SCIENTIFIC ARTICLE

The Effect of Thumb Metacarpophalangeal Hyperextension on Thumb Axial Load and Lateral Pinch Force in a Cadaver Model of Thumb Trapeziectomy and Flexor Carpi Radialis Suspensionplasty

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Purpose The purpose of our study was to investigate, in a cadaver model, the effect of increasing thumb metacarpophalangeal (MCP) joint hyperextension on thumb axial load and key pinch force after thumb trapeziectomy and flexor carpi radialis suspensionplasty. We developed a cadaveric model to test whether thumb MCP joint hyperextension after trapeziectomy would have a negative effect on key pinch force and increase loads across a reconstructed thumb carpometacarpal (CMC) joint.

Methods We created a cadaveric biomechanical model that varied thumb MCP joint hyperextension while measuring thumb CMC axial and key pinch force under standardized loads. Direct observations were made of how key pinch and axial thumb CMC force change with increasing thumb MCP joint hyperextension. We measured the thumb key pinch force and axial thumb CMC joint load with the thumb MCP joint in 0°, 10°, 20°, 30°, 40°, 50°, and 60° of hyperextension.

Results There was a 0.88 N (2.4%) increase in axial force across the thumb CMC per every 10° of increasing thumb MCP joint hyperextension. We found a 0.53 N (4.4%) reduction in key pinch force for every 10° of increasing thumb MCP joint hyperextension. Therefore, at 60° of thumb MCP joint hyperextension, the axial force across the thumb CMC increased by 5.3 N (14.6%) and the key pinch force was weakened by 3.2 N (26.6%).

Conclusions With progressive thumb MCP joint hyperextension after thumb CMC arthroplasty, we found a decrease in key pinch force and an increase in axial thumb CMC joint force. The decrease in key pinch force was larger than the relatively small increase in thumb CMC force.

Clinical relevance This study helps elucidate the biomechanics of the thumb CMC joint after resection arthroplasty with thumb MCP joint hyperextension and helps understand the interplay between these 2 conditions. *(J Hand Surg Am. 2022;■(■):1.e1-e7. Copyright © 2022 by the American Society for Surgery of the Hand. All rights reserved.)*

Key words Carpometacarpal osteoarthritis, CMC resection arthroplasty, metacarpophalangeal joint hyperextension, MCP joint fusion, thumb arthritis.

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CURRENT LITERATURE ON THE treatment of thumb metacarpophalangeal (MCP) joint hyperextension in patients with thumb carpometacarpal (CMC) joint osteoarthritis has demonstrated conflicting results. Specifically, the threshold for when adjunctive thumb MCP joint stabilization procedures should be considered in conjunction with thumb CMC resection arthroplasty is not well defined in the literature. Many publications are limited to small case series and technique articles.[1–4] As a result of the limited evidence and guidance in the literature, many surgeons often rely on anecdotal experience to make decisions about the treatment of thumb MCP joint hyperextension.[5,6] However, the decision to operate on a thumb MCP joint should be individualized and is never based on a single radiographic measurement.

Moineau et al[7] reported that untreated MCP hyperextension of 26° contributed to postoperative weakness, worse radiographic outcomes, and worse hand function following thumb CMC arthroplasty. Poulter et al[8] found that in patients with MCP hyperextension <30°, there was no difference in outcomes between patients who did and did not have surgical correction of their MCP hyperextension; this finding was also reported by Brogan et al.[9] However, Pilato et al[10] also found that hyperextension >20° after surgery following thumb CMC arthroplasty was associated with worse functional outcomes. Additionally, Yoshida et al[11] found that healthy asymptomatic patient volunteers had an average MCP joint hyperextension of 35°.

Our goal was to expand the understanding of how thumb MCP joint hyperextension has an impact on the biomechanics of the reconstructed thumb after resection arthroplasty and flexor carpi radialis (FCR) suspensionplasty. We investigated this using a cadaveric biomechanical model.

