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Original Research

Biomechanical Evaluation of Opponensplasty for Low Median Palsy: A Cadaver Study

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Purpose: Impaired thumb opposition associated with advanced carpal tunnel syndrome may be treated by opponensplasty at the time of open carpal tunnel release. However, it is unclear which opponensplasty technique achieves the greatest functional improvement. This study aimed to compare the biomechanics of thumb opposition after Camitz, modified Camitz, and Burkhalter opponensplasties.
Methods: We used 6 fresh-frozen cadaveric arms. Each procedure was reproduced on each arm: Camitz opponensplasty, modified Camitz opponensplasty involving palmaris longus transfer routed around the flexor carpi ulnaris pulley, and Burkhalter opponensplasty. Arms were fixed with the wrist in 0° flexion and the forearm in neutral pronosupination, and sensors were placed on the thumbnail, radial styloid, and dorsal aspect of the second metacarpal head. The donor tendon was pulled using a mechanical testing machine with a maximum force of 25 N, and the locations of the sensors in thumb opposition were recorded. The first web space and thumb pronation angles were measured for each procedure and compared.
Results: The mean first web space and pronation angles produced using 25 N were 55° and 20°, 57° and 26°, and 53° and 29° for the Camitz, modified Camitz, and Burkhalter opponensplasties, respectively. The first web space angle was significantly larger after modified Camitz opponensplasty compared with Burkhalter opponensplasty with 25 N loading. Camitz opponensplasty resulted in a significantly smaller pronation angle compared with modified Camitz and Burkhalter opponensplasties with 25 N loading.
Conclusions: The modified Camitz opponensplasty produces a relatively balanced biomechanical outcome in terms of the first web space and pronation angles. Conversely, Burkhalter opponensplasty has been shown to be a favorable technique for improving pronation.
Clinical relevance: Modified Camitz opponensplasty with a pulley offers effective restoration of thumb opposition, including pronation. On the other hand, Burkhalter opponensplasty represents a suitable option not only for patients with high median palsy and injury to the palmar aponeurosis but also for those who require improved pronation.

Carpal tunnel syndrome is a neuropathy characterized by chronic compression of the median nerve at the wrist, with a prevalence of 3%.[1,2] Conservative management can achieve sufficient improvement for most patients, and the surgical approach of carpal tunnel release (CTR) can improve symptoms when conservative management fails. However, advanced carpal tunnel syndrome can cause thenar muscle paralysis, which inhibits opposition of the thumb, which is critical in normal hand function.[3] For these patients, when the lesion is irreparable, opponensplasty by tendon transfer is recommended, followed by open CTR.[4] Opposition is a complex motion involving palmar abduction, thumb pronation, and metacarpophalangeal joint

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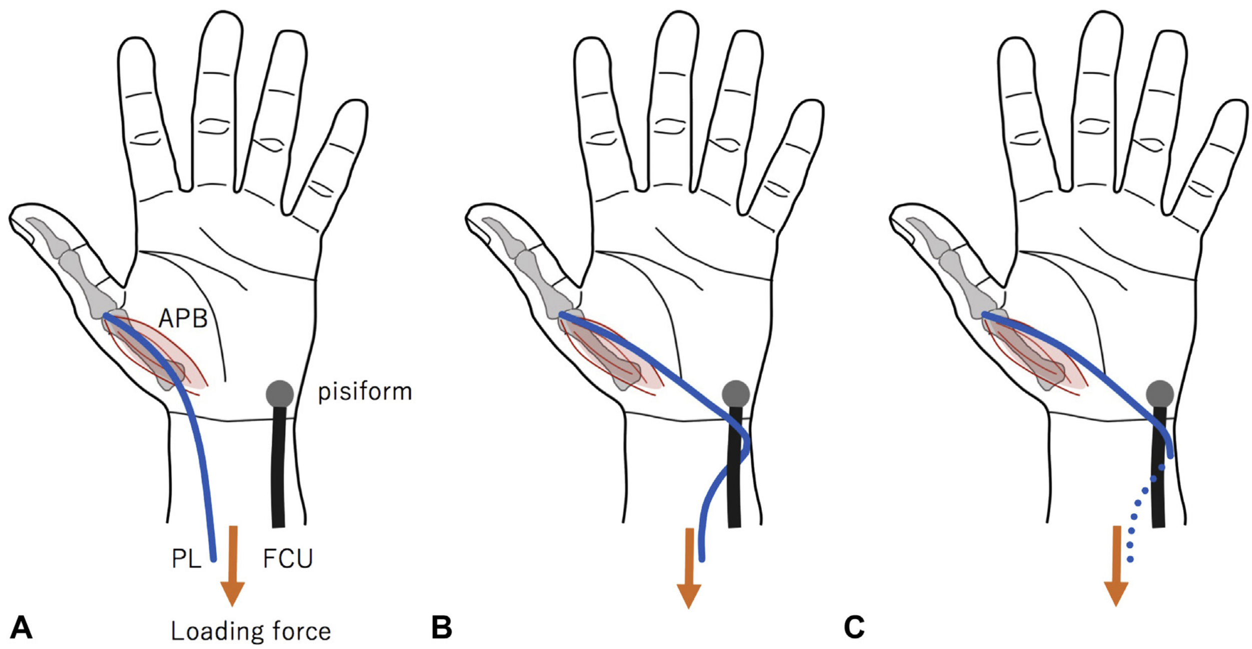

Figure 1. Schema of the surgical procedures. **A** Camitz procedure. **B** Modified Camitz procedure (around-the-FCU tendon transfer). **C** Burkhalter method. In the current study, we used the Burkhalter method to pull the PL tendon, which was rerouted to the dorsal side of the arm, to avoid resuturing the insertion site. The donor tendon was inserted into the APB tendon in all cases.

