least three years previously (Table 1). We included only patients who were unable to grasp objects with a tip-to-tip precision grip preoperatively. We excluded patients who were listed for secondary surgery at the time of our investigation. Of 13 patients recruited, six patients had a functional thumb and the toes had been transferred to two selected rays of the second to fourth ray to oppose the thumb. In six other patients, one toe had been transferred to the first ray to oppose the other toe on one of the finger rays. One patient (pt. 3) had undergone free pollicisation of the ring finger — the only digit present preoperatively — and double toe transfer to rays 3 and 4. The patients were between one and 13 years of age at operation and all were five years or older at the time of the present study. All patients understood the lifting tasks and could cooperate sufficiently.

The patients attended an interview and a clinical assessment before the tests of precision grip. Patients and parents were interviewed about the use of the operated hand in activities of daily living. To validate this information the clinical examiner observed the patients when they performed bimanual tasks that involved opening a jar and connecting and disconnecting pieces of Lego™ and Duplo™. A children's hand therapist measured the active range of motion at each joint in the transferred digits, the tactile detection thresholds using Semmes—Weinstein (S—W) filaments and the static 2-point discrimination with the Dellon—Mackinnon Discriminator®. The Local Research Ethics Committee at St. James's University Hospital granted permission for this study. We received informed consent from both patients and parents.

Precision grip task

Sitting on a chair, the patients grasped a small test object placed on a low table, lifted it straight up to about 5—10 cm and replaced it (Fig. 1A). With the normal hand, they used a precision grip between the tips of the index finger and the thumb. With the operated hand, the patient grasped the object either between two transferred digits or between the natural thumb and the preferred transferred digit.

Each participant performed one lifting series with each hand. Each series consisted of 19 trials, during which the weight of the test object was altered (0.11, 0.26 and 0.55 kg) in an order unpredictable to the patient (see Fig. 1B). It started with a lift of the medium weight (0.26 kg) followed by six lifts with each of the three weights. Each series was performed first with the normal and then with the operated hand. The first trial of each series was regarded as a practicing trial and not included in the data analysis. The test object measured, for

Table 1 Patients and clinical results

	Sex	Diagnosis[a]	Patients				Tactile sensibility			Motor function		Transfer integration
			Double toe transfer to (side)	Age[b] (op)	Age (FU)	FU (years)	S—W filaments[c] Radial—Ulnar	S2PD[d] Radial—Ulnar	ROM[e] Radial —Ulnar	Maximum pinch (N) Transfer—normal	Pinch strength ratio (%)	
1	F	TA (thumb)	ray 3, 4 (L)	13	20	6	(3.22) — *4.17*	(4) — *7*	N — *25*	30.2/66.2	45.6	Always; *frequent injuries*
2	F	SBD (thumb)	ray 2, 4 (R)	12	17	4	(2.44) — *4.31*	(3) — *>12*	N — 80	15.0/59.5	25.2	Always
3	M[f]	TA (BJ)	ray 3, 4 (L)	8	12	4	2.83 — 3.84	5 — 5	*0* — 80	12.3/30.4	40.5	Always
4	M	TA (no BJ)	ray 1, 4 (L)	3 (4)	13	9	3.61 — *4.31*	4 — *>12*	80 — 70	*8.5*/31.4	27.1	Mostly; *problems with small objects*
5	F	SBD (BJ)	ray 1, 3 (L)	4 (5)	13	9	3.22 — 2.83	4 — 5	*15* — 85	12.0/23.0	52.2	Always
6	M	TA (BJ)	ray 1, 2 (R)	3	9	6	2.44 — 2.83	5 — 6	*35* — *25*	*3.1*/19.7	15.8	Mostly; *problems with small objects*
7	F	SBD (thumb)	ray 3, 4 (L)	1 (1)	9	8	(2.44) — 2.44	(3) — 4	N — 90	15.9/20.4	77.9	Always
8	M	SBD (thumb)	ray 3, 4 (L)	1	7	5	(3.61) — 3.61	(3) — 5	N — 110	10.5/22.9	45.9	Mostly; also thumb—hypothenar opposition
9	M	TA (BJ)	ray 1, 3 (R)	1	7	5	2.83 — 3.61	4 — 5	50 — *30*	11.8/22.7	52.0	Always
10	M	SBD (no BJ)	ray 1,3 (L)	1	7	5	2.44 — 3.61	3 — 5	*20* — *10*	*3.0*/21.0	14.3	Mostly; *problems with large objects*
11	M	SBD (thumb)	ray 1, 4 (L)	2	6	4	(3.61) — 2.83	(3) — 3	N — 60	14.0/28.1	49.8	Mostly; *problems with cutlery*
12	M	SBD (no BJ)	ray 3, 4 (R)	1	5	3	3.61 — 3.61	3 — 3	*40* — *0*	*8.4*/21.2	39.6	Always; *problems with cutlery*
13	F	SBD (thumb)	ray 2, 3 (L)	1	5	3	(2.44) — 2.44	(2) — 3	N — 90	12.0/11.8	101.7	Always

[a] The diagnosis was transverse absence (TA) or symbrachydactyly (SBD). The preoperative status of the first ray regarding the presence of a thumb or the basal joint (BJ) is given in brackets.

