Opposition of the thumb: An anatomic and biomechanical study of tendon transfers

Tendon transfers for opposition of the thumb were anatomically and biomechanically studied to help determine the optimal criteria for selecting the best motor unit for a transfer. Forearm and hand muscle volume, mean fiber length, and cross-sectional area were measured in eight fresh specimens of the upper extremity to determine which muscles best replace lost thenar muscle strength. In a separate group of 18 specimens, the effective moment arms for abduction and flexion of the first metacarpal were calculated in vitro and from biplanar radiographic techniques to determine the effect of eight different opposition transfers on thumb abduction, rotation, and strength. Results of these studies demonstrate that the transfers of flexor digitorum superficialis (FDS) of the long finger and extensor carpi ulnaris best replaced lost thenar muscle strength and provided maximal abduction and near full thumb rotation. The transfers of the extensor carpi radialis longus and the FDS of the ring finger replaced 60% and 40% of required thenar muscle strength, respectively. The palmaris longus was the least effective transfer, having good abduction but weak flexion and opposition. Motion, balance, and strength of tendon transfers must be considered for effective thumb opposition. (J HAND SURG 9A:777-86, 1984.)

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Bunnell1 emphasized the value to mankind of an opposable thumb and set forth the framework for surgical restoration. He and others demonstrated that thumb opposition is a key factor in providing motion and strength for both prehensile pinch and grasp.2

Opposition of the thumb results from angulatory motion (abduction) at the carpometacarpal (CMC) joint and flexion and rotation of both the CMC and metacarpophalangeal (MP) joints.3 Active muscles include the abductor pollicis brevis (APB), the opponens pollicis (OPP), and the superficial head of the flexor pollicis brevis (FPB). The simultaneous actions of these muscles affect both the trapeziometacarpal and MP joints to produce thumb opposition. The abductor pollicis longus (APL) and the extensor pollicis brevis (EPB) contribute only indirectly to opposition by extension of the first metacarpal, while the extensor pollicis longus...
at or near the pisiform,\textsuperscript{4, 11, 12} around the PL\textsuperscript{5, 7} and the flexor carpi ulnaris (FCU),\textsuperscript{1, 7} or under the transverse carpal ligament\textsuperscript{6, 6} have been proposed. Tendon insertions into the APB,\textsuperscript{12} the superficial portion of the FBP,\textsuperscript{5} the ADD,\textsuperscript{13} the dorsoulnar aspect of the proximal phalanx,\textsuperscript{1} or combinations of these tendon units\textsuperscript{1} have been recommended, with different rationales for each procedure. While the main guidelines for appropriate opponensplasty transfers have been outlined and reviewed by several authors,\textsuperscript{1, 2, 16, 17} some questions remain: What is the most effective donor muscle to replace lost thenar strength? What is the preferred pulley location to provide the desired direction of action? What are the optimal insertion techniques for full rotation of the thumb? The specific aim of this article is to understand better the anatomic and biomechanical principles involved in thumb opposition and to determine which tendon transfers best restore thumb function.

Methods and material

To effectively study the concept of tendon transfers to restore thumb opposition, three interrelated experiments were performed: (1) anatomic study of the mechanical function of thumb muscles, (2) quantitative measurement of hand and forearm muscle volume, mean fiber length, and cross-sectional area, and (3) biomechanical analysis of eight opponens transfers.

Anatomic study. The first study was a dynamic analysis of the contribution of thumb intrinsic and extrinsic muscles to thumb opposition. Function of the APB, the OPP, and the superficial portion of the FBP was observed in five fresh-frozen and thawed upper limb specimens by applying 200 gm of traction to the tendon of origin. The extrinsic muscles (APL, flexor pollicis longus [FPL], and EPL) were similarly studied. A consistent direction of action for each tendon was maintained with use of the carpal tunnel and forearm fascia as the pulley. The wire suture attached to the tendon was then directed to a mechanical pulley to which the 200 gm load was attached. Tendon load may have varied slightly because of frictional forces and pulley effect. With the tendon load applied, the effect on abduction, flexion, and rotation of the thumb metacarpal was recorded and the moment arm of each muscle was measured by a ruler from the trapeziometacarpal joint center of rotation (located in the base of the thumb metacarpal)\textsuperscript{3} through a perpendicular distance to the center of the tendon or muscle under study.

