Palmar Abduction: Reliability of 6 Measurement Methods in Healthy Adults

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Purpose The aim of the current study was to assess reliability of 6 palmar thumb abduction measurement methods: conventional goniometry, the Inter Metacarpal Distance, the method described by the American Medical Association, the method described by the American Society of Hand Therapists, and 2 new methods: the Pollexograph-thumb and the Pollexograph-metacarpal.

Methods An experienced hand therapist and a less-experienced examiner (trainee in plastic surgery) measured the right hands of 25 healthy subjects. Palmar abduction was measured both passively and actively. Means and ranges for palmar abduction were calculated, and intrarater and interrater reliability was expressed in intraclass correlation coefficients, standard errors of measurement, and smallest detectable differences.

Results Mean active and passive angles measured with goniometry resembled values measured with the Pollexograph-thumb method (approximately 60°). Mean angles found with the Pollexograph-metacarpal method were approximately 48°. Mean active and passive distances for the Inter Metacarpal Distance were 64 mm. Mean active and passive distances found with the American Society of Hand Therapists method were 97 to 101 mm, and mean distances found with the American Medical Association method were 67 to 70 mm for active and passive measurements. Intraclass correlation coefficients for the Pollexograph-thumb, Pollexograph-metacarpal, and the Inter Metacarpal Distance indicated good and significantly higher intrarater agreement for active and passive measurements than intraclass correlation coefficients of conventional goniometry, the American Society of Hand Therapists method, and the American Medical Association method, which showed only moderate agreement. For interrater reliability, the same measurement methods were found to be most reliable: the Pollexograph-thumb, Pollexograph-metacarpal, and the Inter Metacarpal Distance.

Conclusions We found that the Pollexograph-thumb, Pollexograph-metacarpal, and the Inter Metacarpal Distance are the most reliable measurement methods for palmar abduction. *(J Hand Surg 2009;34A:523–530. © 2009 Published by Elsevier Inc. on behalf of the American Society for Surgery of the Hand.)*

Key words Assessment, goniometry, hand, palmar abduction, reliability.

FOR PALMAR ABDUCTION, many different definitions have been reported in the literature.[1–5] One often-used definition is "the movement in which the thumb metacarpal moves away from the index metacarpal, perpendicular to the plane of the palm."[2] Another frequently used definition is "the angle between the first and second metacarpals with the thumb maximally abducted."[1,3,4]

As there is no consensus on the definition, there is also no consensus on the optimal measurement method

