

Biomechanics of the Steindler Flexorplasty Surgery: A Computer Simulation Study

Katherine R. Saul, MS, Wendy M. Murray, PhD, V.R. Hentz, MD,
Scott L. Delp, PhD, *Stanford, CA*

Purpose: Our goal was to investigate the capacity of a Steindler flexorplasty to restore elbow flexion to persons with C5-C6 brachial plexus palsy. In this procedure the origin of the flexor-pronator mass is moved proximally onto the humeral shaft. We examined how the choice of the proximal attachment site for the flexor-pronator mass affects elbow flexion restoration, especially considering possible side effects including limited wrist and forearm motion owing to passive restraint from stretched muscles.

Methods: A computer model of the upper extremity was used to simulate the biomechanical consequences of various surgical alterations. Unimpaired, preoperative, and postoperative conditions were simulated. Seven possible transfer locations were used to investigate the effects of choice of transfer location.

Results: Each transfer site produced a large increase in elbow flexion strength. Transfer to more proximal attachment sites also produced large increases in passive resistance to wrist extension and forearm supination.

Conclusions: To reduce detrimental side effects while achieving clinical goals our theoretical analysis suggests a transfer to the distal limit of the traditional transfer region. (*J Hand Surg* 2003; 28A:979-986. Copyright © 2003 by the American Society for Surgery of the Hand.)

Key words: Computer simulation, Steindler flexorplasty, upper-extremity model.

From the Biomechanical Engineering Division, Mechanical Engineering Department; Department of Functional Restoration, School of Medicine; and the Bioengineering Department, Stanford University, Stanford, CA; and Rehab R&D Center, VA Palo Alto HCS, Palo Alto, CA.

Received for publication April 17, 2003; accepted in revised form August 18, 2003.

Supported by the Whitaker Foundation, Medtronic Foundation Stanford Graduate Fellowship, and the Rehabilitation Research and Development Service of the Department of Veterans Affairs (#B2785R).

No benefits in any form have been received or will be received by a commercial party related directly or indirectly to the subject of this article.

Reprint requests: Katherine R. Saul, MS, Biomechanical Engineering Division, Stanford University, James H. Clark Center, Rm S-348, Mail code 5450, 318 Campus Dr, Stanford, CA 94305-5450.

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0363-5023/03/28A06-0014\$30.00/0
doi:10.1016/S0363-5023(03)00484-2

Damage to the brachial plexus produces considerable deficits in upper-extremity function. The pattern of injury includes a C5-C6 rupture 73% to 86% of the time in obstetric cases¹ and at least 35% of the time in adult traumatic cases.² In C5-C6 brachial plexus palsy innervation of the deltoid, biceps, brachialis, and brachioradialis is lost. The clinical presentation includes an adducted shoulder, internally rotated arm, and extended elbow.³ Tendon transfer or nerve repair surgeries result in good or excellent recovery of function in up to 75% of cases when targeting shoulder muscles, 48% of cases targeting the biceps, and less than 35% for reconstructions at or below the elbow that do not involve the biceps.⁴ Because of the relatively high occurrence of C5-C6 injuries the investigation of surgical reconstructions used to restore function after this type of injury is of particular interest.

One of the earliest procedures for restoring function to the elbow, the Steindler flexorplasty, is still preferred by many surgeons.⁵ In this procedure the origins of the flexor-pronator mass—including the pronator teres (PT), flexor carpi radialis, flexor carpi ulnaris, palmaris longus, and a portion of flexor digitorum superficialis—are moved proximally onto the humeral shaft, 4 to 6 cm above the medial epicondyle of the humerus, thereby increasing their elbow flexion moment arms. The bony medial epicondyle may be transferred along with the muscles, causing the muscle origins to be up to 2 cm anterior to the surface of the humerus.⁶ In an effort to decrease the incidence of pronation contractures frequently seen after the originally described procedure, Mayer and Green⁶ modified the Steindler flexorplasty by moving the muscle attachment laterally toward the center line of the humeral shaft. The degree to which this modification accomplished its goal is unclear because pronation contractures still are seen after surgery.