[b] Three patients underwent asynchronous toe transfers with the age at the second transfer given in brackets.

[c] Tactile sensibility was measured with Semmes—Weinstein (S—W) filaments. Values in brackets indicate the sensibility of the natural thumb. Sensory thresholds suggesting diminished protective sensation (>3.61) and abnormal S2PD (>6 mm) are highlighted in italic.

[d] The static 2-point discrimination (S2PD) with a Dellon—Mackinnon Discriminator®.

[e] Range of motion (ROM) represents the total active range and 'N' indicates normal ROM in a thumb present preoperatively.

[f] Patient 3 underwent free pollicisation of the normal ring finger at the time of synchronous double toe transfer. The results of sensibility and motor function for the radial digit refer to the transferred ring finger.

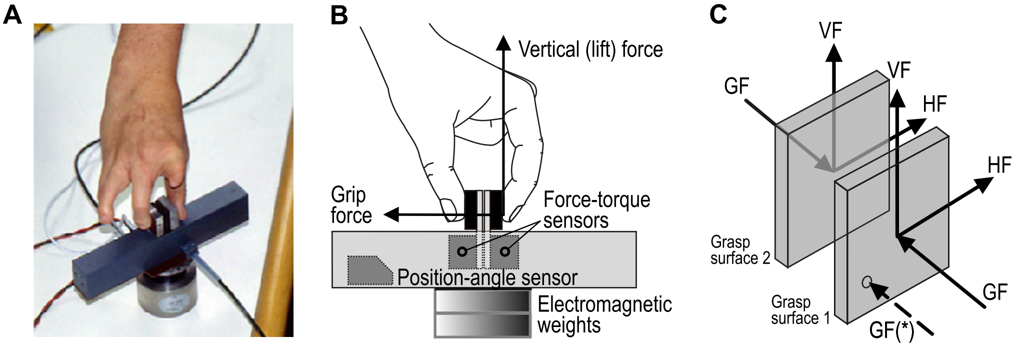

Figure 1 Test object and force reference frames. (A) A patient lifts the instrumented test object in a two-finger precision grip between the abnormal thumb and the preferred transferred digit. (B) The test object carried two opposing grasp surfaces attached to a force—torque sensor, a position sensor and two computer-controlled electromagnetic weights to alter object mass without visual cues before lift-off. (C) The grip force (GF), the vertical lift force (VF) and the horizontal force (HF) were measured separately for each digit. Malpositioning of the digits causes differences in the horizontal and vertical position of the points of grip force attack (GF*) and have to be met by additional tangential forces for preventing object rotation.[16]

each digit, the *grip force* along an axis perpendicular to the parallel grasp surfaces. Tangential to the grasp surfaces it measured the *vertical* (*lift*) *force* and the *horizontal force* (Fig. 1B and C). A position sensor measured the object's vertical position. The maximum voluntary grip force in three separate 'squeeze' trials by each pair of digits used in the task represented the pinch grip strength. A more detailed description of the apparatus and the procedure can be found in an earlier paper.[16]

Data analysis

A flexible data acquisition and analysis system (SC/ZOOM, Physiology Section, IMB, Umeå University) continuously sampled the signals provided by the test object. Grip and horizontal forces are reported as the mean of the absolute forces recorded at both digits if not indicated otherwise and the tangential force was calculated as the vector sum of the vertical and horizontal forces.

For each trial, the coordination of grip and vertical forces, measured during the period of force increase between contacting and lifting the object, was analysed by linear regression. During the following (holding) phase when the object was aloft, forces were measured at the instance of maximal object elevation. In each patient we used these data to analyse grip force adjustment to weight by linear regression and by an ANOVA with weight (0.11, 0.26 and 0.55 kg) and hand (normal and operated) as factors. These data were also used for the analysis of tangential forces. In comparison of ratios between forces and populations of correlation coefficients we used the non-parametric Mann—Whitney test. In all tests, the probability selected as significant was $p < 0.05$.

Results

Clinical assessment

Table 1 summarizes the clinical results. All patients had normal tactile sensibility in the transferred digits except two who underwent toe transfer as adolescents (pts. 1 and 2) and one (pt. 4) who achieved normal sensibility in one, but not in the other transferred digits. The postoperative motor function after toe transfer was more variable and was poor in two patients with exceptionally weak pinch strength and limited active range of movement (pts. 6 and 10). All three patients who had a toe transferred onto the first ray without a competent basal joint (pts. 4, 10 and 12) had a very weak pinch grip (<10 N). Most of the patients whose transfers opposed a normal or vestigial thumb (pts. 1, 2, 7, 8, 11 and 13) had a stronger pinch grip than the patients who grasped between both transfers.

