Gait & Posture 41 (2015) 1–6

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Winner of the 2014 Gait and Clincial Movement Analysis Society Best Paper Award

Quantitative assessment of dynamic control of fingertip forces after pollicization

Nina Lightdale-Miric [a,b], Nicole M. Mueske [a], Sudarshan Dayanidhi [c], Jennifer Loiselle [d], Jamie Berggren [d], Emily L. Lawrence [e], Milan Stevanovic [a], Francisco J. Valero-Cuevas [c,e], Tishya A.L. Wren [a,b,e,*]

[a] Children's Orthopaedic Center, Children's Hospital Los Angeles, Los Angeles, CA, USA
[b] Orthopaedic Surgery Department, Keck School of Medicine, University of Southern California, Los Angeles, CA, USA
[c] Division of Biokinesiology and Physical Therapy, University of Southern California, Los Angeles, CA, USA
[d] Division of Rehabilitation Medicine, Children's Hospital Los Angeles, Los Angeles, CA, USA
[e] Department of Biomedical Engineering, Viterbi School of Engineering, University of Southern California, Los Angeles, CA, USA

ARTICLE INFO

Keywords:
Pollicization
Dexterity
Strength–dexterity
Hand function
Surgical outcome

ABSTRACT

Dexterity after finger pollicization (reconstruction to thumb) is critical to functional outcomes. While most tests of hand function evaluate a combination of strength, coordination, and motor control, the Strength–Dexterity (S–D) paradigm focuses on the dynamic control of fingertip forces. We evaluated 10 pollicized and 5 non-pollicized hands from 8 participants ages 4–17 years (2 female, 6 male; 10.6 $\pm$ 4.5 years). Participants partially compressed and held an instrumented spring prone to buckling between the thumb and first finger to quantify dynamic control over the direction and magnitude of fingertip forces. They also completed traditional functional tests including grip, lateral pinch, and tripod pinch strength, Box and Blocks, and 9-hole peg test. Six of 10 pollicized hands and all non-pollicized hands had S–D scores comparable to typically developing children. However, dynamical analysis showed that pollicized hands exhibit greater variability in compression force, indicating poorer corrective action. Almost all pollicized hands scored below the normal range for the traditional functional tests. The S–D test *Z*-scores correlated moderately with *Z*-scores from the other functional tests ($r = 0.54$–0.61; $p = 0.02$–0.04) but more weakly than amongst the other functional measures ($r = 0.58$–0.83; $p = 0.0002$–0.02), suggesting that the S–D test captures a different domain of function. A higher incidence of radial absence in the hands with poor S–D scores (3/4 vs. 0/6 in hands with normal S–D scores, $p = 0.03$) was the only clinical characteristic associated with S–D outcome. Overall, these results suggest that while most pollicized hands can control fingertip forces, the nature of that control is altered.

1. Introduction

Hand function combines independent finger movements, reaction speed, strength, hand–eye coordination, and precise neuromuscular control of task-specific fingertip forces. Human development of fine motor skills has been studied predominately with functional measures involving the whole arm such as the ability to complete manual tasks (e.g., moving pegs around a board, picking up objects, fastening buttons, etc.) which generally evaluate a combination of strength, coordination, and gross and fine motor control. This study attempts to isolate and quantify a critical component of hand function – control of low-level fingertip force magnitudes and directions – in children with congenital thumb hypoplasia or aplasia who have undergone surgical reconstruction.

Thumb hypoplasia/aplasia accounts for up to 16% of all congenital hand deformities and can result in a 40% loss of hand function [1]. Reconstructive options are limited and most commonly include radial-most digit pollicization, toe to thumb transfer, or distraction lengthening [2]. Assessment of outcomes after finger pollicization in children with thumb hypoplasia has demonstrated decreased strength and performance on timed tests of function, yet patients and parents tend to rate their satisfaction and quality of life unexpectedly high [3–6].

