Functional Loss With Displacement of Medial Epicondyle Humerus Fractures: A Computer Simulation Study

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Background: Assessment and management of the medial humeral epicondyle fracture remains controversial, with conflicting reports of displacement direction and consequent functional deficits unclear. The purpose of this study was to define biomechanically likely directions of medial epicondyle fracture displacement and to determine possible changes in muscle function related to that displacement.

Methods: A 3-dimensional computer model of the upper extremity was used to simulate the consequences of medial epicondyle fracture displacements from 1 to 20 mm in the anterior, medial, and inferior directions relative to the humerus with the elbow at 90-degree flexion and neutral forearm rotation (a replication of accepted positions for clinical strength testing). Muscle length and force were calculated following displacement. Maximum isometric wrist flexion moments were calculated over the full range of wrist motion based on known force-generating properties of the muscles.

Results: Anterior displacement resulted in shortened muscles and reduced wrist flexion moment, with a decrease in strength averaging 2% for every 1 mm of anterior fragment displacement at neutral wrist position (maximum decrease of 39% with 20 mm displacement). In contrast, displacement in the medial and inferior directions resulted in stretched muscles and increased wrist flexion moments and therefore are not biomechanically likely.

Conclusions: Computer simulation of a medial epicondyle fracture suggests that anterior displacement could result in a dramatic loss of initial muscle strength and function. Medial displacement is unlikely to occur in vivo due to consequential muscle lengthening, suggesting that alternatives to the historical use of AP radiographs to assess displacement of this fracture are needed.

Clinical Relevance: Our work provides a biomechanical explanation for anterior displacement of medial epicondyle fractures observed radiographically and motivates alternative methods of fracture assessment. A functional basis for determining acceptable displacement of medial epicondyle fractures is suggested; however, all individual clinical factors should be considered.

Key Words: medial epicondyle, fracture, acceptable displacement, loss of function

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Treatment for medial epicondyle humerus fractures ranges from conservative management to surgical intervention, with available literature supporting both.[1,2] There are absolute indications for operative management, including an open fracture or an entrapped intra-articular fragment,[3,4] as well as relative indications, including: valgus instability, ulnar neuritis, and various amounts of fragment displacement.[5] The hypothesis for recommending surgery when a fragment is displaced is that a displaced fragment may result in pain, instability, nonunion, and muscle weakness.[3,4] Historical publications over the past 50 years have suggested that the primary displacement vector is medial, as measured on the anteroposterior (AP) radiographs,[1–8] and many authors have proposed a variety of thresholds for acceptable measures, ranging from 2 mm to 2 cm of medial displacement.[3–5]

However, it is unclear whether AP radiographs measuring medial displacement are accurate reflections of the true anatomic fragment displacement. Interobserver agreement for measurements of medial displacement is only 46%.[9] Moreover, a recent CT comparison study reported up to 15 mm of anterior displacement seen in a cohort of fractures believed to be nondisplaced medially by AP radiographs.[10] If true displacement is indeed anterior and not medial, then historical utilization of the AP radiograph may be inappropriate to direct surgical indications. Thus, it is critical to reexamine the biomechanics of medial epicondyle fracture, as well as the functional consequences of medial epicondyle displacement if anterior displacement is present.

The primary purpose of this study was to determine plausible directions of epicondyle fragment displacement following a fracture based on the biomechanics of the elbow joint and the involved musculature. Further, we sought to evaluate the potential magnitude of functional deficits associated with displacement of the flexor-pronator muscle origins in each anatomic direction using a computer simulation of medial epicondyle fracture displacement.