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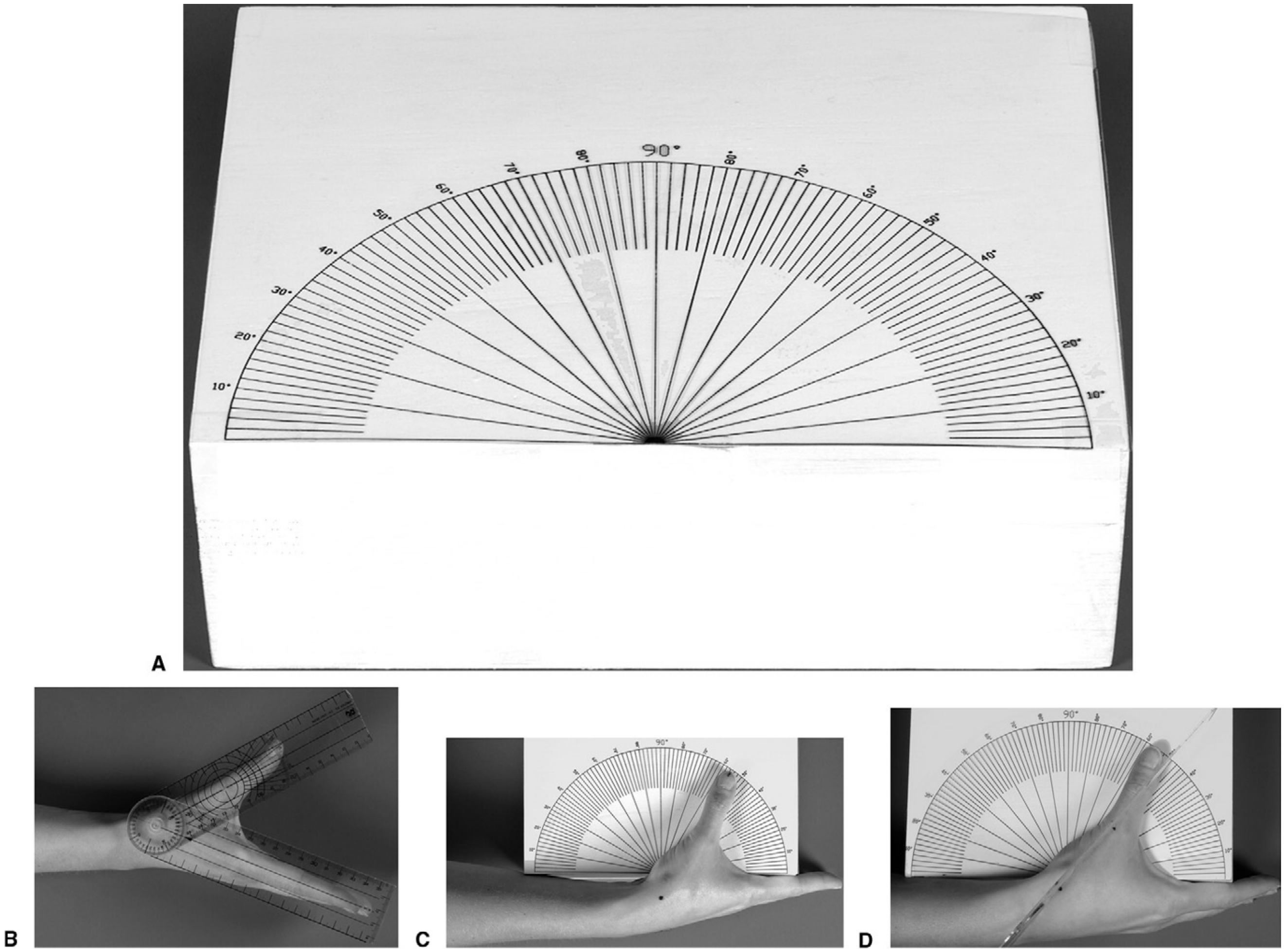

FIGURE 1: **A** The Pollexograph with protractor on top. **B** An active measurement with a conventional goniometer. The goniometer is placed over the first and second metacarpals. **C** Position of hand and forearm on the Pollexograph during a Pollexograph-thumb measurement. Two landmarks are visible: the CMC joint marking and the nail marking that facilitates angle readings. **D** A Pollexograph-metacarpal measurement; the ruler is placed over the first metacarpal. Possible laxity in the metacarpophalangeal and IP joints is left out of the measured angle.

for palmar thumb abduction.[1,5–9] Several authors have measured palmar abduction angles,[1-4,9] whereas others used distances between anatomic reference points.[5,8,10] For these measurements, different devices have been used, such as goniometers,[8] calipers,[8] triangular pieces of wood with known angles,[6] torque-controlled devices,[9] and 3-dimensional video camera systems.[11–14] All these existing methods have disadvantages that complicate daily clinical use, such as low reliability (eg, conventional goniometry)[8] or measurement complexity (eg, 3-dimensional video camera systems).[11–14] We therefore designed the Pollexograph (Fig. 1A) to allow reliable and easy palmar thumb abduction measurements in daily clinical care.

The Pollexograph design is based on the concept that hand position should be standardized to obtain repetitive and reliable measurements. Because palmar abduction is a motion in 1 plane, it should be assessed in this plane along a smooth surface.