Muscle quantitation measurements. In the second part of the study, eight fresh-frozen and thawed, surgically amputated specimens were dissected to obtain
quantitative measurements of hand and forearm muscle volumes, muscle fiber length, and cross-sectional area. The technique of individual muscle dissection and measurement is identical to that described by Brand et al. Individual hand and forearm muscles were exposed by anatomic dissections (Fig. 1). Muscle mean fiber length for individual hand and forearm muscles was determined (Fig. 2) in the resting position as the length between the tendon of origin and the tendon of insertion. Muscle volume was determined by water displacement techniques. Physiologic cross-sectional area was calculated by dividing muscle volume by mean fiber length.

From these quantitative studies, thenar muscle volume, mean fiber length, and physiologic cross-sectional area were compared with similar measurements of potential tendon transfer units. The physiologic cross-sectional area of individual muscles divided by that of all muscles in the hand and forearm is the same as the tension fraction, and the individual percentage of volume is the same as the mass fraction that was described by Brand et al.

Opponens transfers in vitro. In the third portion of the study, eight tendon transfers for thumb opposition were performed in 18 fresh cadaver specimens by techniques as described by their originators (Figs. 3 and 4). The FDS tendons of the long and ring fingers were transferred through the carpal tunnel and first metacarpal or through a pulley loop of the FCU with Bunnell or Brand insertions. The EIP and EDQ were transferred both distally and proximally to the pisiform with insertions similar to those of Bunnell and Riordan. The ADQ was transferred on its neurovascular pedicle, with a dual insertion into the APB. The PL was lengthened with palmar fascia and inserted directly without a pulley into the APB or it was transferred around an ulnar pulley of forearm fascia with an APB insertion. Finally, the ECU and ECRL were transferred into the EPB and EPL, respectively, with the donor tendon passed ulnarily around the distal forearm proximal to the pisiform.

After each of the tendon transfers, the effect on thumb opposition was measured by applying a 500 gm weight load on each of the tendons (Fig. 5). A wire suture was placed through the transferred tendon close to the pisiform, so that the direction of tendon pull would be similar. The pulley in the hand consisted of a split portion of FCU, the pisiform fascia, the palmar and forearm fascia, or the carpal tunnel (depending on the technique of tendon transfer performed). The wire suture was then directed proximally to a mechanical pulley and loaded with a 500 gm weight. Because of different vectors of applied load, the force delivered to each transfer was a factor of the angle of tendon pull. No attempt was made to measure the exact load applied.

After application of the tendon forces, palmar ab-
duction of the thumb was measured in centimeters from the third metacarpal head and in degrees between the first and the second metacarpal. The flexion-extension stance of the MP joint also was determined. Thumbnail rotation was measured by a T-marker placed parallel to the dorsal surface of the nail. Moment arms for each tendon transfer were measured from biplanar radiographs taken with a background metal grid (Fig. 6). Small Kirschner wires (K-wires), previously placed in the transferred tendon, could be identified on the biplanar radiographs. Abduction and flexion moment arms for each of the transferred tendons could then be calculated separately from the center of rotation of the thumb trapeziometacarpal joint. Specific pulley location, direction of action, and tendon insertion technique for each of the transfers were noted. Tendon transfers performed are the more commonly described and clinically applied. This study was not intended to measure each muscle transfer through each pulley or with every feasible tendon insertion technique.