Because of the relatively low success rate for reconstructions at or below the elbow it is important to characterize the level of improvement that can be expected and to identify the factors that limit postoperative function. For example, the Steindler flexorplasty dramatically increases the elbow flexion moment arms of the flexor-pronator muscles, causing these muscles to undergo much greater changes in length with elbow flexion. These muscles have relatively short fibers compared with the native elbow flexors.^{7,8} It is unclear how such an architectural mismatch may limit functional restoration after Steindler flexorplasty.

This study sought to answer 3 questions regarding the Steindler flexorplasty. First, to what degree can elbow flexion strength be restored? Second, what are the consequences of increasing the moment arms of muscles with relatively short fibers? Finally, how does the choice of proximal attachment site affect elbow flexion strength and the function of the forearm and wrist?

Materials and Methods

We used a 3-dimensional computer model of the upper extremity^{9,10} to simulate the biomechanical consequences of the surgical procedure. The model represents the bone geometry, joint kinematics, origin-to-insertion paths, and architectural parameters of 32 muscles of the upper extremity. By using this model we were able to calculate the moment arms and lengths of each muscle. The force generated

when a muscle is not active and is stretched (ie, its passive force) and the isometric force generated when a muscle is maximally active (ie, its active force) can be computed. The total force a muscle can generate is the sum of these 2 quantities. The computer graphics-based model allows muscle-tendon paths to be altered interactively to simulate various surgical procedures and allows for muscles to be paralyzed by turning off their active properties.¹¹⁻¹³

Muscle-tendon paths are defined by a series of points and surfaces that characterize anatomic constraints and allow simulation of the muscle-tendon path over a broad range of joint motion. The model accounts for the fact that many muscles of the upper limb cross multiple joints (eg, the flexor carpi ulnaris crosses the elbow and the wrist). The lengths, moment arms, and force-generating capacity of individual muscles are calculated as a function of all of the joints each muscle crosses. Moment arms are computed by using the model as the change in muscle-tendon length with respect to the joint angle.^{13,14} Comparing experimentally measured moment arms^{15,16} with the model predictions indicates that our model accurately represents moment arms of the elbow and wrist muscles.^{9,10} The active force and the passive force a muscle produces in a given joint posture are determined based on its physiologic cross-sectional area, fiber length, tendon length, and pennation angle. These architectural parameters were obtained from previous anatomic studies.^{7,8,17-19}

An objective measure of strength is the moment produced by muscles about a joint. Experimental studies measure isometric joint moments produced by unimpaired^{20,21} and impaired subjects^{22,23} using devices that restrain joint rotation. In these tests the subjects are instructed to maximally flex or extend against the resistance provided by the device, and the moment they produce is recorded. We can estimate this important strength measure using the computer model of the upper extremity. To do so, the moment produced by an individual muscle crossing the joint of interest is calculated using the model by multiplying its total force and its moment arm. We then sum the individual moments produced by each of these muscles. This result is an estimate of the joint moment-generating capacity. The joint moments estimated with the computer model are in close agreement with experimental measurements of joint moments about the elbow and wrist generated by unimpaired subjects.^{9,20}

Because muscles produce both active force and passive force, joint moments also have active and

passive components that can be evaluated separately using the model. The passive component of the joint moment is the moment produced when the muscles that cross the joint are not active. The passive joint moment also can be measured experimentally and increases as the joint is moved toward the limits of its range of motion.²¹ Passive moments resist motion, and excessive passive moments can limit joint range of motion and the ability to produce a movement.²⁴ At a given joint the passive joint moment is calculated using the model by multiplying each muscle's passive force by its moment arm, and then summing the passive moments produced by each muscle that crosses the joint. The passive force properties for each muscle are based on known muscle passive properties,²⁵ the operating ranges for the muscles when available,^{8,16} and the passive moments measured on live human subjects.²¹ The muscles in the model begin to develop passive force when stretched beyond the optimal fiber length.⁹