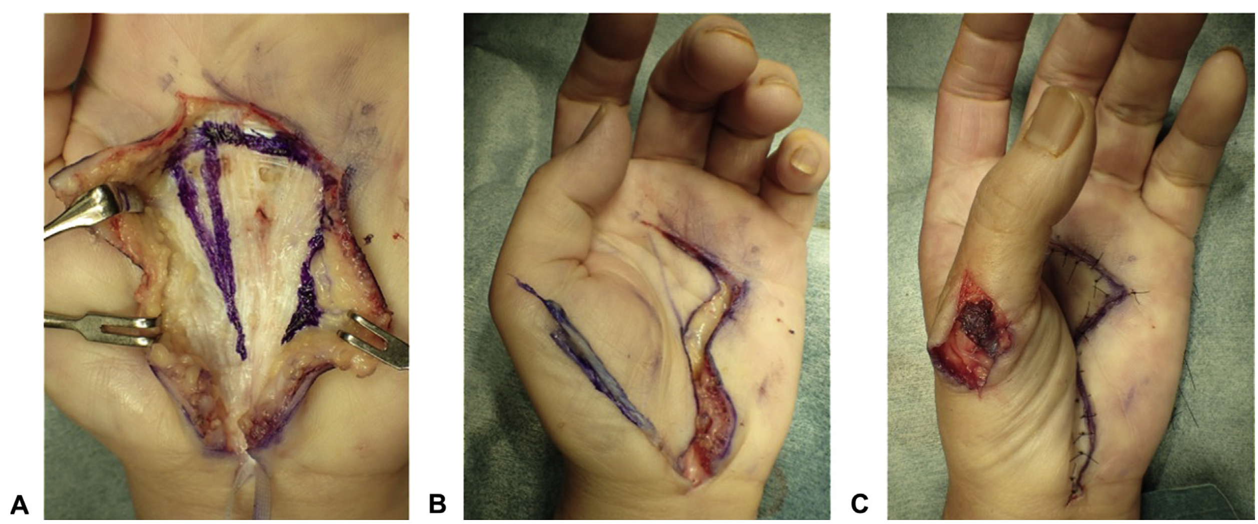

Figure 2. Surgical photographs of the Camitz method. **A** Deploying palmar aponeurosis. **B** Transferring the palmar tendon. **C** Tendon insertion into the extensor pollicis brevis tendon.

flexion. Therefore, there are various techniques for opponensplasty. Palmaris longus (PL) transfer was first described by Bunnell[5] in 1924, followed by Camitz[6] in 1929, and it involves simple methods that can be performed simultaneously with open CTR without the need for tendon graft.[7,8] Good clinical outcomes have been reported for Camitz opponensplasty,[9,10] but this procedure may not enable the restoration of thumb pronation.[11,12] Therefore, numerous modifications have been reported, such as the use of a pulley between the path of the donor tendon,[13,14] a different donor tendon,[15] or a different insertion site.[15,16]

Extensor indicis proprius (EIP) tendon transfer in opponensplasty was first described by Burkhalter et al[17] and has been reported to result in good thumb pronation and abduction in the case of median nerve palsy.[18–22] Burkhalter opponensplasty is known to be mechanically advantageous because the tendon travels in a straight line and does not require a pulley. Furthermore, the traction direction is most suitable for thumb pronation.[23] However, this technique is not widely used by hand surgeons, whereas Camitz opponensplasty is popular and widely used in this field.

We hypothesized that Burkhalter opponensplasty would be a more effective procedure than Camitz opponensplasty in restoring opposition. We aimed to ascertain thumb opposition as determined by first web space and pronation angles after Camitz opponensplasty, modified Camitz opponensplasty with a flexor carpi ulnaris (FCU) pulley, and Burkhalter opponensplasty.

