



Contents lists available at ScienceDirect

Journal of Hand Surgery Global Online

journal homepage: www.JHSGO.org

Original Research

Dynamic Thumb Circumduction Measured With a Wearable Motion Sensor: A Prospective Comparison of Patients With Basal Joint Arthritis to Controls



Viviana M. Serra Lopez, MD, MS,^{*} Rikesh A. Gandhi, MD,^{*} David P. Falk, MD,^{*} Josh R. Baxter, PhD,^{*} John R. Lien, MD,[†] Benjamin L. Gray, MD, MSCE^{*}

^{*} Department of Orthopaedic Surgery, University of Pennsylvania, Philadelphia, PA

[†] South Main Orthopaedics, University of Michigan, Ann Arbor, MI

ARTICLE INFO

Article history:

Received for publication March 23, 2021

Accepted in revised form May 11, 2021

Available online June 4, 2021

Key words:

Motion sensor
Range of motion
Thumb CMC arthritis

Purpose: The purpose of this study was to compare the active range of motion in patients with thumb carpometacarpal (CMC) arthritis to healthy controls. A secondary objective of this study was to examine the feasibility of using wearable motion sensors in a clinical setting.

Methods: Asymptomatic controls and patients with radiographic and clinical evidence of thumb CMC joint arthritis were recruited. The experimental setup allowed participants to rest their forearm in neutral pronosupination with immobilization of the second through fifth CMC joints. An electromagnetic motion sensor was embedded into a thumb interphalangeal joint immobilizer, and participants were asked to complete continuous thumb circumduction movements. Data were continuously recorded, and circumduction curves were created based on degrees of motion. Peak thumb abduction and extension angles were also extracted from the data.

Results: A total of 29 extremities with thumb CMC arthritis and 18 asymptomatic extremities were analyzed. Bilateral disease was present in 64% of patients. Patient age range was 35–83 years, and the control group age range was 26–83 years. The most affected extremities had Eaton stage 3 disease (38%, N = 11). The average maximum thumb abduction was $53.9^\circ \pm 19.6^\circ$ in affected extremities and $70.8^\circ \pm 10.1^\circ$ for controls. Average maximum thumb extension was $50.0^\circ \pm 15.2^\circ$ in affected extremities and $58.4^\circ \pm 9.1^\circ$ for controls. When comparing patients with Eaton stage 3 and 4 disease to controls, average maximum abduction and extension decreased with increasing disease stage (42.3° , 46.1° , and 70.8° for abduction, respectively, and 58.4° , 43.3° , and 41.3° for extension, respectively).

Conclusions: We observed more severe motion limitations with increasing Eaton stage, and statistically significant differences were seen with stage 3 and 4 disease. A wearable motion sensor using a portable experimental setup was used to obtain measurements in a clinical setting.

Type of study/level of evidence: Diagnostic II.

Copyright © 2021, THE AUTHORS. Published by Elsevier Inc. on behalf of The American Society for Surgery of the Hand. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Pain and stiffness from osteoarthritis of the thumb carpometacarpal (CMC) joint limit hand function during activities of daily living. One of the most common types of osteoarthritis, thumb CMC

Declaration of interests: No benefits in any form have been received or will be received related directly or indirectly to the subject of this article.

Corresponding author: Viviana M. Serra Lopez, MD, MS, Department of Orthopaedic Surgery, University of Pennsylvania, 3737 Market St, 6th Floor, Philadelphia, PA 19104.

E-mail address: viviana.serralopez@pennmedicine.upenn.edu (V.M. Serra Lopez).

<https://doi.org/10.1016/j.jhsg.2021.05.002>

2589-5141/Copyright © 2021, THE AUTHORS. Published by Elsevier Inc. on behalf of The American Society for Surgery of the Hand. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

arthritis has a radiographic prevalence ranging from 14% to 36% in patients over the age of 55, with greater radiographic joint destruction in women compared to men.^{1,2} Previous studies have shown that thumb CMC arthritis can lead to significant decreases in thumb extension, adduction, and pronosupination.³

Evaluating dynamic thumb circumduction in the clinical setting remains a challenge. Typically, thumb CMC mobility is measured using standard goniometry to monitor functional status and disease progression. These static range of motion (ROM) measurements occur in 2 planes: flexion-extension and abduction-adduction. However, the use of goniometry may be affected by both patient

