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Long Term Functional Outcomes After Early Childhood Pollicization

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Abstract

Study Design: Retrospective Cohort

Introduction: Pollicization creates a thumb from another finger to treat hypoplasia/aplasia. Important outcomes include strength, function, dexterity, and quality of life.

Purpose of the Study: To evaluate mid- to long-term outcomes and examine predictors of outcome after early childhood pollicization.

Methods: 8 children who underwent 10 pollicizations (age at surgery ≤ 5 years) were evaluated 3 to 15 years after surgery. Anthropometrics, range of motion, and basic medical history were obtained. Participants completed an upper extremity questionnaire (PODCI) and functional tests including grip and pinch strength, Box and Blocks, 9-hole pegboard, and strength-dexterity (S-D) tests.

Results: Almost all pollicized hands had poor strength and performed poorly on the traditional functional tests. Six of 10 pollicized hands had normal dexterity scores but were less stable in maintaining a steady-state force. Predictors of poorer outcomes included older age at surgery, reduced metacarpophalangeal and interphalangeal range of motion, and radial absence.

Discussion: Early childhood pollicization resulted in poor strength and overall function, but normal dexterity was often achieved using altered control strategies.

Conclusions: Most children will likely obtain adequate dexterity despite weakness after pollicization, but older children and those with the most severe involvement may have poorer outcomes.

Key Words: pollicization; dexterity; thumb; surgical outcome; functional outcome

Level of Evidence: IV

1. Introduction

Thumb hypoplasia or aplasia accounts for up to 16% of all congenital hand deformities and is bilateral in 12-63% of patients [1]. Absence of the thumb results in a loss of up to 40% of hand function [2]. Surgical options to reconstruct the thumb include toe to thumb transfer, distraction lengthening, and pollicization [3]. Pollicization is the process of creating a thumb from the next most radial finger. It involves surgical translocation of the radial most digit into a position of thumb function. Nerves and arteries are rotated on a pedicle, and muscle and tendon transfers are performed to create a “new” thumb that can perform the functions of flexion, extension, abduction, adduction, and opposition. Pollicization changes the anatomy of the hand, but the brain must also adapt to accommodate and control the new structural setup. Brain imaging studies have shown that neuroplasticity occurs after thumb reconstruction with increased brain activity in regions that control the thumb [4].

Most assessments of hand function involve functional testing that evaluates the ability to perform specific tasks, the time it takes to perform those tasks, or the quality of movement during task performance. Many established functional measures are available such as Box and Blocks[5], Jebsen Taylor[6], peg board[7], Functional Dexterity Test (FDT)[8], Assisting Hand Assessment (AHA)[9], ABILHAND-Kids[10], Melbourne Assessment (MA2)[11], and Shriners Hospitals Upper Extremity Evaluation (SHUEE)[12]. These tests generally examine whole arm function, assessing a combination of strength, coordination, and gross and fine motor control. To focus specifically on manual dexterity and neural control for fingertip force magnitude and direction, the Strength-Dexterity (S-D) test can be used [13-15]. Subjective assessments have also been performed using questionnaires such as the Michigan Hand Outcomes Questionnaire (MHQ)[16], Canadian Occupational Performance Measure (COPM)[17], Disability of Arm, Shoulder, and Hand (DASH)[18], Pediatric Outcomes Data Collection Instrument (PODCI)[19], and Short Form 36 (SF-36)[20].

Existing studies of outcomes after early childhood finger pollicization for thumb hypoplasia have demonstrated decreased strength and performance on functional tests compared to age-matched norms and non-operated contralateral hands [21-25]. Despite their functional limitations, patients and parents tend to rate their satisfaction and quality of life unexpectedly high [26-29]. Less is known about the recovery and development of neuromuscular control of fingertip forces after pollicization. Neural and muscular contributors to dexterous manipulation are particularly plastic during development and improve over an extended period[30-33], and thumb absence and reconstruction are likely to alter the brain via this process of neuroplasticity.

1.1 Purpose of the Study

The purpose of this study was to evaluate mid- to long-term outcomes after early childhood pollicization using a combination of functional tests and questionnaires, as well as the S-D test and to examine potential predictors of surgical outcomes. This evaluation may help to guide surgical intervention and rehabilitation strategies to maximize musculoskeletal and neural control capabilities in this population.

2. Materials and Methods

This study examined 8 children who had undergone pollicization surgery to address thumb hypoplasia or aplasia (10 pollicized hands, Blauth V) at a young age (≤ 5 years) (Table 1). Two children had bilateral involvement; all but 2 children were diagnosed with VACTERL Association[34]; 1 child with VACTERL and bilateral involvement also had Klippel-Feil syndrome[35]. Pollicization was performed between 1994 and 2010 by a single surgeon at a single hospital using the modified Buck-Gramcko technique [36]. Post-operative care consisted of 6 weeks of casting, 6 months of night splinting, and 6 months of a home rehabilitation program with or without occupational therapy services. The time since pollicization ranged from 2.9 to 15.7 years (mean ± standard deviation, 8.2 ± 4.1 years). The average age at testing was 10.6 ± 4.5 years (range 4-17) (Table 1). Written assent and consent were obtained from the participants and their parents or legal guardians following IRB-approved protocols.

2.1 Surgical Technique

A modified Buck-Gramcko surgical technique was utilized (Figure 1). Manual compression was used to exsanguinate the extremity and the tourniquet was elevated to 200mmHg. The dorsal skin was incised primarily to identify the critical dorsal veins, and then the palmar incision was completed to identify the radial and ulnar neurovascular bundles to the index and middle fingers. Using 8-0 nylon, the radial digital artery to the middle finger was divided just distal to the common branching. The common nerve was microdissected in line with the fascicles to the level of the carpal tunnel. The A1 pulley was opened; next the middle finger was spread away from the index finger and the transverse intermetacarpal ligament was released.

The tendons of the first dorsal and palmar interossei muscles were harvested for transfer.