Related to limited motor and sensory recoveries, several patients reported difficulties using the operated hand in activities of daily life. For example, frequent injuries to her toe transfers forced patient 1 to change job from cook to landscape gardener. This presumably related to poor protective sensation, as her grip between the normal thumb and the transferred digits was strong enough to support heavy manual work. By contrast, both patients 6 and 10 with a weak grip and limited mobility of the digits reported problems manipulating objects.

Precision grip task

With one exception, all patients could perform the task with their operated hand. Table 2 lists the numbers of failed attempts to lift the object and occasional drops when aloft. Patient 6 consistently failed to lift the object with the operated hand, but was also unable to lift the heavy weight (0.55 kg) with the normal hand. Although a weak pinch force may have accounted for the poor performance of the operated hand, the anatomically normal hand showed no obvious force limitations.

Grip force adaptation to object weight

Fig. 2 shows the fingertip forces of the operated hand for one patient with a strong grip but abnormal sensibility (pt. 1) and for one with good motor function and normal sensibility (pt. 5) during lifts with each of the three weights (0.11, 0.26 and 0.55 kg). In both patients, the grip force increased with increases in the total vertical force (thick traces) applied to overcome the weight of the object. For each of the 12 patients who could lift objects of the different weights with both hands (Table 2) there was a significant positive correlation between weight and grip force when the object was aloft. Importantly, this was applied not only to the normal hands ($0.38 < r^2 < 0.93$; median $r^2 = 0.81$), but also to the operated hands ($0.76 < r^2 < 0.98$; median $r^2 = 0.87$). Fig. 3 exemplifies this correlation by showing data from all lifts by either hand of three different patients. These results indicate that the patients reliably adapted grip forces with their transferred toes to object weight, which is essential for upholding a stable grasp when lifting objects of various weights.[14]

To assess possible differences between the operated and normal hands in this respect, we run a two-way ANOVA with weight and hand (operated and normal) as factors on the grip force data from each of the 12 patients. Apart from a main effect of weight in all patients reflecting the robust correlations between weight and grip force for both hands, the ANOVAs indicated a significant difference between the hands for seven patients (Table 2). One patient (pt. 1) used higher grip forces with the operated hand (Fig. 3B). The operated hand in six patients used a weaker grip (for one example, see Fig. 3C). Different slopes of the relationship between weight and grip force characterized the difference between the normal and operated hands, which was verified by significant interaction effects between weight and hand.

Table 2 Grip force modulation to weight

Patient	Unable to lift N/T[a]	Drop N/T[b]	Main effect of hand[c]	
1	0/0	0/0	***	+
2	0/0	*0/1*	*	−
3	0/0	*0/5*	$p = 0.13$	
4	0/0	*0/5*	***	−
5	0/0	0/0	***	−
6	*6/18*			
7	0/0	0/0	***	−
8	0/0	0/0	***	−
9	0/0	0/0	$p = 0.89$	
10	*0/6*	*0/1*	*	−
11	0/0	*0/2*	$p = 0.15$	
12	0/0	*0/1*	$p = 0.27$	
13	0/0	*1/0*	$p = 0.14$	
	$n = 18/18$			

Significant p-values are shown as $*p < 0.05$, $**p < 0.01$ and $***p < 0.001$.

[a] Number of trials from a total of 18 during which the patient was unable to lift the object or dropped it once lifted.

[b] Number of trials from a total of 18 during which the patient was unable to lift the object using the normal hand (N) and the toe transfers (T).

[c] A significant main effect by hand (ANOVA) indicated differences in the grip force level for normal and operated hands. The grip forces using the toe transfers could be higher (+) or lower (−) than with the normal hand.

Parallel coordination of grip and lift forces during the loading phase

Lifting objects of various weights smoothly with maintained grasp stability requires a coordinated increase of grip and vertical load force during the period of isometric force increase before object lift-off.[14] In contrast to the holding phase, the forces during this 'loading phase' depend on both the current weight and that of the object experienced in the previous trial.[17] Fig. 4 shows how the youngest patient of this study (pt. 13, aged 5) applied coordinated vertical lift and grip forces with both hands during the loading phase in trials with the medium weight (0.26 kg). The two top trials were preceded by lifts with the lighter object (0.11 kg), which the patient anticipated in the current trials. Both forces increased in parallel to the point of expected object lift-off (arrows in Fig. 4) followed by a second phase of slower parallel force increase until the object actually lifted off. The situation was reverse for trials preceded by lifts with the heavier object (0.55 kg) where the patient initially generated a strong force drive accounting for a marked force overshoot in expectation of the heavier weight (bottom trials in