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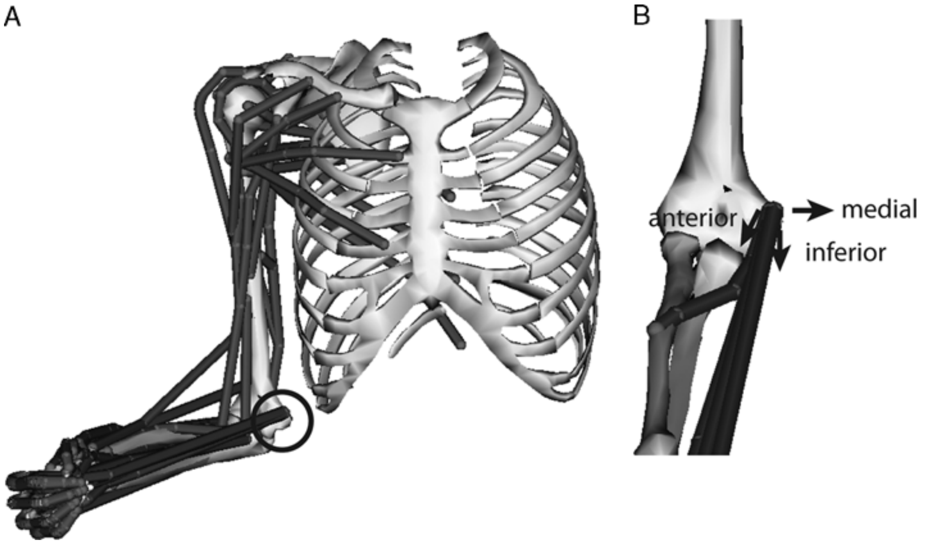

FIGURE 1. A, Three-dimensional upper limb model, fixed in 90 degrees elbow flexion and neutral forearm rotation. The origins of the muscles attached to the medial epicondyle (circled) were displaced to represent a fracture and subsequent displacement of the medial epicondyle. B, Fracture displacement was simulated for medial, anterior, and inferior directions.

METHODS

A previously developed and validated 3-dimensional computer model of the upper extremity was used to simulate the biomechanical consequences of medial epicondyle fracture displacement.[11] The model represents the bone geometry, joint kinematics, origin-to-insertion paths, and architectural parameters of 32 distinct muscles of the upper extremity, including 17 muscles actuating the wrist and forearm and the extrinsic finger muscles. The individual compartments of the flexor and extensor digitorum muscles are represented by 4 segments corresponding to the 4 digits. The muscles crossing the wrist and forearm in the model included: extensor carpi ulnaris, extensor carpi radialis brevis and longus, extensor digitorum communis (divided into 4 parts), extensor pollicis longus and brevis, extensor indicis propius, extensor digiti minimi, pronator teres (PT), pronator quadratus (PQ), flexor carpi radialis (FCR), flexor carpi ulnaris (FCU), flexor digitorum superficialis (FDS, divided into 4 parts: FDSL, FDSR, FDSI, FDSM), flexor digitorum profundis (FDP, divided into 4 parts: FDPL, FDPR, FDPM, FDPI), flexor pollicis longus (FPL), abductor pollicis longus (APL), and palmaris longus (PL).

Simulations were performed using a custom Matlab (The Mathworks, Natick, MA) scripting interface to OpenSim version 3.0 (Stanford, CA), an open-source musculoskeletal modeling software platform.[12] A medial epicondyle humerus fracture was simulated by altering the origin of the affected muscles. Displacements of the origins of muscles attached to the medial epicondyle were made from 1 to 20 mm (in 1 mm intervals) in the anterior, medial, and inferior directions relative to the axis of the distal humerus. The muscles attached to the medial epicondyle, and therefore the only muscles whose origins were altered, included: FCR, FCU, FDSL, FDSR, PL, and PT (Fig. 1). The paths of the muscles were allowed to move with the muscle origin but were constrained not to intersect with bones, other muscles, or the soft-tissue envelope.

To evaluate the biomechanical consequences of medial epicondyle displacement, we first evaluated the change in muscle length due to the displaced epicondyle, and the resulting force-generating capacity. The force a muscle produces at a given joint posture depends on its physiological cross-sectional area, fiber length, tendon length, and pennation angle. These architectural parameters were obtained from previous anatomic studies[13–17] and from imaging studies of the muscles of the arm.[18] The passive force is the force generated when a muscle is not active and is stretched. The active force is the force generated when a muscle is neurally activated. The total force a muscle can generate is the sum of these previous 2 forces.