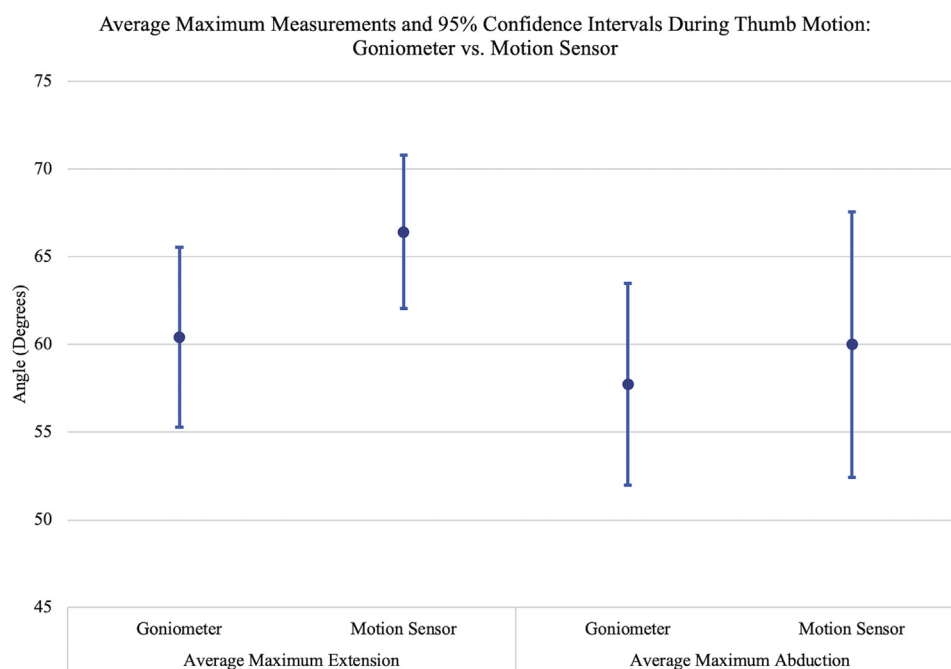


Figure 1. Average maximum thumb flexion and abduction across 3 trials of 4 asymptomatic extremities are shown, measured with standard goniometry and the electromagnetic motion sensor using the experimental setup. Bars demonstrate the 95% confidence interval for each measurement.

factors, such as edema or joint deviation, and interobserver measurement variability.^{4,5} In addition, the saddle-shaped configuration of the first CMC joint also allows for circumduction, which allows the thumb to perform multiplanar movements. Advanced imaging techniques such as computed tomography can quantify multiplanar thumb kinematics; however, these approaches cannot practically be implemented into clinical care.^{6–8} Thumb circumduction has also been described with the use of motion sensors in both patients with thumb CMC arthritis and healthy volunteers.^{3,9} However, the application of wearable sensors in the clinical setting is not well documented.

The purpose of this study was to describe the effects of thumb CMC arthritis on motion using a wearable motion sensor and to determine the feasibility of using a wearable motion sensor as a tool in the clinical setting. We hypothesized that thumb CMC arthritis would limit the dynamic ROM in patients with advanced disease. Specifically, we hypothesized that thumb circumduction would be increasingly limited with increasing disease severity.

Materials and Methods

Pilot testing

Pilot testing was performed to test the feasibility of implementing the use of the motion sensor. We compared the motion sensor measurements to manual goniometry, the clinical gold standard.¹⁰ The maximum extension and abduction angles were recorded in 4 healthy extremities with both goniometry and the previously described experimental setup by the same surgeon. Analysis of the data showed an overlap of the 95% confidence intervals (Fig. 1).