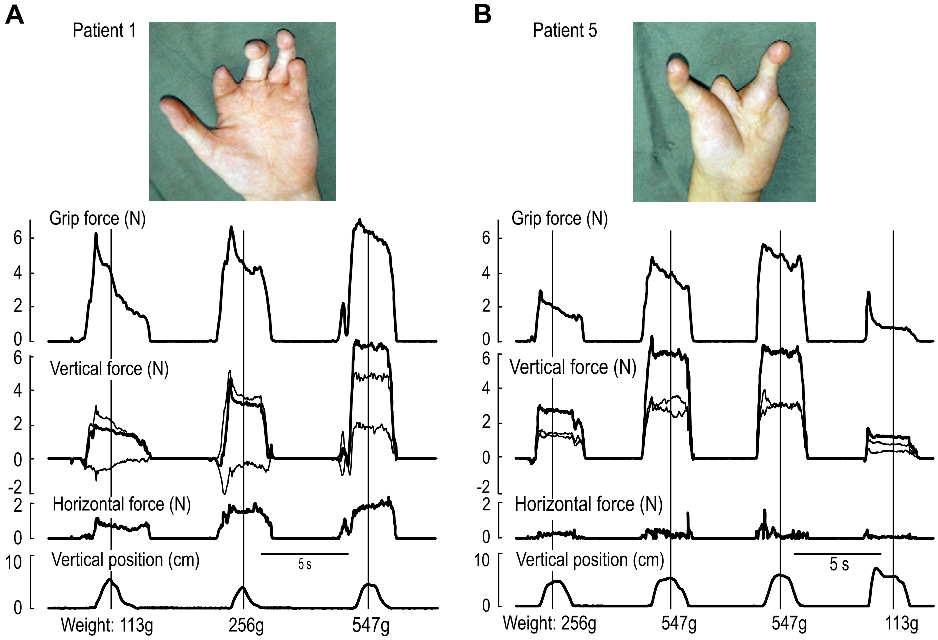

Figure 2 Force traces and position signals of consecutive lifts in two selected patients using the operated hand. Vertical markers indicate times when force measurements were taken to represent forces during the holding phase with the object in mid-air. The grip force at that time is approximately proportional to the total vertical lift force (thick traces), which reflects object weight. (A) Patient 1 applied virtually all the vertical force with one digit. A substantial horizontal force was generated as well. (B) Patient 5 shows a balanced distribution of vertical forces between both digits and a negligible amount of horizontal force (pt. 5). Note the lower grip forces as compared to patient 1 for trials of corresponding weight.

Fig. 4). Note that the parallel development of grip and vertical force during the loading phase is expressed both by the normal and the operated hands.

Fig. 5 illustrates the parallel force coordination by plotting the grip force against the vertical force for trials by all patients. An approximately straight line would indicate a coordination representative for normal adults.[14] By contrast, a force coordination characteristic for very young children shows a sequential force increase first in grip, then in vertical force and results in a curve with an initially steep slope and then more flat trajectory.[18] In agreement with successful adaptation of grip force to object weight, all 12 patients who could lift the 0.26-kg-object showed rather smooth parallel coordination of grip and vertical forces, including the youngest children (pts. 12

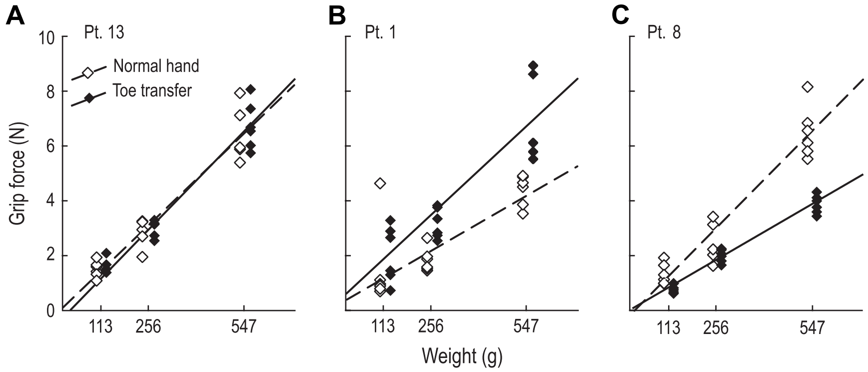

Figure 3 Grip force adaptation to object weight. Relationship between grip force and object weight shown for (A) one of the five patients whose behaviour with toe transfers and normal hands did not differ significantly, (B) the patient who used higher grip forces with the operated hand and (C) one of the six patients who used lower grip forces with the operated hand. Each symbol refers to a single trial and the lines were obtained by linear regression.

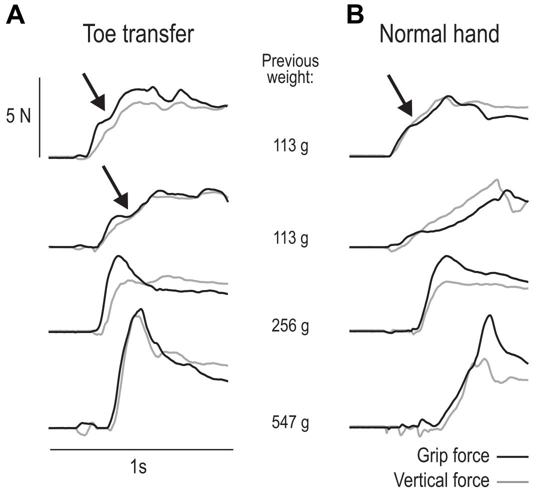

Figure 4 Parallel coordination of grip and vertical forces in trials with medium weight (0.26 kg) by one patient (pt. 13). Superimposed grip and lift forces during the loading phase of lifting trials in single trials preceded by lifts of the same (0.26 kg), a lighter (0.11 kg) or heavier (0.55 kg) weight. Parallel coordination of forces is equally seen in the operated (A) and in the normal (B) hand. Variations in force rate within both groups of trials reflect weight prediction based on object weight in the preceding trial. The arrows indicate the point where object lift-off is expected based on the previous trial with the lighter weight (0.11 kg).