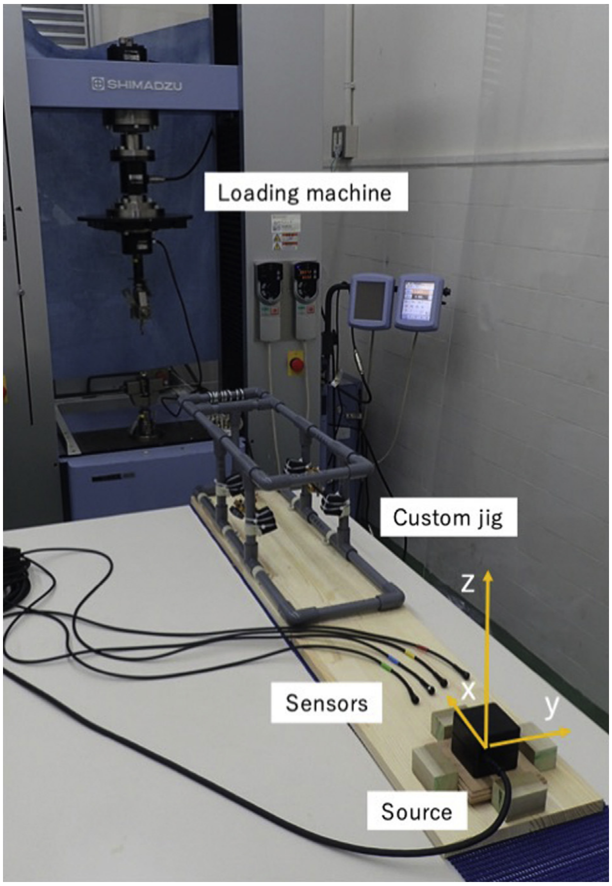

Figure 3. The test apparatus, including the FASTRAK system, custom jig, and universal testing machine. The FASTRAK system is an electromagnetic motion-tracking system that tracks the position (x, y, and z Cartesian coordinates) and orientation (azimuth, elevation, and roll) of the sensors in 3-dimensional space. The jig is made from a wooden table and an antimagnetic frame.

Figure 4. A cadaver arm mounted and fixed with a Kirschner wire. The cadaver arm is mounted on the antimagnetic frame with the wrist fixed at 0° flexion and the forearm is fixed in neutral position.

Materials and Methods

We used 6 fresh-frozen cadaver arms (3 matched pairs of cadaver arms: one male and two females). Mean age of specimens was 86 years (range, 80–95 years). Each specimen was visually inspected for signs of previous trauma, scarring, or arthritis. Specimens with any of those signs were excluded from the analysis. Each arm was transected at a point one-third proximal to the humerus. The cadaver arms were thawed at room temperature immediately before testing. Saline spray was used during investigations to prevent them from drying out.

Surgical procedure and preparation

We performed 3 surgical procedures (Camitz opponensplasty, modified Camitz opponensplasty, and Burkhalter opponensplasty) on each cadaver in the following order. First, we performed the Camitz procedure on cadaveric arms[5,6] by carrying out PL transfer to insert the abductor pollicis brevis (APB). The schema of the surgical procedure is shown in Figure 1. A longitudinal skin incision was made on the bulge of the PL starting 2 cm proximal to the wrist crease and continuing as a zigzag incision along the palmar crease. The longitudinal fibers of the palmar aponeurosis following the PL tendon were dissected until the transverse fibers of the palmar aponeurosis were present (Fig. 2A). The PL tendon was then identified and freed from the forearm. The PL tendon and palmer aponeurosis were transferred to the insertion site of the APB[24] (Fig. 2B). The end of the PL tendon was secured to the APB insertion using interlacing sutures in 2 weaves with 4-0 FiberWire suture (Arthrex Inc, Naples, FL) (Fig. 2C). For traction testing, we located the muscle–tendon junction of the PL by making another longitudinal incision on the palmar side of the forearm. The proximal point of the PL tendon was cut, tied with nylon thread, and looped so that it could be pulled using a mechanical testing machine during traction testing.

We prepared for PL transfer by passing the tendon around the FCU (as per modified Camitz opponensplasty) to create a pulley.[7,14,25] The looped proximal end of the transferred PL tendon was passed through the pulley, and traction was directed toward the medial epicondyle.

The final step of the surgical procedure was to create a path for the ulnar subcutaneous tunnel, as in Burkhalter opponensplasty.[17] We did not use the EIP tendon, according to the original Burkhalter method, but instead used the PL tendon by rerouting to remove the need to resuture the insertion site of the APB. We created the path in the subcutaneous region of the palm toward the ulnar side of the wrist, made a small oblique incision at the halfway point of the ulnar side of the forearm, and pulled the proximal end of the transferred PL tendon through and toward the EIP muscle. The technique in this study was defined as the Burkhalter simulation opponensplasty.

Thumb opposition and motion analysis

We used a FASTRAK system (Polhemus Inc, Colchester, VT), which is a 3-dimensional motion-tracking system (Fig. 3) for spatial analysis. This system enables measurement and recording of the position and orientation of the sensor in a consistent electromagnetic field of 40 Hz. The source emits an electromagnetic field that is detected by sensors to determine the location and angular orientation of each sensor relative to the source with a root-mean-

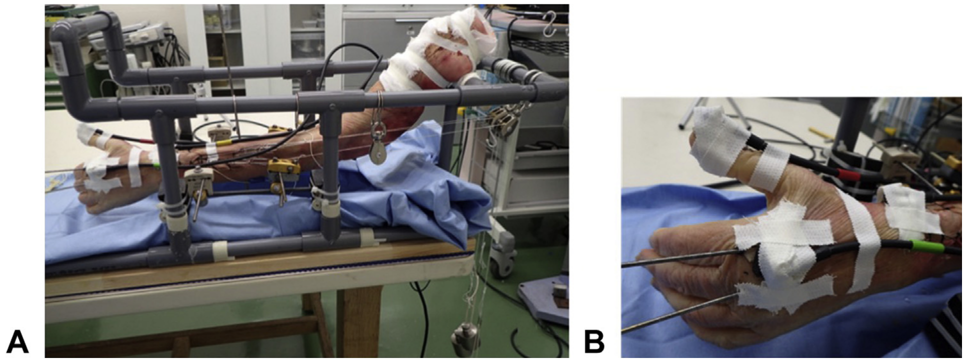

Figure 5. Reproduction of natural thumb opposition at rest. **A** The extensor pollicis brevis, abductor pollicis longus, and extensor pollicis longus tendons were weighted at 200 g. **B** Sensor location. Sensors were placed on the thumbnail, radial styloid, and distal head of the second metacarpal.