Given previous reports in the literature using pooled clinical data that show decreased pinch strength and diminished postoperative patient satisfaction scores with significant thumb MCP joint hyperextension, we wanted to determine whether there is an observable underlying biomechanical cause that could help explain these clinical findings.[5] To our knowledge, this has not been studied in the laboratory before.

MATERIALS AND METHODS

Specimen preparation

We used 8 fresh-frozen cadaveric hand-to-midforearm specimens for this study. We began with 10 specimens per our budget and used 2 for testing setup and preparation. The specimens were all left side and included 6 men and 2 women with an average age of 62 years (range, 40−80 years). Each specimen was inspected radiographically prior to experimentation to ensure there was no notable thumb or wrist arthritis or other deformities. Each specimen was thawed at room temperature for approximately 24 hours before experimental manipulation and underwent a single freeze/thaw cycle prior to experimentation. A standard dorsal approach to the thumb CMC joint was used through the interval between the abductor pollicis longus and extensor pollicis brevis tendons. A longitudinal capsulotomy was made, capsular flaps elevated, and the trapezium removed in one piece with a McGlamry elevator.

The entire FCR tendon was transected proximally and pulled through the dorsal thumb CMC approach. The tendon sheath was fully released to the base of the index finger metacarpal. A heavy nonabsorbable suture was passed 3 times through the FCR tendon using running locking Krackow sutures (Fig. 1). The appropriate level for the exit point of these sutures was determined by reducing the thumb metacarpal in the appropriate position and draping the FCR tendon over the base of the thumb metacarpal. This allowed determining where the sutures should enter and exit the FCR tendon and enter and exit the base of the thumb metacarpal. The suture was then passed through the base of the thumb metacarpal using a heavy needle, first in a proximal to distal and then in a distal to proximal direction. The suture was then passed back a second time through the FCR tendon. This suture was then tied tightly while holding the thumb metacarpal reduced. The remainder of the FCR tendon was trimmed and discarded. This completed suspensionplasty of the thumb metacarpal at the thumb CMC joint. Although this is not the way in which a classic ligament reconstruction and tendon interposition is performed, the technique described above was used because this is how multiple senior authors at our institution perform this procedure.

A threaded Steinmann pin was then placed through the capitate, and a second pin through the radioulnar interosseous space at the proximal portion of the specimen. These 2 pins secured the specimen to the testing jig (Figs. 2, 3). Weights were then attached to the flexor pollicis longus, abductor pollicis longus, extensor pollicis brevis, extensor pollicis longus, abductor pollicis brevis), and flexor pollicis brevis (FPB) tendons. To reproduce the anatomic pull of the adductor pollicis, a long suture was routed

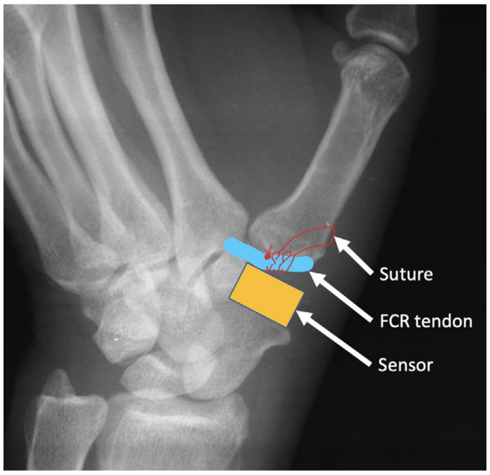

FIGURE 1: Schematic of how the FCR ligament reconstruction (FCR tendon is shown in blue) is attached to the base of the thumb metacarpal with a suture (shown in red) was configured, and how the CMC force sensor (orange rectangle and labelled as "Sensor") fits into the thumb CMC joint.

