

# Biomechanical Properties of the Brachioradialis Muscle: Implications for Surgical Tendon Transfer

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**Purpose:** To understand the mechanical properties of the brachioradialis (BR) muscle and to use this information to simulate a BR-to-flexor pollicis longus (FPL) tendon transfer for restoration of lateral pinch.

**Methods:** The BR mechanical properties were measured intraoperatively. Passive elastic properties were measured by elongating BR muscles at constant velocity while they were attached directly to a dual-mode servomotor. Sarcomere length was measured intraoperatively and *in situ* by laser diffraction with the elbow fully extended. Then both the mechanical and structural properties were programmed into a surgical simulator to test the hand surgeon's decision making when tensioning muscles in a simulated BR-to-FPL tendon transfer.

**Results:** Passive mechanical BR properties were highly nonlinear. Under slack conditions sarcomere length (mean  $\pm$  standard deviation) was  $2.81 \pm 0.10 \mu\text{m}$  ( $n = 4$ ), corresponding to an active force of 93% maximum. Sarcomere length of the BR measured *in situ* with the elbow fully extended and the forearm in neutral rotation was  $3.90 \pm 0.27 \mu\text{m}$  ( $n = 8$ ), corresponding to an active force of only 23% maximum. Surgeons, who tensioned the BR for transfer into the FPL using only tactile feedback from the surgical simulator, attached the muscle at a passive tension of  $5.87 \pm 0.97 \text{ N}$ , which corresponded to a sarcomere length of  $3.84 \mu\text{m}$  and an active muscle force of 27% maximum. Passive BR tension when both tactile and visual information were provided to the surgeon was significantly lower ( $2.42 \pm 0.72 \text{ N}$ ), corresponding to a sarcomere length of  $3.56 \mu\text{m}$  and a much higher active muscle force of 45% maximum.

**Conclusions:** When these data were used to model pretransfer and posttransfer function dramatic differences in predicted function were obtained depending on the tensioning protocol chosen. This emphasizes the point that the decision-making process used during muscle tensioning has a profound effect on the functional outcome of the transfer. (*J Hand Surg* 2005;30A:273–282. Copyright © 2005 by the American Society for Surgery of the Hand.)

**Key words:** Hand surgery, sarcomere length, modeling, tendon transfer, surgical simulation.

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Received for publication July 28, 2004; accepted in revised form October 11, 2004.

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

Supported by the Department of Veteran's Affairs, Rehabilitation Research and Development (San Diego #A2626R and Palo Alto #B2785R); NIH Grants AR40539 and HD044822; the Swedish Research Council Grant 11200; Göteborg University; and Myogenesis, Inc (La Jolla).

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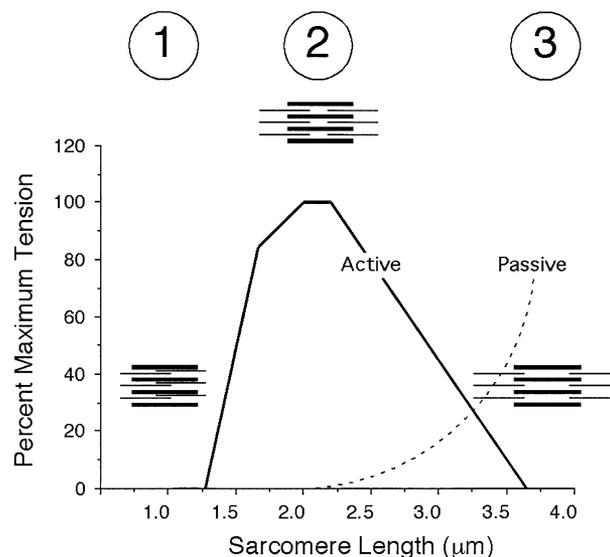
doi:10.1016/j.jhsa.2004.10.003

One of the most critical steps in performing a surgical tendon transfer, is the tensioning of the donor muscle as it is reattached to the recipient site. Correct tensioning of a transferred muscle is critical for proper muscle force production, for use of tenodesis to aid function, and to provide the necessary appearance that accompanies the transfer. Unfortunately, for most surgeons proper tensioning of muscle-tendon units remains an art. A scientific rationale for proper tensioning of a transfer requires information such as the normal operating range of the muscle, the passive mechanical properties of the muscle, and the muscle sarcomere length at the time of transfer. In general, none of these parameters is known for muscles of the upper extremity.

In an attempt to provide criteria for the tensioning procedure numerous recommendations for proper tensioning have been proposed that are based on the feel of the muscle, the excursion of the muscle determined intraoperatively, the joint posture, or a combination of all of these.<sup>1-7</sup> Almost invariably these recommendations are based on assumptions regarding the relationship between a muscle's feel (ie, its passive tension sensed intraoperatively) and its function, which—with few exceptions<sup>8</sup>—is never actually measured.

