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Original Research

# The Effect of Metacarpal Shortening on Finger Strength and Joint Motion: A Cadaveric Biomechanical Study

Alfonso Mejia, MD, MPH, [*] Asher Eli Lichtig, MD, [*] Arnab Ghosh, BTech, [†] Akshay Balasubramaniyan, BE, [†] Daniel Mass, MD, [*] Farid Amirouche, PhD [*, ‡]

[*] Chicago Department of Orthopaedics, University of Illinois, Chicago, IL
[†] Chicago Department of Mechanical and Industrial Engineering, University of Illinois, Chicago, IL
[‡] Department of Orthopaedic Surgery, NorthShore University Health System, Evanston, IL

A R T I C L E I N F O

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*Purpose:* Discrepancies exist between previous biomechanical and clinical studies when determining acceptable metacarpal shortening after metacarpal fractures. This study aimed to determine the amount of acceptable shortening after a metacarpal fracture before finger motion and strength is compromised.
*Methods:* We defrosted ten fresh-frozen cadaveric hands. A screw-driven external fixator was placed to stabilize the metacarpal, then a 15.0-mm section of the index metacarpal was excised and replaced with a three dimensional—printed, custom-designed polyethylene insert. The hand was then mounted on a custom testing rig, and the index finger was flexed using the flexor digitorum profundus tendon. Joint angles and fingertip force were recorded as the finger was flexed. Incrementally smaller inserts were placed, and testing was repeated.
*Results:* The average joint angles of the intact condition for the metacarpophalangeal, proximal interphalangeal, and distal interphalangeal joints were (54 [SD = 13], 79 [SD = 21], and 73 [SD = 10]), respectively. There were no statistically significant changes to any joint angle with any amount of shortening. The maximal fingertip contact pressures were 41 N (17), 31 N (12), 24 N (14), 19 N, (11), and 14 N (8) for the 15 mm, 12.5 mm, 10 mm, 7.5 mm, and 5 mm inserts, respectively. All changes in fingertip force by insert size were statistically significant.
*Conclusion:* Metacarpal shortening does not affect flexion range of motion regardless of the amount of shortening, but it significantly affects finger strength. The loss of strength after shortening was approximately 6.5% per mm of shortening for the fractured metacarpal.
*Clinical Relevance:* When viewed in the context of the hand as a whole and the contribution of the index finger to grip being only 23.5%, it is unlikely that any shortening will significantly affect the average patient regarding grip strength. However, for a patient who requires fine motor strength, any amount of shortening may affect their finger function and needs to be addressed.



Metacarpal fractures are one of the most common types of fractures treated, accounting for 33% of hand fractures.[1] They are the most common fracture of the hand for professional athletes.[2] Functional concerns after metacarpal fractures are related to extensor lag and grip strength,[3,4] as well as cosmetic concerns.[5] There has been no consensus as to the acceptable amount of shortening after fractures to avoid unsatisfactory outcomes in either clinical or biomechanical studies. Previous research evaluated the force to reach maximal extension and flexion after metacarpal shortening in cadavers and found changes after only 3.0 mm.[6,7] Other studies assessing the effect of shortening found that 6.0 mm of shortening, on average, resulted in no extension lag because most hands had a degree of hyperextension at baseline.[8] A theoretic study predicted loss of interosseous muscle function with metacarpal shortening and found that 2.0 mm of shortening would

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**Corresponding author:** Asher Lichtig, MD, Department of Orthopaedics, University of Illinois, 835 S. Wolcott Ave, Suite E-290, Chicago, IL 60612.

*E-mail address:* eli.light19@gmail.com (A.E. Lichtig).