Thus, the Pollexograph measures the movement in which the thumb metacarpal moves away from the index metacarpal, perpendicular to the plane of the palm. A box shape was chosen so that the thumb would be forced to move in the plane perpendicular to the hand. A protractor on top is divided in steps of 2° to conform to the scale of many conventional goniometers. The protractor runs from 0 to 90° from the left to the middle and from the right to the middle, making the Pollexograph applicable for left and right hands. To optimally align the hand and to read the palmar abduction angle on the Pollexograph, the examiner marks a number of anatomic points on the hand. First, to allow the thumb to move freely in the right plane, it is important to place the thenar crease exactly on the edge of the box. Therefore, the thenar crease is marked before placing the hand. In addition, because rotation during palmar abduction originates from the carpometacarpal (CMC) joint, we chose to mark this joint so that it can be aligned with the 90° line on the protractor. Finally, the middle distal part of the nail is marked to facilitate angle readings.

The above-mentioned Pollexograph-thumb measurement measures the angle between the first metacarpal and the palm of the hand, plus the angle produced by possible laxity in the metacarpophalangeal (MCP) and interphalangeal (IP) joints. Therefore, we also evaluated an alternative Pollexograph application, Pollexograph-metacarpal, in which a ruler is placed over the first metacarpal to better resemble conventional goniometry measurements by excluding laxity in these 2 joints.

In a previous study, 14 hand therapists measured active and passive palmar abduction in a healthy subject with the Pollexograph and with a conventional goniometer using the method as described by Brand,[1] Hartigan et al.,[3] and Tubiana et al.[4] We found systematic differences between the palmar abduction measured with the Pollexograph-thumb and with conventional goniometry that could be explained by systematic differences in the angle that is measured. However, more importantly, we found a large decrease in variation between measurements on the same subject with the Pollexograph compared with that in conventional goniometry, indicating better reliability. In addition, Pollexograph-thumb intrarater reliability was also assessed in 21 patients with a hypoplastic thumb, showing excellent reliability with intraclass correlation coefficients (ICCs) of 0.98 for passive range of motion and 0.99 for active range of motion.

The goal of this study was to compare intrarater and interrater reliability of the Pollexograph (thumb and metacarpal) with the most common alternative measurement methods for palmar abduction: conventional goniometry,[1,3,4,15] the Inter Metacarpal Distance (IMD),[8] the American Society of Hand Therapists method (ASHT method),[10] and the method described in "Guides to the Evaluation of Permanent Impairment" of the American Medical Association (AMA method).[5]

MATERIALS AND METHODS

Subjects

Measurements were performed on the right hands of 25 healthy subjects recruited at the Erasmus MC, Rotterdam. Subjects had no prior injury to the upper extremity or systemic conditions affecting the muscular or nervous system. The group consisted of 9 men and 16 women, of whom 3 were left-handed. Mean age of the subjects was 30 years (standard deviation ± 7 years).

This study was approved by the medical ethics committee, and written informed consent was obtained from each subject.

Measurements

All measurements were performed once by an experienced examiner (a hand therapist) and twice by a less-experienced examiner (a trainee in plastic and reconstructive surgery) to assess both intrarater and interrater reliability. To prevent testers from being influenced by the values of prior tests, retest values were written down on a new form by the other tester. Measurement order was also randomized to prevent examiners from remembering previous measurement values. After each measurement, skin markings were removed, because marking differences contribute to measurement errors and therefore affect reliability. Total time to perform all measurements by 1 examiner was approximately 10 minutes per subject. The retest was performed a few days after the test.

We performed active and passive palmar abduction measurements with *angular methods* (1) conventional goniometer, (2) Pollexograph-thumb method, (3) and Pollexograph-metacarpal method, and with *distance methods* (4) IMD method, (5) AMA method, and (6) ASHT method.

For conventional goniometry measurements, the same 18-cm goniometer was used. During active measurements (Fig. 1B), the subject was asked to hold the thumb in maximal abduction, and the goniometer was placed over the first and second metacarpals. For passive measurements, the same angle was determined while the examiner held the thumb in maximal palmar abduction.