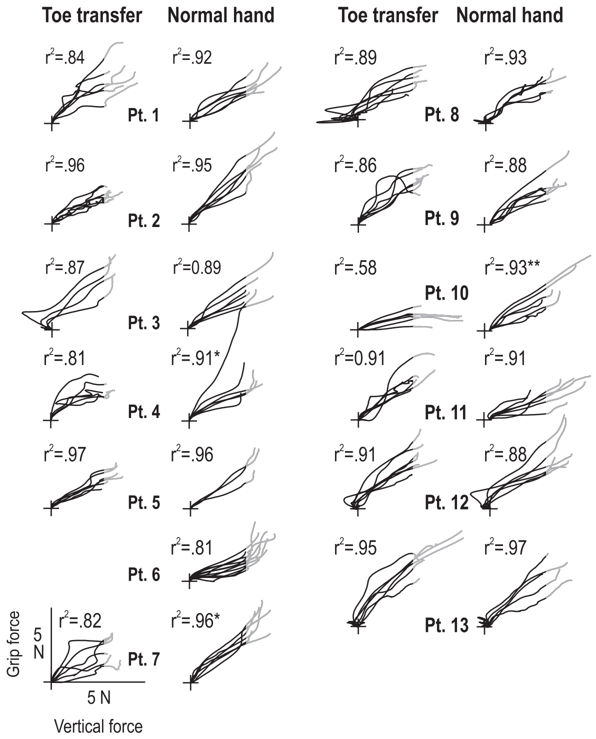

Figure 5 Parallel coordination of grip and vertical forces in trials with medium weight (0.26 kg) for all patients and hands. Grip force plotted against the sum of vertical forces generated by the two digits between the instance of fingertip—object contact and object lift-off (black part of the curves). Initially during trials patients occasionally applied a negative vertical force indicating downward pressure onto the object that was accompanied by a small increase in grip force for grasp stability. The r^2-values (obtained by linear regression) represent the mean values of the coefficient of determination obtained for the curves of each hand and patient Three patients showed significant differences between hands in the r^2-values (Mann—Whitney test; $^{*}p < 0.05$, $^{**}p < 0.01$).

and 13; Fig. 5). Visual comparison of the curves in Fig. 5 between the normal and operated hands for individual patients suggested that the coordination was quite similar between the pairs of hands of most patients. However, there were differences in three patients (pts. 4, 7 and 10) as assessed by linear regression, where the mean r^2-values of the operated hand were significantly smaller than for the normal hand.

Increased tangential forces

The lifts shown in Fig. 2 reveal further details about the fingertip forces applied by patients. In patient 1, one digit applied virtually all vertical forces used to lift the object while the other digits partly generated negative vertical forces, i.e. forces directed downwards (Fig. 2A). By contrast, the vertical lift force applied by patient 5 was equally partitioned between the digits (Fig. 2B). Furthermore, unlike patient 5, patient 1 generated considerable horizontal forces (cf. Fig. 2A and B).

Because the patients held the object approximately to level, the discrepancy in vertical force between the digits and the generation of horizontal forces was accounted for by a difference in the vertical and horizontal positions of the points of grip force attack by the two digits. A difference in the vertical position would cause change in object elevation unless counteracted by asymmetric vertical tangential forces. Similarly, a difference in the horizontal position would lead to rotation of the object in the horizontal plane unless counteracted by horizontal tangential forces. To analyse vertical force imbalances in all patients, we calculated the fraction of the total vertical force generated by the normal or the reconstructed thumb (Fig. 6A). This measure was 0.5 (i.e. 50%) if the vertical force was equally distributed between the pair of digits engaged. For all but one (pt. 6) of the normal hands, the vertical forces were evenly distributed between the digits. By contrast, this measure was significantly different from 0.5 for the operated hands in seven patients. The most loaded digit could be either the radial