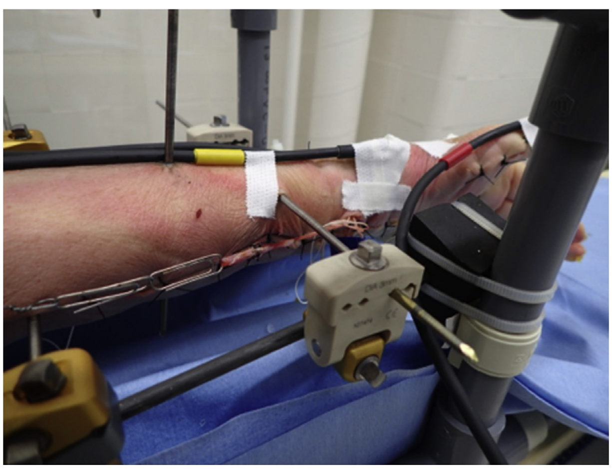

Figure 6. The transferred palmaris longus tendon that was pulled through clips and a soft wire using a universal testing machine.

square accuracy of 0.76 mm for the x, y, or z positions and 0.15° for receiver orientation within 300 mm.

Before performing spatial analysis, we mounted the cadaveric arms that had undergone Camitz opponensplasty in a custom jig made from plastic pipe, carbon rod, and wood (Figs. 3, 4). The cadaveric arms were placed in a position with the wrist at 0° flexion and the forearm in a neutral position. The position was maintained by fixing with nonmagnetic titanium Kirschner wires (φ1.2 mm for fingers, φ2.0 mm for wrists, and φ3.0 mm for forearms) between the head of the second and third metacarpals and the radius, and between the radius and the ulna at the one-third and two-third points of the forearm (Fig. 4). The proximal tendons of the extensor pollicis brevis, abductor pollicis longus, and extensor pollicis longus were pulled proximally with 200 g weight per tendon to reproduce natural thumb abduction[23] (Fig. 5A). Sensors were placed on the thumbnail, radial styloid, and distal side of the second metacarpal (Fig. 5) and fixed with tape (Johnson and Johnson, New Brunswick, NJ) onto the low-repulsion mat to ensure secure fixation. Thumb opposition was reproduced using a universal testing machine (Autograph AG-20kN Xplus, Shimadzu, Kyoto, Japan) to pull the PL tendon at a speed of 1.0 mm/s through clips and a soft wire. The loading forces were recorded at 100 Hz (Fig. 6) and set to a maximum of 25 N to minimize any effects on the soft tissue at the insertion site of the transferred tendon that might have occurred because of traction. We had previously estimated the maximum muscle power to be 64.39 N for the PL tendon and 60.81 N for the EIP tendon (Table 1).[23,26,27] After monitoring the spatial changes after Camitz opponensplasty, the PL tendon was rerouted according to the modified Camitz and Burkhalter simulation opponensplasty procedures. This was done by pulling the looped proximal end of the PL tendon through the pulley and ulnar subcutaneous path without reattaching the sensors or resuturing the insertion site.

Table 1
Estimated Muscular Force of PL and EIP

Estimated Muscular Force, N	Total	10%	20%	30%
PL	64.37	6.44	12.88	19.32
EIP	60.81	6.08	12.16	18.24

We measured the first web space angle and thumb pronation angle to evaluate thumb opposition (Fig. 7). The first web space angle was defined as the angle made by the line between the radial styloid and second metacarpal head and the line between the radial styloid and thumbnail. The thumb pronation angle was defined as the change in web space angle before and after the PL tendon pull test.

We analyzed both of those angles at 10%, 20%, and 30% of the maximum force of the PL and EIP noted earlier and at the maximum loading (25 N). Table 1 shows the loading force of each muscle based on the estimated force determined previously.[23,26,27]

Statistical analysis

Web space angles were compared using one-way analysis of variance with repeated measures, and Tukey's method was used to evaluate the thumb opposition angle according to the 3 types of opponensplasty. $P < .05$ was considered statistically significant; we calculated 2-sided 95% confidence intervals (CIs).

Results

The first web space and pronation angles both increased with increasing traction force (Fig. 7). Table 2 shows the mean and CIs of the first web space and thumb pronation angles after Camitz, modified Camitz, and Burkhalter simulation opponensplasties and the statistical comparison among the procedures.