For Pollexograph-thumb measurements (Fig. 1C), 3 landmarks were indicated on the hand: (1) the middle, most proximal part of the first metacarpal, indicating the carpometacarpal joint, (2) the thenar crease, and (3) the middle, distal part of the thumb nail. During measurements, the subject was seated at a table with the elbow in 90° flexion and the wrist in a neutral position. The hand was placed on the Pollexograph with the thenar crease on the edge of the box and the CMC joint marking aligned with the 90° line of the protractor (Fig. 1C). The lower arm was positioned parallel to the box with the fingers pointed slightly ulnar. When the hand was placed accurately, the thumb could move without interference by the box surface or edge. During measurements, the other fingers were fixed against the box by the examiner. Maximal palmar abduction of the

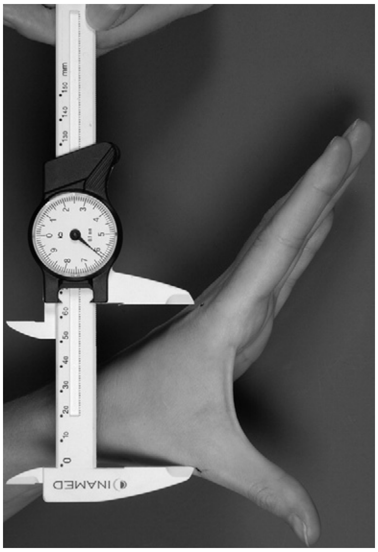

FIGURE 2: Active IMD measurement performed using a caliper.

thumb was read from the nail marking position above the protractor.

The Pollexograph-thumb measures the angle between the mid-nail of the thumb and the palm of the hand. This angle is influenced by possible laxity in the MCP and IP joints (Fig. 1C). Therefore, we also evaluated an alternative Pollexograph application measuring the angle between the first metacarpal and the palm of the hand. These Pollexograph-metacarpal measurements were performed largely similarly as described for the Pollexograph-thumb method. The first 2 skin markings (CMC joint and thenar crease) remained the same; the third marking was placed on the mid-distal head of the first metacarpal (metacarpal 1 marking). During measurements, a ruler was placed over the CMC marking, the metacarpal 1 marking, and the protractor (Fig. 1D). When the thumb was maximally abducted, the value was read from the ruler position above the protractor.

We performed a distance measurement method of the thumb web space IMD, introduced by Murugkar et al.[8] For these measurements, the mid-dorsal points of the first and second metacarpal heads were marked, and 2 caliper points were placed on the markings while the thumb was in maximal palmar abduction (Fig. 2). The maximal distance was read in millimeters from the scale.

The second distance method was adapted from the opposition measurement method described in "Guides to the Evaluation of Permanent Impairment" of the American Medical Association (AMA method).[5] An adaptation was made because only methods for measuring radial abduction and opposition were described and not for palmar abduction.

Following this method, the largest possible distance was recorded from the distal palmar crease directly over the third MCP joint to the flexor crease of the IP joint. Normal distance to the IP crease is described as 80 mm in adults.[5]

The third distance measurement method we performed was the method described by the American Society of Hand Therapists (ASHT method).[10] The maximal distance was measured from the distal palmar crease directly over the third MCP joint to the tip of the thumb. A normal range from the distal palmar crease to the thumb tip is unknown.

Statistical analysis

Using statistical software (SPSS version 14.0; SPSS Inc, Chicago, IL), we calculated means, standard deviations (SDs), and ranges of the whole group. Differences in mean values of the different methods indicate systematic differences between measurement techniques.

Both intrarater reliability (examines the ability of a single tester to obtain consistent results on repetitive measures) and interrater reliability (the amount of agreement between measurements by different testers) were assessed. Reliability was calculated using ICC and its 95% confidence interval. The ICC is a measure of agreement between test and retest values measured in the same subject. It ranges from 0 to 1, where an ICC of 0 means no agreement between test and retest, and an ICC of 1 means perfect test–retest reliability.[16,17] The first test of the less-experienced examiner and the test of the more experienced examiner were used to assess interrater reliability.

Additionally, 2 absolute reliability indices were calculated, expressing the difference between test and retest in the original measurement units (degrees and millimeters): standard error of measurement (SEM) and smallest detectable difference (SDD). Not being proportional, as is ICC, the SEM is only determined by physical causes of error and statistical uncertainty of estimating that error. The SEM includes both random and systematic components of measurement error and was calculated with the estimated variance components, where the SEM is the square root of the error variance.[18–20]

From the SEM, the smallest detectable difference ($SDD = 1.96 \times \sqrt{2} \times SEM$) was determined. The SDD is specifically valuable for clinical use because with this index an examiner can distinguish between a measurement error and a real (treatment) change. Only a difference that exceeds the SDD can be considered a real (nonerror) change in an individual patient.[20] For example, an SDD of 5° indicates that a follow-up measurement should differ by at least 5° from a baseline measurement to be sure that there is a real (nonerror) change in abduction angle in an individual subject.