To evaluate the potential change in function associated with epicondyle displacement due solely to changes in muscle path, we evaluated the maximum isometric wrist flexion moment-generating capacity of the muscles crossing the wrist. The moment-generating capacity of muscles crossing a joint is an objective measure of strength, and is analogous to clinical measurements of joint strength using a dynamometer. The total moment produced by muscles at a joint is a sum of the moments produced by each individual muscle. The moment produced by an individual muscle crossing the joint of interest is calculated using our model by multiplying its total force and its moment arm (a measure of the distance of the muscle from the joint rotation center). The moment arm for each muscle is determined by the model according to the path of the muscle and the posture of the joint it crosses. In these simulations, we assumed that the muscles were maximally active and evaluated the isometric moment produced by the muscles throughout the range of wrist movement.

We performed the simulations with the elbow in 90-degree flexion and the forearm in a neutral posture

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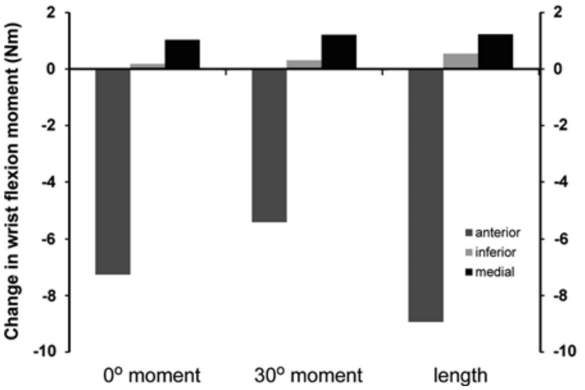

FIGURE 2. Change in simulated wrist flexion moment (at 0 and 30 degrees of wrist flexion) and in muscle length relative to an unimpaired arm following 10 mm of epicondyle displacement. Anterior displacement results in large decreases in wrist moment, whereas displacements in the inferior and medial directions result in increased joint moment-generating capacity. The change in moment-generating capacity for each case is determined by the change in length of the muscle; anterior displacement is associated with substantial muscle shortening, whereas inferior and medial displacement stretches the muscle fibers.

(midway between full pronation and full supination), over the full range of wrist motion (−70-degree wrist flexion to 70-degree wrist extension). These postures are consistent with accepted positions of in vivo clinical strength testing, which suggests keeping the elbow held at 90-degree flexion, holding the forearm rotation anywhere from end of range supination to end of range pronation, and wrist position at neutral, "slight extension," or 30-degree extension.[19] All muscles that could contribute to wrist flexion were fully activated in the simulation.

In addition to wrist flexion strength, it is also known that grip strength is related to the flexor-pronator muscle mass, which plays a role in maintaining wrist posture in conjunction with the wrist extensors when performing gripping activities, with at least 25-degree wrist extension necessary to maximize grip strength.[20] That same study found that the mean self-selected position of the wrist was 35-degree wrist extension. Therefore, for the purposes of statistical analysis, joint moments were evaluated in the functional wrist position of 30-degree wrist extension (equally between 25 and 35 degrees).

Data were analyzed using the statistical software SPSS Version 12.0 (SPSS Inc., Chicago, IL). A linear regression was performed to obtain the average change in wrist moment-generating capacity given a change in displacement for both neutral and 30 degrees of wrist extension (position of function) wrist posture.

RESULTS

The first aim of the simulation was to determine the clinically possible directions of medial epicondyle displacement based on muscle length and force changes following displacement. For medial and lateral displacements of the medial epicondyle, there was overall increase in fiber length due to overall lengthening of the muscles in the tested posture (Fig. 2). Muscle lengthening was associated with an increase in muscle force-generating capacity for these displacements as muscle operating range was shifted to a more advantageous region of the force-length curve (eg, FCR, Fig. 3). Anterior displacement was associated with shortened muscles and reduced force-generating capacity, a more clinically likely scenario.