beginning dorsally between the third and fourth metacarpal and then overlying the volar surface of the transverse head of the adductor pollicis and finally attaching to the adductor pollicis insertion into the lateral aspect of the thumb proximal phalanx. Force contributions from the opponens pollicis muscle were not individually included; as in previous studies, its contribution was combined with the FPB.[12,13]

To enable adequate thumb MCP joint passive hyperextension, the volar plate was released off the thumb distal metacarpal. Where needed, a portion of the thumb MCP joint accessory collateral ligaments were also released. An external fixator was also placed on the radial side of the thumb metacarpal and proximal phalanx, spanning the MCP joint, taking care not to tether any structures with the pins (Fig. 3). Thumb MCP joint hyperextension was set manually, measured with a goniometer, and the external fixator tightened.

Sensor setup and tendon loading

Two force sensors (FlexiForce, Tekscan) were then added to the testing construct. One sensor was inserted between the distal pole of the scaphoid and the base of the thumb metacarpal. The sensor took the place of the excised trapezium, preventing the base of the first metacarpal from subsiding all the way to the distal pole of the scaphoid (Fig. 1). This attempted to recreate the position of the first metacarpal relative to the scaphoid in the setting after thumb CMC reconstruction such that the biomechanics would be representative of this healed state. In some specimens, 1 or 2 k-wires were inserted into the base of the index metacarpal to stabilize the sensor and maintain it in an appropriate position. This thumb CMC sensor allowed the measurement of a purely axial compressive force at the base of the thumb metacarpal.

A second sensor was inserted between the pulp of the thumb and a metal support that served as a surrogate for the radial side of the middle phalanx of the index finger (Figs. 3, 4). During early prototype testing, we attempted to position the sensor between the thumb and index finger but found it to be unstable in some cases. To minimize variability in testing between specimens, the metal bracket was positioned to act as a surrogate for the index finger and provided consistent testing conditions. This allowed measuring lateral thumb key pinch force.

We used a data acquisition system (FlexiForce ELF, Tekscan). A force sensor (FlexiForce B201, Tekscan, Norwood, Massachusetts) with a low load range (0−111N) was used for key pinch force, and a B201 sensor with a medium load range (0−667N) was used for the axial thumb CMC joint force (Fig. 4). These sensors were selected to provide enough range to prevent saturation at the high end of the measurement, but without compromising resolution. A custom 3D printed housing was designed (Autodesk Fusion 360, v 2.0.10148) and an stereolithography (STL) file was created (Slic3r v1.3 software) and printed (FlashForge Creator Pro) out of polylactic acid to ensure the sensor was loaded in a purely axial fashion. This allowed all the force to be transmitted through the sensor without bypassing it and causing data loss (Fig. 5).

Based on previously published studies and available literature, specific weights were hung off each tendon to produce a net 9.81 N of key pinch force.[12−14] These weights are summarized in Table 1. The weights were kept the same for each cadaver; this provided a consistent tendon force between specimens.

Data acquisition

We directly measured key pinch force and axial thumb CMC force using the sensors as the thumb MCP joint was progressively hyperextended from 0° to 60° in 10° increments. These 2 force values were obtained at 0° of thumb MCP joint hyperextension, then at 10° of thumb MCP joint hyperextension, and so on until 60°. This provided us with 7 sets of force data per cadaver.

RESULTS

We observed that as thumb MCP joint hyperextension increased, the axial force across the thumb CMC joint slowly increased (Fig. 6). We noted a 0.88 N

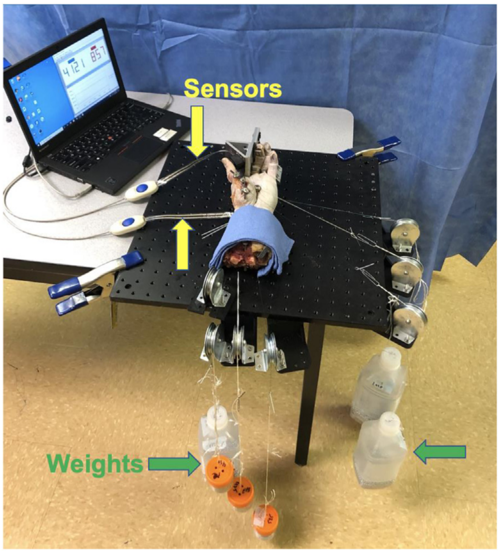

FIGURE 2: Overview of our testing setup, including a cadaveric hand and distal forearm specimen with weights attached to the tendons, sensors (as shown by yellow arrows), hanging weights (as shown by green arrows), and a laptop for data collection.