To test for statistically significant differences among reliability, SEMs for all measurement methods were compared by using the methods described by Schreuders and colleagues[21] and Stratford and Goldsmith[22] for dependent samples. Calculating statistically significant differences allows differentiation between reliability data that may appear rather similar. A p value $\leq$.05 was considered significant.

RESULTS

Mean values

Table 1 shows means, SDs, and ranges of angular and distance measurement methods for palmar abduction. It can be seen that mean active and passive angles measured with goniometry were comparable with Pollexograph-thumb values. Goniometry and Pollexograph-thumb means ranged from 57° to 64°, whereas Pollexograph-metacarpal mean angles were smaller, ranging from 47° to 49°.

Mean active and passive distances of the AMA method were 67 to 70 mm from the distal palmar crease to the IP joint. Mean distances of the ASHT method were 97 to 101 mm to the thumb tip for active and passive measurements, and mean active and passive IMD method distances were 63 to 64 mm.

Reliability data

Table 2 shows intrarater and interrater reliability for angle and distance measurements for palmar thumb abduction. Five of 6 intrarater ICCs of the Pollexograph-thumb, Pollexograph-metacarpal, and IMD methods indicated excellent agreement (ICCs 0.81–0.95) for active and passive measurements, whereas ICCs for conventional goniometry, the ASHT method, and the AMA method showed less agreement between test and retest (ICCs 0.55–0.78). Smallest detectable differences for the Pollexograph (thumb/metacarpal) were significantly smaller than for conventional goniometry, and SDDs for the IMD method were also significantly smaller than for the ASHT method and AMA method.

Table 3 shows p values of the SEM comparison of the intrarater and interrater reliability data for angular and distance measurement methods. For intrarater reliability, Pollexograph (thumb/metacarpal) SEMs were significantly smaller ($p = .016$ and $p = .004$) than conventional goniometry SEMs. The IMD method had significantly smaller SEMs ($p < .001$ and $p < .001$) compared with those of the AMA method and the ASHT method, indicating that the IMD method is more reliable.

For interrater reliability, the same measurement methods were found to be most reliable: the Pollexograph-thumb, Pollexograph-metacarpal, and the IMD.

TABLE 1. Means, SDs, and Ranges of Angular and Distance Methods for Palmar Abduction

Method	Mean ± SD (°)	Range (°)
Goniometer		
Active palmar abduction	57 ± 6	45–70
Goniometer		
Passive palmar abduction	64 ± 8	49–78
Pollexograph-thumb		
Active palmar abduction	62 ± 5	54–72
Pollexograph-thumb		
Passive palmar abduction	63 ± 4	56–70
Pollexograph-metacarpal		
Active palmar abduction	47 ± 5	35–56
Pollexograph-metacarpal		
Passive palmar abduction	49 ± 6	36–58
	Mean ± SD (mm)	Range (mm)
AMA (IP joint)		
Active palmar abduction	67 ± 7	53–80
AMA (IP joint)		
Passive palmar abduction	70 ± 6	56–85
ASHT (thumb tip)		
Active palmar abduction	97 ± 8	75–111
ASHT (thumb tip)		
Passive palmar abduction	101 ± 8	84–115
IMD		
Active palmar abduction	63 ± 6	53–76
IMD		
Passive palmar abduction	64 ± 5	55–76

DISCUSSION

The goal of our study was to compare reliability of the most common measurement methods for palmar thumb abduction. Although conventional goniometry may be used most often in daily clinical practice, it was found to be unreliable. The significantly smaller SDDs and SEMs for intrarater and interrater reliability indicated that the Pollexograph-thumb, Pollexograph-metacarpal, and the IMD methods were the most reliable methods for measuring palmar abduction.