Fig. 3. Pulley placement for tendon transfers: 1, proximal to pisiform (ECRL, ECU); 2, rotated on pisiform (ADQ); 3, distal to pisiform (EIP); 4, tendon loop of FCU; and 5, carpal tunnel of palmaris longus fascia.

Fig. 4. Tendon insertion techniques (as described by various originators): 1, APB; 2, FPB and dorsal hood; 3, APB and EPL and dorsal hood; 4, APB and first metacarpal; 5, EPL and EPB; and 6, APB and EPL. Combined insertions of Brand and Riordan preferred for median-ulnar palsy.

Results

Anatomic study. From direct observation after loading each intrinsic and extrinsic tendon, we noted that the APB was the prime mover for thumb opposition, providing abduction, flexion, and rotation for both the trapeziometacarpal joint and the MP joint.\textsuperscript{21-23} Rotation of the first metacarpal occurred as a function of thumb trapeziometacarpal joint abduction and flexion movements. Increased thumb opposition was observed to follow increased thumb flexion and abduction, and there did not appear to be any direct rotational pull from the APB or OPP muscles.
The APL was observed to be an effective thumb extensor but a weak abductor based on its short abductor moment arm. Tendon slips from the APL and PL contributed to thumb abduction (and opposition) by interconnecting musculotendinous fibers to the APB tendon of insertion. The FPL, EPL, and EPB had no direct action on thumb opposition.

The OPP and the superficial FPB were secondary motors for opposition. The OPP originated deep but parallel to the radial-half of the APB. Its fibers were shorter radially near the joint, while the ulnar fibers were longer, the latter providing a definite mechanical advantage as a result of their greater moment arm. The opponens primarily flexed and abducted the first meta-
Fig. 6. Biplanar radiographic technique of moment arm measurements: ADQ tendon transfer moment arm (A) in abduction (9 mm) and (B) in flexion (30 mm) measured from the trapeziometacarpal joint (TRAP) center of rotation. Roentgenographic grid corrects for magnification and divergence of x-ray beam.

Table I. Moment arms at the trapeziometacarpal joint

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Abduction (cm)</th>
<th>Flexion (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>APB</td>
<td>1.5</td>
<td>1.2</td>
</tr>
<tr>
<td>OPP</td>
<td>0.75</td>
<td>2.0</td>
</tr>
<tr>
<td>Superficial FPB</td>
<td>0.50</td>
<td>2.2</td>
</tr>
<tr>
<td>APL</td>
<td>0.25</td>
<td>-1.0</td>
</tr>
<tr>
<td>FPL</td>
<td>-0.5</td>
<td>2.8</td>
</tr>
</tbody>
</table>

The FPB was a stronger flexor than abductor of the thumb. It contributed to first metacarpal pronation as a result of thumb metacarpal flexion and the related obligatory CMC rotation.

Abduction and flexion moment arms of thumb intrinsic and extrinsic muscles were recorded (Table I). The APB was effective in both abduction and flexion, while the OPP, the superficial FPB, and the APL contributed primarily to thumb flexion and extension.

Muscle quantitation measurements. In this part of the study, individual thenar muscle volumes (mass fractions), physiologic cross-sectional area (tension fraction), and mean fiber length (Table II) were compared with forearm extrinsic and hand intrinsic muscles recommended for opponens transfer (Table III). Thenar muscles consist of a combined muscle volume of 12.6 cm³ (2.8% mass fraction), a cross-sectional area of 6.0 cm² (3.8% tension fraction), and an average mean fiber length of 3.5 cm (Table II).

