

# Validation of an Objective Device for Assessing Circumductive Wrist Motion

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**Purpose** Circumduction of the wrist consists of a circular motion combining flexion, extension, and radioulnar deviation without simultaneous supination or pronation of the forearm. This pattern of flexion–extension and radial–ulnar deviation coupling is vital in common tasks; however, its evaluation in hand clinics is limited by the availability and ease of current tools. We present the construct, criterion, test–retest, and inter-rater validity of a new circumduction measurement device.

**Methods** Splint volunteers ( $n = 42$ ) and hand clinic patients ( $n = 51$ ) were studied to assess different aspects of validity and reliability for the circumduction jig. Known-group validation was used to assess construct validity and demonstrate the ability of the device to differentiate between patients with lesser or greater circumduction values. Criterion validity was demonstrated by comparing the circumduction measures of the device to flexion, extension, ulnar deviation, and radial deviation. Test–retest reliability was established by comparing the results of repeated circumduction measures for the hand clinic patients by 2 blinded, independent researchers, and inter-rater reliability was determined by evaluating the correlation in circumduction measures taken on the same patient by different blinded, independent researchers.

**Results** Circumduction measurements significantly decreased (test for trend,  $p < .01$ ) across the 3 different treatments that represented progressively reduced range of motion, establishing construct validity of the device. Flexion, extension, and radioulnar deviation all correlated significantly with circumduction; the correlation values ranged from 0.46 to 0.82 ( $p < .01$ ) among all subjects (93 subjects, 228 measurements). Intra-rater reliability was 0.98 ( $p < .01$ ) for both evaluators, and inter-rater reliability was 0.94 ( $p < .01$ ).

**Conclusions** The present validation study demonstrated criterion, construct, test–retest, and inter-rater reliability for a newly designed circumduction measurement device. (*J Hand Surg* 2008;33A:1293–1300. Copyright © 2008 by the American Society for Surgery of the Hand. All rights reserved.)

**Key words** Circumduction, goniometry, range of motion, wrist joint.

CIRCUMDUCTION HAS BEEN defined as the circular movement of a limb or joint. In the case of the human wrist, circumduction consists of a circular motion combining flexion, extension, and radioulnar deviation without simultaneous supination or pronation of the forearm. This pattern of flexion–extension and

radial–ulnar deviation coupling is vital in common tasks, such as tying shoelaces. Measuring circumduction should be part of the assessment of functional outcomes of trauma and of surgical intervention to the wrist because it more accurately represents the motion path relative to single-planar measurements.<sup>1–4</sup>

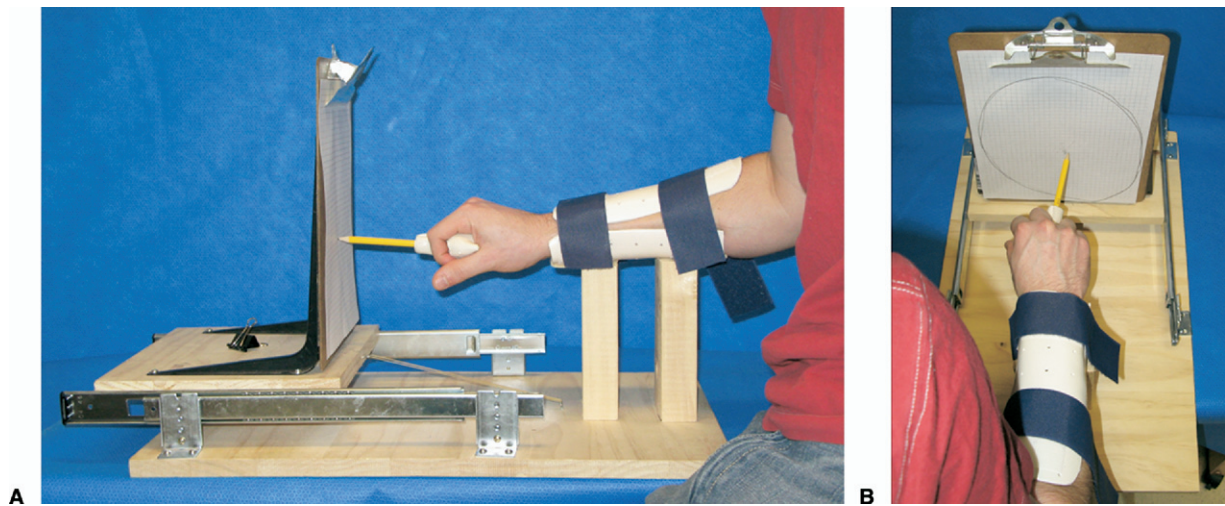
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**FIGURE 1:** **A** Lateral and **B** anterior views of the custom-built jig used to measure circumductive wrist motion. The circle drawn by the subject demonstrates the limits of circumductive motion from a fixed distance from the wrist crease.