We simulated an unimpaired arm with 32 muscles. The preoperative condition of a C5-C6 brachial plexus palsy patient was simulated by paralyzing the biceps, brachialis, and brachioradialis. To simulate the Steindler flexorplasty, the preoperative condition was altered by moving the origins of the PT, flexor carpi ulnaris, flexor carpi radialis, palmaris longus, and a portion of flexor digitorum superficialis proximally onto the shaft of the humerus. An ellipsoidal area was defined as the feasible region of reattachment, with its center 5 cm proximal from the original origin, 0.5 cm medial to the midline long axis of the humerus, and 1 cm anterior to the surface of the humerus (Fig. 1). This is consistent with descriptions of the Steindler flexorplasty surgery.⁶ 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. Using this feasible region, 7 locations were tested as transfer sites, with 6 at the periphery of the region, and one point at the center. The center of the group of origins was placed at each of these locations. Transfer locations are described in relation to the center position; for example, a distal transfer is located 1 cm distal to the center position and a medial transfer is located 0.5 cm medial to the center position. Muscle architectural properties were not changed in any of the simulations.

The consequences of the simulated Steindler flexorplasties were evaluated by comparing various biomechanical parameters in the unimpaired arm with parameters before and after the surgical simulation.

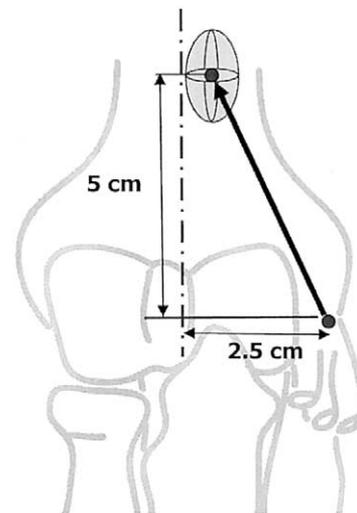


Figure 1. Feasible transfer region. The region is centered 5 cm proximally from the medial epicondyle of the humerus, 0.5 cm medial to the center line (dashed-dotted line) of the humerus, and 1 cm anterior from the surface of the humerus. It encompasses an ellipsoid with radii of 1 cm anterior-posteriorly and inferior-superiorly, and 0.5 cm medial-laterally, consistent with surgical descriptions.⁶ This figure is not drawn to scale.

Parameters of interest included the moment-generating capacity of elbow flexors, the elbow flexion moment arms of the flexor-pronator mass, the active and passive force-generating capacity of the muscles in flexor-pronator mass, and the passive moment generated resisting forearm supination and wrist extension. In all simulations the variable of interest was evaluated over the full range of elbow motion (0° elbow flexion to 130° elbow flexion), while the wrist and forearm were held in a neutral position (0° flexion and 0° deviation for the wrist and halfway between full pronation and full supination for the forearm). The shoulder also was held in a neutral position (0° flexion, 0° abduction, and 0° rotation). Static equilibrium conditions were not required, and muscles that could contribute to elbow flexion were activated maximally in the simulation.

Results

The capacity of the flexor-pronator mass to generate elbow flexion moment increased substantially after a simulated Steindler flexorplasty (Fig. 2). The simulated surgery restored the peak elbow flexion moment to approximately two thirds of normal, representing a nearly 3-fold increase from its preoperative peak. The increase in moment-generating capacity arose primarily from the marked increase in elbow flexion moment arm of the flexor-pronator mass after

