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Original Research

Intraoperative Load Tolerance of the Thumb Carpometacarpal Joint After Resection-Suspension-Interposition Arthroplasty

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Purpose: The objective was to measure the intraoperative load tolerance of the thumb carpometacarpal (CMC) joint after trapeziectomy, tendon suspension, and interposition.
Methods: In this single-center prospective study, preoperative pinch grip, thumb mobility, and hypermobility of the thumb CMC joint were determined by 2 hand surgeons. Patients completed the brief Michigan Hand Outcomes Questionnaire. During surgery and upon removal of the trapezium, the surgeon subjectively rated the degree of thumb CMC load tolerance as "stable," "medium stable," or "unstable." A measurement system with an integrated force sensor was used to measure intraoperative thumb CMC load tolerance. The thumb ray was displaced manually by 10 mm toward the scaphoid, and the counteracting force was measured over the entire displacement. The objective load tolerance was determined as the maximal measured force after trapezium resection, tendon suspension, and interposition. Analysis of variance was used to test for the differences in load tolerance between the surgical steps. Spearman's coefficient was used to find correlations between load tolerance and clinical or patient-reported variables.
Results: Twenty-nine patients with a mean age of 70 years (SD, 8.1 years) were available for analysis. The measured intraoperative load tolerance after trapeziectomy was 15.5 N (SD, 5.4 N) and significantly increased to 18.7 N (SD, 5.5 N) after suspension. Load tolerance only slightly increased after tendon interposition, increasing the force to 20.3 N (SD, 6.7 N). Neither the surgeon's subjective stability rating nor the clinical or patient-reported variables correlated with the measured load tolerance after trapeziectomy.
Conclusions: Our results show that tendon suspension leads to the highest increase in thumb CMC load tolerance during resection-suspension-interposition arthroplasty.
Clinical relevance: Tendon suspension appears to be the most important step in stabilizing the metacarpal base after trapeziectomy, whereas tendon interposition does not seem to have a relevant additional effect regarding load tolerance, at least immediately after surgery.

For thumb carpometacarpal (CMC) osteoarthritis (OA), there is still no surgical treatment that is known to be superior in terms of patient-reported or clinically measured outcomes.[1–6] It is reported that trapeziectomy alone results in fewer adverse events than in combination with suspension and tendon interposition.[2] In contrast, some investigators recommend trapeziectomy with suspension and tendon interposition because of the positive effects on postoperative trapezial space height, key pinch strength, and patient-reported subjective outcomes.[7–9] Although trapezial space height at rest and under stress does not seem to correlate with functional outcomes,[10–12] we believe that suspension-interposition is important for avoiding secondary impingement with the trapezoid or scaphoid.

In biomechanical studies, the joint reaction forces in the CMC joint are twelve times greater than the contact forces at the tip

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of the thumb during a lateral pinch.[13,14] Cooney et al[13] reported compression forces of 12 kg during a simple pinch with 1 kg of applied force and 120 kg at the CMC joint during a strong grasp.

The intrinsic load tolerance of the thumb CMC joint after trapeziectomy has not been investigated in vivo. Joint stability may vary from stable to very lax joints in patients with thumb CMC OA. To date, it remains unclear how each suspension and ligament interposition step contributes to load tolerance, and whether these operative procedures provide added and beneficial stability. Knowledge on the gain in load tolerance after each step would assist the surgeon in deciding whether to carry out a simple trapeziectomy or a more complex suspension and tendon interposition.

The objective of our study was to measure the intraoperative thumb CMC load tolerance during trapeziectomy with suspension and tendon interposition arthroplasty. Furthermore, we analyzed the contribution of the different surgical steps to load tolerance and explored the relationship between preoperative clinical and patient-reported measures. We hypothesized that key pinch and general joint hypermobility at least moderately correlated with intraoperative load tolerance.

Materials and Methods

Setting and patients

This prospective study with a single examination time point was conducted after obtaining approval from the local ethics committee and registration at ClinicalTrials.gov (Identifier: NCT03687775). Patients with primary thumb CMC stage IV OA according to Eaton,[15] who were receiving a trapeziectomy with suspension and tendon interposition according to Weilby[16] were included consecutively. All patients diagnosed with inflammatory disease (ie, rheumatoid arthritis), receiving other surgical thumb CMC treatment (eg, suspension and tendon interposition using the abductor pollicis longus tendon), or those unable to understand the German language were excluded. If 10 mm displacement of the metacarpal could not be achieved in any of the surgical steps, this measure was excluded, but data for the other measures were kept.