Currently, the most widely used assessment tools for measuring circumduction include biaxial electrogoniometers and kinematic tracking devices, which have demonstrated validity, reliability, and clinical utility for some purposes.<sup>3,5</sup> Their utility, however, is limited by the space required and by the cost of multiple components, including electronics cables and computers. Furthermore, these tools are susceptible to measurement errors due to electronic cross-talk, when 1 planar movement causes a false signal in a different plane.<sup>6</sup> Newer generation 3-dimensional tracking devices are usually accurate and precise, but these are not without potential faults, and associated cost and setup times may make them impractical for measuring clinical outcomes in a busy practice.<sup>7</sup>

Our intent was to develop a simpler, more affordable circumduction measurement tool that could accurately and reliably record the functional range of motion (ROM) of a wrist for both clinical and research purposes. The purpose of this study was to determine the construct, criterion, test-retest, and inter-rater validity of this device.

## MATERIALS AND METHODS

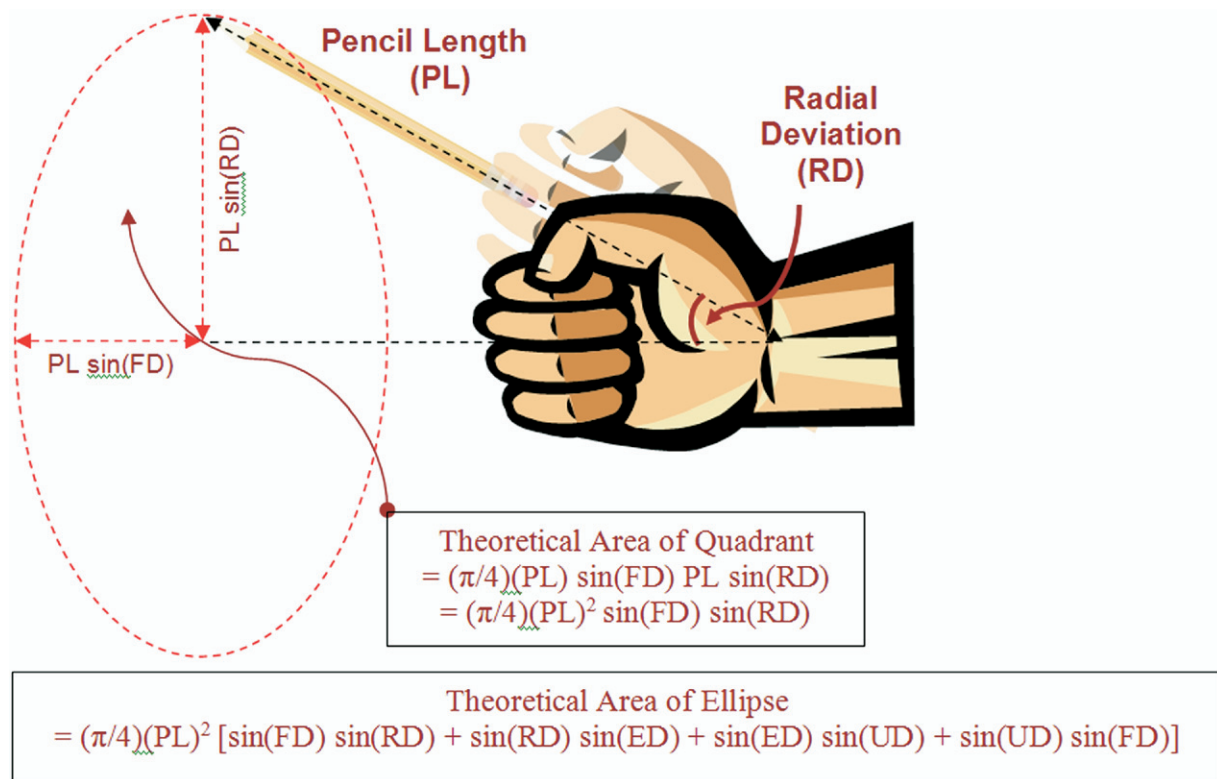
The design of the circumduction jig departs from the current use of either single-planar goniometers or electronic resistor measuring devices that record outcomes in angular degrees of wrist motion. Instead, our design records the area of the base of a cone made by the circular motion of the wrist while in motion.