The metacarpophalangeal (MP) head was cut at the epiphysis, and the shaft of the metacarpal was removed. The epiphysis was sewn into the carpal insertion in 45-degrees of abduction and 120-degrees of pronation. The extensor tendons were separated and shortened with the IP joint in full extension. The extensor digitorum communis (EDC) index was inserted as the abductor, and the extensor indicis proprious (EIP) became the new extensor pollicis longus (EPL). The tendons of the first dorsal and palmar interossei were transferred to the ulnar and radial lateral bands at the level of the new thumb proximal phalanx. The skin was closed transposing the dorsal flaps laterally and maintaining the position of the thumb in relation to the rest of the hand.

2.2 Rehabilitation

Following surgery, the child was placed in a cast for 4-6 weeks. After cast removal, a forearm-based removable night splint was fabricated placing the new thumb in abduction with the IP joint extended, which the child was asked to wear for an additional 6 months. The night splint was intended to maximize the 1st web space. If necessary, tape or a soft splint was used to maintain the new thumb in an abducted position during the day. A thermoplastic day splint was generally not recommended as this does not give the child the opportunity to actively develop the musculature of the new thumb. Additionally, the family was educated in scar management, edema control and ways to promote active movement of the new thumb.

Post-operative therapy primarily consisted of family training to instruct the child's caregiver(s) in thumb passive and active range of motion (ROM) exercises followed by age-appropriate activities to facilitate the use of the pollicized digit as a thumb. Buddy taping all fingers together was a helpful technique to isolate the thumb for more active movement during grasp. Fine motor activities generally began with repetitive radial digital grasp and release of larger objects, moving to static pinches of smaller objects. With more advanced prehensile skills, such as rotation and in-hand manipulation, it was common and acceptable to see compensatory patterns. Four weeks post-surgery each child underwent a standard evaluation. Depending on the child's progress, regular occupational therapy sessions and/or a home exercise program was recommended. Some individuals received occupational therapy 1-2x per week for 6 months to develop these skills, while most children required only a home exercise program with periodic monitoring to ensure continued progress. If hand skills were not progressing as anticipated, the child was scheduled for additional therapy as needed.

2.3 History, Anthropometric Measures, Patient Classification, and Questionnaire

Demographic and anthropometric measures were recorded, and a retrospective chart and x-ray review provided surgical history and Blauth [37] and Bayne [38] classifications. The Blauth classification updated by Manske and McCarroll grades the severity of thumb hypoplasia based on the stability of the carpometacarpal thumb joint as well as the musculature present for thumb opposition [25,39]. The Bayne and Klug radial longitudinal deficiency (RLD) classification updated by James incorporates the stability and presence of the skeletal and muscular radial column of the forearm [40]. All hands had a stable metacarpophalangeal (MP) joint. Radial stability was not measured.

The participant's self-initiated ability to handle objects in daily activities was graded using the Manual Ability Classification System (MACS) [41]. Total Active Motion (TAM) was calculated based on the extension and flexion range of motion of the proximal interphalangeal (PIP) and distal interphalangeal (DIP) joints: TAM = ([PIP Flexion + DIP Flexion] – [Extension Deficit of DIP + Extension Deficit of PIP]) / 175 × 100. TAM was graded as excellent (85-

100%), good (70-84%), fair (50-69%), or poor (0-49%) following Strickland's original classification system[42,43]. The Upper Extremity domain of the parent Pediatric Outcomes Data Collection Instrument (PODCI) was administered and standardized scores and Z-scores were calculated following the instrument's standard instructions and normative data [19].

2.4 Strength

Pinch and grip strength were measured using standard pinch (Baseline Hydraulic Pinch, FEI, White Plains, New York) and grip dynamometers (Hydraulic Hand Dynamometer, Preston, Jackson, MI). Three trials were performed for each motion (grip, lateral pinch, and tripod pinch), and the mean force from the three trials was used for analysis. Pinch strength Z-scores were calculated using normative data from Mathiowetz et al. for ages 6-19 years[44] and Lee-Valkov et al. for ages 3-5 years [45]. Grip strength Z-scores were calculated using normative data from Hager-Ross et al. [46]. Z-scores indicate the number of standard deviations an individual's measurement is above or below the mean of normal. 95% of non-impaired individuals are expected to have Z-scores between -2 and +2 (values within 2 standard deviations of the mean of the normative group).

2.5 Functional Tests

Functional testing was performed using the Box and Blocks[5] and 9-hole peg tests[7]. The Box and Blocks test is an assessment of manual dexterity. It consists of a box with a partition directly in the center, with 150 blocks placed on one side of the box. The participant is given 60 seconds in which to transport one block at a time over the partition, releasing it to the opposite side. The number of blocks transported to the other side is counted. The test is then repeated with the non-dominant hand [44]. Box and Blocks Z-scores were calculated using normative data for the left or non-dominant hand from Mathiowetz et al. for children ages 6-19 years[5] and Jongbloed-Pereboom et al. for children ages 3-5 years [47].

The 9-hole peg test is a standardized and well-established measurement of finger dexterity. The participant is asked to take pegs from a container, one by one, and place them into a pegboard as quickly as possible. The participant must then remove the pegs from the holes, one by one, and replace them back into the container. Scores are based on the time taken to complete the test. 9-hole peg test Z-scores were calculated using normative data for the non-dominant hand from Poole et al. [7].

2.6 Dexterity (S-D Test)

The S-D test assesses the dynamic control of fingertip forces needed for dexterous manipulation. A detailed description of how the S-D test was conducted is provided in Lightdale-Miric et al. [48]; only a brief description is provided here. Essentially, the participant partially compresses a slender, compliant instrumented spring as far as possible between the thumb and first finger and then maintains that maximal level of compression for at least 3 seconds (steady state) (Figure 2). The compression force, which is proportional to the distance the spring is compressed, quantifies the maximal ability of the subject to manipulate an unstable object at very low force magnitudes by dynamically controlling the magnitude and direction of fingertip forces.