Valero-Cuevas and colleagues developed the Strength–Dexterity (S–D) test to dynamically assess the control of dexterous manipulation based on an individual's ability to compress springs

* Corresponding author at: Children's Hospital Los Angeles, 4650 Sunset Boulevard, #69, Los Angeles, CA 90027, USA. Tel.: +1 323 361 4120; fax: +1 323 361 1310.
E-mail address: twren@chla.usc.edu (Tishya A.L. Wren).

http://dx.doi.org/10.1016/j.gaitpost.2014.08.012
0966-6362/

with different properties [7–9]. The S–D test is a well-validated methodology for measuring dexterous manipulation objectively and quantitatively [10]. It has been used successfully to evaluate dexterity in healthy children [11,12], aging [13], and adult clinical populations [14].

The purpose of this study was to use the S–D test to evaluate the dynamical control of fingertip forces after pollicization. Quantification of dexterity by the S–D test provides information on the integrity of the musculoskeletal system [7,14] and the ability of the nervous system to dynamically control musculature [7–9,15]. The S–D test may be helpful in quantifying the outcome of pollicization surgery and understanding differences in control strategies between pollicized and typically developing hands. Such understanding has the potential to guide surgical intervention and rehabilitation strategies to improve musculoskeletal and neural control capabilities in this population.

2. Materials and methods

This study included children who had undergone pollicization surgery to address thumb hypoplasia or aplasia at a young age ($\leq$5 years). Pollicization was performed between 1994 and 2010 by a single surgeon at a single hospital using the modified Buck-Gramcko technique [16]. 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. Eight individuals were tested with 10 pollicized hands (2 bilateral) and 6 contralateral non-pollicized hands. Data from one contralateral hand was lost due to a technical issue, leaving 5 non-pollicized hands for analysis. The time since pollicization ranged from 2.9 to 15.7 years (mean 8.2 $\pm$ 4.1 years). The average age at testing was 10.6 $\pm$ 4.5 years (range 4–17) (Table S1). Written assent and consent were obtained from the participants and their guardians following IRB-approved protocols.

The testing protocol consisted of the S–D test along with other well-established functional measures (grip, tripod pinch, and lateral pinch strength, Box and Blocks, 9-hole peg test). Demographic and anthropometric measures were recorded. Chart and X-ray review provided surgical history and Blauth [17] and Bayne [18] classifications. The participant's self-initiated ability to handle objects in daily activities was graded using the Manual Ability Classification System (MACS) [19]. 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 was graded as excellent (85–100%), good (70–84%), fair (50–69%), or poor (0–49%) following Strickland's original classification system [20,21]. The Upper Extremity domain of the parent Pediatric Outcomes Data Collection Instrument (PODCI) was administered and scored following the instrument's standard instructions [22].

The S–D test challenges the participant to compress a slender, compliant spring as far as possible between the thumb and first finger and then maintain a maximal level of compression for at least 3 s (steady state). This requires precise control of both the direction and magnitude of fingertip forces and directly measures neural control capabilities [8,15]. Depending on the spring characteristics, the test can evaluate different combinations of strength, dexterity, and fingertip force coordination patterns [7]. The spring characteristics were selected so very low forces are needed to compress the spring (<300 g force) and instability increases as the spring is compressed (an inherent property of slender springs). Load cells attached to the ends of the springs measure the compression force exerted by the fingertips, which is proportional to the distance the spring is compressed. The applied force, therefore, 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 (2.9–4.0 cm) were used to accommodate different hand sizes and levels of skill [11]. Longer springs are less stable, and therefore more prone to instabilities. The subject was tested with the shortest spring s/he was not able to compress fully. Multiple trials were performed using this spring, and the maximum steady state compression force was determined for each trial. The mean steady state force over the three maximal trials was converted to a scaled measure, and *Z*-scores were calculated using previously published normative data [11].

In a secondary analysis, variability of the fingertip forces during the maximal sustained compression was used to quantify S–D compression dynamics at the limit of instability. To be able to compare across subjects, this analysis was performed only on the subset of hands using the longest (i.e., most difficult) spring since spring properties may affect the compression dynamics. The first and second derivatives of fingertip forces during the sustained compression (i.e., force 'velocities' and 'accelerations') were calculated and dispersion was quantified using two variables common in dynamical system analysis [11,13,14]: first by their root mean squared (RMS) and second by plotting 'phase portraits' of force vs. force velocity vs. force acceleration. The characteristics of the phase portrait were quantified by the mean Euclidean 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 [11,13].