The device itself has a base of 60 cm × 30 cm and a maximum height of 38 cm; without the clipboard upright, it can be stored in a space as short as 31 cm. It

weighs about 4.5 kg and can be built with supplies from a hardware store for less than \$100 (U.S. dollars). The protocol for proper use is simple and can be appropriately taught to a naive investigator in 15 minutes.

The basic design consists of stabilizing the forearm 19 cm above a base, the minimum space required allowing the wrist to circumduct unimpeded (Fig. 1). The patient is asked to grip a custom-fit utensil support in his or her fist; this support maintains a writing utensil (a wooden No. 2 pencil) along the axis of the radius while the wrist is in a neutral position. The distance from the wrist crease to the tip of the pencil is controlled in each person by fixing the height of the cone at 21 cm (Fig. 2). The length of 21 cm was determined to allow 60° of radioulnar deviation within the restrictions of a standard sheet of paper (U.S. letter-size, 8.5 in × 11 in).

With the patient's forearm resting comfortably in full pronation on the wrist splint, a dorsal component is tightened over the forearm with hook and lube tape straps to reduce pronation and supination throughout the motion. Two sizes of wrist supports and dorsal components are available to better fit larger versus smaller forearms. Once graph paper is securely fixed to the upright clipboard, the patient is instructed to draw the largest circle possible on the graph paper while maintaining a firm grip on the pencil support and without pronating or supinating throughout the motion. To maintain the appropriate motion with adequate pencil support, the patient must have a sufficient arc of motion at the 2nd and 3rd metacarpophalangeal joints and sufficient intrinsic muscle strength.



**FIGURE 2:** Graphical representation of theoretical circumductive area and derivation of equation. Each quadrant of the circumductive circle has 2 unique radii, determined by the pencil length and wrist motion in that particular plane. The sum of 4 quadrants is then used to estimate a theoretical circumductive motion for each subject. RD, radial deviation; UD, ulnar deviation; FD, flexion; ED, extension. Measurements are in angular degrees ( $^{\circ}$ ).

During this procedure, the tip of the pencil is in constant contact with a piece of letter-size graph paper, upright, and supported by a clipboard. The graph paper is mounted on a sliding track, allowing it to move closer to and further from the wrist to adjust for changes in the length vector of the pencil throughout the motion. This is accomplished by an elastic recoil band attached between the sliding support and the stable base to allow recoil resistance against the patient throughout the motion. The amount of resistance against the page can be modified by adjusting the thickness or length of the recoil band (U.S. rubber band sizes Nos. 14, 32, or 63).

To establish the extreme limits of the functional motion path, the patient may make multiple attempts at drawing the largest possible shape. The area within the largest circle is calculated by counting the number of squares within the drawn lines, thereby representing the limits of functional motion. Alternatively, a digital image processing and analysis program such as NIH Image (<http://rsb.info.nih.gov/nih-image/>) can be used to calculate the area included within the drawn circle.

### Subject population

Diifferent aspects of validity and reliability for the circumduction jig were assessed in 2 groups of subjects. For the first group our purpose was to evaluate construct and criterion validity. This group consisted of 42 normal volunteers whose wrist motion was purposely restricted by different splints. The second group was tested to evaluate inter-rater reliability, test-retest reliability, and criterion validity. This group consisted of 51 consecutive patients with a spectrum of hand and wrist pathologies presenting to a tertiary-care orthopedic hand clinic. These patients were recruited from February through May 2007, and IRB approval was obtained for this project.