First web space angle

As Figure 8 shows, the first web space angle increased with increasing traction force. The largest angle was achieved by the

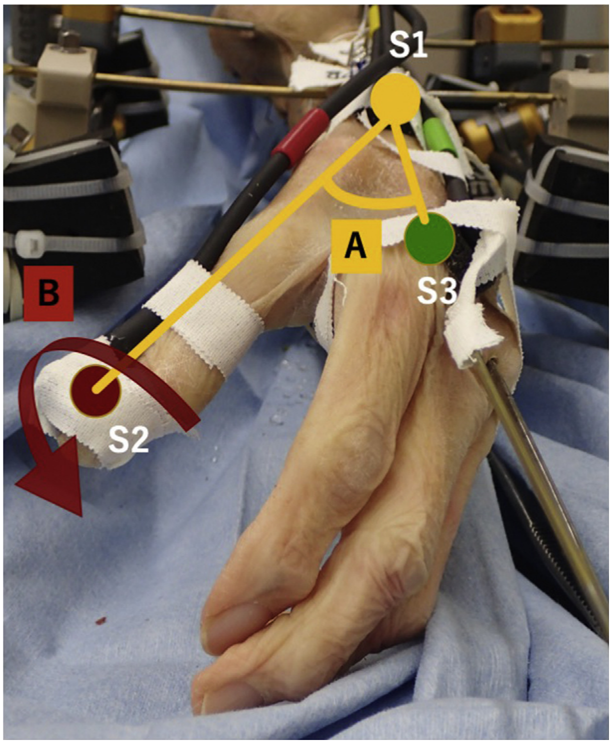

Figure 7. Locations of the sensors and measured angles. The first sensor (S1) was placed on the radial styloid, S2 on the thumbnail, and S3 on the distal side of the second metacarpal. **A** The first web space angle is defined as the angle created by the line between S3 and S1 and that between S2 and S1. **B** The thumb pronation angle is defined as the rotation angle of S2 on the axis of the distal phalanx of the thumb.

modified Camitz opponensplasty, followed by the Camitz opponensplasty, with the Burkhalter simulation opponensplasty resulting in the smallest angle at 20% of the estimated muscular force. After the modified Camitz opponensplasty, the first web space angle increased relatively sharply with increasing traction power at 10% to 20% of the maximum force (Fig. 8). The mean first web space angle was significantly larger at 10% of the maximum muscle force after Camitz opponensplasty (51°; 95% CI, 49.3–52.5) compared with after modified Camitz (48°; 95% CI, 46.4–49.7; $P = .047$). At 20% of the maximum muscle force, there were no statistically significant differences between procedures in terms of the web space angle. At 30% of the maximum muscle force and 25 N, the modified Camitz opponensplasty resulted in a significantly larger first web space angle compared with those of the Burkhalter simulation opponensplasty (56° and 53°; 95% CI, 54.5–57.6; $P = .014$ and 57° and 53°; 95% CI, 55.4–58.7; $P = .008$, respectively) (Table 2).

Thumb pronation angle

The pronation angle increased with increasing traction force. The largest angle was observed after the Burkhalter simulation opponensplasty with 10% and 30% of estimated muscular force and 25 N. At 10% of the maximum muscle force, the angle was significantly smaller after Camitz opponensplasty compared with that after Burkhalter simulation opponensplasty (7°, 95% CI, 3.6–10.4 vs 14°, 95% CI, 10.2–17.0; $P = .03$). At 20% of the maximum muscle force, there were no statistically significant differences between procedures in terms of angles, although Camitz opponensplasty resulted in the smallest angle (16°; 95% CI, 9.5–22.0). At 30% of the maximum muscle force, the Camitz opponensplasty resulted in a significantly smaller angle (19°; 95% CI, 16.7–22.2) compared with that of the modified Camitz (25°; 95% CI, 22.3–27.8; $P = .02$) or the Burkhalter simulation opponensplasty (28°; 95% CI, 24.9–30.4; $P = .002$). With a loading force of 25 N, the thumb pronation angle was significantly smaller after Camitz opponensplasty (20°; 95% CI, 17.5–23.3) compared with that after modified Camitz opponensplasty (26°; 95% CI, 23.2–28.9; $P = .03$) or Burkhalter simulation opponensplasty (29°; 95% CI, 26.5–32.2; $P = .001$).

Discussion

Thumb opposition results from complex actions of the various thenar muscles and is effected by simultaneous movements in multiple directions at the carpometacarpal, metacarpophalangeal, and interphalangeal joints. This movement requires palmar abduction and pronation of the thumb to pinch the thumb pulp toward the finger pulps.[23,28] Although the APB creates the primary movement during thumb opposition and the flexor pollicis brevis and thumb muscles produce secondary movement,[23] thumb reconstruction must reproduce these complex movements using a single mover (a donor tendon) to achieve opposition.