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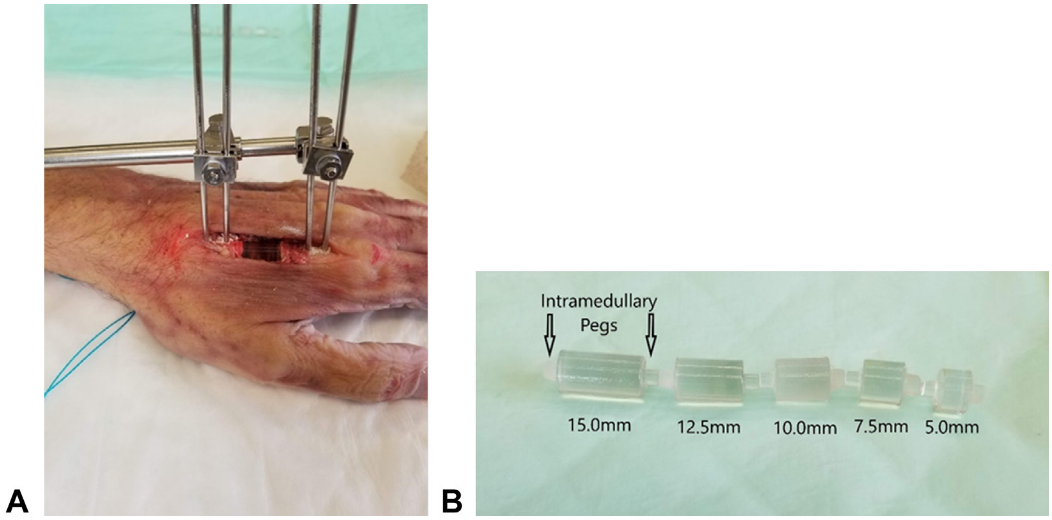


**Figure 1.** **A** Sample specimens in the intact condition with a 15.0-mm insert in place. **B** Various custom-designed 3 dimensional– printed polyethylene inserts with intramedullary pegs (open arrows).

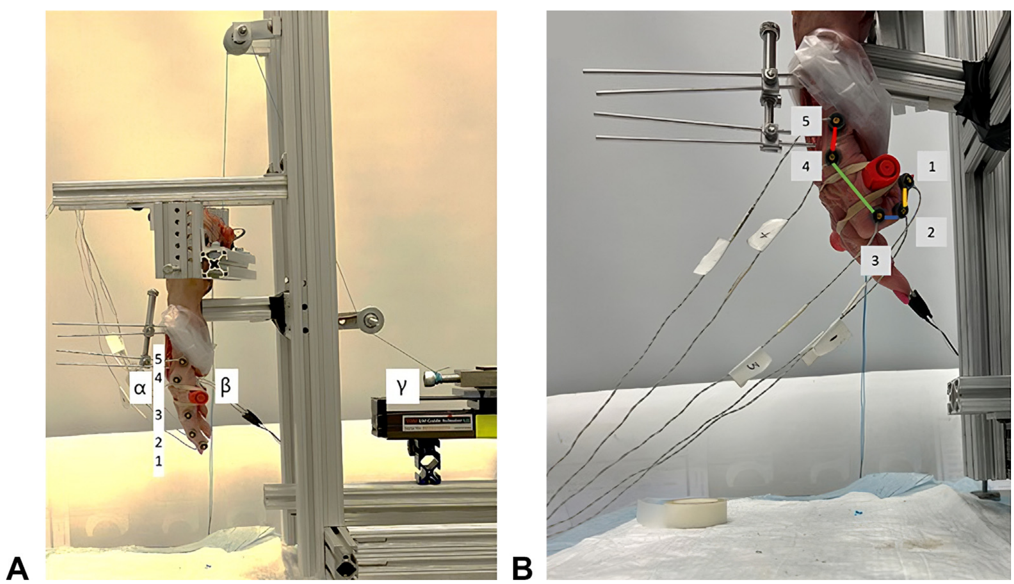


**Figure 2.** Experimental setup demonstrating **A** α motional tracking sensors with 1–5 designation defining the metacarpal, proximal phalanges, middle phalanges, and distal phalanges., β FlexiForce force sensor, and γ connection to the load cell. **B** Close up of fully flexed hand with motion sensing markers, with 1–5 designation again, defining the metacarpal, proximal phalanges, middle phalanges, and distal phalanges.

result in an 8% loss of finger strength and up to 50% loss of power with 10.0 mm of shortening.[9] A recent study evaluated the effect of shortening on finger flexion force at full extension, 50% flexion, and terminal flexion, finding significant changes only at terminal flexion after 5.0 mm of shortening.[10] The broad consensus of the above cadaveric studies is that up to around 5.0 mm in shorting leads to acceptable results. However, clinical evaluations of grip strength after nonsurgical treatment of metacarpal fractures demonstrate little effect, regardless of shortening. With conservative treatments of metacarpal fractures, the injured hand loses no more than 10% of strength and, on average, only 5% of strength compared with the noninjured contralateral side.[11,12]