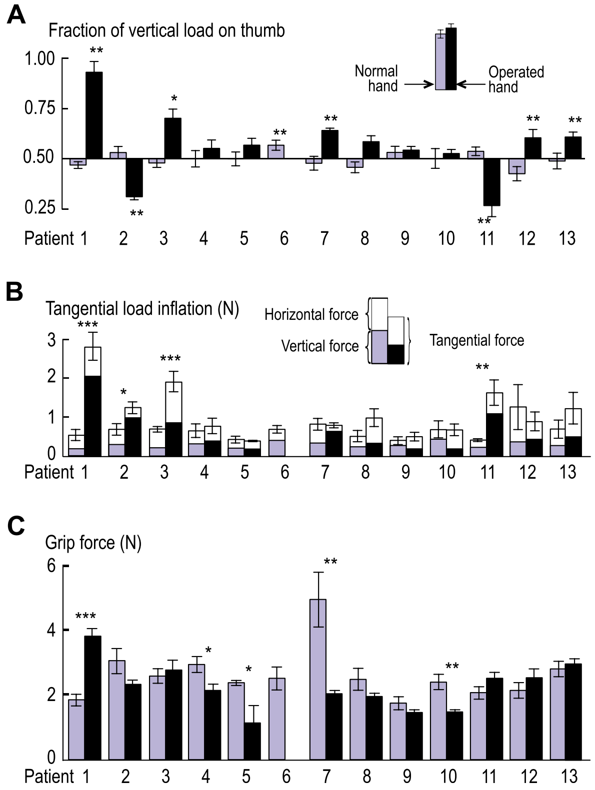

Figure 6 Tangential and grip forces applied in trials with the medium weight (0.26 kg). (A) Fraction of total vertical force taken up by the thumb. Uneven distribution of vertical force between digits is indicated by values significantly different from 0.5. (B) Inflated tangential force on the most loaded digit accounted for by malalignment of the fingertips on the grasp plates with the contribution of horizontal and vertical components indicated. The rise in tangential load with the transplanted hands differed significantly from the contralateral hand in four patients. (C) Grip forces with significant differences between hands are indicated. (A—C) (*, ** and *** refer to *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$, respectively).

(pts. 1, 3, 7, 12 and 13) or the ulnar digit (pts. 2 and 11), the transferred toe (pts. 2, 3, 11 and 12) or the thumb present preoperatively (pts. 1, 7 and 13). Object tilt could not explain these imbalances as there was no significant correlation between object elevation and the fraction of load taken up by the thumb (Spearman's rank correlation). As such, the object tilt for these seven patients was small (range of mean values: 0.08—3.46°).

Both vertical and horizontal asymmetries in the points of grip force attack by the two digits affect the tangential force required to prevent object rotation.[16] The filled segments of the bars in Fig. 6B show the increased tangential force related to misalignments in the vertical positioning of the digits. Although there were significant vertical force imbalances between digits of the operated hand in seven patients (cf. Fig. 6A), the resultant tangential force increases were significantly different between the hands only in the four patients (pt. 1, 2, 3 and 11) with the most pronounced imbalances. For all patients, horizontal forces also contributed to the increased tangential force in both hands (see hollow segments of the bars in Fig. 6B).

Increased tangential force caused by misalignments of the digits increases the demand for grip forces to prevent accidental dropping of the object as compared to a balanced grip. However, of those four patients with significantly inflated tangential loads, only patient 1 used higher grip forces with the operated than with the normal hand (Fig. 6C). The fact that the other three patients (pts. 2, 3 and 11) did not do that might relate to their weak pinch grip with the operated hand. Accordingly, patients 4, 5 and 10 who also had a weak pinch, used significantly lower grip forces with the operated hand as compared to the normal hand even though the tangential forces were similar for both hands (Fig. 6C). There is no obvious explanation for the extremely high grip forces applied by patient 7 with the normal hand.

Discussion

We have shown that patients following second toe-to-hand transfer for congenital hypoplastic digits exhibit physiological principles of grasping when using the transferred digits to lift a small object with a precision grip. They adapted the grip forces to object weight and coordinated grip and lift forces in parallel during phases of isometric force changes. With the operated hand, one-third of the patients generated grip forces in proportion to load forces without obvious differences to their normal hand. Most patients, however, modulated the grip forces within a restricted range possibly related to a weak pinch grip with the transferred digits. Because of extra tangential loads caused by malpositioning of the digits on the object, in some patients there were imbalances in the grip that increased the grip force demands required for grasp stability. This potentially overloads the capacity of such a hand, which typically has a weaker grip than the normal side. Consequently, this may result in an increased rate of slippage, object drop and fatigue further degrading dexterity.

The finding of physiological principles for the precision grip with transferred toes has significance in relation to the development of grasp. A possible different outcome of our study would have been a sequential application of grip and lift forces as seen in young children,[18] which prevents smooth adaptation of forces to object weight. Although children at the age of two years have learned to scale the grip force when they lift objects of different weights, both the rates of force generation and the absolute grip force levels remain highly variable.[19] Smooth parallel coordination of grip and lift forces is not seen before the age 4–6 and undergoes changes well into teenage years.[18] Likewise, anticipatory strategies of grip force adaptation based on previous lifts only emerge before age four and gradually mature until they reach adult patterns by the age of 8–11.[19,20] In the majority of our patients, the toe transfer was performed during this phase of development and our study suggests that their grasping development is similar to children born without anomalies of the hand. Even the youngest children in our study showed parallel coordination of forces that compares well with previous observations on normal children lifting a similar apparatus.[18,21]