### Construct validity

Construct validity was assessed using known-group validation.<sup>8,9</sup> Changes in circumduction measurements related to 3 different splint designs, representing our known groups, were compared within the group of 42 volunteers. These subjects had baseline ROM assessment, as well as 2 different degrees of restricted wrist

splinting. One splint was composed of heat-moldable plastic and represented a highly restricted condition as measured by standard uniplanar ROM measurements. The other splint was made of heat-moldable foam, allowing more flexibility and motion, and reflected a partially restricted motion condition. Highly restricted splints were designed to restrict average flexion–extension arcs to less than 30°, while partially restricted splints were designed to restrict average flexion–extension arcs to less than 80°. Both splints were more restrictive than the baseline unrestricted condition for all volunteers. Standard ROM (flexion, extension, radioulnar deviation, supination, pronation) and circumduction were taken at baseline (unsplinted) and with each splint.

The construct validity assessment focused on the circumduction scores across the 3 treatments. We hypothesized that circumduction scores should significantly decrease as patients moved from baseline to partial restriction to high restriction. The repeated-measures analysis of variance (ANOVA) was applied to test for the hypothesized downward trend across 3 gradually restrictive splints for the establishment of construct validity.<sup>10</sup> In addition, we assessed correlation between treatment and circumduction score.

### Criterion validity

In our study, the established single planar wrist ROM measures represented the gold standard. Criterion validity of the new device was assessed by comparing circumduction measures to flexion, extension, ulnar deviation, and radial deviation.<sup>6,9,10</sup> In addition, ROM values were used to extrapolate a theoretical motion cone, and the pencil length measurements were used to estimate a theoretical circumduction motion based on these values (Fig. 2). Results from both groups were used to estimate the Pearson coefficient of correlation between circumduction measures with each of the different ROM measures, as well as with the theoretical circumduction. Our hypothesis was that the circumduction measures would have a high and statistically significant correlation with other measures, suggesting criterion validity.

### Test–retest reliability

Test–retest reliability was achieved by taking repeated measurements immediately before and immediately after a patient's visit to a hand clinic.<sup>9,10</sup> Repeated circumduction measures were taken for the 51 hand clinic patients by 2 blinded, independent researchers (referred to here as investigator A and investigator B). Pearson coefficients of correlation were estimated between the

scores at the first and the second measurement for each of the investigators. To illustrate the relationship graphically, we plotted second measure vs. first measure as a scatter-plot, superimposing the results for investigator A and investigator B. We then graphed the line of identity, at which correlation is equal to exactly 1.0, to assess the correspondence between the first and second measures.

### Inter-rater reliability

Inter-rater reliability, also referred to as interobserver reliability, is defined as the degree to which different investigators give consistent estimates of the same phenomenon.<sup>11</sup> We assessed inter-rater reliability by evaluating whether there was a statistically significant correlation in circumduction measures taken on the same patient by independent researchers. In 51 hand clinic patients we compared the first evaluations measured by investigator A and investigator B. Pearson coefficients were calculated to assess the correlation, and a scatter-plot with a best fit linear prediction was plotted to graphically illustrate the correlation.

All statistical analysis was performed using statistical analysis software (Stata, version 9.2, College Station, TX).

## RESULTS

Forty-two normal volunteers and 51 hand clinic patients were studied. Demographic information with ROM and circumduction for each group is presented in Table 1.

Circumduction measures significantly decreased (repeated-measures ANOVA,  $p < .01$ , adjusted  $R^2 = 0.84$ ) across the 3 different events that represented progressively reduced ROM (normal =  $471.6 \pm 71.6 \text{ cm}^2$ , partially restricted =  $329.0 \pm 68.4 \text{ cm}^2$ , and restricted =  $180.0 \pm 63.9 \text{ cm}^2$ ), demonstrating construct validation of the device (Fig. 3). This was further confirmed by similar results of alternative tests used to assess statistically significant differences across the 3 groups (the  $t$ -test of means for any 2 groups, a linear regression using groups as a trend indicator, and the Cuzick extension of the Wilcoxon signed-rank test for skewed data). Regardless of the test used, circumduction scores were found to accurately reflect decreasing ROM across the 3 different circumstances.