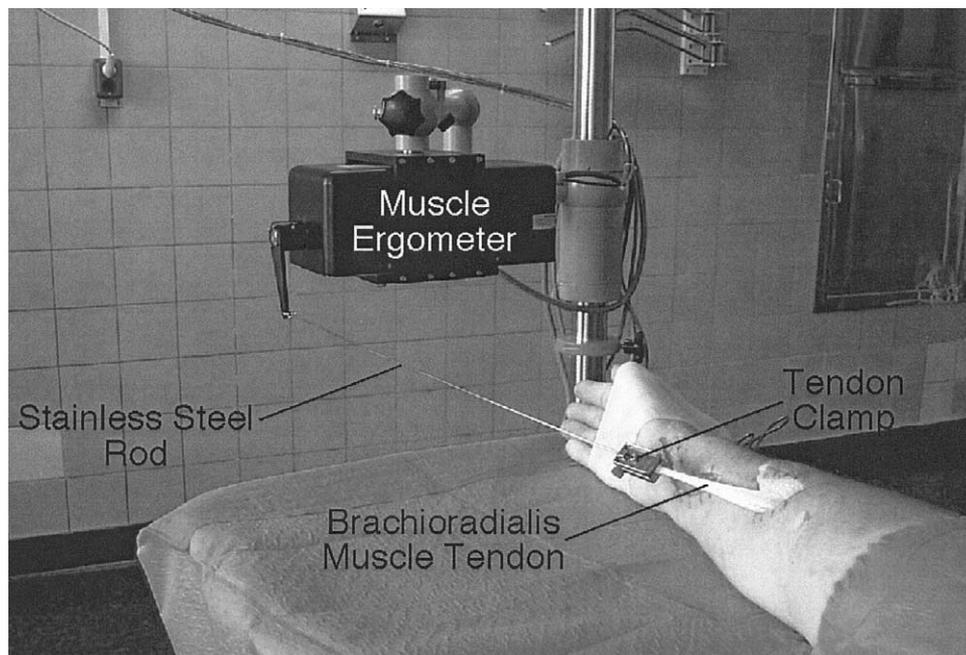
The physiologic explanation for the relationship between muscle feel and active muscle function is that both of these parameters are related uniquely to muscle length (Fig. 1). The mechanistic relationship between muscle sarcomere length and tension was reported almost 40 years ago<sup>9</sup> and the general relationship has been known for over a century.<sup>10</sup> This relationship, referred to commonly as the length-tension relationship, indicates that when a muscle is highly stretched—and thus sarcomeres within the muscle are highly stretched—very little active tension is developed (Fig. 1, position no. 3). Similarly, when a muscle is highly shortened very little tension is developed because myofilaments on 1 side of the sarcomere interfere with force production by myofilaments on the opposite side of the sarcomere (Fig. 1, position no. 1). It is only when the interaction between the actin and myosin filaments is optimal that maximal muscle force is produced (Fig. 1, position no. 2).

Although this active sarcomere length-tension relationship is extremely well founded the relationship between passive muscle tension and active force generation is understood poorly. Indeed, it appears that the amphibian active and passive sarcomere length-tension curves elucidated in the 1960s<sup>9,11</sup>



**Figure 1.** Graphical representation of the relationship between sarcomere length and passive tension (dashed line) and active tension (solid line) elucidated for amphibian skeletal muscle. Circled numbers represent 3 main lengths and the corresponding functions. In position no. 3 muscles are stretched highly and develop low active tension but are under high passive tension. In position no. 1 muscles are slack and develop low active tension and are under low passive tension. In position no. 2 muscles develop maximal tension at fairly low passive tension. The relationship between active and passive tension is not known for almost all upper-extremity muscles.

have been interpreted broadly to apply to all muscles of all species. This is certainly not the case. It has been demonstrated convincingly that at the single-cell level passive tension in skeletal muscle is borne primarily by the giant intramuscular protein titin.<sup>12-14</sup> This approximately 3.5-megadalton protein, the largest ever described, exists in several isoforms such that passive length-tension relationships vary widely among muscles. The most dramatic difference among striated muscle titin molecules is the very short and very stiff human cardiac titin, which has a spring region that is only 186 amino acids long compared with the more compliant human soleus titin, which has a spring region over 1800 amino acids long. This renders cardiac sarcomeres very stiff compared with more compliant soleus sarcomeres; however, muscle passive tension is not due solely to the stiffness of the composite sarcomeres. The extracellular matrix, composed primarily of heavily cross-linked collagen,<sup>15,16</sup> can bear a substantial fraction of the passive tension, especially in mammalian skeletal muscle.<sup>17</sup> The structure of this network is also variable among muscles. Because of the variability in the



**Figure 2.** Experimental method for measuring muscle mechanical properties intraoperatively. Sterile stainless steel clamp is secured to the distal BR tendon. The clamp is attached to a dual-mode servomotor that is under computer control. The muscle is lengthened slowly while passive tension is measured.

structure and composition of the intracellular and extracellular load-bearing networks within skeletal muscles it follows that passive length-tension relationships are highly variable among muscles and are largely unknown for all of the muscles of the human upper extremity.