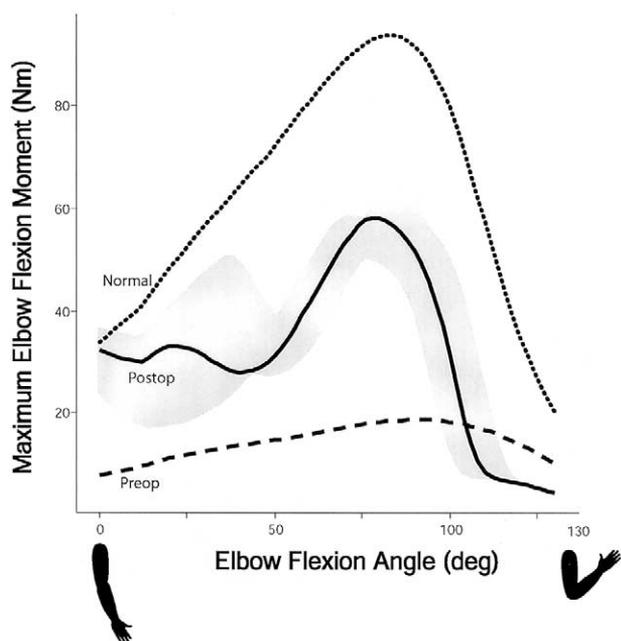


Figure 2. Elbow flexion moment-generation capacity before and after simulated surgery. Zero degrees is full elbow extension and 130° is full elbow flexion. The postoperative capacity of the elbow flexors (solid black curve) is much greater than the preoperative capacity (dashed curve) but less than normal strength (dotted curve). The black line represents results at the center of the feasible region, and the light gray shading indicates the range of results for the entire feasible region. The boundaries of the region do not represent individual transfer positions but rather the maximum and minimum values for the entire feasible region. The peak value of the shaded region is the peak value of the most proximal transfer position, and the lower boundary's peak represents the peak value of the most distal transfer location. The change in shape of the postoperative curve relative to the normal curve is caused by an increase in passive moment as the elbow nears extension.

surgery. The maximum moment arm of the flexor-pronator mass (as shown by the PT in Fig. 3) increased from 1.3 to 7 cm after transfer to the center of the feasible region. A proximal transfer location resulted in a larger moment arm than a distal location. Even the most distal transfer produced a moment arm as large as the biceps brachii. We have used the PT to show many of the results because it was the largest contributor to the elbow flexion moment owing to its large physiologic cross-sectional area. The trends exhibited by the PT are representative of the changes of other muscles of the flexor-pronator mass.

The increase in the elbow flexion moment arm of the flexor-pronator mass imposed a greater length change (excursion) on these muscles during elbow flexion. For example, excursion of the PT increased

from 2.6 cm before surgery to 8.5 cm after surgery. The fibers of the muscles in the flexor-pronator mass are shorter than the fibers of natural elbow flexors. For example, the PT has a fiber length of 5.1 cm, whereas the biceps has a fiber length of approximately 12 cm (Table 1). The ratio of a muscle's fiber length to its excursion (Table 1) determines the variation of active force-generation capacity with joint motion; a ratio of 1 indicates that a muscle operates over its entire active force-length curve. Before surgery the muscles in the flexor-pronator mass had ratios that were less than 1. Thus their fiber length was sufficient to generate active force over the range of motion of elbow flexion. After surgery, however, all muscles in the flexor-pronator mass had ratios greater than 1; thus the excursions of the muscles were greater than their fiber lengths. In this case there were portions of the range of motion over which no active force can be produced. For example, the force-generating capacities of muscles in the flexor-pronator mass before simulated surgery (as shown with PT