The timing of toe transfer in children with congenital hypoplasia of digits remains controversial. Some surgeons believe that the procedure should be performed before the development of a true pinch grip at 11 months of age[6] while others suggest that it is better to wait until age two or later for better size of structures.[22] Regarding the development of grip after pollicisation for aplasia of the thumb, Buck-Gramcko had originally suggested operating early before age one, but later stated that the outcome is similar if the operation is performed before age three.[23] Our findings suggest that the exact timing is not critical. The age of our patients at the time of operation ranged from one to 13 years and all patients developed key features of the physiological grasp. That some patients generated forces in a less coordinated manner with the operated than with their normal hand (see Fig. 5) did not obviously relate to their age at operation. The four patients with the best clinical and physiological outcomes (pts. 5, 9, 11 and 13) had the toe transfers at an age between one and five years. The age of operation of the patients with less good outcomes (pts. 1, 4, 6 and 10) ranged widely between one and 13 years.

However, our findings suggest an age effect on the development of sensibility in transferred digits. Whilst the two patients operated on as adolescents aged 12 and 13 had incomplete touch detection and 2-point discrimination, all patients operated on before the age of eight achieved good sensibility. This agrees with long-established outcomes of clinical tests after peripheral nerve repair showing that recovery of sensibility correlates strongly with the age of the patient at nerve suture.[24,25] Likewise, it corroborates results of sensibility tests in previous series of microvascular toe transfers on younger children[4,6,9,11] as compared to incomplete sensory recovery after toe transfer in adolescents.[26]

Despite abnormal digital sensibility, the two oldest patients successfully adapted the grip forces to object weight (pts. 1 and 2), as did the one patient with normal tactile sensibility in one, but not the other transferred digits (pt. 4). This may be explained by the fact that these patients had one digit with normal sensibility engaged in the precision grip. Furthermore, somatosensory information about the event of lift-off presumably drives the adaptation to weight changes when there is no visual cue to estimate object weight.[15] Such somatosensory information does not depend on fingertip sensation and can be encoded by mechanoreceptors in the proximal hand and arm sensitive to mechanical transients (e.g. FA-II sensors).[15,27,28]

One of these three patients with abnormal digital sensibility consistently used higher grip forces when using the transferred digits (pt. 1). Although we identified inflated tangential loading of the grasp, which presumably contributed to high grip forces in this patient, she may also have used increased grip forces as a compensatory strategy for reduced fingertip sensibility. This is a frequent finding in adult patients with abnormal sensibility after peripheral nerve injury.[16]

Although the majority of patients in this study showed reduced grip strength and limited active range of motion as compared to their normal hand, this was most marked in the three patients without an intact basal joint of the thumb (pts. 4, 10 and 12). A mobile, stable and competent first carpometacarpal joint has previously been recognised as the single most powerful determinant of the clinical outcome of microvascular toe transfer for congenital digital hypoplasia.[12] A further contributing factor to limitations in motor function could be the lack of intrinsic hand muscles. These muscles may be abnormal or absent in patients with congenital hypoplastic digits and the reconstruction of intrinsic tendons during toe transfer is often not possible.[6,12]

In four patients, malalignment of the digits of the operated hand on the object caused increased tangential forces and thereby additional grip force demands for a stable grasp. In spite of the increased demands with the operated hand, only one of these four patients (pt. 1) used significantly higher grip forces with this hand. The other three patients applied grip forces not significantly different from their contralateral hands, which could be due to force limitations (cf. maximum grip strength for pts. 2, 3 and 11 in Table 1). In patients, who are unable to generate higher grip forces, load imbalances may overload the reconstructed digit with a weak grip and are possibly the reason for a higher rate of slippage (cf. pts. 2, 3 and 11 in Table 2). We believe that lack of intrinsic hand muscle function is an important contributor to the malalignments of the digits,[16] but this is difficult to correct surgically. Precise surgical orientation of joints and adequate skeletal fixation during toe transfer, however, would be a crucial step to minimise imbalances in force application during precision grip and thus reduce the demand for fingertip forces. This is particularly important for patients with aplasia of all digits, who would completely depend on the two transferred toes in their grip. Patients with a double toe transfer opposing the thumb may take advantage of the third digit to align the two fingers and stabilise the precision grip against the effects of finger misalignments (Fig. 7).

Conclusion

Children with congenital hypoplasia of digits after free toe transfer develop physiological grip patterns. The age at toe transfer is not critical for the development of a physiological grasp pattern, but for full sensory recovery the operation has to be performed at the age of eight years. Finger malalignment within the grasp is a possible cause for increased demands of fingertip forces with potential adverse effects on manipulation, which underlines the importance of correct surgical orientation of transferred digits.

Figure 7 Stabilisation of the precision grip using the second transferred digit. In patient 1 the double toe transfer opposes a normal thumb and makes it possible to use the third digit for fine-tuning of forces and for stabilisation. By contrast, patients with aplasia of all digits completely rely on a potentially less stable 2-digit pinch grip with the transferred toes, where correct surgical orientation of skeletal elements is crucial to minimise imbalances in force application (cf. Fig. 2 B).