Of the transferred muscles (Table III), the FDS of the long finger and the ECU muscles closely approximated thenar muscle strength and potential excursion. The ECRL and the FDS of the ring finger had approximately 80% and 60%, respectively, of the required thenar muscle strength. Other motors for transfer (EIP, EDQ, PL, ADQ) were significantly weaker, with muscle cross-sectional areas ranging from 1.6 to 2.1 cm² and tension fractions of 1.0% to 1.5%, in comparison with a total thenar muscle area of 6.0 cm² (tension fraction 3.8%).
Table II. Thenar muscle mass and volume

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Muscle volume (cm³)</th>
<th>Mean fiber length (cm)</th>
<th>Cross-sectional area (cm²)</th>
<th>Tension fraction (%)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>APB</td>
<td>4.9</td>
<td>3.3</td>
<td>1.7</td>
<td>1.1</td>
</tr>
<tr>
<td>OPP</td>
<td>4.2</td>
<td>2.4</td>
<td>3.5</td>
<td>1.8</td>
</tr>
<tr>
<td>FPB†</td>
<td>3.5</td>
<td>4.8</td>
<td>0.8</td>
<td>0.9</td>
</tr>
<tr>
<td>Total</td>
<td>12.6</td>
<td>10.5</td>
<td>6.0</td>
<td>3.8</td>
</tr>
</tbody>
</table>

(% Mass fraction = 2.8%)‡

*Percent tension fraction is equal to muscle area divided by total area of each hand-forearm specimen.
†Superficial head.
‡Percent mass fraction is equal to muscle volume(s) divided by total hand-forearm muscle volume.

Table III. Selected hand and forearm muscle measurements (potential transfers)

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Mean muscle volume (cm³)*</th>
<th>Mean fiber length (cm)*</th>
<th>Cross-sectional area (cm²)*</th>
<th>Tension fraction (%)‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>FDS of long finger</td>
<td>39.0</td>
<td>6.8</td>
<td>5.8</td>
<td>3.7</td>
</tr>
<tr>
<td>ECU</td>
<td>28.0</td>
<td>4.5</td>
<td>6.2</td>
<td>4.1</td>
</tr>
<tr>
<td>FDS of ring finger</td>
<td>24.0</td>
<td>7.5</td>
<td>3.2</td>
<td>2.2</td>
</tr>
<tr>
<td>ECRL</td>
<td>38.0</td>
<td>9.4</td>
<td>4.0</td>
<td>3.1</td>
</tr>
<tr>
<td>EPL</td>
<td>10.2</td>
<td>5.4</td>
<td>1.9</td>
<td>1.1</td>
</tr>
<tr>
<td>EIP</td>
<td>8.6</td>
<td>5.5</td>
<td>1.7</td>
<td>1.1</td>
</tr>
<tr>
<td>EDQ</td>
<td>9.4</td>
<td>5.8</td>
<td>1.6</td>
<td>1.0</td>
</tr>
<tr>
<td>Palmaris longus</td>
<td>9.0</td>
<td>4.9</td>
<td>1.8</td>
<td>1.0</td>
</tr>
<tr>
<td>ADQ</td>
<td>9.0</td>
<td>4.5</td>
<td>2.1</td>
<td>1.5</td>
</tr>
</tbody>
</table>

*†Superficial hand-forearm measurements.
‡Percent tension fraction is equal to muscle area divided by total area of each hand-forearm specimen.

Table IV. Opposition measurements in vitro

<table>
<thead>
<tr>
<th>Transfer</th>
<th>Abduction (palmar)</th>
<th>Thumbnail rotation*</th>
<th>MP joint motion</th>
<th>Moment arm (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Abduction</td>
</tr>
<tr>
<td>FDS from long and ring fingers</td>
<td>5.6 cm/59°</td>
<td>70°-135° (65°)</td>
<td>Flexion 25°</td>
<td>18</td>
</tr>
<tr>
<td>ECU and ECR</td>
<td>5.3 cm/50°</td>
<td>82°-118° (36°)</td>
<td>Extension 10°</td>
<td>16</td>
</tr>
<tr>
<td>RP</td>
<td>5.0 cm/52°</td>
<td>72°-138° (66°)</td>
<td>Flexion 20°</td>
<td>15</td>
</tr>
<tr>
<td>ADQ</td>
<td>4.0 cm/37°</td>
<td>97°-145° (48°)</td>
<td>Flexion 15°</td>
<td>10</td>
</tr>
<tr>
<td>EDQ</td>
<td>4.5 cm/42°</td>
<td>88°-138° (50°)</td>
<td>Flexion 15°</td>
<td>10</td>
</tr>
<tr>
<td>PL</td>
<td>3.0 cm/35°</td>
<td>90°-138° (48°)</td>
<td>Flexion 10°</td>
<td>12</td>
</tr>
</tbody>
</table>