Four different springs of equal stiffness (0.86 N/cm) and diameter (0.9 cm) but varying lengths (2.9 to 4.0 cm) were used to accommodate hands with different sizes and abilities [32]. Each participant used the shortest spring that he or she was not able to fully compress. S-D Z-scores were calculated based on the mean steady state force over 3 maximal trials [32]. Additional dynamical analysis was performed on the hands that used the longest spring (5 hands). Phase portraits of force vs. force velocity (first derivative) vs. force acceleration (second derivative) were produced and characterized using mean Euclidean distance (ED), which represents the mean distance of the cloud of points from the origin per unit time. Greater Euclidean distance indicates larger dynamical dispersion and suggests weaker corrective actions by the neuromuscular controller enforcing the sustained compression[32,49]. The compression dynamics were also characterized in terms of the root mean square (RMS) of the compression force, which indicates the level of deviation from maintaining a completely stable force. The dynamical results were compared to previously published control data from 12 children and 60 adults [48].

2.7 Statistical Analysis

Linear regression (for continuous variables) and Mann-Whitney rank sum tests (for binary variables) were used to evaluate the relationship between the outcome measures and possible predictors of outcome. The predictors examined included age at surgery, time since pollicization, angle of first web, ratio of thumb to next finger length, MP flexion, IP flexion, MP extension deficit, IP extension deficit, touch pad, and radial longitudinal deficiency. Euclidean distance from the dynamical analysis was also compared between pollicized and control hands using Mann-Whitney rank sum tests. Statistical analyses were performed in Stata (version 12.1, StataCorp LP, College Station TX).

3. Results

3.1 Strength

Strength was below normal in almost all pollicized hands (Figure 3). The average Z-scores were below -3 for all three types of strength tested (grip, lateral pinch, and tripod pinch) (Table 2). Only two hands had grip strength in the normal range (Z-scores: -1.4 and -1.3), and only one had tripod pinch strength in the normal range (Z-score: -0.8). All three of these hands were from different participants. Although the strength of these three hands fell in the normal range, it remained below average. All hands scored below the normal range in lateral pinch strength.

3.2 Functional Tests

Similarly, almost all pollicized hands scored below normal on the traditional functional tests. Pollicized hands scored particularly poorly on the pegboard test, where all hands scored below the normal range with very low scores (Figure 3, Table 2). Only one hand performed in the normal range for the Box and Blocks test (Z-score: -1.1). This hand also scored in the normal range for grip strength. Total Active Motion was graded as good for 1 hand, fair for 4 hands, and poor for 5 hands.

3.3 Dexterity

In contrast, 6/10 pollicized hands had normal dexterity scores (Z-scores: -1.3 to 1.0). Four pollicized hands had S-D scores at least 2.4 standard deviations below normal (Z-scores: -2.4, -3.0, -3.0, -3.1). These four hands with poor dexterity came from different individuals, one of whom had bilateral pollicization with good outcome on the other side.

Although many hands achieved a normal magnitude of compression force, interestingly, the manner in which that force was achieved differed from normal. Pollicized hands were less steady in maintaining the steady-state force, with a more erratic (less smooth) force trajectory and greater dispersion in force, velocity, and acceleration. This is quantified by a significant difference in the mean Euclidean distance (ED) which characterizes the phase plots ($p = 0.047$), where a greater ED in the pollicized hands (mean ± standard deviation, 0.47 ± 0.12) compared with control hands (0.34 ± 0.16) indicates less refined control over maintenance of the steady state force. In addition, the pollicized hands exhibited large variability in mean force velocity (rate of correction) for a given amount of error (RMS) [48], suggesting large variability among individuals in the neural control mechanisms used.

3.4 PODCI Questionnaire

On the upper extremity domain of the PODCI questionnaire, 6/8 patients representing 7/10 pollicized hands had scores in the normal range (Z-scores: -1.2 to -0.3). One unilaterally pollicized participant had a PODCI Z-score of -3.3, and one bilaterally pollicized participant had a Z-score of -9.3.

3.5 Predictors of Outcome

Grip and pinch strength tended to decrease when surgery was done at an older age (Table 3, Figure 4). PODCI scores also tended to decrease with older age at surgery because the two participants with low PODCI Z-scores underwent pollicization at older ages (2.5, 3.1, and 5.0 years; one participant had two hands pollicized at different times). In contrast, the functional outcomes (Box and Blocks, pegboard, S-D) showed no relationship to age at surgery, and there was no significant relationship between time since pollicization and any of the outcome measures.

Outcomes were not related to the angle of first web or the ratio of thumb to finger length. Grip and tripod pinch strength tended to increase with greater MP flexion range of motion (ROM) and higher TAM score, and tripod pinch strength also increased with greater IP flexion ROM. Increased MP extension deficit was associated with decreased grip and lateral pinch strength and lower Box and Blocks and pegboard scores. Increased IP extension deficit also showed a trend towards lower grip and lateral pinch strength, as well as lower PODCI scores, but not lower functional test scores. Tripod pinch strength was higher in the 3 hands with positive touch pad (Z-score mean ± standard deviation: -2.6 ± 0.9) compared with the 7 hands not able to touch pad (-3.8 ± 0.2) ($p = 0.05$), but touch pad ability did not affect grip or lateral pinch strength ($p > 0.19$). Hands with positive touch pad also scored higher on the Box and Blocks (-2.8 ± 1.1 vs. -5.0 ± 1.1, $p = 0.03$) and pegboard (-6.5 ± 3.3 vs. -19.5 ± 17.4, $p = 0.09$) tests, but not on the S-D test ($p = 0.31$).