(2.4%) increase in axial force across the thumb CMC per every 10° of thumb MCP joint hyperextension. This is equivalent to a 5.33 N (95% confidence interval [CI], 5.21-5.46 N) (14.6% [95% CI, 12.3% to 17.0%]) increase in axial force across the thumb CMC as the thumb MCP joint hyperextension increased from 0° to 60°.

Additionally, we noted that the lateral thumb-to-index finger pinch force decreased as thumb MCP joint hyperextension increased (Fig. 7). Lateral pinch force decreased by 0.53 N (4.4%) for every 10° of thumb MCP joint hyperextension. This is equivalent to a 3.19 N (95% CI, 2.99-3.38 N) (26.6% [95% CI, 20.5% to 32.9%]) decrease in key pinch force when thumb MCP joint hyperextension increases from 0° to 60°.

DISCUSSION

We found that with increasing thumb MCP joint hyperextension, less force is transmitted to the pinch, and more is transmitted to the thumb CMC joint. Specifically, we found a 5.33 N (14.6%) increase in thumb CMC axial force as the thumb MCP joint hyperextension is increased from 0° to 60°. We also found a 3.19 N (26.6%) decrease in key pinch force when thumb MCP joint hyperextension increases from 0° to 60°. These percentages may seem notable, but the absolute force changes are small. It is unclear whether these smaller changes in CMC and pinch force would translate to a clinical effect.

If our findings translate to the clinical environment, then the reconstructed thumb with MCP joint hyperextension may be prone to lower pinch when compared to one without thumb MCP joint hyperextension. Although we found lower pinch and higher CMC forces, this may have some clinical impact on some at-risk patients (eg, weaker before surgery), but no impact on other patients. After CMC reconstruction, the resolution of pain could produce substantially more pinch strength in some patients if the preoperative weakness was from pain inhibition. If that were the case, a small loss of pinch strength after surgery could be irrelevant. We have ill-defined parameters that represent a failed CMC arthroplasty (longitudinal collapse, loss of pinch, subsidence, etc)—these do not necessarily correlate to poorer functional outcomes.

Importantly, many studies in the literature suggest a single angle cutoff for when MCP hyperextension should be treated with fusion.[1,2,9,15] Our results show that the biomechanical changes resulting from MCP hyperextension are linear in nature. Therefore, our study does not support a single MCP hyperextension angle cutoff. MCP hyperextension should be considered a continuous variable and considered in the clinical context of a patient's pathology, as is routinely done today, when considering MCP joint arthrodesis or tenodesis in conjunction with CMC resection arthroplasty. Certainly, most MCP joints with hyperextension do not cause symptoms and do not require any treatment, regardless of the degree of hyperextension.

Some of our results were dissimilar to other publications. Cooney and Chao used a theoretical mathematical model to show that CMC force was 12 times that of key pinch force.[13] That study was done with a native trapezium intact, which is different from our biomechanical model. However, our CMC sensor restored a portion of the CMC joint height. Therefore, we would expect the biomechanics to be somewhat like the native state, though not the same. Our empiric data from cadaveric testing showed the CMC:key pinch force ratio to be closer to 3−5×, which is much lower than the 12× ratio found in Cooney and Chao's theoretical mathematical model. The thumb CMC joint is a complex biomechanical system, and we believe that it is possible that the necessary assumptions that they made could be prone to error. As such, on the basis of our observations in this study, it is possible that the true CMC:key pinch force ratio may be closer to 3−5, even in the native state. Additional biomechanical work would be needed to confirm this hypothesis.