TABLE 2. Intrarater and Interrater Reliability for All Methods for Palmar Abduction Expressed With Use of SEM, SDD, and ICC

Method	Active/ Passive	Intrarater Reliability			Interrater Reliability		
		SEM °	SDD °	ICC and (95% CI)	SEM, °	SDD, °	ICC and (95% CI)
Goniometer	Active	4.3	11.8	0.55 (0.34–0.87)	5.2	14.4	0.31 (−0.18–0.77)
Goniometer	Passive	3.5	9.7	0.76 (0.69–0.94)	5.9	16.5	0.37 (−0.42–0.79)
Pollexograph-thumb	Active	2.5	7.0	0.71 (0.62–0.93)	2.6	7.1	0.66 (0.53–0.91)
Pollexograph-thumb	Passive	2.0	5.5	0.82 (0.78–0.96)	3.3	9.0	0.59 (0.42–0.89)
Pollexograph-metacarpal	Active	2.3	6.4	0.82 (0.78–0.96)	3.7	10.3	0.57 (0.38–0.88)
Pollexograph-metacarpal	Passive	2.7	7.5	0.81 (0.76–0.95)	3.5	9.7	0.61 (0.45–0.89)
		SEM, mm	SDD, mm		SEM, mm	SDD, mm	
AMA (IP joint)	Active	4.1	11.4	0.72 (0.63–0.92)	6.6	18.4	0.24 (−0.40–0.73)
AMA (IP joint)	Passive	3.9	10.9	0.65 (0.51–0.90)	5.0	13.9	0.52 (0.28–0.86)
ASHT (thumb tip)	Active	4.4	12.3	0.78 (0.72–0.94)	5.6	15.6	0.55 (0.34–0.87)
ASHT (thumb tip)	Passive	4.5	12.6	0.72 (0.63–0.93)	6.2	17.2	0.52 (0.29–0.86)
IMD	Active	1.2	3.3	0.95 (0.95–0.99)	2.2	6.1	0.82 (0.79–0.96)
IMD	Passive	1.4	4.1	0.92 (0.90–0.98)	2.4	6.5	0.79 (0.78–0.96)

TABLE 3. p Values for Intrarater and Interrater Reliability Comparing SEMs of Angular and Distance Methods

Measurements	SEM	SEM	Intrarater Reliability p Value	SEM	SEM	Interrater Reliability p Value
Active						
Pollexograph-thumb vs. goniometer	2.5	4.3	.016	2.6	5.2	.002
Pollexograph-metacarpal vs. goniometer	2.3	4.3	.004	3.7	5.2	.085
Pollexograph-thumb vs. Pollexograph-metacarpal	2.5	2.3	.664	2.6	3.7	.714
AMA (IP joint) vs. ASHT (thumb tip)	4.1	4.4	.583	6.6	5.6	.104
IMD vs. AMA (IP joint)	1.2	4.1	<.001	2.2	6.6	<.001
IMD vs. ASHT (thumb tip)	1.2	4.4	<.001	2.2	5.6	<.001
Passive						
Pollexograph-thumb vs. goniometer	2.0	3.5	.003	3.3	5.9	.004
Pollexograph-metacarpal vs. goniometer	2.7	3.5	.221	3.5	5.9	.014
Pollexograph-thumb vs. Pollexograph-metacarpal	2.0	2.7	.140	3.3	3.5	.714
AMA (IP joint) vs. ASHT (thumb tip)	3.9	4.5	.315	5.0	6.2	.104
IMD vs. AMA (IP joint)	1.4	3.9	<.001	2.4	5.0	<.001
IMD vs. ASHT (thumb tip)	1.4	4.5	<.001	2.4	6.2	<.001

The SEMs per measurement method were compared, resulting in p values for both intrarater and interrater reliability.

There are many definitions of palmar abduction as well as different measurement methods. Tubiana et al.,[4] Hartigan et al.,[3] and Brand et al.[1] all measured the angle between the first and second metacarpal with a goniometer when the thumb was maximally abducted. Normal values ranged from 40° to 80° in the study of Tubiana et al., whereas Brand et al. reported the normal range of the palmar abduction angle as 40° to 50°. Harvey et al.[9] found a mean passive palmar abduction angle of 56° (range, 53° to 60°) in a healthy population.