Most previous biomechanical studies have evaluated the effect of shortening on what has been described as grip strength; however, limitations exist in their extrapolation to a clinical setting. One of the previous studies evaluated the effect on the force required to reach flexion but did not describe how terminal flexion was defined and did not evaluate changes to finger strength.[7] Other studies evaluated extension alone without evaluating effects on flexion.[8] One of the previous studies described the impact of shortening with a constant force load and variable excursion despite anatomic limitations to both.[10] None of these studies have evaluated any changes in a finger flexion motion. Although it has been demonstrated that shortening can induce an extension lag,[8] and that changes in flexion occur only at terminal flexion,[10] it has not been shown whether shortening affects the ability to reach terminal flexion.

This study intended to determine the effect of incremental metacarpal shortening on finger strength and motion and the force required to reach terminal flexion. We believe that through detailed experiments accounting for anatomic limitations and evaluating the results in the border context of previous studies we can reduce the discrepancy between past biomechanical projects and the clinical outcomes observed. We hypothesize that shortening will

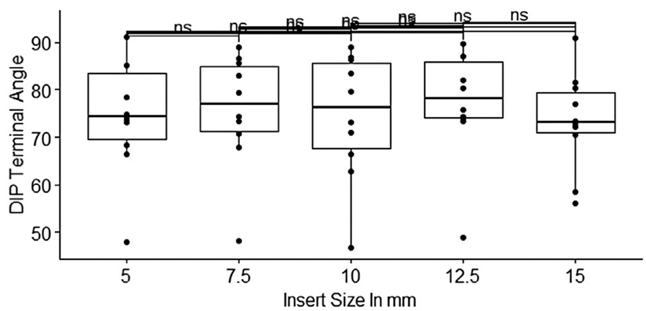


**Figure 3.** Box and whisker plots of DIP terminal flexion angle by insert length with comparisons and significance marked. DIP, distal interphalangeal; ns, not significant.

still allow for terminal flexion and that with constant excursion, there will be notable effects in finger strength.

## Materials and Methods

### *Dissection and external fixator placement*

Ten fresh-frozen cadaver hands and forearms with an average age of 61.9 years were used. The specimens were thawed for at least 24 hours before dissection and experimentation. All the specimens were free from previous trauma, surgeries, or deformities. A dorsal approach was used to expose the second metacarpal from the carpometacarpal joint to the MP joint. The soft tissue and muscular attachments to the metacarpal shaft were elevated from the metacarpal using a standard elevator to expose the metacarpal surface along the shaft. A synthesis dynamic external fixator using 2.4-mm pins was placed such that the closest pins were at least 20.0 mm apart on the dorsal aspect of the metacarpal. Care was taken to ensure that the external fixator pins did not extend past the volar side of the metacarpal such that at no point did the fixator restrict the flexion tendons. When placing the pins, the volar side of the metacarpal was palpated to ensure that there was no tactile bump or evidence that the pin had extended past the volar side of the bone to a large enough degree that it would affect movement. If a protruding point could be palpated, the pin was redrawn until it was no longer notable. A 15.0-mm section of the metacarpal was then marked and excised using a sagittal saw. The external fixator was lengthened using the integrated screw lengthener, and then, to fill in the excised bone, specially designed 3 dimensional−printed polyethylene inserts with intramedullary pegs were used (Fig. 1A). The inserts were designed with an overall width of 8.0 mm to mimic the metacarpal shaft. They had intramedullary pegs measuring 3.0 mm in diameter and 3.0 mm in length attached to secure the insert to the proximal and distal bone fragments. The three dimensional−printed 15.0-mm insert was then placed in the 15.0 mm section of the excised bone, and the external fixator was tightened to compress the end of the bones against the insert and secure it in place. Therefore, the 15.0-mm insert represented the intact condition for experimentation (Fig. 1B). Next, using a volar incision approximately 5.0 cm proximal to the wrist, the tendon of the FDP (flexor digitorum profundus) to the second digit was identified and isolated. A 45.4 kg fishing line was then sutured to the FDP tendon to facilitate finger flexion. Given that we were evaluating changes at the fingertip and that the FDP tendon is the only one that reaches the fingertip, we decided to only use the aforementioned tendon. If, during the dissection and suture processes, the flexor digitorum superficialis was accidentally pulled tighter than the FDP, then the FDP would not be able to fully exert force on the fingertip at maximal flexion, which could affect the results. Furthermore, because the motion was generated through a single-load cell, muscles with different excursion distances could not be used; therefore, intrinsics, such as the lumbricals and FDP, could not be used given the experiment setup limitation. Finally, two 2.4 mm (0.09 in) K-wires were placed across the proximal radius and ulna to facilitate mounting on the testing rig and prevent any rotation around the wrist.