Because there is an unknown relationship between muscle passive tension and active tension for upper-extremity muscles the purpose of this study was to measure intraoperatively the biomechanical properties of the brachioradialis (BR) muscle and then to model the force-producing properties of the BR after a simulated transfer into the flexor pollicis longus (FPL) muscle. This transfer, common in tetraplegia surgery, is used to create key pinch in patients with cervical spinal cord lesions at the C6 level (according to the ASIA classification) or classified as Ocu3 or higher (according to the International Classification). These passive mechanical properties were then programmed into a dual-mode servo motor and 34 hand surgeons were asked to tension the simulated BR to its appropriate length based on tactile feedback alone. Finally, based on the known sarcomere length-tension relationship of the BR, surgeons were provided subsequently both visual feedback of muscle sarcomere length and tactile feedback and were asked to again tension the BR.

## Methods

### Intraoperative Measurements

All procedures described in this study were performed with the full approval of the Institutional Review Boards at the University of California, San Diego; Department of Veteran's Affairs Medical Centers (San Diego and Palo Alto); and Göteborg University, Sweden. All patients studied ( $n = 8$ ) were having tendon transfer of the BR into either the FPL ( $n = 4$ ), the adductor pollicis brevis and extensor pollicis longus ( $n = 1$ ) the flexor digitorum superficialis or profundus ( $n = 2$ ), or the extensor carpi radialis brevis ( $n = 1$ ) secondary to tetraplegia.

To measure the BR mechanical properties a custom-designed servo motor system (Myogenesis, Inc, La Jolla, CA) was developed that permitted controlled elongation of the released BR via a sterile clamp (Fig. 2). After the BR was released thoroughly to the elbow, resulting in over 30 mm of muscle excursion,<sup>18</sup> it was deformed linearly over the range from slack length ( $L_s$ ) to  $L_s + 35$  mm at a strain rate of about 3%/sec. Slack length was defined as the length when measured muscle tension was at the noise level of the motor's force-sensing system (0.01 N).

During mechanical elongation sarcomere length was measured by laser diffraction to estimate the active tension relationship corresponding to the pas-

sive tension recorded. In 4 cases sarcomere length was measured without passive tension measurements because the intraoperative mechanical device was unavailable. Sarcomere length was measured from bundles in the midregion of the BR using methods described previously that yield values accurate to within  $0.05 \mu\text{m}$ .<sup>19,20</sup>

### Biomechanical Modeling

To predict the normal BR active and passive operating ranges and the active and passive operating ranges for a reattached BR we implemented a computer graphics-based model of the upper extremity.<sup>21,22</sup> The operating range of the normal BR was defined in the model based on *in vivo* measurements of BR sarcomere length with the elbow fully extended ( $n = 8$ ). The average measured *in situ* sarcomere length was first normalized by optimal sarcomere length, and then the ratio of measured sarcomere length to optimal sarcomere length was used to calculate BR muscle fiber length at full extension when the muscle was passive. Strictly speaking fiber length refers to muscle fascicle length because there is evidence that muscle fibers do not extend the entire length of the fascicle. Because all sarcomeres are identical it is possible to normalize all measured sarcomere lengths to the optimal sarcomere length (ie,  $2.7 \mu\text{m}$ ). This is simply a mathematical tool and does not add further assumptions to the biomechanical model. A more detailed version of this normalization procedure is presented by Zajac.<sup>23</sup> Based on previous studies muscle fiber length was defined as 173 mm at an optimal sarcomere length of  $2.7 \mu\text{m}$ .<sup>19,24</sup>