In this study, conventional goniometry values ranged from 45° to 70° for active measurements and from 49° to 78° for passive measurements. Thus, these values were most comparable with Tubiana's results.

A limitation of this study is that we have not yet validated Pollexograph measurements and that reliability was tested in a relatively small population of 25 healthy subjects. Future studies are needed to assess reliability in several different patient groups. In addition, the study is limited to subjects with normal anatomy of the hand. Future studies should also indicate the usefulness of these techniques in patients with anatomic deformities, such as contractures in patients with hand spasticity. It should be noted that in our study, a retest was only performed by the less-experienced examiner and not also by the experienced examiner. We decided to do this because when good reliability is found with a less-experienced examiner, reliability will most probably be higher in an experienced examiner.

Although the Pollexograph-metacarpal measures the orientation of the first metacarpal, similar to conventional goniometry, we found that mean goniometry angles were 5° to 10° larger than Pollexograph-metacarpal means. The smaller mean angles found for the Pollexograph-metacarpal may be explained by the fact that it measures the angle between the palm of the hand and the first metacarpal and not the angle between the first and second metacarpals. In fact, in both Pollexograph methods, it is more precise to say that the orientation of the thumb or first metacarpal is measured relative to the plane of the hand at the palmar side. Therefore, our Pollexograph means cannot be directly compared with conventional goniometry means. Although this may be a limitation to the current method, we believe that it is more important to have a measurement method that is better standardized and therefore more reliable than conventional goniometry. Because of the shape of the palm of the hand, the Pollexograph method introduces an offset-angle relative to the second metacarpal that does not influence comparison between subjects or between repeated measurements on the same subject.

Intrarater and interrater reliability of palmar abduction measurements has been reported in several studies. Harvey et al.[9] designed a complex torque-controlled device to measure passive palmar abduction and compared their new device with a caliper that measured the distance between the first and second metacarpal heads with the thumb maximally abducted. The intrarater ICC of their new device was 0.78 and the ICC of the caliper method was 0.83. The intrarater ICC of the less-complex Pollexograph in our study was 0.82, comparable with Harvey's device. Murugkar et al.[8] compared the IMD method with conventional goniometry and found a good interrater ICC of 0.84 for passive IMD measurements and a very poor ICC of 0.26 for conventional goniometry. We found ICCs of 0.82 and 0.79 for active and passive interrater reliability for the IMD and ICCs of 0.31 and 0.37 for conventional goniometry. Thus, both studies showed unacceptable low reliability for conventional goniometry and excellent reliability for the IMD method.

While often used, an ICC has the disadvantage of being a ratio of the between-subject variation and the overall variation, therefore depending on variation within (healthy) hands. In some cases, it may therefore be more informative to have absolute reliability indices such as SEMs and SDDs. With these indices, it is possible to distinguish between measurement errors and real changes.[18] Because our study is the first to calculate SEMs and SDDs for palmar abduction, these results could not be compared with other studies. In addition to not being dependent on variation between subjects, the SDD has the advantage of being easily interpretable in a clinical setting, because it indicates the value that should be exceeded to conclude the presence of a real (nonerror) change in an individual patient.[20]

We believe that the IMD method is appropriate for follow-up of individual adults; however, it may not be comparable between subjects owing to differences in hand size or for follow-up measurement in children owing to the changes in the sizes of their hands. Alternatively, angular measurements allow comparison for a single subject as well as between subjects because the measurements are not influenced by hand size. If the Pollexograph-thumb and Pollexograph-metacarpal would prove to be reliable in children, we would recommend using these 2 methods, because distance measurements are influenced by change in length of a child's hand during follow-up, whereas angular measurements are not. Thus, solely based on reliability, we recommend using the IMD method; however, based on reliability and applicability we would recommend using the Pollexograph.

Because palmar abduction can be diminished in several conditions, it is important to have a device that reliably assesses impairment. With a reliable device, clinicians will be able to quantify this impairment and assess intervention efficacy postoperatively. We believe that the design of the Pollexograph and marking of the anatomic reference points we chose contributed to standardization of hand position and therefore resulted in more reliable palmar abduction measurements than did the conventional method.