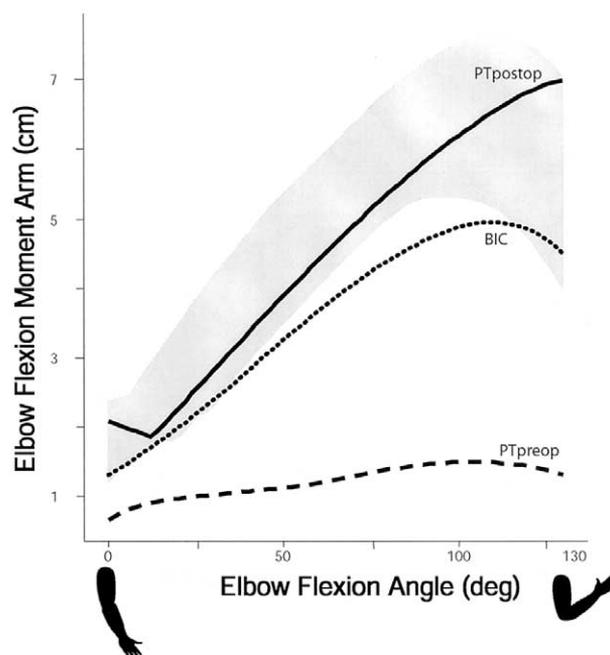


Figure 3. Elbow flexion moment arms before and after simulated surgery. The postoperative (solid black curve) moment arm of the flexor-pronator mass (as represented by the PT) is larger than both the preoperative moment arm (dashed curve) and the moment arm of the biceps (BIC, dotted curve). The black curve represents results at the center of the feasible region and the light gray shading indicates the range of results for the range of feasible transfer sites. The upper boundary of the region represents the most proximal transfer position, and the lower boundary represents the most distal transfer location.

Table 1. Characteristics of Paralyzed and Surgically Altered Muscles

Muscle	Abbreviation	Fiber Length (cm)	Preoperative Excursion (cm)*	Preoperative Excursion to Fiber Length Ratio [†]	Postoperative Excursion (cm)	Postoperative Excursion to Fiber Length Ratio [†]
Flexor-pronator mass						
Pronator teres	PT	5.1‡	2.6	0.51	8.5	1.67
Flexor carpi radialis	FCR	6.3§	2.2	0.35	9.9	1.57
Flexor carpi ulnaris	FCU	5.1§	1.6	0.32	7.3	1.43
Flexor digitorum superficialis	FDS	7.1§	2.0	0.28	9.5	1.34
Palmaris longus	PL	6.4§	2.4	0.38	9.7	1.52
Natural elbow flexors						
Biceps	BIC	12.0‡	7.5	0.63	—	—
Brachialis	BRA	8.9‡	3.9	0.44	—	—
Brachioradialis	BRD	17.9‡	12.6	0.70	—	—

*Excursion is the change in length of the muscle for 0 to 130° of elbow flexion. This value is determined with the forearm in neutral forearm rotation and the wrist in neutral flexion and deviation.

[†]The excursion to fiber length ratio is a measure of the variation of active force-generating capacity with joint motion.

[‡]Values for fiber length are from Murray et al.⁸

[§]Values for fiber length are from Lieber et al.¹⁹

before surgery in Fig. 4) were relatively constant. After surgery the active force-generating capacities varied widely with elbow flexion angle. Substantial passive force was developed with the elbow extended and no active force was generated when the elbow was flexed beyond 110° (shown with PT after surgery in Fig. 4). Passive muscle force that is developed when a muscle is stretched cannot be modulated voluntarily and may limit range of motion.

The computer simulations showed that passive forces generated by muscles of the flexor-pronator mass affected the passive characteristics at the wrist and forearm. Passive wrist flexion moments increased from 0 Nm before surgery to a peak value of 5.9 Nm after surgery in elbow extension (Fig. 5A). The proximal transfer produced a passive wrist flexion moment as high as 9.3 Nm. The simulation showed an increase from 0 Nm to a peak value of 6.3 Nm of passive forearm pronation moment (Fig. 5B). These results are consistent with development of flexion and pronation contractures after surgery.