Participant selection

This study was performed in an outpatient clinic setting at an urban academic center. After institutional board review approval,

patients with radiographic and clinical evidence of thumb CMC joint arthritis were enrolled after written informed consent was obtained. Clinical evidence of thumb CMC joint arthritis was initially established by patient history, namely difficulty with pinch and grip activities, and pain at the base of the thumb. Diagnosis of thumb CMC arthritis was then confirmed with a physical examination via a positive grind test and tenderness with direct palpation over the trapeziometacarpal joint. We obtained baseline data from all participants, including age, hand dominance, and previous treatments for thumb CMC arthritis. To test our hypothesis that the disease severity explained the amount of thumb disability, we enrolled patients with varying severity of thumb CMC osteoarthritis. We characterized the disease stage using the grading scale developed by Eaton and Littler.¹¹ Participants with bilateral hand involvement were included in the study population, with each hand recorded as a separate entry. Exclusion criteria included any surgical management for first CMC joint arthritis. Controls were recruited from the outpatient clinic setting and were healthy individuals with no symptoms of thumb CMC arthritis. Criteria included a negative history of pain at the base of the thumb and no tenderness to palpation or discomfort with ROM on examination. Radiographs were not routinely obtained for controls unless they were clinically indicated for another condition. Individuals who had no symptoms of thumb CMC arthritis on the contralateral hand were eligible to participate as controls.

Experimental setup

We developed a portable, tabletop experimental setup to measure thumb CMC motion in a clinical setting (Fig. 2). We used an electromagnetic motion tracking system (PATRIOT, Polhemus) that robustly characterized the absolute position and orientations to an accuracy of 1.52 mm and 0.40°. Because this electromagnetic motion sensor was affected by metallic objects, we built the positioning jig out of polyvinyl chloride sheeting. The jig positioned the individual's elbow in neutral pronosupination and immobilized the

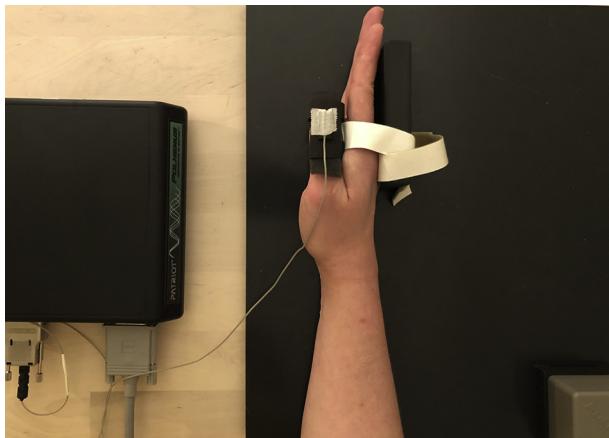


Figure 2. Top view of the experimental setup is shown with the hand in the starting position, defined as 0° of abduction and extension. The motion sensor is embedded into a thumb interphalangeal joint immobilizer. This is connected to the electromagnetic motion sensor system, shown in the right lower corner of the image, which generates the electromagnetic field. The system's electronic unit is shown in the left side of the image and interfaces with the host computer to calculate position and orientation.

Table 1
Characteristics of Participants and Controls

Characteristic	Participants	Controls
Number of participants	19	12
Median age (range)*	65 (35–83)	65 (26–83)
Female sex, percentage*	68%, N = 13	75%, N = 9
Number of extremities	29	18
Eaton classification (N = 29)†		
Stage 1	10.3%, N = 3	
Stage 2	31.0%, N = 9	
Stage 3	37.9%, N = 11	
Stage 4	20.7%, N = 6	
Previous treatments (N = 29)		
Bracing	46%	
CMC joint corticosteroid injection	29%	
Hand therapy	7%	

* Sex and age are shown for the individual study participants.
† Eaton classification stage is shown for the number of extremities tested.

second through fifth carpometacarpal joints using plastic support and a Velcro strap around the palm. The design allowed for testing both the right and the left hand without requiring adjustment of the experimental setup. We embedded the motion sensor into a thumb interphalangeal joint immobilizer that was designed and custom-printed for this study (Fig. 2). During pilot testing and development, we designed the sensor housing to align with 0° of abduction and 0° of extension at the beginning of each trial while the hand was placed in a neutral position, as shown in Figure 2. Once the hand was placed into what we visually verified to be a neutral position, data recording was started, and that position set the reference for 0° of abduction and 0° of extension. We defined flexion-extension as motion in a vertical plane and abduction-adduction as motion in a horizontal plane. By visually confirming that the hand did not move during data collection, we characterized thumb CMC motion as the absolute rotations in the vertical and horizontal planes of the motion tracking system.

Patients were asked to complete 5 continuous thumb circumduction movements, starting from the previously described position. These were performed in a clockwise direction for the right hand and a counterclockwise direction for the left. During each circumduction movement, we continuously recorded motion data using a custom-developed interface (LabVIEW, National Instruments).