Grip strength (-4.7 ± 0.1 vs. -2.7 ± 1.2, $p = 0.08$), pegboard scores (-21.2 ± 15.8 vs. -5.8 ± 2.4, $p = 0.02$), and dexterity (-2.8 ± 0.3 vs. -0.8 ± 1.4, $p = 0.09$) tended to be lower in the 3 hands with an absent radius (Bayne IV). Three of 4 hands with dexterity measures below the normal range had an absent radius, compared with 0/6 hands with normal dexterity ($p = 0.03$). A MACS classification of I (handles objects easily and successfully) was associated with higher pegboard test Z-scores (-3.8 ± 1.1 vs. -13.3 ± 11.8, $p = 0.01$), and all hands with below-normal dexterity had MACS classifications above level I.

Among the two participants who had undergone bilateral pollicization, strength and functional test scores tended to be slightly better, but still below normal, for the dominant hand. Both dominant pollicized hands had dexterity Z-scores in the normal range (-0.3 and -1.0 for dominant side vs. -3.0 and -1.3 for non-dominant side).

3.5 Contralateral Hands

Most non-pollicized contralateral hands had strength, function, and dexterity scores within the normal range. Of 5 non-pollicized contralateral hands (data from one contralateral hand was missing), one had below-normal lateral (Z = -2.7) and tripod (Z = -2.3) pinch strength with normal grip strength (Z = -0.2) and another had below-normal Box and Blocks (Z = -2.0) and pegboard (Z = -4.1) scores (Table 2). Yet another participant had a PODCI upper extremity score below the normal range (Z = -3.3).

4. Discussion

Hypoplastic or aplastic thumbs have been reconstructed via finger pollicization for almost 50 years [26] yet there are few functional prognostic guidelines for the surgeons and rehabilitation therapists caring for these children. Understanding of the role of neural control and neuromuscular plasticity as well as anatomy and biomechanics of the new thumb after pollicization is important for maximizing functional gains in these children. This study not only examined strength and function but also quantified fingertip forces and examined the role of neuroplasticity up to 15 years after early childhood pollicization.

4.1 Strength and Function

Outcomes after pollicization in children have been evaluated previously using timed tests such as the pegboard style Functional Dexterity Test (FDT) and Jebsen Hand Function Test (JHFT) [6,8] and parent/patient questionnaires about quality of life and the ability to complete tasks such holding a pencil, buttoning a shirt, texting, or playing video games. Netscher, et al. found positive outcomes in two JHFT subtests (page turning and checker stacking) and patient/parent assessments of thumb appearance and function in children with pollicized digits and no radial dysplasia, despite poor strength and performance on the pegboard test [22]. De Kraker, et al. found high patient and parent satisfaction with surgical outcome despite diminished strength and range of motion in a series of 40 patients ages 5-25 years [21].

The results of this study support the previous findings of diminished strength and overall function in pollicized hands. Using the S-D test, however, we were also able to quantify finger-to-thumb dexterity, which showed better outcomes than any of the more global tests of hand function. The S-D test correlates only moderately with traditional functional tests, suggesting that the S-D test captures a different domain of function[48,50]. Our combined results indicate that although children with pollicization lack strength and/or gross motor coordination, they are able to stabilize an unstable object by dynamically controlling fingertip forces to a point. Therefore, these children are likely to achieve high levels of independence with self-care, writing, and small object manipulation.

4.2 Anatomy and Range of Motion

Past studies have documented that the pre-surgical anatomy of the arm, hand and finger to be pollicized directly impacts post-surgical outcomes[21,51]. Manske et al. demonstrated reduced range of motion and strength in the new thumb joints[25]. The results of the current study showed that anthropomorphic measures as well as active and passive range of motion of the joints of the new thumb correlate with strength and function. De Kraker, et al. demonstrated that grip and pinch strength are significantly lower in severe RLD compared with mild RLD[21]. Our findings support these results through the relationship between Bayne and Klug classification and outcomes. In addition, increased severity often involved abnormalities of the radial most finger. If the radial most finger has reduced pre-operative range of motion, joint contracture, or absence of musculature, outcomes after pollicization may be compromised.

4.3 Non-Pollicized Hands

The non-pollicized contralateral hands of unilaterally pollicized children in our study had moderately reduced strength but normal S-D scores and only slightly reduced performance on the Box and Blocks and pegboard tests. Previous studies have reported strength and functional deficiencies in the “normal” hands of children with unilateral thumb hypoplasia/aplasia compared with the dominant hand of children without thumb deformity[22,25]. Our results suggest that despite reduced strength, dexterity is usually maintained in the contralateral hands of children with unilateral thumb hypoplasia/aplasia.

4.4 Dexterity

A unique component of this study was the dynamic assessment of finger dexterity using the S-D test. The S-D test allows assessment of not only whether the task can be completed, but also how precisely it is performed, providing insight regarding the underlying neural control strategies employed during low-force dexterous manipulation. The S-D test evaluates continuous dynamical features during steady-state compression rather than offer discrete measures of functional performance; thus providing more information about the neuromuscular system than standard clinical measures and further enhancing its utility as a performance metric. While most pollicized hands achieved magnitudes of compression force within the normal range during the S-D test (2-3N), they exhibited clear differences in compression dynamics compared with control hands, complementing results observed between control and clinical populations in older adulthood [52] and suggesting altered neural control mechanisms for the regulation and dynamical control of fingertip force directions in the reconstructed joint.

Dynamical control of fingertip force direction underlies fine motor tasks and the deficits in compression dynamics may explain the patients' difficulties in performing standardized measures of upper extremity performance such as the 9-hole pegboard and Box and Blocks tests. We have previously demonstrated that dexterity as defined by the S-D test is closely correlated with measures of strength and whole-arm function, but also quantifies a different functional domain in typically developing children[50]. In this study, we extend those results to highlight the deficits of neural control mechanisms in the presence of a clinical condition (e.g., pollicization).