Joint moments and muscle moment arms were most affected by proximal-distal changes in attachment location (Fig. 6). A 1-cm proximal change in transfer location from the most distal transfer location resulted in an approximately 13% increase in peak active elbow flexion moment. Peak active elbow flexion moment changes were not as large as peak passive moment changes, which ranged from a 24% increase in peak passive pronation moment to a 50% increase in peak passive wrist flexion moment. Changes resulting from a 1 cm lateral displacement

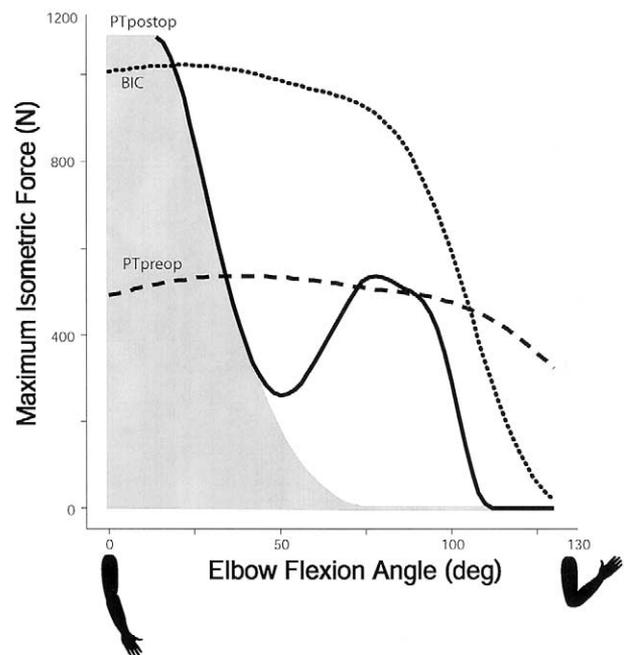


Figure 4. Total force generation (active plus passive) before and after simulated surgery. The PT has relatively constant force generation over the range of elbow flexion before surgery (dashed curve). The profile for biceps (BIC) features some variation within the active range of force-generation (dotted curve). The postoperative (black solid curve) profile for PT features widely varying force generation with a high level of passive force generation in elbow extension and no active force-generating capacity when the elbow is flexed more than 110°. The dark shading indicates the region of the force profile owing to passive force.

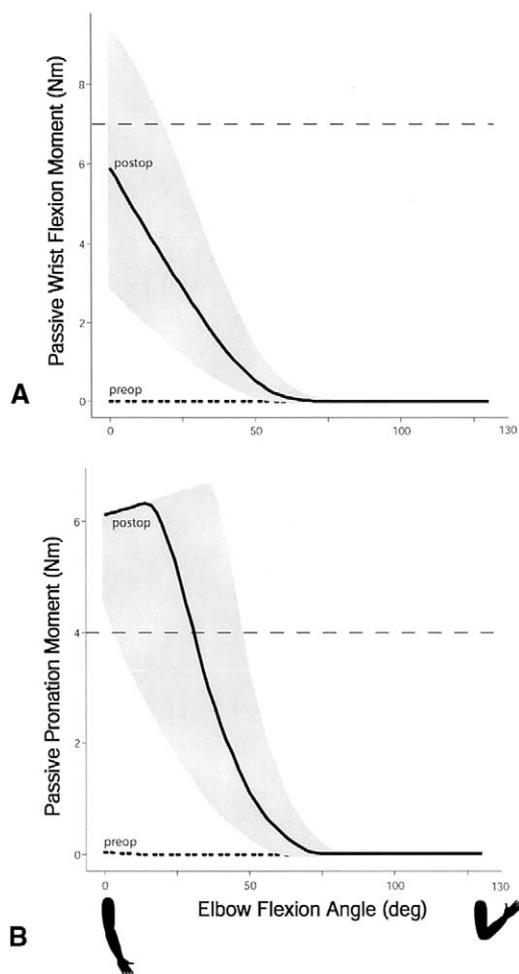


Figure 5. Passive moments at the wrist and forearm. The dotted curves represent the passive moment at the joint before surgery and the solid curve represents the postoperative passive moment at the center of the feasible region. The shaded region represents the range of results for the entire feasible region. The upper boundary of the region represents the most proximal transfer position, and the lower boundary represents the most distal transfer location. (A) The dashed line represents the maximum active wrist extension moment capacity. (B) The dashed line represents the maximum active forearm supination moment capacity.