REFERENCES

1. Brand PW. Deformity in leprosy. In: Cochrane RG, ed. Leprosy in theory and practice. 2nd ed. Bristol, UK: John Wright & Sons Ltd, 1964:485–496.
2. International Federation of Societies for Surgery of the Hand. Terminology for hand surgery. Edinburgh, UK: Harcourt Health Sciences, 2001:53.
3. Hartigan BJ, Stern PJ, Kiefhaber TR. Thumb carpometacarpal osteoarthritis: arthrodesis compared with ligament reconstruction and tendon interposition. J Bone Joint Surg 2001;83A:1470–1478.
4. Tubiana R, Thomine JM, Mackin E. Examination of the hand and wrist. London: Martin Dunitz Ltd, 1998:195–196.
5. American Medical Association. Guides to the evaluation of permanent impairment. 4th ed. Chicago, IL: American Medical Association, 1993:28–29.
6. Shrinivasan H. Reconstructive surgery in treatment of deformities of hand. In: Dharmendra, ed. Leprosy. Bombay: Kothari Medical Publishing House, 1978:567–617.
7. Schwanholt C, Stern PJ. Brief or new: measuring cone for thumb abduction/extension. Am J Occup Ther 1984;38:263–264.
8. Murugkar PM, Brandsma JW, Anderson AM, Khadka G, Yam P. Reliability of thumb web measurements. J Hand Ther 2004;17:58–63.
9. Harvey L, de Jong I, Goehl G, Armstrong B, Allaous J. A torque-controlled device to measure passive abduction of the thumb carpometacarpal joint. J Hand Ther 2006;19:403–408.
10. American Society of Hand Therapists. Clinical assessment and recommendations. 2nd ed. Chicago, IL: American Society of Hand Therapists, 1992:64–65.
11. Su FC, Kuo LC, Chiu HY, Chen-Sea MJ. Video-computer quantitative evaluation of thumb function using workspace of the thumb. J Biomech 2003;36:937–942.
12. Chiu HY, Lin SC, Su FC, Wang ST, Hsu HY. The use of the motion analysis system for evaluation of loss of movement in the finger. J Hand Surg 2000;25B:195–199.
13. Degeorges R, Parasie J, Mitton D, Imbert N, Goubier JN, Lavaste F. Three-dimensional rotations of human three-joint fingers: an opto-electronic measurement. Preliminary results. Surg Radiol Anat 2005; 27:43–50.
14. Kuo LC, Su FC, Chiu HY, Yu CY. Feasibility of using a video-based motion analysis system for measuring thumb kinematics. J Biomech 2002;35:1499–1506.
15. de Kraker M, Selles RW, Schreuders TAR, Hovius SER, Stam HJ. J Hand Surgery 2009 (in press).
16. Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1986;1:307–310.
17. Rousson V, Gasser T, Seifert B. Assessing intrarater, interrater and test-retest reliability of continuous measurements. Statistics Med 2002;21:3431–3446.
18. Roebroeck ME, Harlaar J, Lankhorst GJ. The application of generalizability theory to reliability assessment: an illustration using isometric force measurements. Phys Ther 1993;73:386–401.
19. Shavelson RJ, Webb NM, Rowley GL. Generalizability theory. Am Psychol 1989;44:922–932.
20. Roebroeck ME, Harlaar J, Lankhorst GJ. Reliability assessment of isometric knee extension measurements with a computer-assisted hand-held dynamometer. Arch Phys Med Rehab 1998;79:442–448.
21. Schreuders TA, Roebroeck M, van der Kar TJ, Soeters JN, Hovius SE, Stam HJ. Strength of the intrinsic muscles of the hand measured with a hand-held dynamometer: reliability in patients with ulnar and median nerve paralysis. J Hand Surg 2000;25B:560–565.
22. Stratford PW, Goldsmith CH. Use of the standard error as a reliability index of interest: an applied example using elbow flexor strength. Phys Ther 1997;77:745–750.