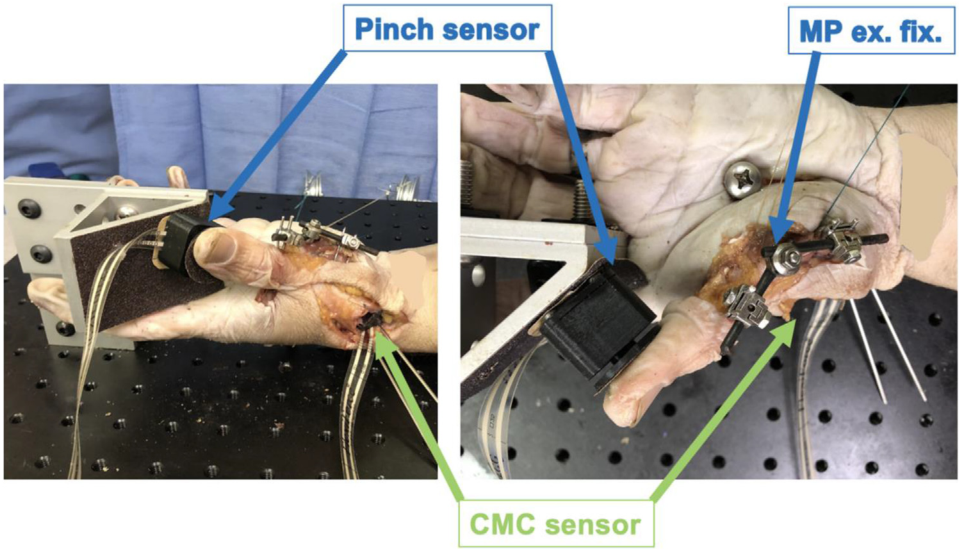

FIGURE 3: Testing setup and jig, adjustable external fixator (abbreviated as "MP ex. fix." and noted by blue arrow), pinch sensor (noted by blue arrows), and CMC sensor (noted by green arrows).

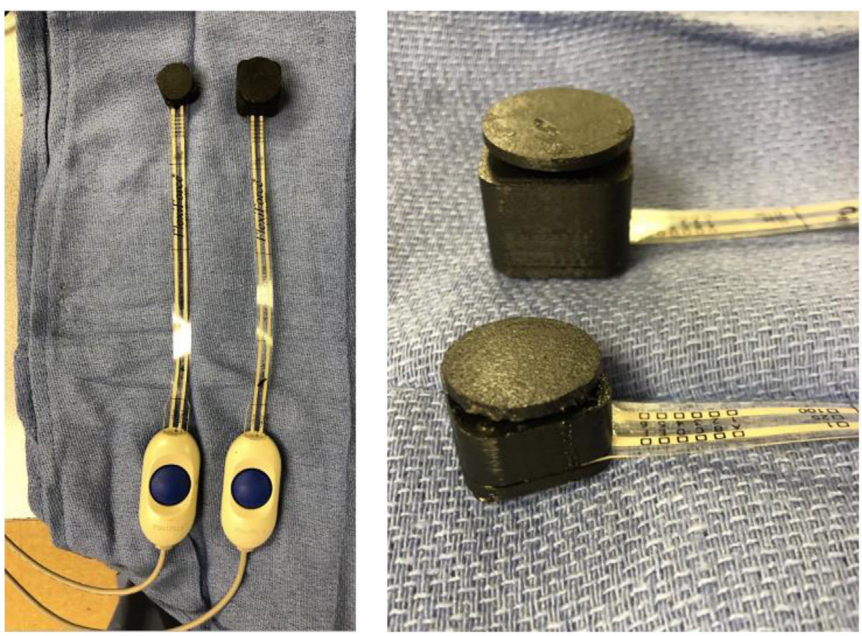

FIGURE 4: Sensors inserted into their respective 3D printed sensor housing. The shorter sensor (left side of left image; bottom of right image) measures thumb CMC force, whereas the taller sensor (right side of left image; top of right image) was used to measure thumb-to-index finger key pinch force.