4.5 Neuromuscular Plasticity

Although children exhibit the plasticity needed to adapt their control systems to control fingertip forces after pollicization[51], differences in hand and thumb use may alter the development of neural control capabilities[52] or cortical circuitry for hand control[14,53]. The neural control for hand function has a prolonged phase of development[30] featuring improvements in the ability to control fingertip force direction[32] as well as improved connectivity in descending neural pathways[31]. In addition, there are periods of critical development during childhood when the corticospinal system is most plastic and amiable to change[54,55]. Changes in cortical structure after pollicization[51], nerve transfer[56,57], hand graft[58], and both thumb[59] and muscle reconstruction[60] have been previously reported. Motor cortex plasticity has also been reported in response to therapy after injury to the motor cortex[61-63] and incomplete spinal cord injury[64]. Even children who sustain injury to the central nervous system (with intact anatomy), such as children with cerebral palsy, retain a certain level of neuroplasticity into adolescence, showing improvements in hand function after intense therapy[65,66]. Children undergoing pollicization have an intact neural system, increasing the potential for cortical plasticity and motor relearning with appropriate hand use following pollicization[51]. This highlights the need for future studies evaluating the near- and long-term changes in cortical function after treatment and therapy.

Neuroplasticity and adaptive ability are assumed to be greater when surgery is performed at a younger age, which is the current trend in treatment protocols[51,67]. While we found no effect of age at surgery on functional testing outcomes, all patients in this study underwent surgery by the age of five years. Younger age at surgery did have a positive impact on strength, in contrast to the findings of Manske et al. who found no relationship between age at surgery and measures of strength[25]. Larger studies including patients who underwent surgery at an older age are needed to fully understand the effect of age at surgery on plasticity. The results of the current study, together with past research and current knowledge on neuroplasticity and development, strongly suggest that pollicization is effective. However, therapeutic strategies could be further developed to take advantage of neuroplasticity to improve the dynamic control of fingertip forces. While the current clinical emphasis on developing strength and range of motion should continue, the development of dexterity at low force magnitudes is also important and should be promoted through neuroplasticity.

4.6 Limitations

Limitations of this study include its small sample size and cross-sectional design. Larger longitudinal studies are needed to understand changes in function over time as rehabilitation progresses and as the children develop and mature. Different rehabilitation programs need to be evaluated to determine if they can improve a child's dexterity after pollicization. In addition, all surgeries in this study were performed by a single surgeon, which does not allow for comparison of different surgical techniques. Subtle differences in surgical technique such as final thumb length, metacarpal excision amount, the presence or transfer of intrinsic muscles, and extensor and flexor tendon shortening likely affect pollicization outcomes. Additional research is needed to evaluate the effects of different surgical and rehabilitation options on strength, function, and dexterity outcomes after pollicization.

5. Conclusions

In conclusion, early childhood pollicization resulted in poor strength and functional test scores 3 to 15 years after surgery. However, most patients were able to achieve near-normal control over low-magnitude fingertip forces, which is a key component of dexterity and in-hand object manipulation. Older age at surgery and more severe deformity including radial absence are possible predictors of poorer outcome after pollicization. In addition, reduced MP and IP range of motion appear to be predictive of lower performance on functional tests.

Control of fingertip forces despite low strength and gross motor ability seems to be achieved through neuromuscular plasticity which enables patients to perform the dexterous task after pollicization using altered control strategies. Parents and children undergoing pollicization may be counseled that they will likely obtain adequate dexterity despite weakness after surgery although older children and those with the most severe disease involvement may have poorer outcomes. Post-operative therapy protocols promoting neuroplasticity may result in increased life-long function for the child.

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Figure Legend

Figure 1: Hand with thumb aplasia before and after pollicization.

Figure 2: The S-D test challenges the participant to compress a slender, compliant spring between the thumb and first finger.

Figure 3: Outcome Z-scores. The grey band indicates the normal range of ±2.

Figure 4: Relationship between tripod pinch strength and age at pollicization ($p = 0.04$).

Table 1: Characteristics of the study participants

Participant	Sex	Side	Dominant Hand	Original Diagnosis	Age at pollicization (yr)	Age at test (yr)	Time since pollicization (yr)	Bayne classification
1	F	Right	Left	None	2.7	9.9	7.2	II
2	F	Left	Left	VACTERL, Klippel-Feil Syndrome	3.1	13.9	10.8	III
2	F	Right	Left	VACTERL, Klippel-Feil Syndrome	5.0	13.9	8.9	IV
3	M	Right	Left	VACTERL	3.4	15.2	11.7	IV
4	M	Right	Left	VACTERL	2.5	5.3	2.9	IV
5	M	Right	Left	VACTERL	3.5	11.2	7.6	I
6	M	Left	Right	None	1.2	16.9	15.7	I
6	M	Right	Right	None	1.2	16.9	15.7	I
7	M	Left	Right	VACTERL	2.0	7.3	5.4	II
8	M	Right	Left	VACTERL	1.8	5.1	3.3	II