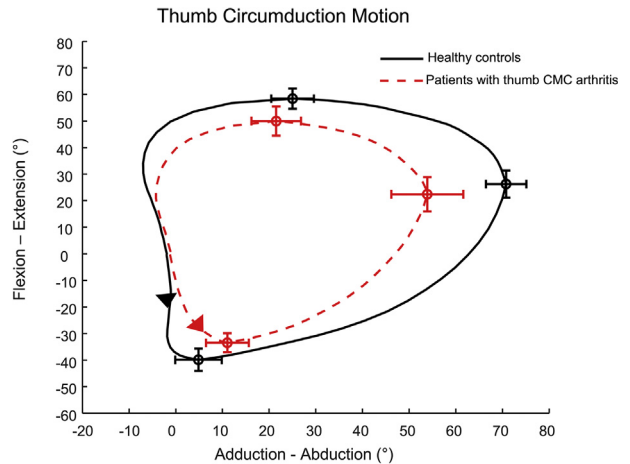


Figure 3. Circumduction curves for patients and controls. Arrowheads show the direction of motion during the trials. Error bars are shown at the value for average maximum abduction, extension, and flexion, demonstrating the 95% CI. Flexion is represented by negative numbers in the y axis.

From these data, we calculated circumduction curves based on degrees of motion, and we extracted measurements of peak thumb abduction, extension, and flexion angles. All testing was performed by 1 investigator who was not blinded to the participant's status.

Data analysis

We compared thumb motion between the control group and patient cohorts to test our hypothesis that thumb CMC arthritis would limit the dynamic ROM in patients with advanced thumb disease. First, we used one-way *t* tests to determine if patients with CMC arthritis had reduced thumb abduction, flexion, and extension compared to the control cohort. We then calculated the area inside the circumduction curve that we defined as the adduction-abduction (x axis) and flexion-extension (y axis) profiles. While this “circumduction area” had units with no direct clinical meaning (degrees squared), we calculated the percentage change in total circumduction area as a surrogate measure of thumb mobility. During the initial analysis, we found that the peak thumb abduction, flexion, and extension values occurred at different instances of the circumduction movement. Therefore, we resampled circumduction data so these peak thumb angles would align. We applied a Bonferroni correction to account for multiple comparisons ($\alpha = 0.05 / n$). *P* values less than or equal to .05 were considered significant. Data analysis was performed by a separate investigator who was not blinded to the participant status as control or patient. A priori power analysis indicated that 16 participants and controls would provide 80% power to detect a difference of 15° in the mean maximum ROM between groups.

Results

A total of 19 participants were enrolled with varying severities of thumb CMC osteoarthritis for a total of 29 affected thumbs. Most of the extremities tested had Eaton stage 3 disease (N = 11). The majority of the participants were women (68%), and the average age was 65 years (range, 35–83 years). A total of 18 extremities served as controls from 12 individuals, and the average age was 65 years (range, 26–83 years). Table 1 summarizes the characteristics of the controls and participants.

Circumduction curves for patients with thumb CMC arthritis and controls are shown in Figure 3. Patients with thumb CMC

Table 2
Average Maximum Thumb Abduction, Extension, and Flexion in Extremities With Thumb CMC Joint Arthritis and Controls Across Trials

Group Tested	Average Maximum Abduction, Degrees (SD)	<i>P</i> value*	Average Maximum Extension, Degrees (SD)	<i>P</i> value*	Average Maximum Flexion, Degrees (SD)	<i>P</i> value*
Controls	70.8 (10.1)	-	58.4 (9.1)	-	39.9 (8.7)	-
Affected extremities	53.9 (19.6)	.001	50.0 (15.2)	.019	33.5 (11.1)	.978
Eaton stage 1	67.2 (22.1)	.321	62.5 (9.2)	.759	43.8 (4.2)	.233
Eaton stage 2	68.8 (15.1)	.344	59.7 (12.4)	.617	33.8 (11.0)	.935
Eaton stage 3	42.3 (14.6)	<.001	43.3 (14.3)	.001	29.0 (11.1)	.997
Eaton stage 4	46.1 (17.0)	<.001	41.3 (12.6)	.001	36.1 (11.4)	.801

* Listed *P* values are in comparison to the control group. For this reason, a *P* value is not reported in the "Controls" row.