Pinch and grip strength were measured using standard pinch (Baseline Hydraulic Pinch, FEI, White Plains, New York) and grasp meters (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 was compared against normative data from Mathiowetz et al. [23] for ages 6–19 years and Lee-Valkov et al. [24] for ages 3–5 years. Grip strength was compared against normative data from Hager-Ross and Rosblad [25].

The Box and Blocks test is an assessment of manual dexterity. Participants transferred blocks over a partition one at a time as fast as possible, and the number of blocks transferred in 60 s were counted [23]. Box and Blocks *Z*-scores were calculated using normative data for the left or non-dominant hand from Mathiowetz et al. [26] for ages 6–19 years and Jongbloed-Pereboom et al. [27] for ages 3–5 years.

The 9-hole peg test is a standardized measurement of finger dexterity. The participant was asked to take pegs from a container, one by one, and place them into a pegboard as quickly as possible. The participant then removed the pegs, one by one, and replaced them back into the container. Scores were based on the time taken to complete the test and compared against normative data for the non-dominant hand from Poole et al. [28].

Pearson's correlation was used to evaluate the relationship between dexterity *Z*-scores and age-normalized *Z*-scores from the other functional tests. To evaluate potential predictors of surgical outcome, clinical characteristics were compared between hands with good versus poor S–D outcome using non-parametric Fisher's exact or Mann–Whitney rank sum tests. 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

Dexterity scores for 6/10 pollicized hands were within the normal range (*Z*-scores −1.3 to 1.0) (Fig. 1). Four pollicized hands had S–D scores more than 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

Table 1
Correlation between Z-scores for the different functional tests. All correlations were statistically significant at $p < 0.04$.

	Dexterity (S–D)	Grip	Lateral pinch	Tripod pinch	Box and blocks	9-Hole pegboard
Dexterity (S–D)	1.00					
Grip	0.57	1.00				
Lateral pinch	0.54	0.83	1.00			
Tripod pinch	0.56	0.72	0.81	1.00		
Box and blocks	0.60	0.83	0.79	0.70	1.00	
9-Hole pegboard	0.54	0.68	0.65	0.58	0.79	1.00

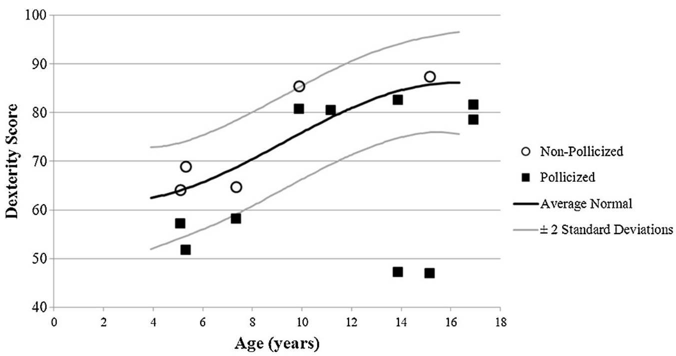

Fig. 1. S–D scores as a function of age for pollicized and non-pollicized hands. Normative data showing mean and 95% confidence limits are from Dayanidhi (2013a).

bilateral pollicization with good outcome on the other side. All non-pollicized hands had S–D scores within the normal range (Z-scores −0.9 to 1.9).

Age-matched dexterity Z-scores correlated moderately with Z-scores from all of the other functional tests ($r = 0.54$–0.61; $p < 0.04$) (Table 1), but these relationships were generally weaker than the correlations amongst the other functional measures ($r = 0.58$–0.83; $p < 0.02$), suggesting that the S–D test captures a different domain of function. In addition, almost all pollicized hands scored below the normal range for the traditional functional tests (Table S2) despite having 6/10 pollicized hands achieve normal S–D maximal compression forces. This suggests that the participants maintained reasonable control of very low magnitude fingertip forces despite deficits in maximal voluntary strength and gross motor function.