### *Mounting and testing procedures*

Once each specimen was fully prepared for experimentation, each was mounted on a custom-built testing rig (Fig. 2A). The hand was placed such that the cross ulna and radius pins supported the weight of the hand and prevented rotation, and a brace at the wrist prevented nonanatomic flexing of the wrist when attempting to flex the finger alone. The fishing line attached to the FDP tendon was placed through a pulley and attached to a custom-built loading rig. In addition, an embedded force sensor (FlexiForce, Tekscan) was placed on a cylindrical plastic piece and secured to the palm to measure the force exerted by the fingertip on flexion. A small plastic button was glued to the fingertip to allow a more precise force transmission from the fingertip to the sensor. Regarding the custom build loading rig, a custom electromechanical rig was built with a stepper motor (Nema 34), and a linear stage motor (THK Model No: KR30H) coupled with a S-type load sensor (HT Seonsor Technology, TAS501) and pressure sensor (FlexiForce, Tekscan) was created. Using a force gauge and successively adding preknown load blocks (10 N), the S-type load cell was calibrated to convert the raw data into force−Newtons with the calibration code provided by the manufacturer. The same was performed for the FlexiForce sensor. The load cell and FlexiForce sensor were controlled by a single microcontroller board (Arduino) and a custom embedded C code. Another microcontroller controlled the stepper motor with its own custom embedded C code. The two codes have a feedback loop to preload the tendon to eliminate any slack in the fishing line. Rotational stepper motor input was converted into linear motion by the linear stage for which simple mechanical calculations were performed. The FDP tendon was pulled using the motor until the tip of the index finger contacted the FlexiForce sensor, and the sensor started recording pressure values, which was designated as the starting position.

Finally, motion-tracking sensors (Optotrak Certus, NDI) were placed along the finger at every joint to facilitate the tracking of joint angles (Fig. 2B). In total, five markers were used for the index finger. The placement of markers was as follows: marker 1 at the tip of the index finger, marker 2 at the distal interphalangeal joint, marker 3 at the proximal interphalangeal joint, marker 4 at the MCP (metacarpophalangeal) joint, and marker 5on the metacarpal. Vectors were drawn between the markers and were used to determine the angle formed between the joints. Each marker records the x, y, and z coordinates used in the vector calculation to determine the joint angles (Fig. 2B).

### *Calibration*

Before the experimental runs began, each hand was calibrated to an excursion distance specific to that hand, which was then held contact for each run on that specific specimen. To do so, a continuous load was applied to flex the finger, whereas the fingertip force exerted on the sensor was monitored. Once the finger had fully flexed and contacted and began exerting force on the sensor, the force was observed to increase until the hand began to flex at the wrist against resistance. At this point, the force exerted by the finger on the force sensors plateaued. The point where the wrist flexed against the restraint and fingertip flexion force plateaued was used as the contact excursion distance for every subsequent test of that hand. This represented an approximation for the

**Table**
Excursion Used for Each Hand

| | Hand 10 | Hand 9 | Hand 8 | Hand 7 | Hand 6 | Hand 5 | Hand 4 | Hand 3 | Hand 2 | Hand 1 |
|---|---|---|---|---|---|---|---|---|---|---|
| Excursion (mm) | 80 | 55 | 60 | 60 | 75 | 55 | 50 | 55 | 50 | 50 |