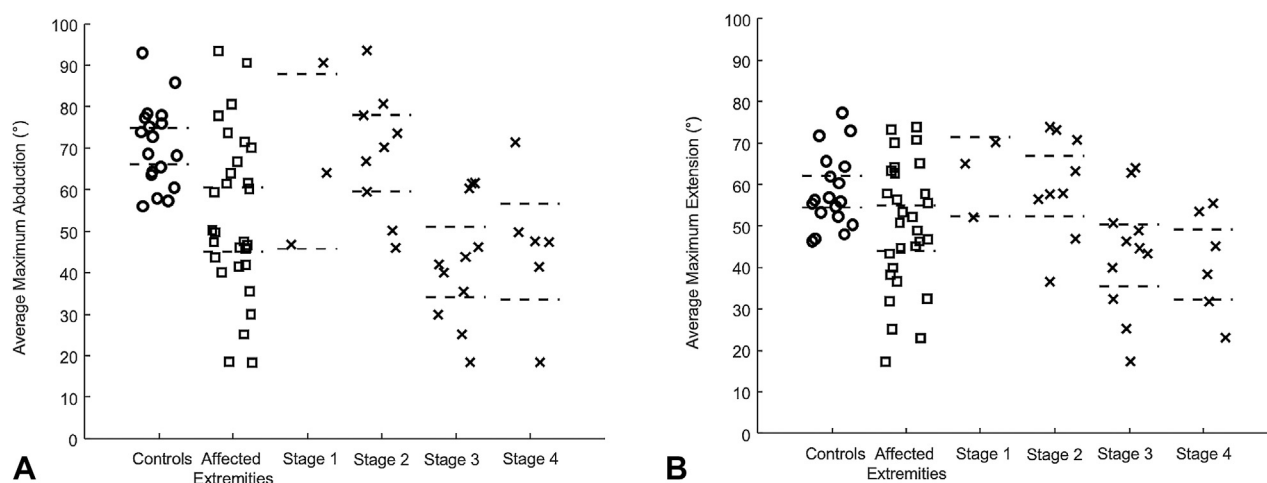


Figure 4. Scatter plots showing average maximum values for **A** abduction and **B** extension in degrees. 95% confidence intervals are indicated by dashed horizontal lines. Eaton stages are shown on the x axis.

arthritis were found to have a reduction in their circumduction envelope by 36% ($P < .001$) when compared with controls.

When stratified by the Eaton stage, we found that with increasing severity of the disease, patients generally lost increasing amounts of ROM (Table 2). The average maximum abduction angles in controls were 70.8°, compared with 67.2° in extremities with Eaton stage 1 disease (5.0% decrease). Extremities with stage 4 disease had an average maximum abduction of 46.1°, or a 29.3% decrease compared with controls. While no difference was seen when comparing controls to patients with Eaton stage 1 and 2 disease, a significant difference was obtained in participants with Eaton stage 3 and 4 disease for abduction and extension. No significant difference was noted between controls and participants when comparing flexion. Figure 4 shows scatter plots of the data presented in Table 2 for abduction and extension.

Table 3 shows the difference between mean maximum thumb abduction and mean maximum thumb extension when comparing extremities with thumb CMC arthritis to controls. Overall, all affected extremities had a decrease in abduction of 16.9° when compared with controls and a decrease in extension of 8.4° when compared with controls.

Discussion

Because of the unique anatomy of the thumb CMC joint, assessment of global thumb motion remains a difficult task in the clinical setting.¹² Goniometry is often used as an outcome measure because of its ease of access. However, its use in measuring thumb ROM in patients with thumb CMC arthritis has shown variable inter-rater reliability.⁴ The use of a motion sensor mitigates this type of error, especially since patients may not be seen by the same

provider during follow-up. While electromagnetic sensors have been used as educational tools for monitoring the improvement of skills of surgeons and emergency department providers, they may also have a role in monitoring functional limitations associated with the progression of arthritic disease in patients.^{13,14} Since degenerative changes seen in thumb CMC arthritis are thought to arise from incompetent ligaments that typically provide stability during motion, dynamic assessments are preferred to evaluate ROM of the thumb CMC joint.⁶ Our study demonstrates that measuring dynamic thumb ROM in an outpatient setting is practical when using a motion sensor with a desktop arrangement. This device is portable and can sit on any flat surface. The sensor is commercially available, and the setup can be designed with easily available materials. A software interface can also be designed to collect data and output specific values, thus making the necessary measurements immediately available to the clinician. Performing the measurements takes less than 5 minutes and can be done by any trained office personnel. All of these reasons make this a feasible arrangement that can be incorporated into a clinical setting.