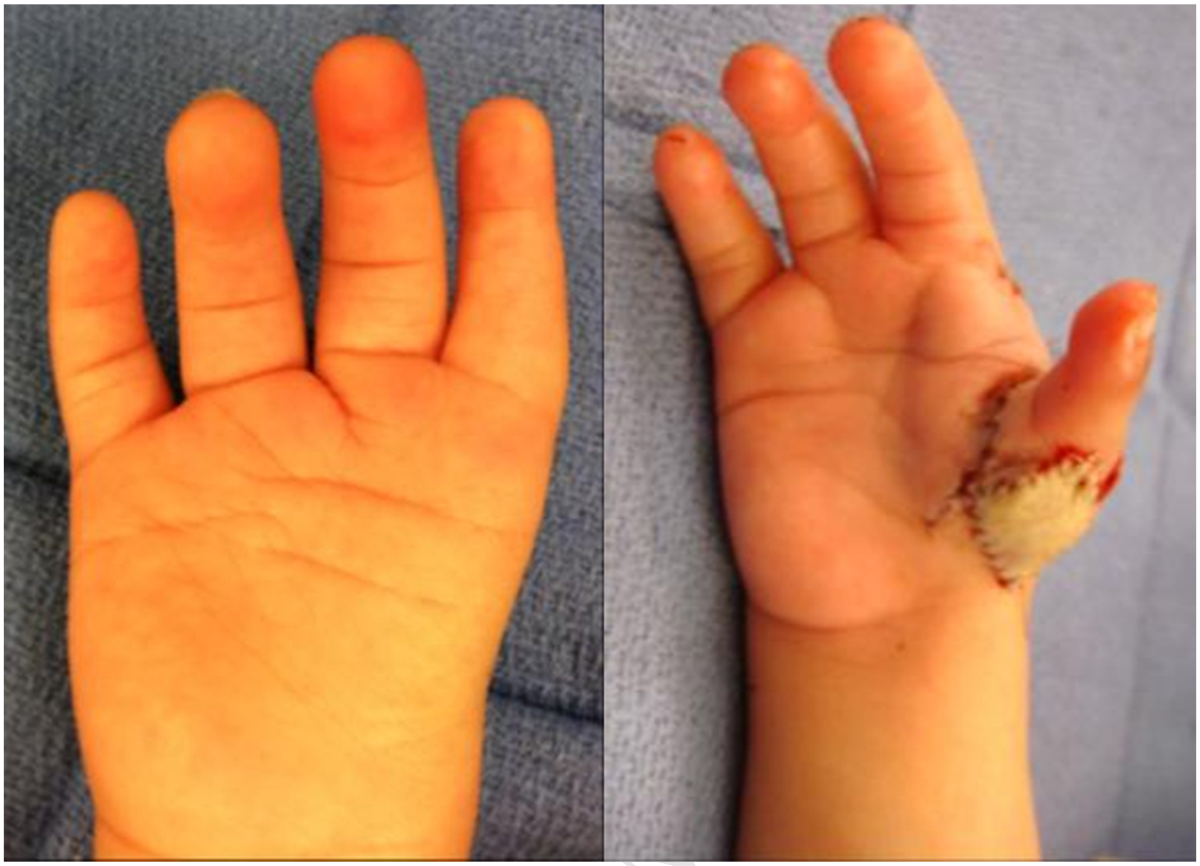
Table 2: Z-score results for the outcome measures. Z-scores below -2 fall below the normal range.

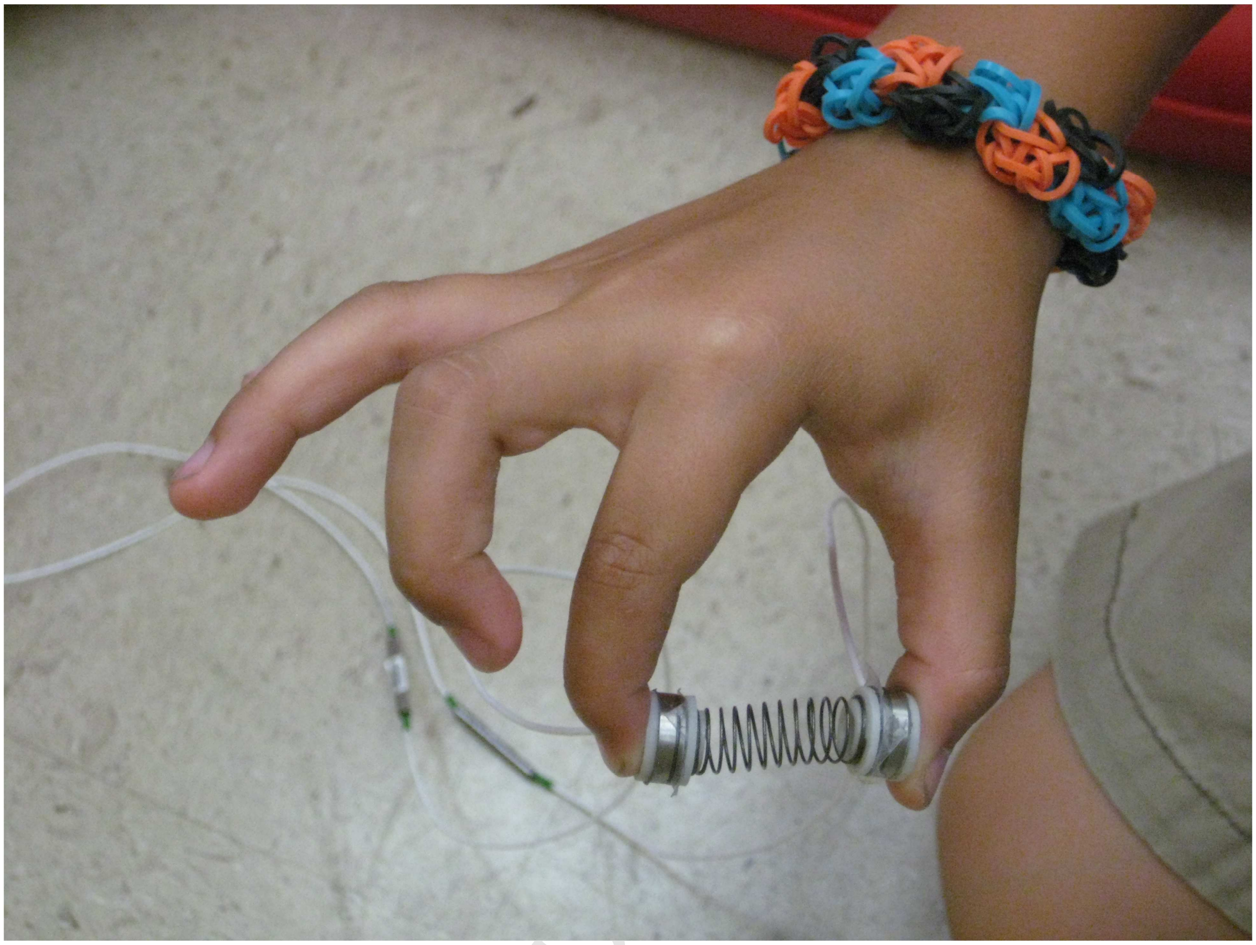
	Pollicized			**Contralateral**		
	N	**Z-score Mean ± SD (range)**	**Below normal range N (%)**	**N**	**Z-score Mean ± SD (range)**	**Below normal range N (%)**
Grip*	9	-3.1 ± 1.3 (-4.7, -1.3)	7/9 (80%)	5	-0.7 ± 1.1 (-1.9, 0.8)	0/5 (0%)
Lateral pinch	10	-3.7 ± 1.0 (-5.1, -2.6)	10/10 (100%)	5	-1.7 ± 0.7 (-2.7, -0.6)	1/5 (20%)
Tripod pinch	10	-3.0 ± 0.9 (-4.0, -0.8)	9/10 (90%)	5	-1.3 ± 0.7 (-2.3, -0.3)	1/5 (20%)
Box & blocks	10	-3.4 ± 1.5 (-6.2, -1.1)	9/10 (90%)	5	-0.5 ± 0.9 (-2.0, 0.2)	1/5 (20%)
9-hole pegboard	10	-10.4 ± 10.7 (-39.4, -2.6)	10/10 (100%)	5	-0.5 ± 2.1 (-4.1, 1.2)	1/5 (20%)
Dexterity (S-D)	10	-1.4 ± 1.5 (-3.1, 1.0)	4/10 (40%)	5	0.5 ± 1.1 (-0.9, 1.9)	1/5 (20%)
PODCI	10	-2.8 ± 3.5 (-9.3, -0.3)	3/10 (30%)	5	-1.2 ± 1.2 (-3.3, -0.3)	1/5 (20%)