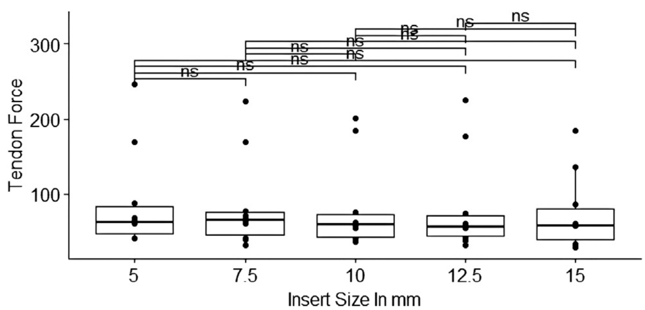


**Figure 4.** Graph of force required to reach terminal excursion. ns, not significant.

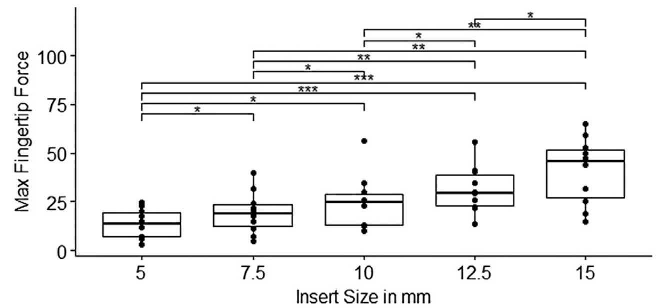


**Figure 5.** Graph of maximum fingertip force. *$P < .05$, **$P < .01$, and ***$P < .001$).

maximum possible excursion the specific hand would allow. To determine the starting point for each hand for the above calibration and each subsequent test, the tendon was attached loosely to the load cell and pulled on until there was any resistance from the tendon, and a value was recorded on the load cell. This ensured that for each run, regardless of changes to the fishing line or relative changes to the tendon length, as it may increase with shortening, the starting point of flexion was held constant.

### *Testing*

Once a constant excursion had been determined, four runs per insert length were performed. At each run, the excursion was held constant to the calibrated distance, and the maximal fingertip flexion force was recorded at the complete excursion. At the same time, the Optotrack motion sensors measured the precise angles of the MCP, proximal interphalangeal, and distal interphalangeal joints. The force required by the load cell to reach the predetermined excursion distance was also recorded for each run. After four runs, the insert was removed, the next insert that was 2.5 mm shorter was placed, and the experiments were repeated until a total shortening of 10.0 mm was induced. Therefore, 10 mm of shortening was used as the maximum for two main reasons, but the main one was on the basis of patient-reported data. To our knowledge, there have not been reports in clinical outcome studies where patients demonstrated 10 mm of shortening. [9,12] The second was that, to our knowledge, there are no current recommendations or indications for surgeries that do not include 10 mm of shortening. Therefore, it would not occur clinically where surgery was an option and 10 mm of shortening was observed and yet surgery would not be indicated. As such, there was no need to go beyond 10 mm, because doing so made the hand bend in a nonanatomic manner. The results of testing were then analyzed using one-way repeated measure analysis of variance by insert length to determine the effect of shortening on the various measurements described. Finally, a linear regression model was created to approximate percentage of changes by the amount of shortening.

## Results

### *Terminal joint angles*

The average terminal joint angle for the MCP, proximal interphalangeal, and distal interphalangeal joints for the intact condition was 54° (SD, 13), 79° (SD, 21), and 73° (SD, 10), respectively. At a maximum shortening of 10.0 mm, the angle was 55° (SD, 11), 77° (SD, 20), and 74° (SD, 12). There were no statistically significant changes in the terminal flexion angle at any amount of shortening for any of the various joints. A representative graph of the joint angles can be seen in Figure 3. The graphs of the two other joints appear very similar, with no significant changes.

### *Tendon force and excursion*

The force required to reach the calibrated excursion distance was recorded for each insert length. The average excursion for experimentation after calibration was 59.0 mm (SD, 10.05 mm), ranging from 50.0 to 80.0 mm (Table). The graph of tendon force to insert length can be seen in Figure 4. The average force for intact was 73 N (SD, 50 N) and 88 N (SD, 67 N) for 10.0 mm of shortening, but no differences were statistically significant (Fig. 4).