Our findings also allow us to better understand the functional limitations in patients with arthritis at different stages of disease severity. We observed more severe motion limitations with increasing Eaton stage, with the greatest limitations seen with stage 3 and 4 disease. The prevalence of basal thumb pain has been associated with a higher Eaton stage, thus it is expected that worsening disease leads to increased limitations in ROM.¹⁵ We found that reduced abduction motion was more pronounced than losses in thumb extension. The thumb CMC joint is placed in a position of abduction-flexion during palmar pinch and abduction-extension during grasp.¹⁶ Therefore, we expect these differences

Table 3
Mean Difference in Maximum Thumb Abduction and Extension in Extremities With Thumb CMC Joint Arthritis Compared to Controls Across Trials

Group Tested	Difference in Abduction Compared to Controls, Degrees (95% Confidence Interval)	Difference in Extension Compared to Controls, Degrees (95% Confidence Interval)
Affected extremities	16.9 (12.6–21.2)	8.4 (4.9–11.9)
Eaton stage 3	28.5 (25.0–32.0)	15.1 (11.8–18.4)
Eaton stage 4	24.7 (20.8–28.6)	17.1 (14.1–20.1)

seen in our patient population to negatively affect tasks such as picking up cylindrical or spherical objects.

Previous studies have examined the ROM of the thumb of healthy volunteers and patients with thumb CMC arthritis. These have been performed using multiple skin surface markers and different reference points.^{3,9,17,18} Using a reference axis of the thumb metacarpal, Cooney et al¹⁷ measured median arcs of 53° in flexion-extension and 42° in abduction-adduction during functional ROM in healthy volunteers. During circumduction, Gehrman et al³ found a ROM of 59° in flexion-extension and 63° in abduction-adduction. An earlier study by Chèze et al⁹ reported an average of 70° of flexion-extension and 41° in abduction-adduction during a thumb circumduction movement. In comparison, we found ROM of 98.3° in flexion-extension and 77.8° in abduction-adduction. The variability in measurements could be explained by the different measurement systems, the number of sensors, and the reference points used.

When comparing the envelopes of the circumduction plots, participants had smaller circumduction envelopes when compared with controls. This is in agreement with data reported by Gehrman et al,³ who found that the area of the circumduction envelope in patients with Eaton stage 3 and 4 thumb CMC arthritis was 49% when compared with controls.

This study has multiple strengths. Range of motion is evaluated across all Eaton stages, which allows for greater comparison and overall generalizability. In addition, the testing conditions are uniform throughout the study with the same investigator instructing patients in the motions to be performed and collecting data. While immobilizing the thumb interphalangeal joint could account for the differences seen in our measurements compared to other studies, it also allows us to decrease variability in angle measurements that may have resulted from flexion or hyperextension of the interphalangeal joint, as seen in previous studies examining thumb motion.¹⁹

This study has several limitations that should be considered. Despite a negative history and physical examination, controls do not undergo a radiographic evaluation of the thumb CMC joint to confirm that there are no degenerative changes. Additionally, it is important to note that we derive the thumb position relative to the established coordinate system, therefore motion at the thumb CMC is not directly measured. However, by characterizing thumb motion as the relationship of the tip of the thumb with respect to the hand, our approach is highly relevant to activities of daily living. Additionally, we do not quantify thumb pronosupination in our study. Another limitation of this study is that the thumb metacarpophalangeal (MCP) joint was not immobilized. Previous studies have shown that the thumb MCP joint can contribute up to 10° of extension during activities of daily living; however, baseline values of MCP joint motion are not obtained to correct for this.²⁰

We have shown that with a desktop electromagnetic motion sensor we can identify ROM differences in patients with thumb CMC arthritis compared with controls. The ability to obtain and monitor dynamic thumb ROM in an efficient manner can provide an objective measurement of disease progression. This allows for standardization of measurements across observers in the clinical

research setting as well. Finally, a tool like this can be used to quantify thumb motion before and after surgical intervention given the variety of surgical options for management of thumb CMC arthritis.