Fig. 2 shows example phase plots from the dynamical analysis for a pollicized hand and an age-matched control hand. The pollicized hand clearly demonstrates a more erratic (less smooth) force trajectory and a greater dispersion in force, velocity, and acceleration, which is reflected in a much larger mean Euclidean distance (0.56 vs. 0.23). Similar results were seen overall with the mean Euclidean distance being significantly larger in the group of pollicized compared with control hands ($p = 0.048$) (Fig. 3). In addition, compared with typically developing children and adults, pollicized hands exhibited a high floor on mean force RMS and a wider range of mean force velocity (Fig. 4), indicating poorer control over the steady state force and large variability among subjects in the individual control mechanisms used.

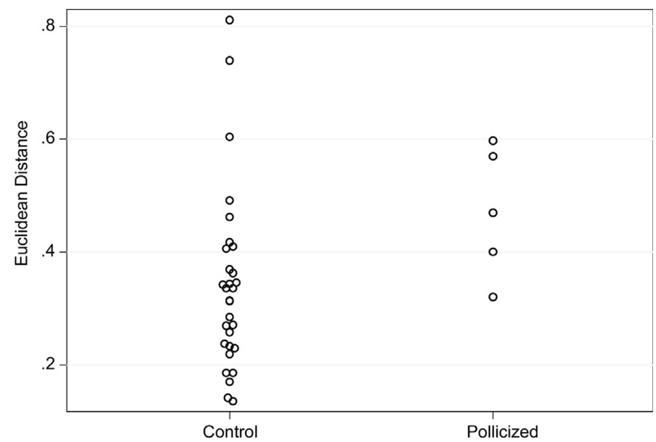

Fig. 3. Comparison of Euclidean distance from dynamical analysis between pollicized and control hands using the longest spring.

Because of the heterogeneity and small number of hands tested, it was difficult to identify clinical characteristics predictive of the S–D outcome (Table S3). The only significant factor was radial absence; 3/4 hands with poor dexterity had an absent radius, compared with 0/6 hands with good dexterity ($p = 0.03$). No hands with poor dexterity had a MACS score of I, and 3/4 had poor TAM scores. Touch pad, stable MP, and angle of the first web did not differ between pollicized hands with good versus poor dexterity.

4. Discussion

Finger pollicization for thumb reconstruction in children with hypoplastic or aplastic thumbs was popularized almost 50 years ago and accepted surgical techniques vary little. Outcomes after pollicization have been reported, but few studies provide prognostic guidelines for clinicians to follow in the care of these children. In addition, dexterous manipulation has a prolonged phase of improvement during childhood and adolescence [11,12],

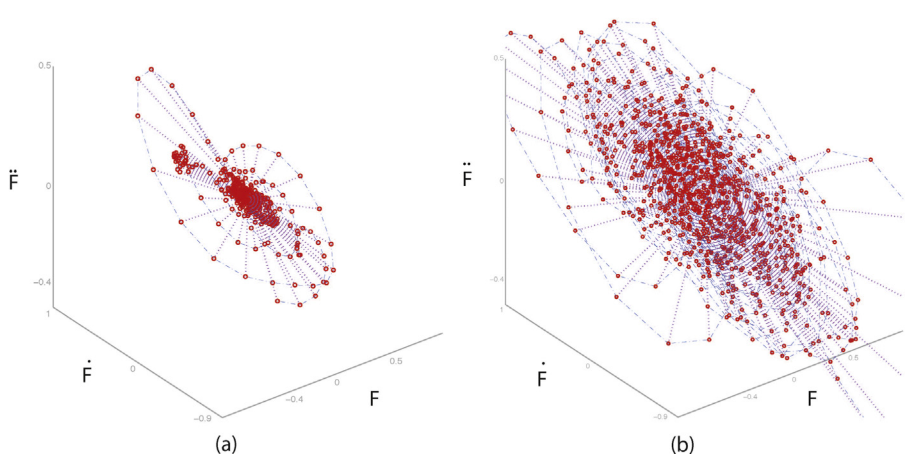

Fig. 2. S–D test phase portraits illustrate greater dispersion (i.e., less effective or different control strategy) in the pollicized hand. Compression dynamics for (a) a representative 9 year old control and (b) pollicized hand of a 9 year old child. Mean Euclidean distance characterizing the phase portrait was 0.23 for the control and 0.56 for the patient.