The selection of donor muscle to be used as the power source, the site of the pulley, and the insertion position of the transferred tendon all influence the mechanical performance of contralateral reconstruction. Cooney et al[23] reported that the average fiber length of the thenar muscle is 3.5 cm and the average fiber lengths of the PL and EIP tendons are 4.9 and 5.5 cm, respectively, which makes these tendons suitable donors. Various studies reported the influence of the insertion position of the transferred tendon.[23,29,30] Skie et al[29] carried out a biomechanical study comparing the reconstructions of various tendon insertion sites and reported the Riordan method[31] to be a good and balanced method that involves insertion of the transferred tendon into the extensor pollicis longus and dorsal hood.[29] A biomechanical evaluation of thumb opposition revealed insertion into the flexor pollicis brevis and radial-dorsal-extensor hood or APB insertion sites to provide optimal opposition.[30] We inserted the transferred PL tendon into the APB according to Camitz's[6] method and assessed the results of opponensplasty with the transferred tendon at different directions without changing the insertion site or transferred tendon. Our quantitative assessment revealed that Camitz opponensplasty resulted in a significantly larger first web space angle at the beginning of opposition than that of the modified Camitz opponensplasty with an around-the-FCU pulley. However, the modified Camitz opponensplasty resulted in a significantly larger first web space angle during subsequent loading compared with that of Burkhalter simulation opponensplasty. Therefore, the Camitz opponensplasty can restore the first web space angle more than the modified Camitz and Burkhalter simulation opponensplasty can. On the other hand, in the pronation angle, we demonstrated that both the modified Camitz and Burkhalter opponensplasties produced a significantly bigger angle than the Camitz, with no significant difference between modified Camitz and Burkhalter (Table 2). Moreover, when we compared the difference in pronation angle of the Camitz with the modified Camitz and Burkhalter, the maximum differences were 6° and 9° with a 25-N traction force, respectively. The clinical importance of these results should be further evaluated, however, to determine whether restoration of pronation will contribute to regaining thumb pronation or tip-pinching function.

Whether Camitz opponensplasty can restore thumb pronation remains controversial.[12] MacDougal[32] proposed modifying this procedure using a pulley on the ulnar side of the flexor retinaculum based on the theory of Bunnell,[5] who emphasized that the transferred tendon should be directed toward the pisiform. The pulley is used to change the direction of pull with minimal friction, thus

Table 2
First Web Angles, Pronation Angles, and Statistical Comparison of Procedures

		Camitz (n = 6)		m-C (n = 6)		Burkhalter (n = 6)		*P* Value			
Variable	Traction Force	Mean	95% CI	Mean	95% CI	Mean	95% CI	C vs m-C*	C vs B*	m-C vs B*	Analysis of Variance
First web	10%	51	49–52	480	46–50	49	47–50	.047	.756	.148	.048
	20%	52	49–55	55	52–58	51	48–53	.268	.752	.089	.096
	30%	54	52–55	56	54–58	53	51–54	.138	.369	.014	.017
	25 N	55	53–56	57	55–59	53	51–55	.170	.200	.008	.011
Pronation	10%	7	4–10	12	9–16	14	10–17	.078	.031	.845	.029
	20%	16	9–22	23	16–29	20	14–26	.230	.574	.751	.255
	30%	19	17–22	25	22–28	28	25–30	.023	.002	.330	.002
	25 N	20	17–23	26	23–29	29	26–32	.025	.001	.208	.002

B, Burkhalter; C, Camitz; m-C, modified Camitz.
* *P* values for pairwise group comparisons were adjusted for multiplicity using Tukey's procedure. Procedures were compared using one-way analysis of variance with repeated measures.

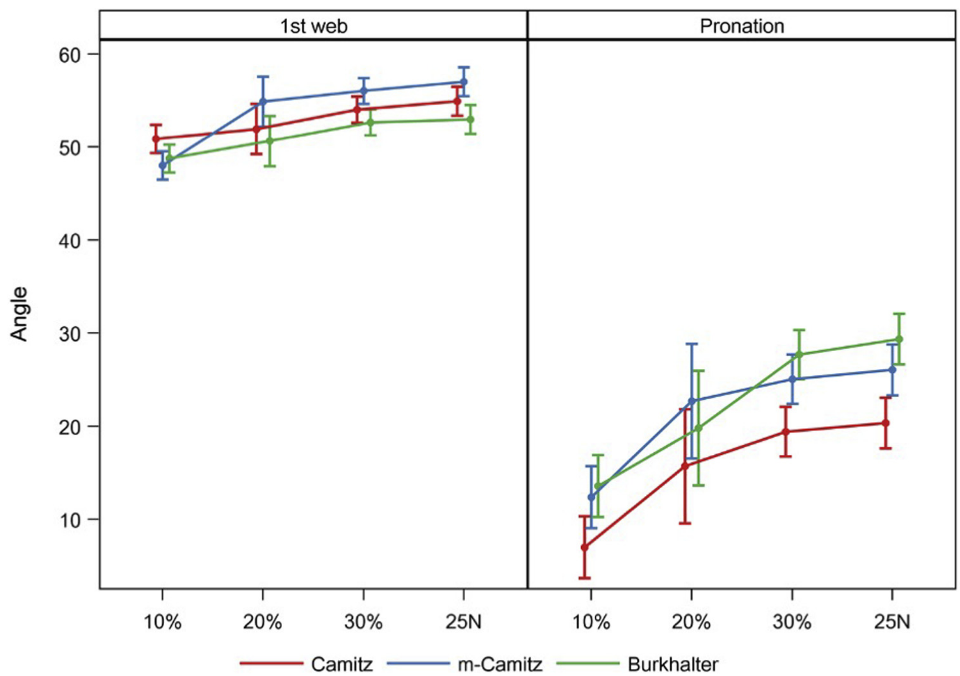

Figure 8. The measured first web space and pronation angles at 10%, 20%, and 30% of the maximum force of the PL and at 25 N.

avoiding loss of muscle power.[32] We found Camitz opponensplasty to produce a significantly smaller pronation angle than those of the other 2 procedures. In EIP transfer, this improves the efficiency of the pulley near the pisiform.