The second aim of this study was to determine the magnitude of potential functional deficits associated with displacement of the flexor-pronator muscle origins. Wrist flexion moment-generating capacity decreased with anterior displacement, but increased with displacement in either a medial or inferior direction (Fig. 2) due to the muscle lengthening and associated increase in potential active force. Upon closer evaluation of the effects of anterior displacement, our simulations suggest more marked decreases in moment-generating capacity with progressive anterior displacement of the medial epicondyle. In a neutral wrist posture, wrist flexion moment decreased an average of 2% for every 1 mm of anterior displacement. In 30-degree extension, position of function for the

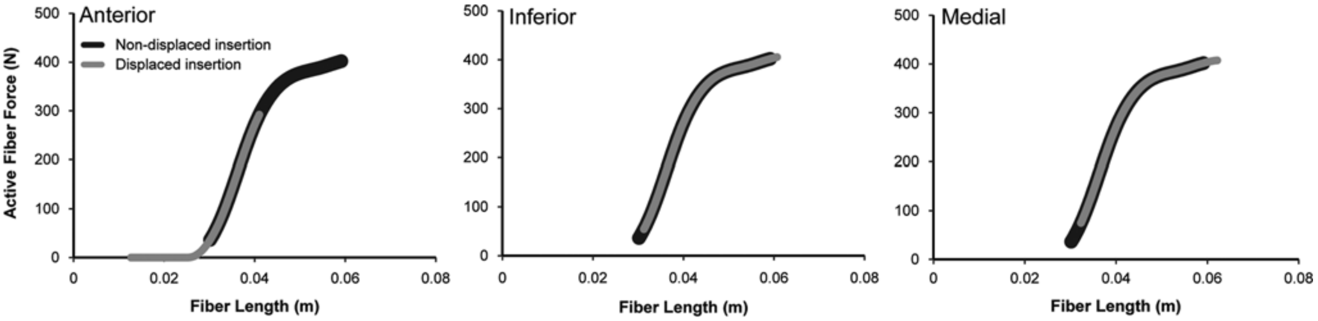

FIGURE 3. Force-length operating range during wrist flexion following simulated displacement of 20 mm for the flexor carpi radialis. The change in muscle lengths associated with epicondylar displacement results in altered fiber force-generating capacity. Anterior displacement shortens the muscle substantially, resulting in some postures for which active muscle force generation is not possible biomechanically. Inferior and medial displacements stretch the muscle, so that when activated the muscles are in a more advantageous region on the force-length curve, thereby increasing the force-generating capacity.

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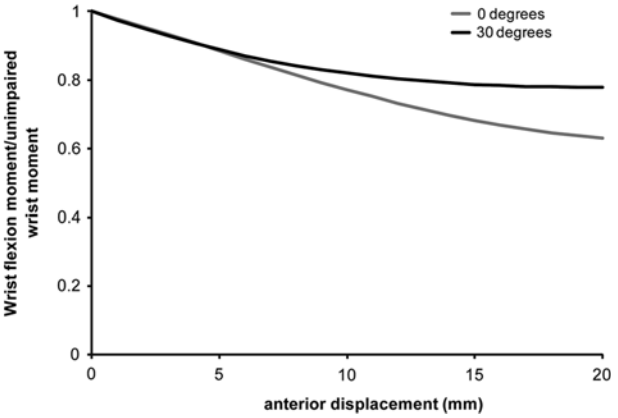

FIGURE 4. Wrist flexion moment as a function of anterior displacement of the medial humeral epicondyle, normalized by unimpaired wrist moment. Results are shown for 0 and 30 degrees of wrist extension. Moment decreases an average of 2% for every 1 mm anterior displacement in the neutral position.

wrist,[19] the wrist flexion moment decreased by an average of 1.4% for every 1 mm of anterior displacement (Fig. 4).