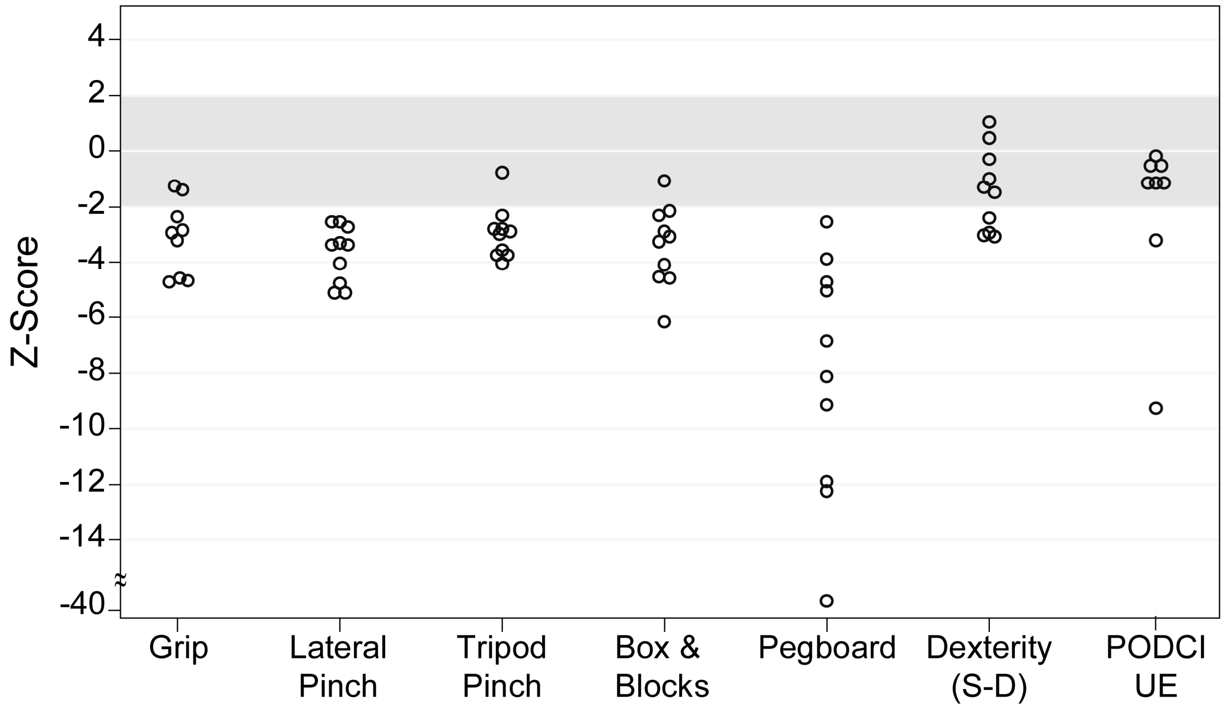
* Data from one hand was missing.

Table 3: Relationship between clinical characteristics and outcome measures (Z-scores) based on linear regression.