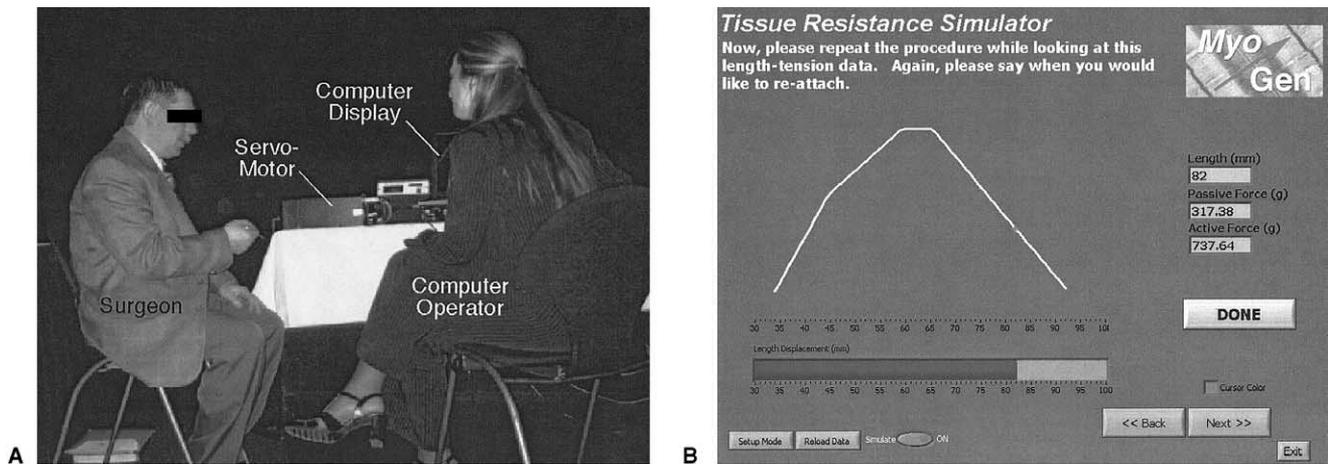
Muscle fiber shortening with activation was estimated as described by Zajac,<sup>23</sup> and fiber length change with elbow joint rotation was calculated assuming full muscle activation. The model thus estimates the change in length with joint rotation based on moment arm<sup>21</sup> and optimal fiber length<sup>18,25</sup> while accounting also for tendon compliance.<sup>23</sup> A model of the BR-to-FPL tendon transfer was developed assuming the line of action of the transfer was identical to the path of the BR at the elbow joint and the path of the FPL at the wrist and thumb joints. The fiber length of the transferred BR was calculated using the same technique as the nontransferred BR but was modified based on the sarcomere lengths obtained from the surgical simulation described later. Fiber length change with elbow flexion for the BR-to-FPL transfer was estimated with both the forearm and

wrist in neutral and the thumb in a lateral pinch posture.

Fiber lengths calculated using the model were superimposed on the active and passive force-length curves to illustrate the operating range of the fully activated muscle during elbow flexion. We assumed that fiber shortening is homogeneous and tendon force-length and muscle active force-length curves are scaled as described previously.<sup>23,26</sup> Brachioradialis average peak active force was determined by multiplying the cross-sectional area of the BR ( $1.8 \text{ cm}^2$ )<sup>27</sup> by the specific tension ( $22.5 \text{ N/cm}^2$ ).<sup>28</sup>

### Surgical Simulation

Having measured BR passive mechanical properties and BR sarcomere lengths we were able to create a BR simulator that provided a surgeon with the actual feel of the BR and (if selected) a graphical, real-time display of BR sarcomere length and active and passive tension as a surgeon pulled on the simulated muscle. This device was used to measure the passive tension and corresponding sarcomere length and active tension that the surgeon chose under 1 of 2 conditions: (1) tactile feedback only or (2) tactile feedback and visual feedback using a computer display. This test was performed during a hand surgery conference held in Christchurch, New Zealand. To perform the test the surgeon held a hemostat attached to the servomotor programmed to feel like the BR based on the average passive length-tension properties of the muscle (Fig. 3A). The surgeon was informed simply that the BR was to be transferred to the FPL, which could be required for a patient with a spinal cord injury at the C6 level. They were informed that the BR was to be transferred with the elbow in full extension and the wrist and thumb in the neutral position. No specific functional goals of the transfer were provided to the surgeons. Initially each surgeon was interviewed for demographic information such as nationality, number of BR-to-FPL transfers performed, and age. The surgeon then tensioned the simulated BR based on tactile feedback alone and the computer operator marked the passive tension level after the surgeon decided on the appropriate tension. Then the surgeon was provided with the tactile sensation of the BR and the BR predicted active length-tension relationship (Fig. 3B). While looking at the relationship and feeling the simulated BR the surgeon was again asked to tension the BR appropriately. After indicating that the tension was correct the operator again marked this passive tension level. The surgeon's grip strength was then



**Figure 3.** (A) Experimental stimulation performed at the recent Hand Surgery Conference held in Christchurch, New Zealand. The surgeon held a hemostat attached to the servomotor programmed to feel like the BR based on the average passive length-tension properties of the muscle. (B) Display provided to surgeons when both tactile and visual feedback were provided during the simulation described in the Methods section. Shown is the BR active length-tension curve (solid white line) that displays in real time a dot corresponding to the active tension associated with the passive tension chosen by the surgeon. Thus as the surgeon pulls on the “muscle” the dot moves along the active curve. Also shown in real time are muscle length as a filled bar at the bottom and specific active and passive tensions (to the right).

measured with a custom dynamometer and each surgeon was asked to not discuss the test or its results with anyone during the conference.

Statistical comparison between values chosen by surgeons with and without visual feedback was made by repeated-measures analysis of variance.<sup>29</sup> Linear regression was used to measure associations between choices made during the simulation and demographic data.<sup>30</sup> Data are presented in the text as mean  $\pm$  standard deviation unless otherwise noted.