This study had several limitations. This was a biomechanical study, and like all laboratory studies, it may not translate to clinical practice or *in vivo* thumb function and biomechanics. The environment of a healed thumb CMC joint after resection arthroplasty may be much different than the conditions tested. This study used 8 total specimens; although this is a low number of specimens, confidence intervals were narrow, indicating the number of specimens is likely appropriate. Assumptions were made regarding the amount of force used for tendon loading, as there are no perfect guidelines available in the literature. Our force sensors measure force directed along only a single axis. Although every effort was made to orient the sensors directly in-line with the direction of force transmission, it is possible that there were small amounts of shear forces present that were not measured. It is possible that there were either normal

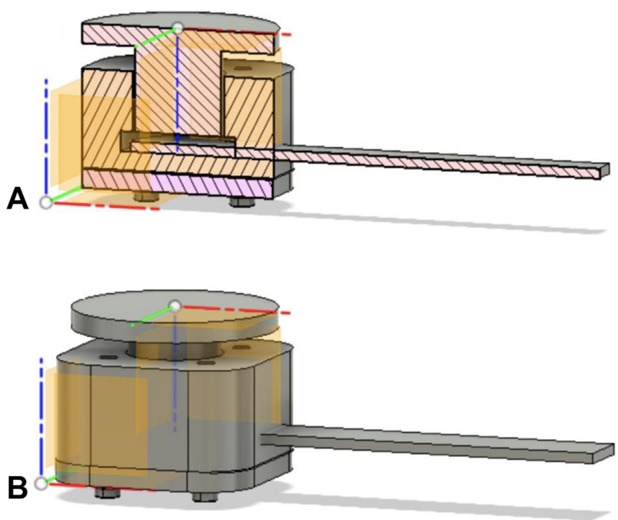

FIGURE 5: The sensor-holder design 3-dimensional model in the Autodesk Fusion 360, including a **A** cross section and **B** full body design. The sterolithography (STL) files to print these 3-dimensional designs have been made publicly and are freely available here: https://www.thingiverse.com/thing:4839993.

TABLE 1. Individual Weights Applied to Each Respective Tendon

Tendon	Weight (g)
Flexor Pollicis Longus	1500
Abductor Pollicis Longus	500
Extensor Pollicis Brevis	500
Extensor Pollicis Longus	500
Abductor Pollicis Brevis	1000
Flexor Pollicis Brevis	1000
Adductor Pollicis	2000