DISCUSSION

Acceptable displacement for medial epicondyle humerus fractures that are not entrapped in the joint is long debated, with an initial publication highlighting the arguments in 1950.[4] Smith stated the concerns that contemporaries emphasized as reasons for surgical management: growth disruption, pain and disability, weakness of the flexor-pronator muscle mass, and ulnar nerve dysfunction. Although he did not actually test muscle strength and his assessment of their function was subjective, he observed that none of the 143 children he treated had issues regarding muscle weakness. In that same decade, another group reported on 300 consecutive elbow fractures in children, 9% of which were medial epicondyle fractures.[3] They also noted no appreciative loss of function with conservative management but did not specify displacement. However, over the past half century, the demands placed on the child and adolescent elbow have changed, resulting in increased stress and injury.[21] Objective measures of function in the current generation of children with displaced medial epicondyle fractures may reveal clinically significant deficits.

Since that time, multiple reports in the literature have suggested different relative indications for surgical management, including: 2, 3, and 5 mm of medial displacement based on AP radiographs.[2,6–8] However, all studies based their conclusions on better outcomes related to a reduction in nonunion rates and did not explore functional outcomes. Moreover, these measurements of displacement were obtained through AP plain film radiographs, which have reportedly low reliability and accuracy in this context, with interobserver disagreement noted 54% of the time.[9] Even when trying to improve the measures by estimating anterior displacement with 45-degree internal oblique radiographs, the accuracy is only 60%.[22]

Our simulations suggest that medial displacements are biomechanically unlikely, as they would result in stretched muscles and potentially improved strength; this may explain some of the variability exhibited by reliance on AP radiographs. When simulating both medial and inferior displacement of the fracture, we found that the muscle fibers of the FCR, FCU, FDS, and PL lengthen relative to the intact model. Lengthening the fibers places the muscles at a more advantageous position on the force versus length curve (Blix curve), allowing for an increase in force production.[23] A fracture is unlikely to displace in a direction that increases force production, unless there is an opposing stronger muscle forcing the displacement; and in the setting of the medial epicondyle, there are no such opposing forces. In contrast, anterior displacement of the medial epicondyle results in shortened muscles and potential functional deficits. Therefore, these results provide additional insight into the recent radiographic evidence that indicates anterior displacement (relative to the distal humerus with the elbow at 90 degrees) in the clinical setting; and furthermore suggests that displacement noted on AP radiographs does not accurately represent meaningful displacement.[10]

Our results further suggest that anterior displacements could result in potential losses of strength due solely to the biomechanical consequences of altered muscle path. Those deficits are greatest in the positions of function (0- to 30-degree wrist extension). The flexor-pronator mass, which is displaced by medial epicondyle fractures, is also known to affect grip strength by stabilizing wrist posture when performing gripping activities.[20] Minimal anterior displacement—2 or 5 mm—is associated with decreased wrist flexion moment by 5% to 12%, respectively. Larger displacements, such as 10 or 20 mm, have larger decreases of 21% to 39%, respectively. This is the first study to identify the biomechanical consequences for deficits in muscle strength through medial epicondyle displacement. Further quantitative clinical study of forearm muscle function is warranted to validate the magnitudes of these computer simulation findings, as those results could have significant impact on the treatment of displaced medial epicondyle fractures.

There are limitations to this current study. This upper limb computational model has not been previously used specifically to simulate medial epicondyle fractures. However, it is developed to be used for biomechanical analysis of a wide range of orthopaedic and neuromuscular conditions, and fundamentally is a mathematical library of existing anatomic and functional measurements from a wide range of studies of individual muscles and overall behavior of the upper limb. It has previously been used to successfully simulate orthopaedic conditions and procedures at the shoulder, elbow, and wrist[24–27]; and, it has specifically been used to predict changes in muscle function secondary to tendon transfers at the elbow involving displaced origins of the flexor-pronator mass.[28]