Of the 33 patients included in this study (Fig. 1), 4 dropped out, and 29 were available for the analysis.

Preoperative assessment

Based on our hypothesis that there will be some correlations between the intraoperative load tolerance measurements and the clinical and patient-reported variables, we performed preoperative assessments on the same day as the surgery. One measure of maximum grip and key pinch strength was done in a standardized sitting position using a Jamar dynamometer (Saehan Corp) and pinch gauge (B&L Engineering), respectively. Possible Z-deformity of the metacarpophalangeal (MCP) joint was measured in degrees during the pinch force assessment. Patient-reported hand function was rated with the German brief Michigan Hand Outcomes Questionnaire ranging from 0 to 100.[17,18] A higher score indicates better overall function. Overall joint hypermobility was measured using the Beighton score.[19] The hypermobility of 9 joints was tested to obtain a final score ranging between 0 (no hypermobility) and 9 (severe hypermobility). It was graded as not being hypermobile if one joint could not be tested, eg, because of pain or an arthroplasty. A score of 4 and higher indicates possible joint hypermobility. Thumb opposition movement was captured with the Kapandji index thumb opposition score ranging from 0 to 10.[20] Additionally, patients were asked to rate their average thumb pain over the last week during activities of daily living and at rest on a 10-point numeric rating scale, where 0 indicates no pain and 10 is extreme pain.

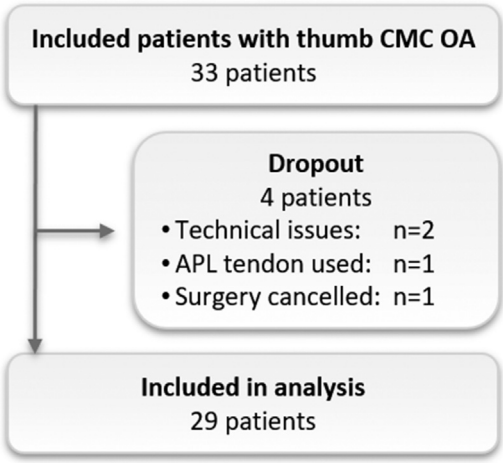

Figure 1. Patient selection diagram. APL, abductor pollicis longus.

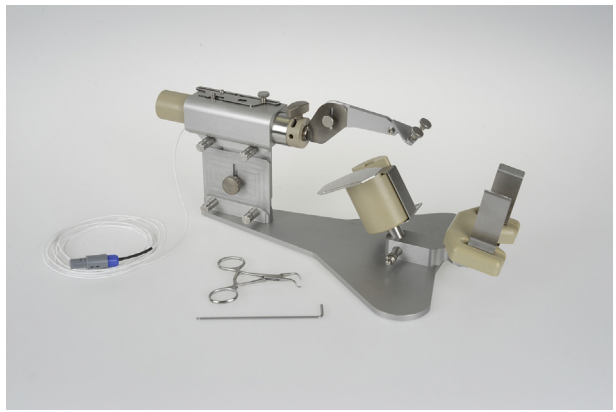

Figure 2. Intraoperative measurement system developed to provide continuous force measurement during the linear displacement of the thumb CMC joint.

Technical setup and validation

A measurement system with an integrated KD24s 100 N force sensor (ME-Meßsysteme GmbH) was developed to measure the thumb CMC joint load tolerance. It provides continuous force measurement during the linear displacement of the first metacarpal base (MC I) (Figs. 2, 3). The displacement of the metacarpal bone was mechanically limited to 10 mm. Data were acquired using an LCV-USB2 digital transducer accompanying VS2 data acquisition software, version 2.13 (Lorenz Messtechnik GmbH). We previously tested its application in a cadaver hand model (Fig. 4 and Video 1, available on the *Journal*'s website at www.jhsgo.org). Measurement reliability was evaluated using 6 mechanical compression springs (Kubo Tech AG), which were each tested 6 times under laboratory conditions. Test-retest reliability was assessed using the intraclass correlation coefficient which was 0.999 (95% CI, 0.998–1.000).