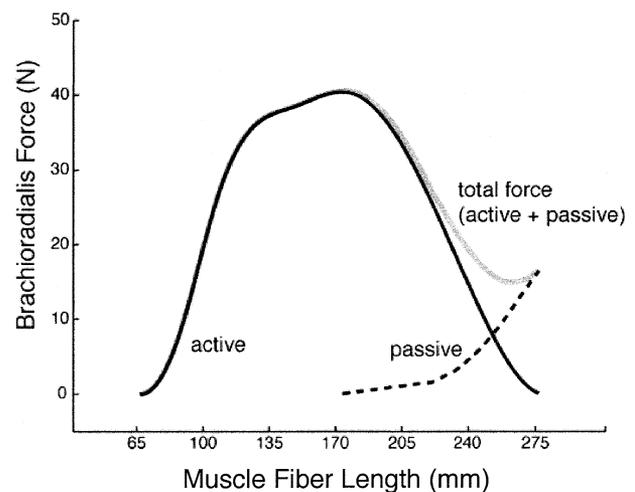
## Results

### Intraoperative Sarcomere Length and Mechanical Properties

Sarcomere length of the BR measured intraoperatively *in situ* with the elbow fully extended and the forearm in neutral rotation was  $3.90 \pm 0.27 \mu\text{m}$  ( $n = 8$ ). Accounting for sarcomere shortening during activation and based on an optimal sarcomere length of  $2.7 \mu\text{m}$  and a maximum sarcomere length for muscle contraction of  $4.26 \mu\text{m}$ ,<sup>19</sup> this corresponds to an active muscle force of 24% maximum. This is very close to the value of 28% that we reported recently on a collection of 22 such measurements on 3 different donor muscles during tendon transfer surgery.<sup>31</sup> When the BR was fully released from underlying tissue and surrounding fascia and connection to adjacent muscles the insertion tendon was divided and the muscle was allowed to retract fully. Sarcomere length measured in the fully retracted BR was

$2.81 \pm 0.1 \mu\text{m}$  ( $n = 4$ ), corresponding to an active muscle force of 93% maximum.

Passive mechanical properties measured during elongation yielded the expected nonlinear passive force-length relationship (Fig. 4, dashed line) as has



**Figure 4.** Active (solid line) and passive (dashed line) properties of the BR muscle. The active length-tension curve is derived from a normalized curve and is scaled to represent the BR based on cadaveric measurements of physiologic cross-sectional area<sup>18</sup> and optimal fiber length. The passive force versus sarcomere length curve was measured *in vivo* in this study. Note that the muscle generates near-optimal tension at a slack sarcomere length where passive tension is zero. The gray curve indicates the total force-generating capacity of the muscle (active force + passive force).

been shown for many other mammalian muscles. These mechanical data were combined with the sarcomere length values measured earlier to create both the active and passive muscle length–tension relationships for the BR (Fig. 4).

### Simulation of Tensioning the Transferred BR

A total of 34 hand surgeons were tested successfully with the surgical simulator. This included 30 men and 4 women from 13 different countries with an age range of 34 to 66 years. Passive tension of the BR when only tactile information was provided to the surgeon was  $5.87 \pm 0.97$  N, which based on the BR biomechanical properties reported above corresponds to a sarcomere length of  $3.84 \mu\text{m}$  and would be predicted to result in an active muscle force of 27% maximum with the elbow in full extension. Passive BR tension when both tactile and visual information were provided to the surgeon was significantly lower ( $p < 0.01$ ) at only  $2.42 \pm 0.72$  N, which corresponds to a sarcomere length of  $3.56 \mu\text{m}$  and would be predicted to result in a doubling of active muscle force to 45% of maximum with the elbow in full extension.

Interestingly, no correlation was observed between the passive tension chosen without feedback and grip strength ( $p = .16$ ,  $r^2 = .06$ ) (Fig. 5A) or between the passive tension chosen without feedback and the number of transfers performed ( $p = .14$ ,  $r^2 = .07$ ) (Fig. 5B). There was also no significant correlation between the adjustment made when adding visual feedback and the number of transfers performed ( $p = .27$ ,  $r^2 = .04$ ). Thus, apparently, the strength and experience of the surgeon were not major factors in determining the choices made during tensioning.