of the origin from the most medial position or anteriorly from the most posterior position caused smaller changes in peak moments. The passive pronation moment was reduced slightly (4% in the simulation) with a 1 cm lateral displacement of the attachment, which is consistent with the stated goals of the Mayer and Green modification of the Steindler flexorplasty.⁶

Discussion

Most surgeons accept the traditional wisdom that successful restoration of elbow flexion by the Stein-

der flexorplasty comes with some trade-offs. It generally is accepted that a postoperative elbow flexion contracture of at least 30° occurs in all patients. In practice the range of wrist extension typically is diminished, particularly with the elbow in extension. Few patients are able to supinate with any force and many cannot supinate at all. The question is whether such negative consequences are necessary to achieve the goal of the surgery.

Our simulations indicate that surgery greatly increases elbow flexion moment-generating capacity by increasing the moment arm of the flexor pronator mass for all of the possible transfer sites. This increase in elbow flexion strength comes at the expense of increased passive moments for wrist flexion and forearm pronation caused by the increased excursions of these muscles imposed by the transfer. The only way to counteract the tendency for passive muscle forces to flex the wrist is with active wrist extension. The model and experimental data²¹ indicate that maximum active wrist extension moment is approximately 7 Nm in an unimpaired arm. Our simulations suggest 7 Nm of active moment is not adequate to counteract the passive wrist flexion moment resulting in some of the postoperative cases. Similarly, to counteract passive forearm pronation, active forearm supination is needed. Maximum active forearm supination moment measured in unimpaired subjects is approximately 17 Nm.²⁶ Our preoperative simulation shows that with the biceps, brachioradialis, and brachialis impaired the maximum supination moment is reduced to 4 Nm. Therefore active supination after C5-C6 brachial plexus palsy is not adequate to overcome the passive pronation moments imposed by the Steindler flexorplasty. When an opposing active moment cannot overcome the passive moment at the wrist and forearm a limited range of motion can be expected, as has been observed clinically.

Varying the location of transfer affects the extent of the trends mentioned earlier. The distal placement of the transfer relieves, to some degree, the passive tension by decreasing the moment arm and excursion of the flexor-pronator mass. The peak elbow flexion moment still is increased substantially relative to its preoperative level. Therefore the surgery can increase elbow strength and minimize passive effects at other joints.

Distal positioning of the transfer reduces the passive effects. Because of the relative insensitivity of the peak elbow flexion moment value and overall moment profile to changes in transfer location, little