Intraoperative load tolerance assessment

Two surgeons performed the surgeries using a dorsal approach. Surgery using half of the flexor carpi radialis (FCR) tendon was performed as described by Weilby[16] with a minor modification. For suspension, the FCR tendon was wrapped only once around the abductor pollicis longus tendon and then several times around the

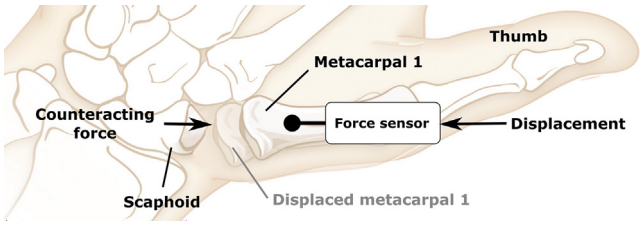

Figure 3. Method to measure thumb CMC joint load tolerance by displacing the first metacarpal bone toward the scaphoid.

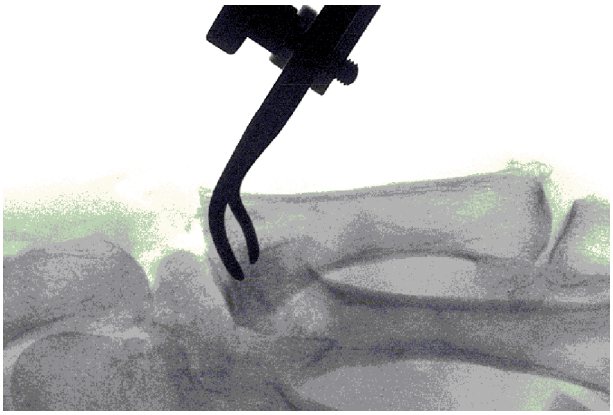

Figure 4. Fixation of reposition forceps at the first metacarpal bone during concept testing within a cadaver trial.

remaining part of the FCR tendon for interposition between the distal part of the scaphoid and the MC I. Osteoarthritis of the remaining scaphotrapezoidal joint was addressed in that we resected either the distal scaphoid or the base of the trapezoid.

After trapeziectomy, the treating surgeon rated thumb CMC load tolerance based on the categories of "stable," "medium stable," or "unstable" by holding the thumb at the proximal phalanx and moving the MC I base toward the wrist, thereby closing the cavity formed by the resected trapezium. This test reflects the direction of movement of our mechanical load tolerance measurement.

For the mechanical measurement during surgery, a standardized hand and pinch grip position was achieved in that the hand was placed around a cylinder tilted in 30° abduction (Fig. 5). This position ensured a stable and congruent alignment of the displacement axis, the sensor measurement axis, and the metacarpal bone axis pointing in the direction of the scaphoid.

A conventional reposition forceps was attached to the base of the MC I and the linear slide. The parallel alignment between the MC I and the linear slide was achieved by adjusting the height of the wrist. The neutral position of the linear slide was achieved when there was no strain within the soft tissue surrounding the trapezial cavity. The MC I base was moved toward the scaphoid by manually displacing the linear slide by 10 mm at a constant rate within 2 seconds (Video 2, available on the *Journal*'s website at www.jhsgo.org). The chosen distance of 10 mm did not exceed the height of a normal trapezium that ranges between 11 mm and 16 mm.[21] Over the total displacement, the counteracting force was measured, where the maximal measured force indicated the apparent load tolerance. A mechanical stop was added to the device at 10 mm, and an additional applied force against the hard stop was not registered. Load tolerance was measured at least 3 times after trapeziectomy, upon applying the suspension with the FCR tendon strip, and finally during interposition of the remaining FCR tendon end. For comparing the load tolerance data, all the surgical steps were completed while the hand was in the standardized pinch grip position as described above.

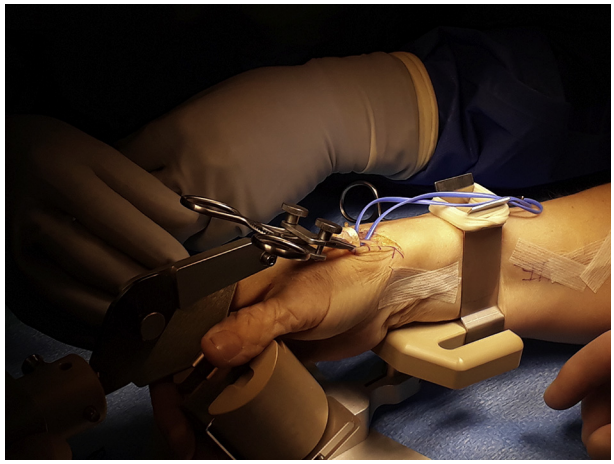

Figure 5. Preparation of the measurement system for quantifying load tolerance in vivo.