The correlation of circumduction motions with each ROM variable is given in Table 2. Flexion, extension, and radioulnar deviation all correlated significantly with circumduction; correlation values ranged from 0.64 to 0.82 ( $p < .01$ ) in the splinted subjects (42 subjects, 126

**TABLE 1. Demographic and Range of Motion Data**

Characteristic	Splint Volunteers* (n = 42)	Hand Clinic Patients (n = 51)
Age, years, mean $\pm$ SD (range)	54.4 $\pm$ 6.5 (45–69)	40.9 $\pm$ 17.9 (18–87)
Gender, %		
Female	59.5	52.9
Male	40.5	47.1
Range of motion, degrees, mean $\pm$ SD		
Flexion	69 $\pm$ 12	65 $\pm$ 17
Extension	62 $\pm$ 8	57 $\pm$ 12
Ulnar deviation	38 $\pm$ 7.0	32 $\pm$ 10
Radial deviation	25 $\pm$ 6	21 $\pm$ 6

\*Unrestricted baseline.

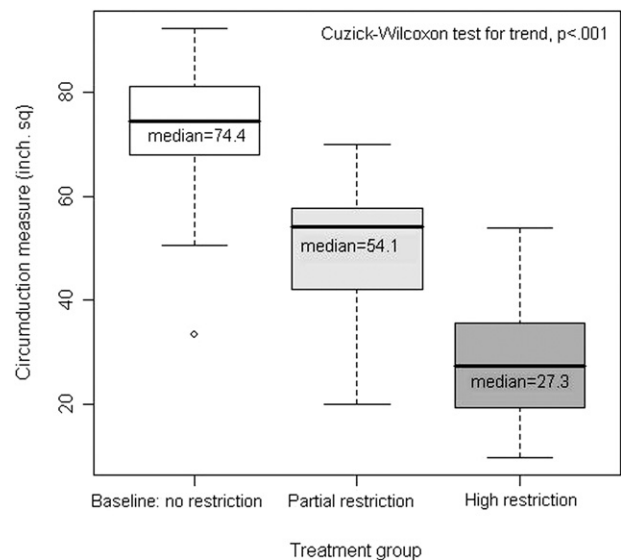
**TABLE 2. Correlation of Wrist Circumduction With Range of Motion Measurements**

Range of Motion	Correlation Coefficient*	
	Splint Volunteers (n = 42)	Hand Clinic Patients (n = 51)
Flexion	0.82	0.68
Extension	0.81	0.70
Ulnar deviation	0.77	0.70
Radial deviation	0.64	0.46
Theoretical circumduction†	0.80	0.77

\*All correlations were significant ( $p < .01$ ).  
†Theoretical circumduction is derived from the 4 range of motion measurements, as shown in Figure 2.

measurements) and from 0.46 to 0.70 ( $p < .01$ ) in the hand clinic subjects (51 patients, 102 measurements). In addition, correlation of the theoretical circumduction values with measured circumduction were 0.80 ( $p < .01$ ) in the splinted subjects and 0.77 ( $p < .01$ ) in the hand clinic subjects, a value higher than the correlation of circumduction with each individual ROM direction (Table 2).

Intraobserver and test-retest reliability results are shown for both investigators in Figure 4. The correlation between the first and second measurement for investigator A was 0.98 ( $p < .01$ ) and for investigator B was also 0.98 ( $p < .01$ ). The inter-rater reliability results are shown in Figure 5. The correlation between measurements by investigator A and by investigator B was 0.94 ( $p < .01$ ). These results are consistent with a

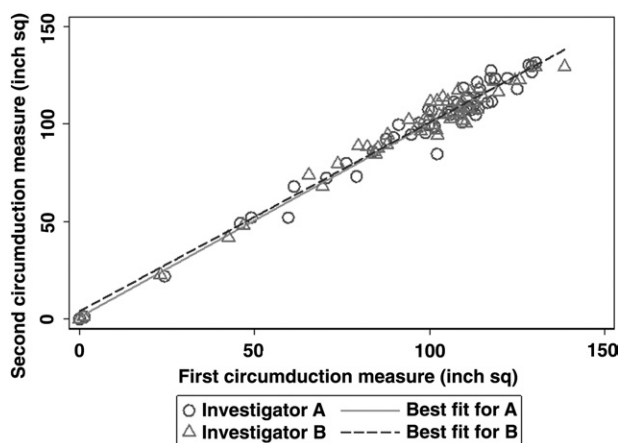


**FIGURE 3:** Evaluation of inter-rater reliability (consistency across investigators). The circumduction measures taken before the visit by investigator A are compared to the circumduction measures taken before the visit by investigator B on the same patient. Investigators were blinded, receiving no information about the other circumduction measure. The line of identity marks the relationship of perfect agreement, and short distance from the line reflects a high degree of inter-rater validity. The correlation between circumduction measures of investigator A and investigator B on the same patients was 0.94 ( $p < .001$ ).