### *Fingertip contact*

The maximum fingertip force by insert was 41 N (SD, 17 N), 31 N (SD, 12 N), 24 N (SD, 14 N), 19 N, (SD, 11), and 14 N (SD, 8) for the 15.0 mm to 5.0 mm inserts, respectively. The change from one insert to another was statistically notable (Fig. 5). When a linear regression model was applied to the fingertip force, it was found that for every 1.0 mm of shortening, there was an approximately 6.5% loss of force (Fig. 6).

## Discussion

There have been many attempts to determine the amount of acceptable shortening after metacarpal fractures before hand function is affected. Endeavors have included both biomechanical-cadaver-based research, as well as clinical outcomes. Previous biomechanical studies have consistently recommended acceptable shortening ranges from 2.0 mm to 6.0 mm with an average of 5.0 mm,[6–10] whereas clinical studies have not seen notable changes, regardless of shortening.[11–13] The discrepancy between previous biomechanical and clinical studies led the authors of this study to reevaluate the question of acceptable shortening after metacarpal fracture and determine a more conclusive biomechanical answer. To do so, we evaluated the biomechanical changes after incremental metacarpal shortening related to finger flexion motion and forces generated while maintaining an anatomic excursion

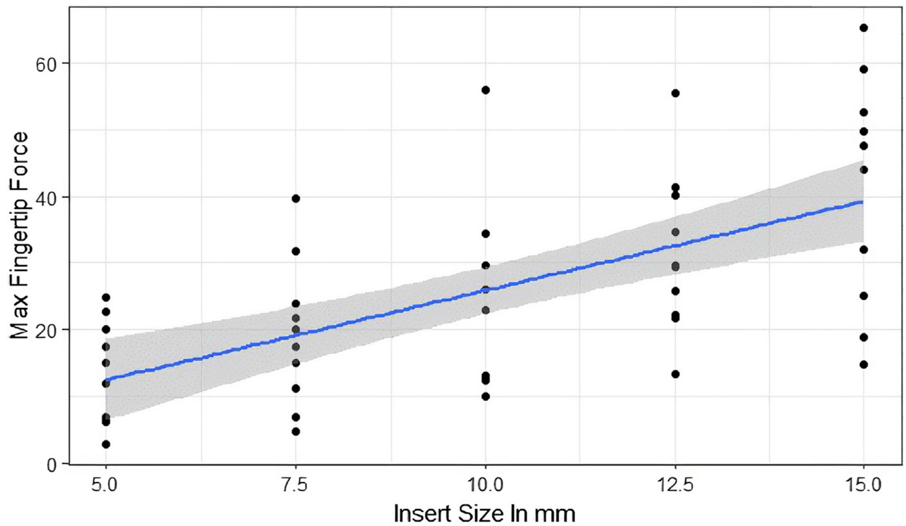


**Figure 6.** Linear regression model of fingertip force by insert length.

distance. The results of this study demonstrate that shortening will not affect the ability of the hand to reach terminal flexion; however, the forces exerted by that finger at terminal flexion will be reduced at each amount of shortening.

In addition, the force needed to reach excursion while trending up is not significantly larger at 10.0 mm of shortening compared with the intact. The ability to reach terminal flexion and do so without substantially more force requirement indicates that patients will likely be able to achieve full flexion range of motion, regardless of shortening. However, the force that was generated from that individual finger will be reduced at any amount of shortening.

When evaluating the results of this study in comparison with previous studies in the context of known clinical outcomes, it is essential to note a serious limitation. Grip strength and gripping, in general, are complex motions that require a coordinated effort from numerous muscles and result from forces generated from the entirety of the hand. Previous biomechanical studies have extrapolated the results of shortening on the finger in question to the hand as a whole.[7,8] However, we do not believe that it is an accurate assessment. When grip strength is broken down to the contributions of each finger, it has been shown that each finger contributes differently to the overall grip strength. For example, as used in this study, the index finger only contributes approximately 23.5% to overall grip strength.[14,15] If the results of this study are interpreted in the context of the contribution to grip strength by the index finger, a 68% loss of power, as seen in this study with 10.0 mm of shortening, would theoretically represent only a 15% loss of overall grip strength. Clinical studies that have evaluated the outcomes of nonsurgical treatment and have found an average of 4.0 mm of shortening with a maximum of 5.0 mm to be acceptable.[16] If 5.0 mm of shortening is used, and the effect on force seen in these results is applied, a maximal amount of grip strength loss would be approximately 10%. There was a discussion as to possible quadriga effects on the results of this study; however, after discussion, it was not believed that it had any effect. Given that quadriga effects are due to tendon shortening and that metacarpal shortening can be considered as tendon lengthening, it was concluded that metacarpal shortening would not prevent normal motion of the other fingers.