Table 1
Patient Characteristics

Variable	n (%)	Mean (SD)
Patients	29	
Sex, female	25 (87)	
Age (y)		70 (8.1)
Kapandji index (0–10)*		9.1 (1.2)
Beighton score (0–9)†		0.8 (1.7)
Brief MHQ (0–100)‡		47 (18)
Pain at rest (0–10)§		4.6 (2.6)
Pain during ADL (0–10)§		6.6 (2.2)
Key pinch (kg)		4.8 (2.4)
Grip strength (kg)		18 (10)
Hyperextension MCP I (°)		3.3 (6.2)

MHQ, Michigan Hand Outcomes Questionnaire; ADL, activities of daily living; MCP I, first metacarpophalangeal joint.
* 0 = worst, 10 = best.
† 0 = best, 9 = worst.
‡ 0 = worst, 100 = best.
§ 0 = best, 10 = worst.

Statistics

Load tolerance data were normally distributed; therefore, means and SD were calculated. Correlations between the objective force measurement and other variables were determined with Spearman's correlation coefficient (r). The differences between the objective load tolerance after trapeziectomy, suspension, and tendon interposition were tested using analysis of variance for repeated measures (ANOVA) with Scheffe post hoc adjustment for multiple comparisons. A post hoc power calculation for repeated measures was conducted using the load tolerance data of the 3 measures. Setting α at 0.05 and including the 29 patients, an effect size of 1.27 for the load tolerance measurements was revealed, and the power of the study was 0.99.

Results

The 29 included patients had a mean age of 70 years (SD, 8.1 years) and a mean Beighton score of 0.8 (SD, 1.7), indicating no joint hypermobility with only slight MCP joint hyperextension of 3.3° (SD, 6.2°) before surgery (Table 1).

Table 2
Correlations (Spearman's Correlation Coefficient) Between the Load Tolerance Measurement After Trapeziectomy and Clinical Variables

Variable	Intraoperative Load Tolerance	Surgeon's Rating	Age	Kapandji Index	Key Pinch	Grip Strength	Brief MHQ	Pain at Rest	Pain During ADL
Surgeon's rating	0.28								
Age	-0.11	0.07							
Kapandji index	0.11	-0.20	-0.31						
Key pinch	0.36	0.05	-0.09	0.45					
Grip strength	0.23	-0.10	-0.21	0.33	0.53				
Brief MHQ	-0.11	-0.06	-0.24	0.40	0.48	0.72			
Pain at rest	0.33	0.02	0.27	-0.16	-0.07	-0.35	-0.61		
Pain during ADL	0.24	-0.10	0.13	-0.31	-0.21	-0.27	-0.34	0.48	
Beighton score	0.18	-0.22	-0.43	0.19	-0.02	0.23	0.03	0.08	0.15

MHQ, Michigan Hand Outcomes Questionnaire; ADL, activities of daily living.

From the collective surgeon ratings of load tolerance, 13 (45%) thumbs were considered stable, 7 were "medium stable," and 9 were considered unstable after trapeziectomy alone. These ratings did not correlate with the intraoperative load tolerance measurements ($r = 0.28$, $P > .05$; Table 2). We found a moderate nonsignificant correlation between the load measurements and the key pinch strength ($r = 0.36$, $P > .05$). In addition, neither the load measurements nor the surgeon rating correlated with any of the other evaluated clinical or patient-reported variables (Table 2).

The intraoperative load tolerance after trapeziectomy was mean 15.5 N (SD, 5.4 N) and this significantly increased to 18.7 N (SD, 5.5 N) after suspension ($P \leq .001$; Fig. 6). Furthermore, load tolerance only slightly increased after tendon interposition, increasing the force to 20.3 N (SD, 6.7 N; $P = .12$). All thumbs could be displaced 10 mm after trapezium excision and suspension except for the thumb of one patient, which could not be fully displaced to 10 mm after interposition because the metacarpal bone abutted the scaphoid. This single measurement point was therefore excluded.