### Brachioradialis Operating Range

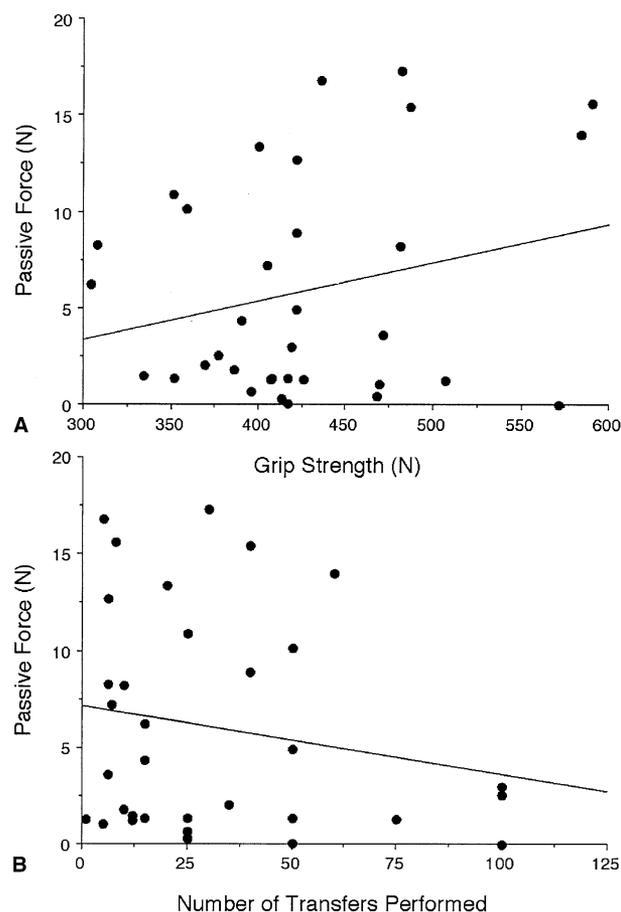
The measured biomechanical and sarcomere length data were integrated into the biomechanical model to predict the BR operating range under 3 conditions: (1) during normal elbow joint motion with the forearm in neutral rotation, (2) after transfer into the FPL at the sarcomere length selected with only tactile feedback during elbow joint motion, and (3) after transfer into the FPL at the sarcomere length selected with both tactile and visual feedback during elbow joint motion.

Under normal conditions the BR was predicted to generate its maximum active force with the elbow flexed to  $94^\circ$  and would generate 24% of maximal force with the elbow in full extension (Fig. 6A). When transferred at the sarcomere length chosen

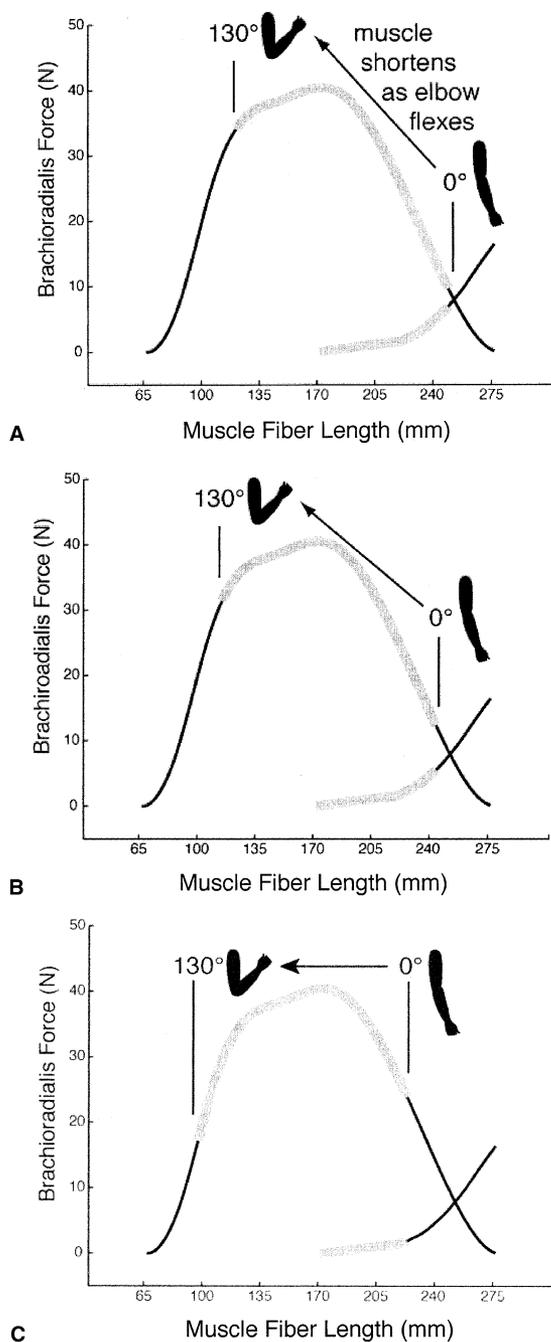
with only tactile feedback the relationship was fairly similar to that seen *in situ*, with maximum active force produced at an elbow flexion angle of  $90^\circ$  and 31% of maximal force produced with the elbow in full extension (Fig. 6B). When transferred at the sarcomere length chosen with both tactile and visual feedback a qualitatively different relationship was observed compared with that seen *in situ*, with maximal force produced at an elbow flexion angle of  $74^\circ$  (ie, the elbow was more extended) and 59% of maximal force produced with the elbow in full extension (Fig. 6C).

## Discussion

The purposes of this study were to define the mechanical properties of the BR muscle *in vivo* and to use this information to measure the decisions made



**Figure 5.** Association between experimental variables measured in this study. (A) Relationship between passive tension chosen without feedback and number of transfers performed ( $p = .14$ ,  $r^2 = .07$ ). (B) Relationship between passive tension chosen without feedback and grip strength ( $p = .16$ ,  $r^2 = .06$ ). Also shown in each graph is the linear regression best fit to the experimental data.