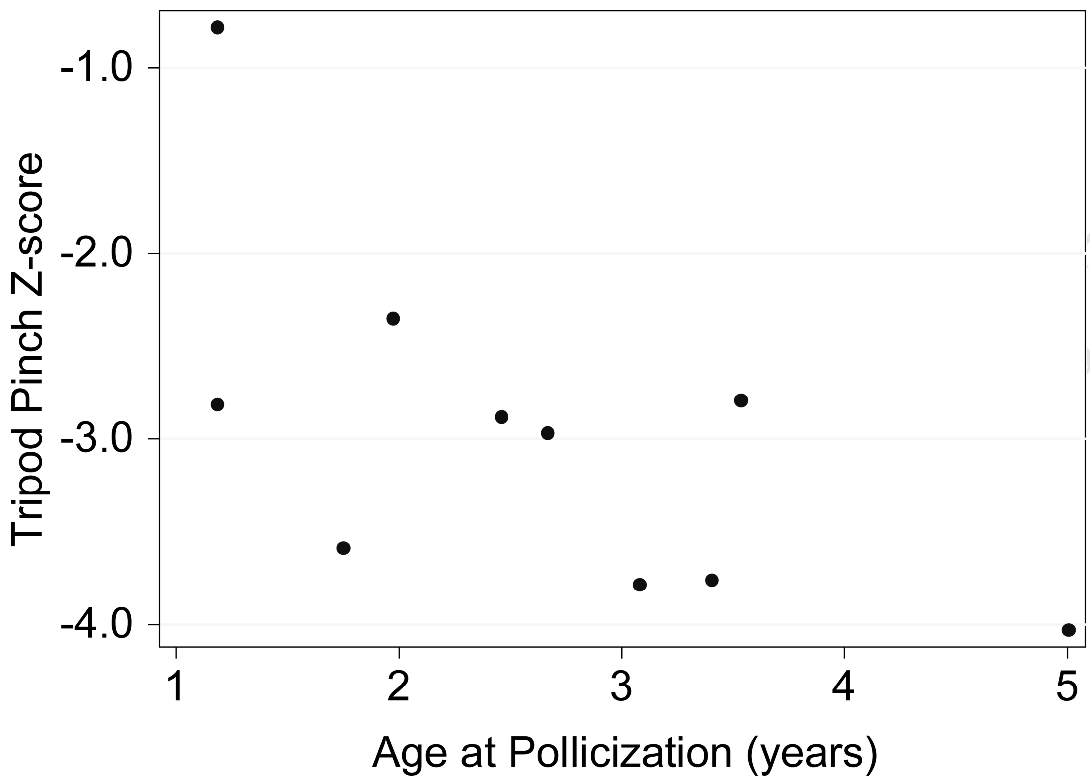
	Grip Strength		**Lateral Pinch Strength**		**Tripod Pinch Strength**		**Box and Blocks**		**Pegboard**		**Dexterity (S-D)**		**PODCI**	
	β (95% CI)	**p**	**β (95% CI)**	**p**	**β (95 % CI)**	**p**	**β (95 % CI)**	**p**	**β (95% CI)**	**p**	**β (95% CI)**	**p**	**β (95% CI)**	**p**
Age at surgery (yr)	-0.62 (-1.39, 0.15)	0.10	-0.51 (-1.06, 0.04)	0.07	-0.52 (-1.01, -0.03)	0.04	-0.54 (-1.44, 0.36)	0.20	-3.81 (-10.47, 2.85)	0.22	-0.11 (-1.12, 0.90)	0.81	-1.86 (-3.74, 0.03)	0.05
Time since surgery (yr)	-0.09 (-0.36, 0.17)	0.43	-0.12 (-0.27, 0.02)	0.09	0.07 (-0.09, 0.23)	0.36	-0.07 (-0.32, 0.19)	0.56	-0.21 (-2.10, 1.69)	0.81	0.06 (-019, 0.32)	0.58	-0.05 (-0.68, 0.57)	0.85
Angle of 1st web (deg)	-0.02 (-0.12, 0.08)	0.65	0.00 (-0.05, 0.05)	0.88	0.00 (-0.05, 0.05	0.97	0.00 (-0.07, 0.07	0.96	-0.35 (-0.80, 0.10)	0.11	-0.02 (-0.09, 0.05)	0.47	0.03 (-0.14, 0.20)	0.70
Ratio thumb/ finger	0.98 (-34.2, 36.2)	0.95	4.4 (-7.1, 15.8)	0.40	1.6 (-9.6, 12.8)	0.75	8.8 (-7.0, 24.6)	0.24	37.2 (-87.0, 161.4)	0.51	-7.9 (-24.3, 8.5)	0.30	-8.7 (-50.2, 32.7)	0.64
MP flexion (deg)	0.03 (-0.004, 0.07)	0.08	0.002 (-0.02, 0.03)	0.85	0.02 (0.001, 0.04)	0.04	0.005 (-0.03, 0.04)	0.75	0.10 (-0.18, 0.37)	0.44	0.01 (-0.02, 0.05)	0.46	0.05 (-0.04, 0.13)	0.24
IP flexion (deg)	0.04 (-0.02, 0.09)	0.16	0.01 (-0.03, 0.05)	0.57	0.03 (0.003, 0.06)	0.03	0.02 (-0.04, 0.08)	0.46	0.21 (-0.21, 0.63)	0.29	0.00 (-0.06, 0.06)	0.99	0.06 (-0.08, 0.20)	0.37
MP extension deficit (deg)	-0.05 (-0.11, - 0.0003)	0.04 9	-0.04 (- 0.08, -0. 009)	0.02	-0.02 (-0.06, 0.03)	0.36	-0.06 (-0.12, -0.006)	0.03	-0.44 (-0.85, - 0.03)	0.04	-0.04 (-0.11, 0.03)	0.19	-0.10 (-0.26, 0.06)	0.19
IP extension deficit (deg)	-0.08 (-0.17, 0.01)	0.08	-0.06 (-0.13, 0.007)	0.07	-0.05 (-0.12, 0.02)	0.12	-0.04 (-0.16, 0.08)	0.43	-0.61 (-1.38, 0.16)	0.10	-0.08 (-0.19, 0.03)	0.13	-0.25 (-0.47, -0.02)	0.04
TAM (%)	0.03 (0.007, 0.05)	0.02	0.01 (-0.01, 0.04)	0.25	0.02 (0.005, 0.04)	0.02	0.02 (-0.02, 0.05)	0.27	0.18 (-0.04, 0.40)	0.10	0.02 (-0.02, 0.05)	0.32	0.06 (-0.01, 0.13)	0.09







Z-Score
4
2
0
-2
-4
-6
-8
-10
-12
-14
-40
Grip
Lateral Pinch
Tripod Pinch
Box & Blocks
Pegboard
Dexterity (S-D)
PODCI UE


-1.0
-2.0
-3.0
-4.0
Tripod Pinch Z-score
1
2
3
4
5
Age at Pollicization (years)

Highlights

- Early childhood pollicization resulted in poorer strength and overall function but normal dexterity using altered control strategies.
- Older age at surgery, reduced metacarpalphalageal and interphalangeal range of motion and radial absence were predictors of poorer outcomes.
- Older children and those with more severe involvement may have poorer strength, dexterity and overall function.