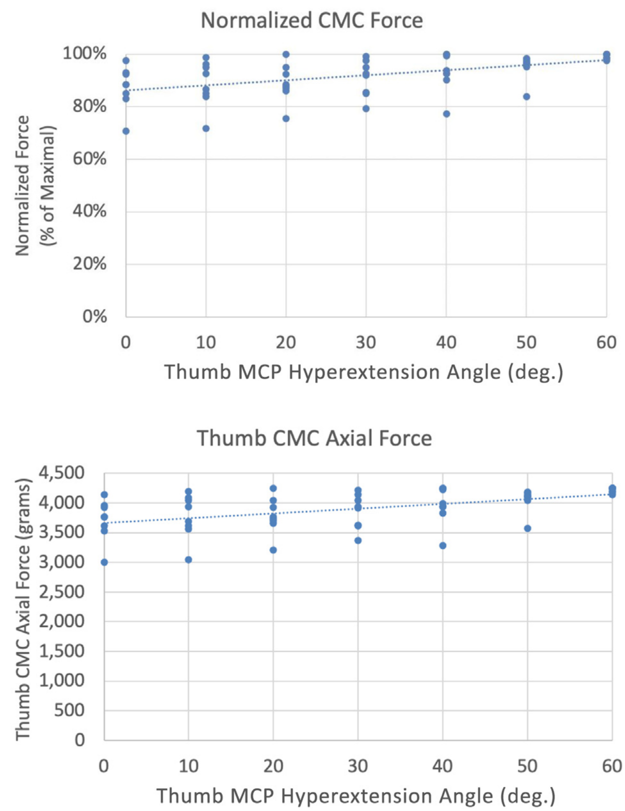

FIGURE 6: Axial force across the reconstructed thumb CMC joint as a function of increasing thumb MCP joint hyperextension.

or pathologic anatomical differences among the cadavers that we did not identify that may have produced different study results; some differences in trends in our data can be noted and we felt it important to include these data. We only measured the total resultant force across the CMC joint; other technology does exist to determine a topographical force distribution map. As such, we were not able to comment on how CMC force location and distribution may have changed with progressive thumb MCP joint hyperextension. We believe this would be interesting to evaluate in a future study because it could have implications on thumb function and potential failure mechanisms of a reconstructed CMC joint. Even though we measured a decrease in key pinch force for a given tendon force, the clinical significance of this is unknown, as a patient would be able to compensate by applying more force to the tendon. A similar study looking at maximal pinch force and its impact on CMC force would also be an interesting investigation in the future. In some testing conditions, thumb interphalangeal joint motion may have been restricted by our testing configuration and this may have altered how the thumb pulp contacted the sensor; the impact of the variation in thumb interphalangeal joint position was not evaluated. We used a metal bracket to substitute for the radial side of the index finger middle phalanx; we did not perform an analysis to determine how this may have had an impact on our results. Our specific suspensionplasty technique was a limitation of the study; other suspensionplasty techniques may have produced different results.

In conclusion, this study demonstrates that with progressive thumb MCP joint hyperextension after CMC resection arthroplasty, there is a decrease in key pinch force and an increase in axial CMC joint force. Since the increase in axial CMC force was relatively small, it may not be clinically significant. The decrease in key pinch force was larger and may be of clinical interest. However, overall these force changes were small, and their significance is unknown.

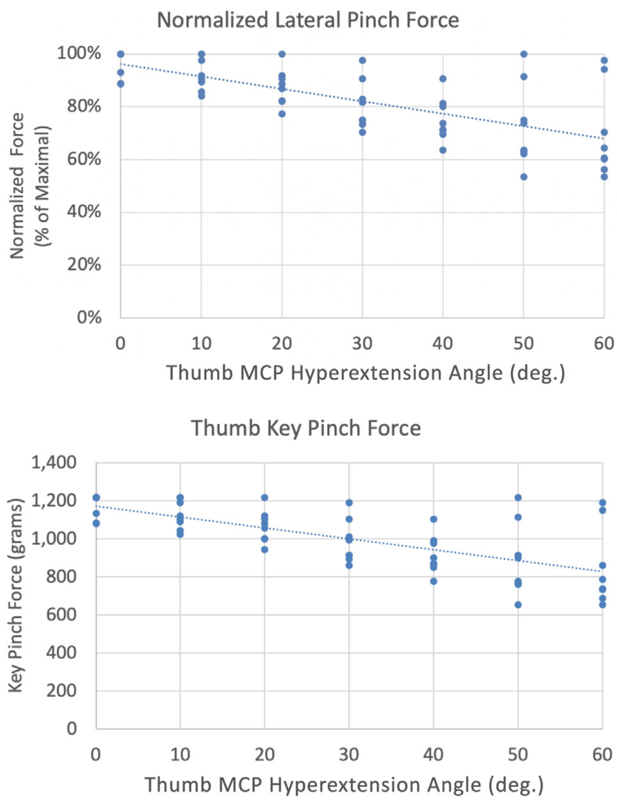

FIGURE 7: Thumb key pinch force as a function of increasing thumb MCP joint hyperextension.