*Total rotation range in parentheses.

With respect to potential excursion, all eight transfers had mean fiber lengths of 6.0 cm or more (range 4.5 to 9.4 cm), which were greater than the average mean fiber length of the thenar muscles (3.5 cm).

Opponens transfers in vitro. After opposition transfers, abduction from the palm (second metacarpal head) was greatest after transfers of the FDS from the long and ring fingers and after ECU and ECRL transfers (Table IV). Abduction was slightly less after ADQ and EDQ transfers, which had a direction of action distal to the pisiform. Thumbnail rotation was highest after FDS and EIP transfers and lowest after ECU and...
transfers performed in this study had more than adequate muscle amplitude (excursion) to provide full abduction, rotation, and flexion to properly position the thumb in opposition to the fingers. With an average excursion of 6.0 cm (range 4.5 to 9.4 cm), all of the tendon transfers will compensate well for lost thumus muscles, which have an average excursion of 3.5 cm. In other words, if the goal of performing a tendon transfer is thumb opposition motion, any of the tendon transfers performed in this study, combined with a proper direction of action, will provide muscle excursion that is extremely beneficial to hand function.

Full thumb opposition is the second goal of opposition transfers. The position of the thumb in full opposition is related to the direction of action and the insertion of the tendon transfer. In this study, we observed that opposition was not significantly affected by varying the tendon insertion, except for those transfers that produced extension of the MP joint. We did not study each of the tendon transfers with each different insertion technique, but studied only those most commonly performed, with the result that different tendon direction of actions could influence insertion effect. However, most radial insertions have a similar effect on thumb opposition. Only when the EPL or EPB was utilized as the tendon of insertion was this not the case. In these instances, thumbnail rotation was approximately 30° to 40° less than with other transfers, and extension of the MP joint was generally associated with supination action of the thumb. Since abduction and pronation of the thumb are essential for opposition, these tendons of insertion seemed less desirable and produced an extension stance that simulated a lack of thumb balance.

In a similar manner, Bunnell’s insertion into the dorsoulnar aspect of the proximal phalanx of the thumb did not appear to be necessary to provide thumb rotation and appeared to have the same disadvantages of extension of the MP joint. We found that tendon transfer insertions into the APB tendon alone resulted in full opposition. Therefore, it appears that more complex insertions such as Riordan’s (APB and EPL tendons) and Brand’s (APB, dorsal joint capsule, and adductor insertion) should be reserved for special circumstances such as combined median and ulnar palsies, in which all intrinsic power to the thumb is lost.

With respect to direction of action of opposition transfers, Bunnell stressed the principle that the transfer be directed toward the pisiform. Our studies confirm this observation. Both motion and force in opposition can be significantly affected by the pulley placement or line of action of the transferred tendon (Fig. 7). Transfers distal to the pisiform, such as those with the ADQ
and EDQ, are directed more for flexion than abduction and should have greater flexion force. Transfers proximal to the pisiform that use an FCU loop as the pulley, such as those with the FDS, will have more abduction action and relatively less first metacarpal flexion. Applying this principle of adjustable tendon placement, there is no truly preferred pulley location. Opposition transfers could be placed either distal or proximal to the pisiform, in order to meet the specific clinical needs of each patient.