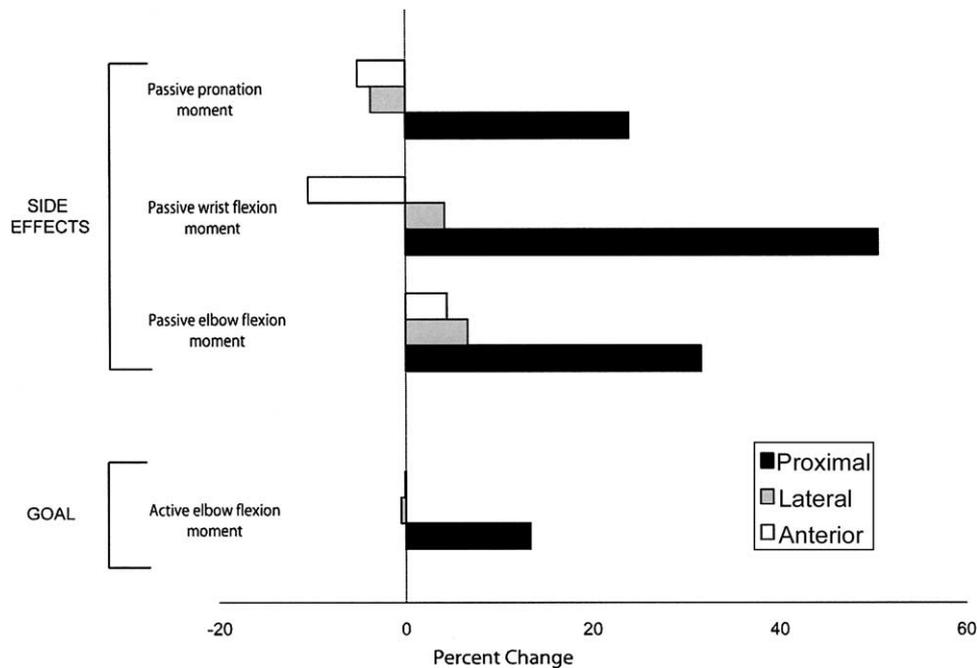


Figure 6. Percent changes in peak values caused by 1-cm variations in transfer location. Moving the origin 1 cm proximally from the most distal transfer location (black bar) causes a marked increase in passive moments at the elbow, forearm, and wrist. Active elbow moment changes are not as large as passive elbow moment changes. Moving the transfer 1 cm laterally from the medial transfer position (gray bar) or 1 cm anteriorly from the posterior transfer position (white bar) results in smaller changes. In particular, a lateral change in transfer location reduces pronation passive moment by a very small amount (4%).

will be lost in terms of elbow flexion strength. In addition, reducing muscle excursion will increase the range of motion over which active force can be generated. We estimated from mechanical descriptions of the inertial properties of the arm^{23,27} that the moment necessary to initiate elbow flexion against gravity would be approximately 4 to 6 Nm. Moment generation, even with the transfer to the distal border of the feasible region should be adequate to meet this functional requirement.

One should consider several limitations of the computer simulation approach we have used. First, our model represents the musculoskeletal geometry of a single adult with average muscle properties. There is wide variation, however, in the characteristics of muscles of individuals and considerable differences between the geometry of adults and children. The model does not take into account disease or injury effects that may affect the passive characteristics or strength of muscles of individual patients. The simulation of the postoperative muscle paths is based on surgical description and a qualitative evaluation of the muscle geometry after surgery. They were not measured via intraoperative digitization or postoperative magnetic resonance imaging. Postoperative moment arms could be affected by this esti-

mation. Postoperative muscle paths are likely to differ between individuals, however, and the muscle paths in the simulation yield reasonable moment arms comparable with natural elbow flexors. Given these limitations, the absolute values of moment arms, forces, and moments presented in this report should not be applied to individual patients. Instead one should use these results to understand, in general, the interplay between elbow strength, transfer site location, and passive resistance to wrist extension and forearm supination.

This simulation does not take into account adaptation of the muscles before or after surgery. Physiologic cross-section and maximal force capacity may be reduced in impaired subjects. Fiber length and tendon length may adapt to altered use. The degree of this adaptation *in vivo* is unclear. By eliminating the complex effects of muscle-tendon adaptation this simulation isolates the acute effects of surgery that occur owing to changes in muscle geometry.

Although computer models of the musculoskeletal system have limitations they provide a theoretical basis for examining how surgical technique and musculoskeletal design affect postoperative function. Our simulation shows that transfers that maximize the elbow flexion moment arms of the flexor-prona-

tor mass produce passive forces in muscles that are difficult or impossible to counteract with active wrist extension or forearm supination with the remaining musculature. Less extensive proximal transfers of the flexor-pronator mass produce substantial increases in elbow flexion strength while minimizing unwanted side effects. These results provide a biomechanical understanding that will assist surgeons in planning this procedure to optimize surgical outcomes for their patients.

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