Unaddressed thumb MCP joint hyperextension may lead to weaker hand function and more stress on a reconstructed CMC joint. These changes appear to happen linearly. Therefore, our findings do not support a single cutoff threshold for treatment of MCP hyperextension. This paper supports that thumb MCP joint hyperextension should be viewed as an entity that causes progressively abnormal biomechanics, and clinicians should consider thumb MCP joint hyperextension in the context of the patient's condition when deciding on a treatment plan.

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REFERENCES

1. Klinefelter R. Metacarpophalangeal hyperextension deformity associated with trapezial-metacarpal arthritis. *J Hand Surg Am*. 2011;36(12):2041−2043.
2. Lourie GM. The role and implementation of metacarpophalangeal joint fusion and capsulodesis: indications and treatment alternatives. *Hand Clin*. 2001;17(2):255−260.
3. Armbruster EJ, Tan V. Carpometacarpal joint disease: addressing the metacarpophalangeal joint deformity. *Hand Clin*. 2008;24(3):295−vii.
4. Zancolli ER III, Perrotto CJ. New transfer for correction of thumb metacarpophalangeal hyperextension in cases with associated surgery for basal thumb osteoarthritis (transfer of the volar half of the abductor pollicis brevis). *Tech Hand Up Extrem Surg*. 2011;15(2):92−93.
5. Brogan DM, Kakar S. Metacarpophalangeal joint hyperextension and the treatment of thumb basilar joint arthritis. *J Hand Surg Am*. 2012;37(4):837−838.
6. Eaton RG, Floyd WE III. Thumb metacarpophalangeal capsulodesis: an adjunct procedure to basal joint arthroplasty for collapse deformity of the first ray. *J Hand Surg Am*. 1988;13(3):449−453.
7. Moineau G, Richou J, Liot M, Le Nen D. Prognostic factors for the recovery of hand function following trapeziectomy with ligamentoplasty stabilisation. *Orthop Traumatol Surg Res*. 2009;95(5):352−358.
8. Poulter RJ, Davis TR. Management of hyperextension of the metacarpophalangeal joint in association with trapeziometacarpal joint osteoarthritis. *J Hand Surg Eur Vol*. 2011;36(4):280−284.
9. Brogan DM, van Hogezand RM, Babovic N, Carlsen B, Kakar S. The effect of metacarpophalangeal joint hyperextension on outcomes in the surgical treatment of carpometacarpal joint arthritis. *J Wrist Surg*. 2017;6(3):188−193.
10. Pilato G, Gamberoni D, Surace MF, Baldo E, Cherubino P. The modified Burton-Pellegrini method for the treatment of trapeziometacarpal arthritis. Medium-term results. *Chir Organi Mov*. 2005;90(3):241−252.
11. Yoshida R, House HO, Patterson RM, Shah MA, Viegas SF. Motion and morphology of the thumb metacarpophalangeal joint. *J Hand Surg Am*. 2003;28(5):753−757.
12. Cooney WP III, An KN, Daube JR, Askew LJ. Electromyographic analysis of the thumb: a study of isometric forces in pinch and grasp. *J Hand Surg Am*. 1985;10(2):202−210.
13. Cooney WP III, Chao EY. Biomechanical analysis of static forces in the thumb during hand function. *J Bone Joint Surg Am*. 1977;59(1):27−36.
14. Ateshian GA, Ark JW, Rosenwasser MP, Pawluk RJ, Soslowsky LJ, Mow VC. Contact areas in the thumb carpometacarpal joint. *J Orthop Res*. 1995;13(3):450−458.
15. Dumont CE, von Campe A. Benefits of additional procedures for metacarpophalangeal hyperextension on simple trapeziectomy in thumb basal osteoarthritis: a biomechanical cadaver study. *J Hand Surg Asian Pac Vol*. 2019;24(2):153−160.