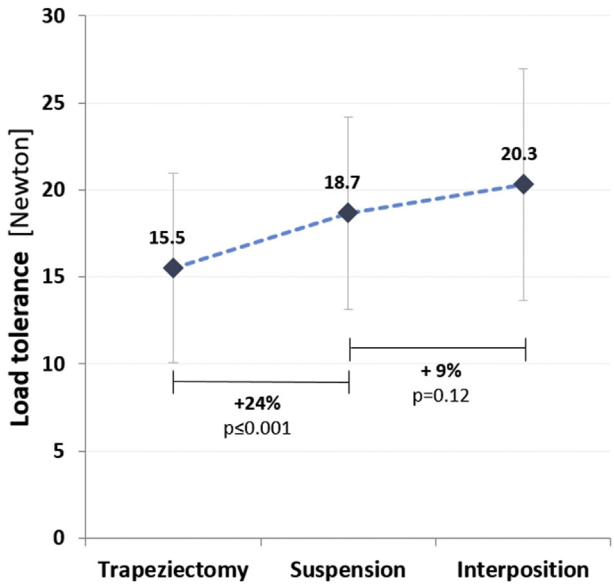

Figure 6. Mean (± SD) load tolerance measured after trapeziectomy, suspension, and tendon interposition. One patient had to be excluded for the interposition measurement because the 10 mm displacement was not attained.

Discussion

The results of our study show that suspension contributes the most to passive thumb load tolerance during resection-suspension-interposition arthroplasty. Tendon interposition does not seem to have a significant additional effect regarding load tolerance, at least immediately after surgery. This indicates that tendon interposition is the least important step. Whereas it would seem logical that additional interposition can enhance the stability of resection arthroplasty, the mechanical properties of the tendon interposition do not seem to increase the resistance against compressing forces, at least not during surgery. However, the interposition step may serve as a buffer to constrain further displacement of the thumb in the medium term[8] and thus avoid secondary impingement with the trapezoid or scaphoid.

In a long-term randomized study that investigated the outcomes of simple trapeziectomy versus trapeziectomy with ligament reconstruction and tendon interposition (LRTI), there were no differences in scaphometacarpal distance and patient-reported outcomes between the 2 interventions after 17 years.[22] In combination with our findings, it can be suggested that tendon interposition is not particularly relevant for long-term clinical and patient-reported outcomes after thumb CMC surgery.

Two in vitro biomechanical investigations compared the trapezial space height after trapeziectomy with and without LRTI.[23,24] Luria et al[24] reported a lack of notable differences in trapezial space height between the 2 procedures, whereas Putnam et al[23] revealed a notably lower trapezial space height after trapeziectomy compared to LRTI under load. However, the trapezial space height does not seem to be correlated with clinical outcomes one year after LRTI.[10]

From a biomechanical standpoint, the achievable postoperative pinch force depends on the active and passive support of the joint provided through muscle activation and the surrounding tissue, respectively. Authors investigating the reaction forces and moments during pinch grip associate the stability of the thumb CMC joint with the surrounding stabilizing ligaments.[25,26] Hence, higher passive stability promotes better overall stability. We believe that an intraoperative stable joint would imply high joint stiffness and reduce postoperative trapezial migration under thumb loading.

We did not find a correlation between the Beighton score of generalized joint laxity and intraoperative joint stiffness. This is in line with Wolf et al,[27] who also reported a low correlation of 0.3 between the Beighton score and subluxation of the thumb CMC joint measured with thumb CMC stress view radiographs in volunteers of varying ages.

Although our system and approach represent a more quantitative way to measure thumb CMC load tolerance than previously reported, this study has several limitations. The stability rating provided by our surgeons after trapezium removal did not correlate with the load tolerance measurements, which may be because of the low sample size and varying reported perceptions of the 2 surgeons. However, this aspect might also result from using our measurement device, which has high test-retest reliability under laboratory conditions but has not been previously tested for

reliability and validity in a larger patient series. As load tolerance data were not available from other studies and could not be estimated before surgery, an a priori sample size calculation was not possible. The investigated passive joint load tolerance, especially the initial evaluations after trapeziectomy, showed broad variability among the patients. However, all the measurements and surgical steps were performed using a single standardized hand position such that errors due to the repositioning of the hand for the same patient could be eliminated. Apparent nonaxial forces in the initial position and during measurement were controlled by adjusting the forceps height and rotation and using a biocompatible low friction material pairing design. In addition, the quantification of load tolerance was simplified by reporting the maximum measured force over a fixed displacement of 10 mm. We only included patients with stage 4 OA, as we routinely perform implant arthroplasty in patients with less severe OA. It should be noted that the measurements are not independent variables, but dependent on the sequence of events such that tendon suspension must be done before interposition. We only tested passive biomechanics and did not measure active stability (which is not possible during general anesthesia), the latter of which is also important when assessing overall thumb function. Lastly, it must be said that our study does not allow any conclusions to be made about the long-term contribution of tendon interposition on joint stability and the prevention of possible proximal migration of the MC I.

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