The location of the pulley and the route of the transferred tendon have been reported to affect pronation significantly, with transfers that are more distal to the pisiform achieving more flexion and contributing more to first metacarpal pronation through increased thumb–metacarpal flexion, carpometacarpal rotation, and abduction, resulting in a greater flexion force.[23] By contrast, transfers more proximal to the pisiform achieve greater abduction but reduced first metacarpal flexion.[23] Our findings support this, confirming that the increasingly distal placement of the pulley results in reduced palmar abduction but a larger pronation angle; the opposite was observed with the increasingly proximal placement of the pulley. The procedures can be ordered as follows, by pulley placement from more distal to more proximal: Burkhalter, modified Camitz, and Camitz opponensplasties. We found more proximal placement to be associated with larger abduction angles and more distal placement to be associated with a larger pronation angle.

Camitz and modified Camitz opponensplasties require only an incision that is almost the same as for open CTR for the harvest of the donor tendon, which results in minimal functional deficit.[8] Minimal postoperative rehabilitation is required to ensure that the PL action is synergic with the APB.[33] The PL tendon is of sufficient length even for an around-the-FCU pulley in modified Camitz opponensplasty. Conversely, Burkhalter opponensplasty requires multiple incisions, and an extension lag of the index finger may occur after the EIP is harvested from the proximal extensor hood.[34,35] Limited tendon length and excursion have been observed after EIP transfer; trans-interosseous transfer is suggested as an alternative.[34] However, although EIP transfer may be a better option for patients with high median palsy, with combined median and ulnar palsies, without a PL tendon, or with an injured aponeurosis, we suggest that it is a better option for patients who require better pronation irrespective of whether the lesion is a low or high palsy.

This study had several limitations. First, the sample size was small. However, the findings are valuable because 3 different methods were evaluated in each arm. Second, we could not evaluate the clinical outcomes or pathological differences between biological tissues because we used cadavers. Despite its popularity, an around-the-FCU pulley can exhibit postoperative proximal migration, resulting in the transferred tendon running along a more longitudinal line.[14] Thus, the pronation angle may decrease over time after modified Camitz opponensplasty. Third, in this study, the order of testing was always Camitz, modified Camitz, and Burkhalter on each arm. Therefore, it is possible that the order of surgical procedures might have affected the outcome. Repeated testing might have resulted in loosening of the sutures and extension of the tendon. However, this mechanics test was evaluated by the tendon traction force rather than the tendon traction distance. Although suture loosening did not occur grossly, even if suture loosening did occur, it did not affect the traction force of the tendon. Therefore, we believe that the impact on the results of this study is insignificant. Finally, we used a superficial sensor to track motion during the loading test with a maximum load of 25 N to minimize stress on the insertion site, although the estimated physiological muscle forces were 64.39 N for the PL and 60.81 N for the EIP. Our observations at the end of loading might reflect the mechanisms that occurred during physiological loading. However, although we limited the maximum load, we were unable to avoid influencing the insertion site. For example, sutures were broken or loose while the PL tendon was pulled, so different biomechanical effects might be observed during actual opposition.

This study clarifies the outcomes of opponensplasty using different routes for the transferred tendon. Modified Camitz opponensplasty produces relatively balanced first web space and pronation angles in thumb opposition, but it carries the risk of proximal migration in the postoperative course. Conversely, Burkhalter opponensplasty is suitable for patients with high median palsy, combined median and ulnar palsies, and injured palmar aponeurosis or those who require improved pronation. Camitz opponensplasty produces insubstantial pronation. A careful assessment of the clinical needs of the patient before intervention may enable therapeutic planning to achieve appropriate thumb movement.