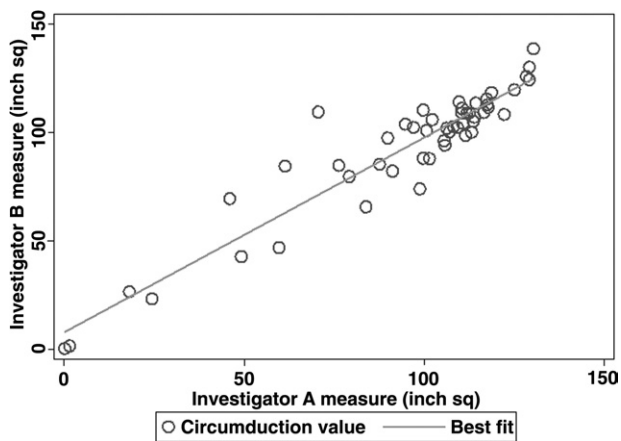
high degree of both validity and reliability for this new device.

## DISCUSSION

Standard uniplanar goniometry of the wrist is widely used to quantitatively assess objective ROM of the



**FIGURE 4:** Evaluation of construct validity by comparison of circumduction measures across 3 different circumstances, with decreasing wrist function: baseline with no restriction, partial restriction, and high restriction. Standard box-plot representation: the horizontal line represents the mean, boxes span the first and the third interquartile range (Q1–Q3), whiskers represent adjacent values, and the circle represents an outlier. Results show a significant downward trend across the groups ( $p < .001$ ), and all groups differ from each other statistically ( $t$ -test for each combination:  $p > .05$ ).



**FIGURE 5:** Evaluation of test–retest reliability (consistency over time). Circumduction measures taken immediately before the visit are compared to measures taken immediately after the visit for the same patient. Results are shown separately for investigator A (squares) and investigator B (circles), who took independent measures on the same patient. The line of identity marks the relationship of perfect agreement, and close distance to the line marks high degree of test–retest validity. The correlation between the first and the second measure for both investigators was 0.98 ( $p < .0001$ ).

wrist.<sup>12–15</sup> However, this technique for measuring wrist motion is limited by its ability to measure angles in only a single plane and only statically during either active or

passive motion. Furthermore, ROM is only measured along 2 axes (flexion–extension, radioulnar deviation), whereas the wrist can move in many different planes. Wrist function is a result of active, dynamic motion along those multiple axes. Since the late 1980s, newer techniques have been used to quantify more representative measures of wrist function, such as circumduction.

It has been recognized that not only total circumductive motion, but also the specific sector or region of motion limitation influences an individual’s functional outcome.<sup>16</sup> Newer devices, therefore, should be able to graphically represent the area of circumduction of a single wrist. The development of the electrogoniometer allowed researchers to accurately and reliably quantify the active, dynamic ROM and circumduction of the wrist during activity.<sup>17–20</sup> Furthermore, the size and weight of the electrogoniometer permit the device to be worn during activity without causing any functional impairment. The reliability and validity of electrogoniometric devices have been reported in several articles.<sup>3,19,21</sup> The system has been described as “inexpensive, portable, light, and comfortable” to wear,<sup>22</sup> but electrogoniometers are still not widely used in clinical practice as quantitative assessments of hand and wrist function. Potential reasons may include cost, availability, the space required for all components, and the requirement for a combination of measuring tools, electrical cables, computers, and printing devices to obtain outcomes. In addition, electrogoniometers have been subject to measurement error, particularly from electronic cross-talk—a problem stemming from both device design and the natural movement of the wrist.<sup>1</sup>

Although the electrogoniometer has the potential to supply clinicians with functional information about dynamic wrist motion, the lack of widespread use suggests the need for newer, and possibly simpler and less expensive designs for quantifying circumductive wrist motion.

Our jig device offers unique differences relative to electronic goniometry for assessment of circumductive motion in terms of portability, very low cost, reliability, simplicity, and rapid results. An important strength lies in its ability to produce immediate results, without the need for additional devices such as a computer or printer, for outcome reports. A notable limitation is the need for the patient to have a sufficient arc of motion at the 2nd and 3rd metacarpophalangeal joints and sufficient intrinsic muscle strength to adequately hold the pencil device. If these criteria are met, however, the patient simply draws his or her outcome, which can

then be visually compared to prior results for subjective and objective analysis of functional improvement.