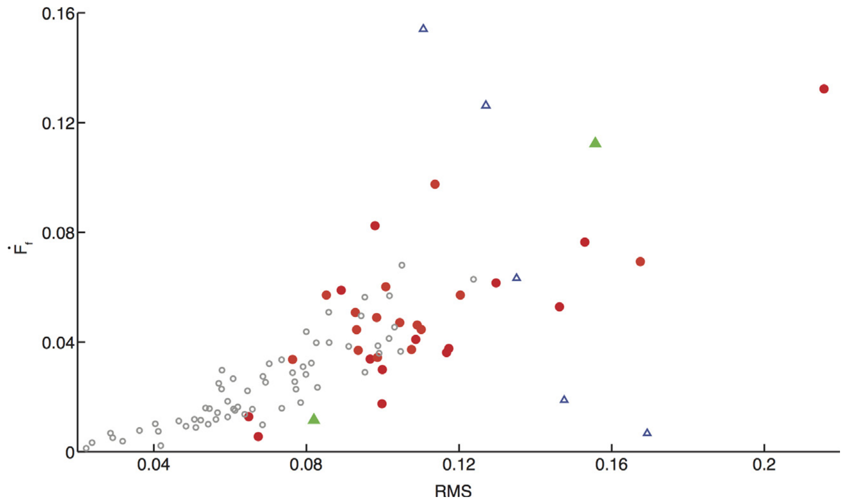

Fig. 4. S–D test compression dynamics. The finger force velocity and force RMS were plotted against each other for a subset of the patients with pollicized (blue empty triangles) and non-pollicized hands (green filled triangles) and both adult (gray empty circles) and pediatric controls (red filled circles). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

but the impact of pollicization on the development of neural control of fingertip forces has not been elaborated. This study successfully quantifies the dynamic interaction between the magnitude and directional control of finger forces in children after pollicization and identifies differences compared to controls. These findings may help explain why after pollicization children who often barely achieve 20% of normal hand strength are still able to complete most activities of daily living and have a high quality of life and satisfaction.

Previous instruments used to evaluate different forms of dexterity in children after pollicization include timed tests such as the Pegboard Functional Dexterity Test (FDT) and Jebsen Hand Function Test (JHFT) [29,30] and parent/patient questionnaires about quality of life and ability to complete tasks such as buttoning a shirt, tying shoelaces, texting, or playing video games. Although these timed, ability, or self-assessment tests are well validated, they provide only a global assessment of function. Netscher et al. [4] studied children with pollicized digits and no radial dysplasia including grip, lateral and tripod pinch, FDT, JHFT, and a satisfaction questionnaire. They found positive outcomes in two JHFT subtests (page turning and checker stacking) as well as patient/parent assessments of thumb appearance and function, despite poor strength and performance on the pegboard test. de Kraker et al. [3] studied pollicized thumb range of motion, strength, sensation, and satisfaction in a series of 40 patients ages 5–25 years. They also found high patient and parent satisfaction with surgical outcome despite diminished strength and range of motion, especially for interphalangeal and metacarpophalangeal extension and interphalangeal flexion.

Our results are consistent with these findings and provide additional insights regarding the fundamental requirements necessary to perform different functional tasks. Pollicized hands had low grip and pinch strength and performed poorly on the Box and Blocks and pegboard tests. However, the S–D scores only moderately correlated with the other functional tests, and hands with poor strength often achieved near normal S–D maximal compression forces. This suggests 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. This supports previous research in typically developing children [10] that the S–D test uniquely quantifies dexterity independent of both strength and whole arm function which is not captured by other commonly used functional tests.