**Figure 6.** Biomechanical simulation of active and passive tension (in Newtons) in the brachioradialis muscle as a function of muscle fiber length (in millimeters) based on sarcomere lengths measured in this study. Schematic elbow is shown corresponding to specific fiber lengths. (A) Normal BR range as elbow is flexed from 0° (full extension) to 130° of flexion. (B) Brachioradialis range as elbow is flexed from 0° to 130° of flexion when inserted at a sarcomere length of 3.84  $\mu\text{m}$ , the mean length chosen by surgeons based only on tactile feedback. (C) Brachioradialis range as elbow is flexed from 0° to 130° of flexion when inserted at a sarcomere length of 3.56  $\mu\text{m}$ , the mean length chosen by surgeons based on both tactile and visual feedback.

by experienced hand surgeons when either tactile or both tactile and visual information were provided at the time of a simulated transfer.

This study showed that the passive properties of BR are such that when the muscle is under zero load (ie, is released to a slack length) it retracts to a sarcomere length of approximately 2.8  $\mu\text{m}$ , which corresponds to near maximal active tension (Fig. 4). This has important implications for surgical manipulation of the BR muscle in that whenever a slight amount of tension is placed on the BR the muscle will be operating on the descending limb of the length-tension curve where active force always decreases with increased length. Of course, this result cannot be generalized to any other muscles. This muscle is one of the few for which this relationship is known and it is obvious that passive mechanical properties vary among different human muscles.

A major factor that determines the passive mechanical properties of skeletal muscle is the giant intramuscular protein titin. As described earlier, many other factors such as the internal muscle microtubular network, the extracellular collagen network, and the intermediate filament cytoskeleton can also affect the passive mechanical properties of muscles.<sup>17</sup> It thus remains to be determined which, if any, of these components dominates the BR passive length-force relationship or any other human skeletal muscle for that matter. This finding, however, clearly indicates that the BR muscle is at risk of being overstretched because significant passive tension places the muscle at relatively long sarcomere lengths where lower forces tend to be generated.

The 3.90  $\mu\text{m}$  sarcomere length measured with the elbow fully extended would be predicted to result in active muscle force generation of only 24% maximum (Fig. 6A). These data were obtained in 2 centers by 2 different surgeons ( $n = 4$  at each center for a total of 8 subjects) so the results are not likely to depend on surgeon or subtle differences between operating theaters. Based on the modeling approach described in the Methods section the measured sarcomere length suggests that the BR muscle, as an elbow flexor, is designed to operate primarily on the descending limb of the length-tension curve (Fig. 6A). This finding now places the BR muscle into a unique class of skeletal muscles for which the physiologic sarcomere length operating range has been measured intraoperatively. The other muscles in this group are the extensor carpi radialis brevis and longus<sup>19,32</sup> and the flexor carpi ulnaris.<sup>33,34</sup> We defined previously the operating range of the wrist flexors

**Table 1. Brachioradialis Muscle Force Calculated From Intraoperative Measurements and Modeling**

Condition	Sarcomere Length at Full Extension $\mu\text{m}^*$	Elbow Angle of Peak Active Force (degrees)	Muscle Force at Full Extension (N)	Mean Muscle Force From 0° to 130° Elbow Flexion (N)
<i>In situ</i>	3.90	94	Active: 9.7 Passive: 6.9	Active: 27.6 Passive: 2.2
Surgeon's choice (tactile feedback)	3.84	90	Active: 12.4 Passive: 5.6	Active: 29.2 Passive: 1.7
Surgeon's choice (tactile and visual feedback)†	3.56	74	Active: 24.0 Passive: 1.9	Active: 33.2 Passive: 0.6
Peak force at 130°	4.69	130	Active: 0.0 Passive: 21.7	Active: 12.3 Passive: 11.1
Peak force at 0°	2.83	0	Active: 40.5 Passive: 0.0	Active: 27.9 Passive: 0.0

\*Measured intraoperatively (*in situ*) or estimated using the surgical-simulation or biomechanical model (all others) when the muscle is not active.  
†This is approximately the sarcomere length that maximizes average muscle force over the range of 0° to 130° of elbow flexion.

and extensors and showed that both the wrist flexors and wrist extensors operate at near-maximal force with the wrist extended. This opposes the general concept that muscles generate their maximum force when the joint is in the midrange of position. The BR muscle now joins this group in that maximal force of the BR is generated with the elbow in a highly flexed position. This may have functional implications for normal feeding and grooming behavior during which the elbow is highly flexed and suggests that the BR is a fairly weak muscle with the elbow extended. Obviously, understanding fully the functional implications of the BR being strongest with the elbow flexed would require measurements of the sarcomere length–tension relationships for the 2 other elbow flexors (brachialis and biceps brachii muscles). If at least one of them showed a relationship opposite to that of the BR the combined action of elbow flexors probably would guarantee sufficient force from full elbow extension to full flexion.