The importance of direct visual comparison relates to the fact that a sector of motion limitation within the circumduction pathway may have a greater effect on function than the total circumduction area as a whole, depending on the location of the motion reduction.<sup>4,16</sup> Furthermore, use of the dorsal clamshell component helps restrict the wrist from pronating or supinating, which has been shown to affect motion capabilities in other directions and ensures a properly oriented image.<sup>2</sup> An additional benefit is that the wrist is positioned and measured in the position of pronation, in which it maintains its greatest ROM capabilities.<sup>23</sup> The wrist is also forced to function against a variable amount of resistance between the pencil and paper, adjustable by the length and strength of the recoil band. This allows the device to measure functional active motion of the wrist. Most importantly, the reliability outcomes described above demonstrate that measurements fall well within the range of acceptable values.<sup>10</sup>

Because the current version of this device uses standard paper as the writing surface and a pencil length of 21 cm, participants were sometimes able to circumduct the pencil off the limits of the page. Even with careful centering of the page to maximize area within the circle, some pieces of the circles were still lost from the page, most commonly in the ulnar and flexion positions. Although the 21-cm pencil length results in the occasional loss of measured area, this occurred only rarely in patients with normal ROM. However, the 21-cm length maximized the sensitivity of the device for patients with reduced wrist motion. Thus, a longer pencil length favors the patient population with restricted wrist motion. In addition, the loss of this area did not appear to affect the reliability or validity of this device, most likely because of the infrequent occurrence and the small fraction of the area lost relative to the total. Future solutions may include using a larger backboard and paper size, as well as shortening the distance from wrist crease to pencil tip.

The correlation results demonstrate that the circumduction jig accurately and reliably measures multiplanar circumductive motion unique from an individual ROM direction. Only patients without uniplanar motion restriction were included in the present study, allowing for criterion validity of our device by comparison to a theoretical circumduction. Although the high correlation between theoretical and actual circumduction suggests that similar results can be obtained without the need for this device, this is not necessarily true. First, pa-

tients wearing hinged wrist splints are inherently limited to uniplanar wrist motion despite retaining full motion within the axes of the hinges. Second, patients with muscle strength sufficient only to resist gravity could potentially have full ROM values when measured with a simple hand-held goniometer. The circumduction jig, which forces patients to overcome the friction between pencil and paper, provides a more reliable measure of functional motion. Lastly, the circumduction jig avoids potential sampling error inherent with using a mathematical equation to derive a single value from 4 independent measurements. Rather, a single measurement is made with a high degree of precision.

Our results indicate that the circumduction jig meets the basic criteria for validity (criterion and construct) and reliability (test–retest and inter-rater). As with any validation, however, the results also leave room for further validation studies. For example, our study did not measure metacarpophalangeal joint ROM, which can be used to evaluate discriminant criterion validity. To reduce the variability introduced through this type of motion, the patients in the study were instructed to grip the pencil holder firmly, a grip that reduces metacarpophalangeal joint movement by flexing the fingers and intrinsic muscles. Furthermore, both inter-rater and test–retest reliability can be evaluated in a different clinical setting (eg, nonacademic or community clinic) and in different patient populations (eg, in older patients).

Our device was designed to assess precise and accurate circumduction measurements in a clinical research setting. Its primary purpose is to allow fast and simple quantification of physiologic wrist arc for patient rehabilitation. In addition, we believe that maximal area values can provide objective measurements for research purposes as well, to be used as an additional ROM outcome for statistical comparisons between groups of patients. The high degree of precision inherent in this device makes it an ideal tool for clinical research studies. In addition, the ability to reliably measure multiplanar motion gives it potential clinical utility as a functional ROM evaluation tool in specific situations in which wrist motion is limited to a uniplanar axis.

The use of a standard uniplanar goniometer is unlikely to be replaced as the fastest and simplest way for measuring both passive and active wrist motion. Although we recognize that our new device may have limited practical clinical utility, our

purpose was to design a new research tool for measuring functional wrist motion in a variety of populations. Validation studies demonstrate criterion, construct, test–retest, and inter-rater reliability, suggesting that the new circumduction jig is an appropriate tool for this use.