Acknowledgments

This work was supported by a Fast Track Grant from the American Foundation for Surgery of the Hand.

References

- Sodha S, Ring D, Zurakowski D, Jupiter JB. Prevalence of osteoarthritis of the trapeziometacarpal joint. *J Bone Joint Surg Am.* 2005;87(12):2614–2618.
- Wilder FV, Barrett JP, Farina EJ. Joint-specific prevalence of osteoarthritis of the hand. *Osteoarthritis Cartilage.* 2006;14(9):953–957.
- Gehrman SV, Tang J, Li ZM, Goitz RJ, Windolf J, Kaufmann RA. Motion deficit of the thumb in CMC joint arthritis. *J Hand Surg Am.* 2010;35(9):1449–1453.
- Jha B, Ross M, Reeves SW, Couzens GB, Peters SE. Measuring thumb range of motion in first carpometacarpal joint arthritis: the inter-rater reliability of the Kapandji Index versus goniometry. *Hand Ther.* 2016;21(2):45–53.
- van Kooij YE, Fink A, Nijhuis-van der Sanden MW, Speksnijder CM. The reliability and measurement error of protractor-based goniometry of the fingers: a systematic review. *J Hand Ther.* 2017;30(4):457–467.
- Goto A, Leng S, Sugamoto K, Cooney WP, Kakar S, Zhao K. In vivo pilot study evaluating the thumb carpometacarpal joint during circumduction. *Clin Orthop Relat Res.* 2014;472(4):1106–1113.
- Kimura T, Takai H, Azuma T, Sairyo K. Motion analysis of the trapeziometacarpal joint using three-dimensional computed tomography. *J Hand Surg Asian Pac Vol.* 2016;21(1):78–84.
- Kawanishi Y, Oka K, Tanaka H, Okada K, Sugamoto K, Murase T. In vivo 3-dimensional kinematics of thumb carpometacarpal joint during thumb opposition. *J Hand Surg Am.* 2018;43(2):182.e1–182.e7.
- Chèze L, Doriot N, Eckert M, Rumelhart C, Comtet JJ. In vivo cinematic study of the trapezometacarpal joint. *Chir Main.* 2001;20(1):23–30.
- Ellis B, Bruton A, Goddard JR. Joint angle measurement: a comparative study of the reliability of goniometry and wire tracing for the hand. *Clin Rehabil.* 1997;11(4):314–320.
- Eaton RG, Lane LB, Littler JW, Keyser JJ. Ligament reconstruction for the painful thumb carpometacarpal joint: a long-term assessment. *J Hand Surg Am.* 1984;9(5):692–699.
- Curran PF, Bagley AM, Sison-Williamson M, James MA. Three-dimensional functional workspace of thumb prehension. *Clin Biomech (Bristol, Avon).* 2019;63:63–72.
- Clinkard D, Holden M, Ungi T, et al. The development and validation of hand motion analysis to evaluate competency in central line catheterization. *Acad Emerg Med.* 2015;22(2):212–218.
- Genovese B, Yin S, Sareh S, et al. Surgical hand tracking in open surgery using a versatile motion sensing system: are we there yet? *Am Surg.* 2016;82(10):872–875.
- Armstrong AL, Hunter JB, Davis TRC. The prevalence of degenerative arthritis of the base of the thumb in post-menopausal women. *J Hand Surg Br.* 1994;19(3):340–341.
- Cooney WP III, Chao EYS. Biomechanical analysis of static forces in the thumb during hand function. *J Bone Joint Surg Am.* 1977;59(1):27–36.
- Cooney WP III, Lucca MJ, Chao EY, Linscheid RL. The kinesiology of the thumb trapeziometacarpal joint. *J Bone Joint Surg Am.* 1981;63(9):1371–1381.
- Luker KR, Aguinaldo A, Kenney D, Cahill-Rowley K, Ladd AL. Functional task kinematics of the thumb carpometacarpal joint. *Clin Orthop Relat Res.* 2014;472(4):1123–1129.
- 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(11):1499–1506.
- Murai T, Uchiyama S, Nakamura K, Ido Y, Hata Y, Kato H. Functional range of motion in the metacarpophalangeal joints of the hand measured by single axis electric goniometers. *J Orthop Sci.* 2018;23(3):504–510.