When there is combined median and ulnar nerve palsy with loss of both abduction and flexion, we believe that a transfer directed distal to the pisiform with Riordan or Brand insertion techniques should be considered. Mechanically, such a transfer would be more rewarding than one proximal to the pisiform because of the increased adduction-flexion strength. Thumb balance must be considered, however, so that thumb prehension is not compromised by transfers with excessive flexion tone. If thumb extension strength is inadequate, such a transfer would be contraindicated. Alternatively, if sufficient muscle-tendon units are available, transfer for both thumb adduction and opposition should be considered.

Finally, with respect to prehensile strength, we have found, as have others, that the force required for strong opposition is related to the cross-sectional area of the transferred muscle. Cross-sectional area of the thenar muscles is 6.0 cm² (3.8% tension fraction). The FDS of the long finger (tension fraction 3.7%) and ECU muscle tendon units (tension fraction 4.1%) are transfers with sufficient muscle tension (force) to fully substitute for lost opposition strength. They would expend the least force in providing thumb opposition, yet retain sufficient forces for power pinch activities. They have adequate excursion, they can be transferred without giving up a great deal to overall hand function, and they have sufficient strength so that even in losing a grade they would still be quite active. The FDS of the ring finger and the ECRL are second best, providing 60% and 80%, respectively, of the force that is normally required and have more than adequate excursion for full opposition.

Several of the other transfers performed in this study, however, do not match lost thenar muscle strength, although they may be adequate depending on the purpose of the transfer. If the function of the tendon transfer is to increase range of motion, that is, positioning the thumb in opposition, all of the transfers studied have sufficient excursion (mean fiber length) to accomplish this assignment. If strength is also needed, only a few transfers qualify. For example, in low median nerve palsy, transfers of such tendons as the EIP, EDQ, and PL should function adequately since the adductor and deep flexor brevis provide strength and their primary purpose is to position the thumb in opposition. In combined median and ulnar palsy, when all thumb intrinsic muscles are lost, a significant loss of pinch force occurs. In these circumstances, restoration of strength is needed through strong motor groups, such as the FDS of the long or ring fingers or wrist extensor transfers.

Opposition of the thumb through tendon transfers can be optimized by the consideration of factors related to muscle physiology. For the proper selection of motor muscle units, absolute strength of a muscle can be related to its physiologic cross-sectional area and excursion of the tendon transfer can be related to its mean fiber length. Work capacity of a muscle can be related to the muscle volume or mass (area × mean fiber length). “Power” is a term more strictly reserved to indicate the time rate at which work is done. By the application of comparative muscle volumes and physiologic cross-sectional areas described herein for thumb opposition, one can select the most appropriate tendon transfer by considering tendon excursion, strength, and a proper direction of action.

Conclusion

A large number of tendon transfers have been described to restore opposition to the thumb. This study examined the most common transfers and evaluated the mechanical factors that would give optimal results. We have found that when many options are available and the associated factors appear to be equal, the FDS of the long or ring fingers and the wrist extensor (ECU, ECRL) muscles best approximate the force and motion required for full thumb opposition and, therefore, are preferred. Wrist extensor transfers, when combined with thumb extensor tendons for their insertion, will provide adequate abduction with MP joint extension but will result in less thumb rotation. Loss of MP flexion in these transfers may result in reduction of pinch strength. Transfers of EIP, EDQ, and ADQ have sufficient mean fiber length (excursion) to provide for full thumb opposition but they lack adequate strength. The PL transfer has good abduction but weak flexion and decreased muscle strength. In selecting tendons for transfer, consideration of strength as well as excursion is important for a successful outcome.

The authors acknowledge the contributions of Dr. Paul Brand in the hand dissection and insights in regard to muscle fiber lengths, excursion, and strength and Dr. R. Michael Gross for his studies on the cross-sectional anatomy.
REFERENCES

5. Royle ND: An operation for paralysis of the intrinsic muscles of the thumb. JAMA 111:612-3, 1938