When viewed in this context, the results of this experiment align closely with clinical outcomes. This study's predicted 10% loss of overall grip strength with 5.0 mm of shortening on one finger aligns with clinical outcomes in which nonsurgical treatment never resulted in more than a 10% loss of strength compared with the uninjured side.[11] Furthermore, no loss of range of motion was observed for patients treated nonsurgically, regardless of the shortening.[12] The distinction between the effects of shortening on that finger and overall hand or grip function is essential when discussing this and previous biomechanical studies. When evaluated in isolation, some biomechanical studies have concluded that there is virtually no amount of acceptable shortening or that the value is 3.0 mm or below.[6,7,9] These conclusions do not account for other contributions to grip strength than just that finger. Clinical studies demonstrating no more than a 10% loss of grip strength have also shown a full return to activity, regardless of the shortening.[12,16] Given this, we believe that a singular cutoff for an acceptable amount of shortening is likely higher than previously reported in biomechanical studies and determined by patient-specific needs. For patients who use their hands only for activities of daily living or non−fine motor skill activities, any amount of shortening is likely acceptable because, at most, they are likely to lose 10% of overall grip strength. However, they will still be able to return to normal function. However, patients needing fine motor skill strength, such as a surgeon, jewelry makers, carpenters, artists, or electricians, may not be able to tolerate any amount of shortening if it involves their most used finger. For such patients, advising them on a 6.5% loss of strength in that finger per mm of shortening may provide guidance and context as to when surgical intervention is needed.

### *Limitations*

This study was limited by the fact that it evaluated only one finger. The effect of shortening may vary by finger, and some fingers may demonstrate an inability to reach terminal flexion. Previous research on the impact of shortening found no difference between the index and little fingers,[8] but that was not performed regarding flexion. However, the authors of this study believe that it is unlikely that will be the case, given the symmetry in clinical outcomes, regardless of which finger is fractured. In addition, the flexion rate was kept slow to ensure that the tendons did not fatigue and rupture due to unnatural speeds of flexion. The effect of flexion speed was not evaluated, and it is possible that the results would change with a change in flexion speed. In addition, this study did not consider the effects of potential hyperextension of the MCP joint with metacarpal shortening and how that could affect finger and hand functions, but given that there was no effect on flexion at that joint, it is unlikely this affected the results.

Another consideration was that this experiment only studies flexion, which was performed for two reasons, but does limit its interpretation. First was an anatomic consideration. One of our primary endpoints was contact pressure, and measuring finger extension pressure was seen as technically very challenging to be performed accurately, which could potentially disrupt the flexion experiment, and it was not particularly clinically relevant as finger extension strength is not a common concern in patients. The second was logistical and technical. In trying to set up the testing apparatus for both flexion and extension, it was found that doing so made the movement of each worse than if performed alone, that is, the flexion motion was more natural and smooth without any connections on the extension side to cause drag or resistance. Therefore, it was decided to focus on one and do it well rather than try to evaluate both and sacrifice the validity of the other. Especially because there have been very similar published works as cited in this manuscript that have quantified the degree of extension lag with incremental metacarpal shortening.[7] Overall, the added technical limitations and complications in conjunction with a lack of strong need led us to focus only on flexion.

In addition, as with previous biomechanical studies, this one was limited by only evaluating the effect using one muscle group. As mentioned, the grip is a complex coordination of movement that is impossible to replicate in a cadaver with consistency and precision. Therefore, models that isolate only one finger and one motion are often used as surrogates. This limits the interpretation; however, this limitation has been discussed thoroughly.

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