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References

1. Atroshi I, Gummesson C, Johnsson R, et al. Prevalence of carpal tunnel syndrome in a general population. *JAMA*. 1999;282(2):153–158.
2. de Krom MC, Knipschild PG, Kester AD, et al. Carpal tunnel syndrome: prevalence in the general population. *J Clin Epidemiol*. 1992;45(4):373–376.
3. Marquardt TL, Nataraj R, Evans PJ, et al. Carpal tunnel syndrome impairs thumb opposition and circumduction motion. *Clin Orthop Relat Res*. 2014;472(8):2526–2533.
4. Burkhalter WE. Early tendon transfer in upper extremity peripheral nerve injury. *Clin Orthop Relat Res*. 1974;(104):68–79.
5. Bunnell S. Reconstructive surgery of the hand. *Surg Gynecol*. 1924;34:259–274.
6. Camitz H. Surgical treatment of paralysis of opponens muscle of thumb. *Acta Orthop Scand*. 1929;65:77–81.
7. Littler JW, Li CS. Primary restoration of thumb opposition with median nerve decompression. *Plast Reconstr Surg*. 1967;39(1):74–75.
8. Kato N, Yoshizawa T, Sakai H. Simultaneous modified Camitz opponensplasty using a pulley at the radial side of the flexor retinaculum in severe carpal tunnel syndrome. *J Hand Surg Eur*. 2014;39(6):632–636.
9. Foucher G, Malizos C, Sammut D, et al. Primary palmaris longus transfer as an opponensplasty in carpal tunnel release: a series of 73 cases. *J Hand Surg Br*. 1991;16(1):56–60.
10. Terrono AL, Rose JH, Mulroy J, et al. Camitz palmaris longus abductorplasty for severe thenar atrophy secondary to carpal tunnel syndrome. *J Hand Surg Am*. 1993;18(2):204–206.
11. Hattori Y, Doi K, Sakamoto S, et al. Camitz tendon transfer using flexor retinaculum as a pulley in advanced carpal tunnel syndrome. *J Hand Surg Am*. 2014;39(12):2454–2459.
12. Naeem R, Lahiri A. Modified Camitz Opponensplasty for severe thenar wasting secondary to carpal tunnel syndrome: case series. *J Hand Surg Eur Vol*. 2013;38(4):795–798.
13. Cooney WP. Tendon transfer for median nerve palsy. *Hand Clin*. 1988;4(2):155–165.
14. Lee DH, Oakes JE, Ferlic RJ. Tendon transfers for thumb opposition: a biomechanical study of pulley location and two insertion sites. *J Hand Surg Eur Vol*. 2003;28(6):1002–1008.
15. Park I-J, Kim H-M, Lee S-U, et al. Opponensplasty using palmaris longus tendon and flexor retinaculum pulley in patients with severe carpal tunnel syndrome. *Arch Orthop Trauma Surg*. 2010;130(7):829–834.
16. Al-Quattan MM. Technique of split flexor carpi ulnaris opponensplasty. *J Hand Surg Am*. 2017;48:1–3.
17. Burkhalter W, Christensen RC, Brown P. Extensor indicis proprius opponensplasty. *J Bone Joint Surg Am*. 1973;55(4):725–732.
18. Lemonas P, Laing T, Ghorbanian S, et al. Extensor indicis proprius opponensplasty—The Burkhalter revisited. *J Hand Microsurg*. 2012;04(2):47–49.
19. Akram M, Farooqi FM, Shahzad ML, et al. Burkhalter opponensplasty; role in isolated median nerve injury. *J Pak Med Assoc*. 2014;64(12 suppl 2):S172–S174.
20. Anderson GA, Lee V, Sundararaj GD. Extensor indicis proprius opponensplasty. *J Hand Surg Br*. 1991;16(3):334–338.
21. Anderson GA, Lee V, Sundararaj GD. Opponensplasty by extensor indicis and flexor digitorum superficialis tendon transfer. *J Hand Surg Br*. 1992;17(6):611–614.
22. Mehta R, Malaviya GN. Evaluation of the results of opponensplasty. *J Hand Surg Br*. 1996;21(5):622–623.
23. Cooney WP, Linscheid RL, An K-N. Opposition of the thumb: an anatomic and biomechanical study of tendon transfers. *J Hand Surg*. 1984;9(6):777–786.
24. Braun RM. Palmaris longus tendon transfer for augmentation of the thenar musculature in low median palsy. *J Hand Surg Am*. 1978;3(5):488–491.
25. Boswick JA, Stromberg WB. Isolated injury to the median nerve above the elbow: a review of thirteen cases. *J Bone Joint Surg Am*. 1967;49(4):653–658.
26. Steindler A. Flexor plasty of the thumb in thenar palsy. *Surg Gynecol Obstet*. 1930;50:1005–1007.
27. Brand PW, Beach RB, Thompson DE. Relative tension and potential excursion of muscles in the forearm and hand. *J Hand Surg Am*. 1981;6(3):209–219.
28. Goto A, Leng S, Sugamoto K, et al. In vivo pilot study evaluating the thumb carpometacarpal joint during circumduction. *Clin Orthop Relat Res*. 2013;472(4):1106–1113.
29. Skie MC, Parent T, Mudge K, et al. Kinematic analysis of six different insertion sites for FDS opponensplasty. *Hand (N Y)*. 2009;5(3):261–266.
30. Roach SS, Short WH, Werner FW, et al. Biomechanical evaluation of thumb opposition transfer insertion sites. *J Hand Surg Am*. 2001;26(2):354–361.
31. Riordan DC. Surgery of the paralytic hand. In: F.C. Reymolds, ed. *American Academy of Orthopaedic Surgeons Instructional Course Lectures*. Vol 16. St Louis: The CV Mosby Co; 1959:79–90.
32. MacDougal BA. Palmaris longus opponensplasty. *Plast Reconstr Surg*. 1995;96(4):982–984.
33. Rymer B, Thomas PBM. The Camitz transfer and its modifications: a review. *J Hand Surg Eur Vol*. 2016;41(6):632–637.
34. Mehta R, Malaviya GN, Husain S. Extensor indicis opposition transfer in the ulnar and median palsied thumb in leprosy. *J Hand Surg Eur Vol*. 1996;21(5):617–621.
35. Al-Quattan MM. Extensor indicis proprius opponensplasty for isolated traumatic low median nerve palsy: a case series. *Can L Plast Surg*. 2012;20(4):255–257.