While a normal magnitude of S–D compression force was achieved by most pollicized hands, compression dynamics clearly differed between pollicized and control hands, reflecting deficits in the underlying neural control. We have previously seen similar cases where adult clinical populations achieve compression force magnitudes similar to controls, but show clear differences in dynamical behavior [14]. Pollicized hands showed greater dispersion in the force trajectories as indicated by the significantly higher mean Euclidean distance in their phase portraits (Figs. 2 and 3) and consistently large force fluctuations, as evidenced by the atypical floor effect in force RMS (Fig. 4). These findings suggest weaker and/or less effective corrective actions by the neuromuscular controller enforcing the sustained compression in the pollicized hands, which may be important when manipulating small or fragile objects in daily life.

The pollicized hands also demonstrated greater variability among individuals in the control strategies used. Children tend to have both higher force velocity and higher force RMS than adults (Fig. 4) since they are still developing and have less robust control strategies [11,12]. While force velocity and its variability among individuals tend to increase as RMS increases among controls, however, the variability is much greater for the pollicized hands. In other words, the pollicized thumbs exhibit not only larger force fluctuations (i.e., RMS), but also greater variability in the speed of response to those fluctuations. These differences likely result from a combination of altered anatomical or soft tissue properties and differences in neural control of the pollicized hands.

Although the force required for full compression in the S–D test is small, maintaining that force in the presence of instabilities presents a challenge for the brain–hand system. Children typically experience a prolonged phase of neural development [31,32] in which manipulation abilities improve [11] and the corticospinal tract associated with fine finger movements becomes more organized [33]. Our results suggest that deficits in hand and thumb use during development may result in differences in neural control capabilities [14] or cortical circuitry for hand control [8,15]. Future work is needed to determine the neural plasticity changes that follow an early change in the skeletal system (i.e., pollicization) that could hinder or facilitate fine motor abilities throughout the lifespan.

Children with thumb hypoplasia/aplasia and radial longitudinal deficiency (RLD) are categorized based on severity. de Kraker et al. [3] demonstrated that grip and pinch strength are significantly lower in severe RLD compared with mild RLD. Our data support these findings, as the hands that had poor S–D outcome were the ones with an absent radius or preoperative abnormalities of the pollicized digit. This provides a prognostic guideline for clinicians as radial absence, in particular, is a risk factor for poor recovery of fingertip force control after pollicization.

The contralateral hands of children with unilateral thumb hypoplasia/aplasia also demonstrate functional deficiencies. Manske and McCarroll [34] demonstrated that the "normal" side in children with unilateral thumb hypoplasia often tested lower than the dominant hand in children without thumb deformity. Netscher et al. [4] also found that apparently normal contralateral hands in unilateral thumb aplasia or severe hypoplasia without radial deficiency were weaker than normal dominant hands. Our results indicate that moderately reduced strength is common in the non-pollicized hands of unilaterally pollicized children, but dexterity as measured by the S–D, Box and Blocks, and pegboard tests is usually maintained.

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 following pollicization. This study utilized a convenience sample of patients with variable age and length of follow-up. In addition, our results may be influenced by having all procedures performed by a single surgeon utilizing a standard modified Buck Gramko technique. Future studies should evaluate other techniques in children matched by severity to determine whether subtle differences in surgical technique such as thumb length or metacarpal excision amount, the presence or transfer of intrinsic muscles, or extensor and flexor tendon shortening can alter pollicization dexterity outcomes. Future studies should also evaluate the individual contributions of skeletal changes, muscle mechanics, and brain function to improvements in dynamic control of fingertip forces.

In conclusion, a key component of dexterity and in-hand object manipulation can be quantitatively evaluated in both typically developing children and children with hand anomalies utilizing the S–D test. At a superficial level, children can achieve near-normal control of low magnitude fingertip forces after pollicization. However, the nature of the dynamic control of fingertip forces is altered and less able to correct for instabilities. Predictably, children with more involved upper extremity differences and radial longitudinal deficiency achieved less control of fingertip forces than children with isolated thumb hypoplasia/aplasia after finger pollicization. These results suggest that after pollicization children exhibit the necessary neuromuscular plasticity to adapt their control strategies for dynamic manipulation, but to a level that is not comparable to that achieved by typically developing children.