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This computer simulation only measures functional disability due to acute displacement and changes in muscle path, and does not represent any adaptation of the affected muscles to prolonged shortening. Immobilization of muscle at lengths at or shorter than resting length results in atrophy accompanied by a decrease in protein synthesis, a reduction in EMG activity of 5% to 15% of normal muscle, and a 40% decrease in the number of sarcomeres, suggesting a retrograde trophic influence on motor nerves.[29,30] Although the effect of immobilization has been studied, few studies describe changes related to fracture-related muscle shortening. A single study assessed shortening effects by measuring quadriceps muscle strength after nonoperative treatment of femur fractures in children,[31] but the results are confounded by possible muscle injury at the time of fracture. The authors found (at a mean of almost 3 y follow-up) that there were deficits in muscle function and performance in 30% of their patients, but none of the deficits were deemed clinically important weaknesses as all the children were symptom free. Other clinical factors may also affect observed strength and function. Pain experienced following fracture may further limit wrist or grip strength in excess of the biomechanical consequences alone.

We explored potential functional consequences of epicondyle displacement for wrist flexion moment only and in a single elbow and forearm posture that replicates the position for testing strength clinically. Many tasks are more complex, and strength profiles for other tasks and other postures may differ. The posture and task were chosen to be consistent with the accepted clinical functional testing.[19] Further, the primary result indicates that the changes in muscle length associated with anterior displacement is the only meaningful and biomechanically likely displacement direction, motivating the development of methods other than AP radiograph for assessing true displacement magnitude.

Despite limitations of computational simulation, this approach provides a theoretical basis to examine how fracture displacement and musculoskeletal anatomy affect function by isolating biomechanical factors from other concurrent factors such as pain or concomitant injury. The present study will guide future clinical research toward specific quantitative functional assessments to verify the magnitude of functional loss associated with displacement of medial epicondyle fractures.

Moreover, this work provides evidence that true fracture displacement is likely to occur predominantly in the anterior direction. These results validate the concern reported in recent publications that current standard AP elbow radiographs are unable to accurately assess fracture displacement and highlight the need for a better modality to measure the true displacement of medial epicondyle fractures. Displacement of a medial epicondyle humerus fracture in the anterior direction can affect wrist flexion strength due to displacement of the flexor/pronator muscle mass origin, and provides a biomechanical analysis that allows surgeons to understand the functional deficits possible with this fracture type. The results of this study provide a foundation to create evidence-based approaches based on wrist function to guide treatment of the elbow medial epicondyle fracture.