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References

1. Netscher DT, Scheker LR. Timing and decision-making in the treatment of congenital upper extremity deformities. *Clin Plast Surg* 1990;**17**(1):113–31.
2. May JW, Smith RJ, Peimer CA. Toe-to-hand free tissue transfer for thumb construction with multiple digit aplasia. *Plast Reconstr Surg* 1981;**67**(2):205–13.
3. Gilbert A. Toe transfers for congenital hand defects. *J Hand Surg* 1982;**7A**:118–24.
4. Lister G. Microsurgical transfer of the second toe for congenital deficiency of the thumb. *Plast Reconstr Surg* 1988;**82**(4):658–65.
5. Foucher G, Moss ALH. Microvascular second toe to finger transfer: a statistical analysis of 55 transfers. *Br J Plast Surg* 1991;**44**:87–90.
6. Foucher G, Medina J, Navarro R, et al. Toe transfer in congenital hand malformations. *J Reconstr Microsurg* 2001;**17**(1):1–7.
7. Shevdovchenko IV. Toe-to-hand transfers in children. *Ann Plast Surg* 1993;**31**:251–4.
8. Kay SP, Wiberg M. Toe to hand transfer in children. Part 1: technical aspects. *J Hand Surg* 1996;**21B**(6):723–34.
9. Kay SP, Wiberg M, Bellew M, et al. Toe to hand transfer in children. Part 2: functional and psychological aspects. *J Hand Surg* 1996;**21B**(6):735–45.
10. Bellew M, Kay SP. Psychological aspects of toe to hand transfer in children. *J Hand Surg* 1999;**24B**(6):712–8.
11. Van Holder C, Giele H, Gilbert A. Double second toe transfer in congenital hand anomalies. *J Hand Surg* 1999;**24B**(4):471–5.
12. Kay SP. Microvascular toe transfer for hypoplastic digits. In: Green DP, Hotchkiss RN, Pederson WC, Wolfe SW, editors. *Green's operative hand surgery*. Edinburgh: Churchill Livingstone; 1998. p. 375–89.

13. Westling G, Johansson RS. Factors influencing the force control during precision grip. *Exp Brain Res* 1984;**53**:277–84.
14. Johansson RS, Westling G. Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects. *Exp Brain Res* 1984;**56**:550–64.
15. Johansson RS, Cole KJ. Grasp stability during manipulative actions. *Can J Physiol Pharmacol* 1994;**72**:511–24.
16. Schenker M, Burstedt MKO, Wiberg M, et al. Precision grip function after hand replantation and digital nerve injury. *J Plast Reconstr Aesth Surg* 2006;**59**:706–16.
17. Johansson RS, Westling G. Coordinated isometric muscle commands adequately and erroneously programmed for the weight during lifting task with precision grip. *Exp Brain Res* 1988;**71**:59–71.
18. Forssberg H, Eliasson AC, Kinoshita H, et al. Development of human precision grip I: basic coordination of force. *Exp Brain Res* 1991;**85**:451–7.
19. Forssberg H, Kinoshita H, Eliasson AC, et al. Development of human precision grip II: anticipatory control of isometric forces targeted for object's weight. *Exp Brain Res* 1992;**90**: 393–8.
20. Paré M, Dugas C. Developmental changes in prehension during childhood. *Exp Brain Res* 1999;**125**:239–47.
21. Forssberg H, Eliasson AC, Kinoshita H, et al. Development of human precision grip IV: tactile adaptation of isometric finger forces to the frictional condition. *Exp Brain Res* 1995; **104**:323–30.
22. Gilbert A. Microvascular procedures. In: Buck-Gramcko D, editor. *Congenital malformations of the hand and forearm*. Edinburgh: Churchill Livingstone; 1998. p. 65.
23. Buck-Gramcko D. Pollicisation. In: Buck-Gramcko D, editor. *Congenital malformations of the hand and forearm*. Edinburgh: Churchill Livingstone; 1998. p. 382.
24. Önne L. Recovery of sensibility and sudomotor activity in the hand after nerve suture. *Acta Chir Scand Suppl* 1962:300.
25. Marsh D. The validation of measures of outcome following suture of divided peripheral nerves supplying the hand. *J Hand Surg* 1990;**15B**:25–34.
26. Spokevicius S, Radzevicius D. Late toe-to-hand transfer for the reconstruction of congenital defects of the long fingers. *Scand J Plast Reconstr Surg Hand Surg* 1997;**31**:345–50.
27. Häger-Ross C, Johansson RS. Non-digital afferent input in reactive control of fingertip forces during precision grip. *Exp Brain Res* 1996;**110**:131–41.
28. Weeks DL, Wallace SA, Noteboom JT. Precision-grip force changes in the anatomical and prosthetic limb during predictable load increases. *Exp Brain Res* 2000;**132**:404–10.