Acknowledgements

We would like to thank Cassie Nguyen for her assistance with data processing. This publication was supported by SC CTSI (NIH/NCRR/NCATS) through grant UL1TR000130. Research reported in this publication was partially supported by the National Institute of Arthritis and Musculoskeletal and Skin Diseases of the National Institutes of Health under Award Numbers R01-0505020 and R01-052345. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health. F.V.C., S.D., and E.L. were partially supported by grants NIDRR H133E080024; NSF EFRI-COPN 0836042; NIH AR050520 and NIH AR052345 to F.V.C. S.D. is currently a postdoctoral fellow in the Muscle Physiology Laboratory, University of California, San Diego.

Conflict of interest statement

F.V.C. holds US Patent No. 6,537,075 on some of the technology used, but has no active or pending licensing agreements with any commercial entity. None of the other authors have any financial or personal relationships with other people or organizations that could inappropriately influence this work.

References

[1] Verdan C. The reconstruction of the thumb. Surg Clin N Am 1968;48:103.
[2] Papadogeorgou EV, Soucacos PN. Treatment alternatives of congenital hand differences with thumb hypoplasia involvement. Microsurgery 2008;28:121–30.
[3] de Kraker M, Selles RW, van Vooren J, Stam HJ, Hovius SE. Outcome after pollicization: comparison of patients with mild and severe longitudinal radial deficiency. Plast Reconstr Surg 2013;131:544e–51e.
[4] Netscher DT, Aliu O, Sandvall BK, Staines KG, Hamilton KL, Salazar-Reyes H, et al. Functional outcomes of children with index pollicizations for thumb deficiency. J Hand Surg 2013;38:250–7.
[5] Aliu O, Netscher DT, Staines KG, Thornby J, Armenta A. A 5-year interval evaluation of function after pollicization for congenital thumb aplasia using multiple outcome measures. Plast Reconstr Surg 2008;122:198–205.
[6] Staines KG, Majzoub R, Thornby J, Netscher DT. Functional outcome for children with thumb aplasia undergoing pollicization. Plast Reconstr Surg 2005;116:1314–23.
[7] Valero-Cuevas FJ, Smaby N, Venkadesan M, Peterson M, Wright T. The strength–dexterity test as a measure of dynamic pinch performance. J Biomech 2003;36:265–70.
[8] Mosier K, Lau C, Wang Y, Venkadesan M, Valero-Cuevas FJ. Controlling instabilities in manipulation requires specific cortical-striatal-cerebellar networks. J Neurophysiol 2011;105:1295–305.
[9] Venkadesan M, Guckenheimer J, Valero-Cuevas FJ. Manipulating the edge of instability. J Biomech 2007;40:1653–61.
[10] Vollmer B, Holmstrom L, Forsman L, Krumlinde-Sundholm L, Valero-Cuevas FJ, Forssberg H, et al. Evidence of validity in a new method for measurement of dexterity in children and adolescents. Dev Med Child Neurol 2010;52:948–54.
[11] Dayanidhi S, Hedberg A, Valero-Cuevas FJ, Forssberg H. Developmental improvements in dynamic control of fingertip forces last throughout childhood and into adolescence. J Neurophysiol 2013;110:1583–92.
[12] Dayanidhi S, Kutch JJ, Valero-Cuevas FJ. Decrease in muscle contraction time complements neural maturation in the development of dynamic manipulation. J Neurosci: Off J Soc Neurosci 2013;33:15050–55.
[13] Dayanidhi S, Valero-Cuevas FJ. Dexterous manipulation is poorer at older ages and is dissociated from decline of hand strength. J Gerontol Ser A: Biol Sci Med Sci 2014;69:1139–45.
[14] Lawrence EL, Fassola I, Werner I, Leclercq C, Valero-Cuevas FJ. Quantification of dexterity as the dynamical regulation of instabilities: comparisons across gender, age and disease. Front Neurol 2014;5.
[15] Holmström L, de Manzano O, Vollmer B, Forsman L, Valero-Cuevas FJ, Ullen F, et al. Dissociation of brain areas associated with force production and stabilization during manipulation of unstable objects. Exp Brain Res 2011;215:359–67.
[16] Buck-Gramcko D. Pollicization of the index finger. J Bone Jt Surg 1971;53A:1605–17.
[17] Blauth W. The hypoplastic thumb. Arch Orthop Unfallchir 1967;62:225–46.
[18] Bayne LG, Klug MS. Long-term review of the surgical treatment of radial deficiencies. J Hand Surg 1987;12:169–79.
[19] Eliasson AC, Krumlinde-Sundholm L, Rosblad B, Beckung E, Arner M, Ohrvall AM, et al. The Manual Ability Classification System (MACS) for children with cerebral palsy: scale development and evidence of validity and reliability. Dev Med Child Neurol 2006;48:549–54.
[20] Strickland JW. Results of flexor tendon surgery in zone II. Hand Clin 1985;1:167–79.
[21] O'Connell SJ, Moore MM, Strickland JW, Frazier GT, Dell PC. Results of zone I and zone II flexor tendon repairs in children. J Hand Surg 1994;19A:48–52.
[22] Daltroy LH, Liang MH, Fossel AH, Goldberg MJ. The POSNA pediatric musculoskeletal functional health questionnaire: report on reliability, validity, and sensitivity to change. Pediatric Outcomes Instrument Development Group. Pediatric Orthopaedic Society of North America. J Pediatr Orthop 1998;18:561–71.
[23] Mathiowetz V, Wiemer DM, Federman SM. Grip and pinch strength: norms for 6- to 19-year-olds. Am J Occup Ther: Off Publ Am Occup Ther Assoc 1986;40:705–11.
[24] Lee-Valkov PM, Aaron DH, Eladoumikdachi F, Thornby J, Netscher DT. Measuring normal hand dexterity values in normal 3-, 4-, and 5-year-old children and their relationship with grip and pinch strength. J Hand Ther: Off J Am Soc Hand Ther 2003;16:22–8.
[25] Hager-Ross C, Rosblad B. Norms for grip strength in children aged 4–16 years. Acta Paediatr 2002;91:617–25.
[26] Mathiowetz V, Ferderman S, Wiemer D. Box and block test of manual dexterity: norms for 6–19 year olds. Can J Occup Ther 1985;52:241–6.