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REFERENCES

1. Bede WB, Lefebvre AR, Rosman MA. Fractures of the medial humeral epicondyle in children. *Can J Surg*. 1975;18:137–142.
2. Woods GW, Tullos HS. Elbow instability and medial epicondyle fractures. *Am J Sports Med*. 1977;5:23–30.
3. Maylahn DJ, Fahey JJ. Fractures of the elbow in children; review of three hundred consecutive cases. *J Am Med Assoc*. 1958;166: 220–228.
4. Smith FM. Medial epicondyle injuries. *J Am Med Assoc*. 1950; 142:396–402.
5. Kamath AF, Baldwin K, Horneff J, et al. Operative versus nonoperative management of pediatric medial epicondyle fractures: a systematic review. *J Child Orthop*. 2009;3:345–357.
6. Papavasiliou VA. Fracture-separation of the medial epicondylar epiphysis of the elbow joint. *Clin Orthop Relat Res*. 1982;171: 172–174.
7. Case SL, Hennrikus WL. Surgical treatment of displaced medial epicondyle fractures in adolescent athletes. *Am J Sports Med*. 1997;25:682–686.
8. Lee HH, Shen HC, Chang JH, et al. Operative treatment of displaced medial epicondyle fractures in children and adolescents. *J Shoulder Elbow Surg*. 2005;14:178–185.
9. Pappas N, Lawrence JT, Donegan D, et al. Intraobserver and interobserver agreement in the measurement of displaced humeral medial epicondyle fractures in children. *J Bone Joint Surg Am*. 2010;92:322–327.
10. Edmonds EW. How displaced are "nondisplaced" fractures of the medial humeral epicondyle in children? Results of a three-dimensional computed tomography analysis. *J Bone Joint Surg Am*. 2010;92:2785–2791.
11. Holzbaur KR, Murray WM, Delp SL. A model of the upper extremity for simulating musculoskeletal surgery and analyzing neuromuscular control. *Ann Biomed Eng*. 2005;33:829–840.
12. Delp SL, Anderson FC, Arnold AS, et al. OpenSim: open-source software to create and analyze dynamic simulations of movement. *IEEE Trans Biomed Eng*. 2007;54:1940–1950.
13. Lieber RL, Jacobson MD, Fazeli BM, et al. Architecture of selected muscles of the arm and forearm: anatomy and implications for tendon transfer. *J Hand Surg Am*. 1992;17:787–798.
14. Murray WM, Buchanan TS, Delp SL. The isometric functional capacity of muscles that cross the elbow. *J Biomech*. 2000;33: 943–952.
15. An KN, Hui FC, Morrey BF, et al. Muscles across the elbow joint: a biomechanical analysis. *J Biomech*. 1981;14:659–669.
16. Jacobson MD, Raab R, Fazeli BM, et al. Architectural design of the human intrinsic hand muscles. *J Hand Surg Am*. 1992;17:804–809.
17. Lieber RL, Fazeli BM, Botte MJ. Architecture of selected wrist flexor and extensor muscles. *J Hand Surg Am*. 1990;15:244–250.
18. Holzbaur KR, Murray WM, Gold GE. Upper limb muscle volumes in adult subjects. *J Biomech*. 2007;40:742–749.
19. Bialocerkowski A, Grimmer KA. Measurement of isometric wrist muscle strength—a systematic review of starting position and test protocol. *Clin Rehabil*. 2003;17:693–702.
20. O'Driscoll SW, Horii E, Ness R, et al. The relationship between wrist position, grasp size, and grip strength. *J Hand Surg Am*. 1992; 17:169–177.
21. Hutchinson MR, Ireland ML. Overuse and throwing injuries in the skeletally immature athlete. *Instr Course Lect*. 2003;52:25–36.
22. Gottschalk HP, Bastrom TP, Edmonds EW. Reliability of internal oblique elbow radiographs for measuring displacement of medial

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epicondyle humerus fractures: a cadaveric study. *J Pediatr Orthop*. 2013;33:26–31.

23. Blix M. Die Lange und die Spannung des Muskels. *Scand Arch Physiol*. 1894;5:149–206.
24. Mogk JP, Johanson ME, Hentz VR, et al. A simulation analysis of the combined effects of muscle strength and surgical tensioning on lateral pinch force following brachioradialis to flexor pollicis longus transfer. *J Biomech*. 2011;44:669–675.
25. Ling HY, Angeles JG, Horodyski MB. Biomechanics of latissimus dorsi transfer for irreparable posterosuperior rotator cuff tears. *Clin Biomech (Bristol, Avon)*. 2009;24:261–266.
26. Crouch DL, Plate JF, Li Z, et al. Biomechanical contributions of posterior deltoid and teres minor in the context of axillary nerve injury: a computational study. *J Hand Surg Am*. 2013;38:241–249.
27. Murray WM, Hentz VR, Friden J, et al. Variability in surgical technique for brachioradialis tendon transfer. Evidence and implications. *J Bone Joint Surg Am*. 2006;88:2009–2016.
28. Saul KR, Murray WM, Hentz VR, et al. Biomechanics of the Steindler flexorplasty surgery: a computer simulation study. *J Hand Surg Am*. 2003;28:979–986.
29. Tabary JC, Tabary C, Tardieu C, et al. Physiological and structural changes in the cat's soleus muscle due to immobilization at different lengths by plaster casts. *J Physiol*. 1972;224:231–244.
30. Booth FW. Effect of limb immobilization on skeletal muscle. *J Appl Physiol*. 1982;52:1113–1118.
31. Hennrikus WL, Kasser JR, Rand F, et al. The function of the quadriceps muscle after a fracture of the femur in patients who are less than seventeen years old. *J Bone Joint Surg Am*. 1993;75:508–513.

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