## REFERENCES

1. Johnson PW, Jonsson P, Hagberg M. Comparison of measurement accuracy between two wrist goniometer systems during pronation and supination. *J Electromyogr Kinesiol* 2002;12:413–420.
2. Palmer AK, Werner FW, Murphy D, Glisson R. Functional wrist motion: a biomechanical study. *J Hand Surg* 1985;10A:39–46.
3. Rawes ML, Richardson JB, Dias JJ. A new technique for the assessment of wrist movement using a biaxial flexible electrogoniometer. *J Hand Surg* 1996;21B:600–603.
4. Salvia P, Woestyn L, David JH, Feipel V, Van S, Jan S, et al. Analysis of helical axes, pivot and envelope in active wrist circumduction. *Clin Biomech (Bristol, Avon)* 2000;15:103–111.
5. Goodwin J, Clark C, Deakes J, Burdon D, Lawrence C. Clinical methods of goniometry: a comparative study. *Disabil Rehabil* 1992;14:10–15.
6. Jonsson P, Johnson PW. Comparison of measurement accuracy between two types of wrist goniometer systems. *Appl Ergon* 2001;32:599–607.
7. McGill SM, Cholewicki J, Peach JP. Methodological considerations for using inductive sensors (3SPACE ISOTRAK) to monitor 3-D orthopaedic joint motion. *Clin Biomech (Bristol, Avon)* 1997;12:190–194.
8. De Vellis RF. Scale development: theory and applications. 2nd ed. *Applied Social Research Methods* 26. Thousand Oaks, CA: Sage, 2003.
9. Kocher MS, Zurakowski D. Clinical epidemiology and biostatistics: a primer for orthopaedic surgeons. *J Bone Joint Surg* 2004;86A:607–620.
10. Hulley SB, Martin JN, Cummings SR. Planning the measurements: precision and accuracy. In: Hulley SB, Cummings SR, Browner WS, Grady D, Hearst N, Newman TB, eds. *Designing clinical research*. 2nd ed. Philadelphia: Lippincott Williams & Wilkins, 2001:37–49.
11. Ebel RL. Estimation of the reliability of ratings. *Psychometrika* 1951;16:407–424.
12. Boone DC, Azen SP. Normal range of motion of joints in male subjects. *J Bone Joint Surg* 1979;61A:756–759.
13. Boone DC, Azen SP, Lin CM, Spence C, Baron C, Lee L. Reliability of goniometric measurements. *Phys Ther* 1978;58:1355–1390.
14. Hagberg M. The measurement of joint motion: part III. Reliability of goniometry. *Phys Ther Rev* 1949;29:302–307.
15. Solgaard S, Carlsen A, Kramhoft M, Petersen VS. Reproducibility of goniometry of the wrist. *Scand J Rehabil Med* 1986;18:5–7.
16. Nagy L, Büchler U. Long-term results of radioscapulohumeral fusion following fractures of the distal radius. *J Hand Surg* 1997;22B:705–710.
17. Minns RJ, Oliver RJ. A digital electrogoniometer for clinical use. *Clin Phys Physiol Meas* 1983;4:89–90.
18. Nicol AC. Measurement of joint motion. *Clin Rehabil* 1989;3:1–9.
19. Ojima H, Miyake S, Kumashiro M, Togami H, Suzuki K. Ranges of dynamic motion of the wrist in healthy young and middle-aged men. *Ergonomics* 1992;35:1467–1477.
20. Rowe PJ, Nicol AC, Kelly IG. Flexible goniometer computer system for the assessment of hip function. *Clin Biomech (Bristol, Avon)* 1989;4:68–72.
21. Ojima H, Miyake S, Kumashiro M, Togami H, Suzuki K. Dynamic analysis of wrist circumduction: a new application of the biaxial flexible electrogoniometer. *Clin Biomech (Bristol, Avon)* 1991;6:221–229.
22. Chang JH, Hsu HY, Su FC. Biomechanical measurement of painful wrist by flexible electro-goniometry. *J Med Biol Eng* 2005;25:33–37.
23. Li ZM, Kuxhaus L, Fisk JA, Christophel TH. Coupling between wrist flexion-extension and radial-ulnar deviation. *Clin Biomech (Bristol, Avon)* 2005;20:177–183.