[27] Jongbloed-Pereboom M, Nijhuis-van der Sanden MWG, Steenbergen B. Norm scores of the box and blocks test for children ages 3-10 years. Am J Occup Ther 2013;67:312–8.
[28] Poole JL, Burtner PA, Torres TA, McMullen CK, Markham A, Marcum ML, et al. Measuring dexterity in children using the Nine-hole Peg Test. J Hand Ther: Off J Am Soc Hand Ther 2005;18:348–51.
[29] Aaron DH, Jansen CW. Development of the Functional Dexterity Test (FDT): construction, validity, reliability, and normative data. J Hand Ther: Off J Am Soc Hand Ther 2003;16:12–21.
[30] Jebsen RH, Taylor N, Trieschmann RB, Trotter MJ, Howard LA. An objective and standardized test of hand function. Arch Phys Med Rehabil 1969;50:311–9.
[31] Lebel C, Beaulieu C. Longitudinal development of human brain wiring continues from childhood into adulthood. J Neurosci 2011;31:10937–47.
[32] Armand J, Olivier E, Edgley SA, Lemon RN. Postnatal development of corticospinal projections from motor cortex to the cervical enlargement in the macaque monkey. J Neurosci 1997;17:251–66.
[33] Bengtsson SL, Nagy Z, Skare S, Forsman L, Forssberg H, Ullen F. Extensive piano practicing has regionally specific effects on white matter development. Nat Neurosci 2005;8:1148–50.
[34] Manske PR, McCarroll Jr HR. Reconstruction of the congenitally deficient thumb. Hand Clin 1992;8:177–96.