Surgeons, given the opportunity to attach the simulated BR muscle using only tactile feedback, pulled the muscle to a passive tension of 5.9 N, which, stated in terms of length, corresponds to a highly stretched sarcomere length of 3.84  $\mu\text{m}$ . Under conditions when the muscle is fully activated this tensioning corresponds to a muscle force of 31% maximum with the elbow extended (Fig. 6B). When surgeons were provided both tactile and visual feedback of the length–tension curve they decreased significantly the passive tension chosen to only 2.4 N, corresponding to a sarcomere length of 3.56  $\mu\text{m}$  ( $p < .01$ ) (Fig. 6C). We predict that this relatively small

7% length change would result in a dramatic increase in active force generation (a nearly 100% increase). This disproportionate change in force with length results directly from the highly nonlinear length–tension properties (Fig. 4) and illustrates the tremendous sensitivities of skeletal muscles to modest length changes.

It is difficult to determine what the correct decision for a surgeon should be regarding tensioning this muscle even with the complete data set in hand. In fact, defining the optimal tension for a transfer may vary based on different functional goals of people who choose to have surgery. Several possible choices for the BR-to-FPL transfer are presented in Table 1. Our analysis suggests that when tensioning the transfer the surgeon influences particularly the joint position where peak active force generation occurs and the proportion of active and passive force the muscle produces. (Examples for full elbow extension are presented in Table 1.) In the initial decision, where only tactile information was provided and the muscle was highly stretched, it can be seen that the muscle actually was placed into a physiologic operating range very similar to the original range (note the similarity between Figs. 6B and 6A). Specifically, after the simulated transfer the BR would generate maximal force with the elbow flexed to 90° compared with 94° in the native configuration and would have similar active and passive force generation relative to the *in situ* condition (Table 1). In the second decision, when both tactile and visual feedback were provided, a lower BR passive

tension was chosen and the operating range shifted to shorter lengths so that the muscle operated fairly symmetrically about the plateau of the length-tension curve. This choice increased the active force the muscle could produce in full extension, increased the mean active force produced over the full range of motion, decreased passive force, and shifted the elbow position at which the peak active force occurred to 74°—20° more extended compared with the first choice. Coincidentally, with visual feedback the surgeon's choice approximated the sarcomere length that maximized active force throughout the range of motion.

If the surgeon desired to have maximum force produced by the transferred BR with the elbow fully flexed (130° in our simulation) our model suggests that no active force development would be possible with the elbow at full extension but that very large passive forces would develop, perhaps allowing use of the hand in extended elbow postures through an enhanced tenodesis effect (Table 1). If the surgeon wished for the peak force to occur at full extension for purposes, say, of improving pinch force while reaching then a shorter sarcomere length would be correct. The surgeon, however, should also consider the consequence of this decision: that no passive force would develop over the full range of elbow motion. As a result compromises in active force development in flexed elbow postures could interfere with the ability to use the hand as the elbow flexed. These different conditions suggest that choices for surgical tensioning will often come with trade-offs and it is important to understand how to both maximize the positive and minimize the negative consequences to achieve the desired functional goals for a particular patient.

Although not evaluated explicitly in this study the operating range of the BR-to-FPL transfer will also vary with the positions of the wrist and thumb. It is clear from this discussion that there are many options and that defining the optimal protocol for tensioning any transfer is complex. This discussion emphasizes the important point that the functional requirements of tendon transfers must now be refined. With the sophisticated measuring and modeling tools currently available it is incumbent on surgeons and their colleagues to define specific functional requirements of a transfer by specifying both the action required and the limb configuration where maximizing force production of the transferred muscle will most benefit the patient (eg, restoration of wrist extension with maximal strength at 30° of extension).

## Limitations of the Study

Of course, there are a number of assumptions and limitations built into this study. The major assumption of this study is that sarcomere length measured in a large muscle both is representative of the entire muscle and is a good predictor of function. Based on previous studies in large canine muscles and cadaveric human muscles<sup>35</sup> we believe these assumptions to be reasonable. In addition the model assumes that the muscle is activated uniformly throughout the range of motion so that muscle force changes represent muscle properties and not the properties of the nervous system. This may be a significant limitation in that neural training effects and neural drive mechanisms have not been well studied for the tetraplegic patient population. Finally, the surgeon was provided only with a single tendon to tension during the procedure even though in practice tensions in 2 tendons (donor and recipient) are often adjusted. Thus, there is a possibility that the simulation provided here was not realistic.

To the extent that these assumptions do not represent significant flaws in the study design, however, this study showed the manner in which muscle properties and intraoperative decision-making interact to yield functional results after tendon transfer. It is important to define these relationships for all of the commonly transferred muscles of the upper extremity.

We thank Dr Sam Ward for providing helpful comments on a draft of this manuscript and Dr István Turcsányi (Hungary) for help in creating Fig. 3A. We also thank Joe Spinozzi of Cyth Systems, Inc (San Diego, CA) for helpful suggestions in the development of the surgical simulator.

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