Quantitative Evaluation of the Posterior Deltoid to Triceps Tendon Transfer Based on Muscle Architectural Properties

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The architectural properties of the posterior deltoid muscle and the 3 heads of the triceps were measured using microdissection techniques to determine whether substitution of triceps function by the posterior deltoid is architecturally appropriate. Muscles from 10 fresh cadaver specimens were fixed by high-pressure perfusion using buffered formaldehyde. Muscle architectural properties, including pennation angle, fiber bundle length, sarcomere length, and physiologic cross-sectional area, were determined. Fiber bundle length varied significantly among the deltoid (123.1 $\pm$ 7.8 mm), medial (64.5 $\pm$ 3.8 mm), lateral (66.5 $\pm$ 5.4 mm), and long (85.3 $\pm$ 9.5) heads of the triceps. The physiologic cross-sectional area of the posterior deltoid was significantly less than the total triceps area and was predicted to provide only approximately 20% of the maximum isometric tension of the combined triceps heads. These data demonstrate that the long fibers of the posterior deltoid render it a very suitable transfer to provide elbow extension because of its tremendous excursion and also show why useful functional results seem relatively independent of posterior deltoid tension at the time of surgery. (J Hand Surg 2001;26A:147–155. Copyright © 2001 by the American Society for Surgery of the Hand.)

Key words: Muscle architecture, tendon transfer, biomechanics, surgery.

Restoration of elbow extension after spinal cord injury is a major functional goal of tetraplegia surgery. Elbow extension is required not only to reach against gravity, but to adequately position the hand for useful activities of daily living. One useful surgical method used to restore elbow extension is the transfer of the posterior portion of the deltoid muscle into the triceps tendon. A number of investigators have reported that this transfer provides adequate strength and excursion for elbow extension.

One factor that affects the function of a tendon transfer is the matching between the original functional properties of the donor and recipient muscles. A transferred muscle must provide both adequate excursion and force production for the task required. These functional properties are primarily determined by a muscle’s architecture (ie, the number and arrangement of muscle fibers); architectural mismatch in tendon transfer can result in a functional compromise. For example, we recently demonstrated that in flexor carpi ulnaris (FCU) to extensor digitorum communis (EDC) tendon transfer, the relatively short fibers of the FCU did not provide adequate
excursion to perform the functions of the multiarticu-
lar EDC. In fact, because of the very short FCU fibers, this particular transfer was sensitive to exces-
sive stretch at the time of surgery. Potential poor
functional outcome of this transfer could be amelio-
rated by judicious choice of muscle length and ten-
sion during the transfer itself.

In addition to architectural matching between do-
nor and recipient muscles, sufficient mobilization of
the donor muscle must be achieved. The axillary
nerve, which traverses the deep deltoid surface, and
the radial nerve, which approaches the posterior del-
toid distal aponeurosis, however, are highly consid-
ered when mobilizing the deltoid for transfer. There
are no quantitative evaluations of the confidence
intervals for these nerves in the anterior-posterior
and proximal-distal directions. This information
would assist the surgeon in deciding the extent to
which the donor muscle could be mobilized.

A third factor that affects functional outcome is the
stability of the repair site. We recently demonstrated
that in the traditional posterior deltoid to triceps trans-
fer, slippage of as much as 23 mm could occur during
the immobilization and rehabilitation period, which
could affect the force-generating properties of this mus-
cle. The functional importance of a 23-mm slippage,
however, can only be determined based on knowledge
of the length of the muscle fibers within the posterior
deltoid and their relative length at the time of the
attachment. If deltoid fibers are extremely short, 23 mm
of slippage would represent a large fraction of their
physiologic range and could render the transfer useless.
Conversely, if the fibers are extremely long, 23 mm
may not result in any significant functional impairment.
Unfortunately, there are no architectural data available
in the literature regarding the fiber lengths of the pos-
terior deltoid or the triceps muscles; thus, it is impos-
sible to quantify the architectural similarities between
these muscles or to estimate the functional effect of
such tendon slippage. Therefore, the purpose of this
investigation was to measure the detailed architectural
properties of the posterior deltoid and triceps muscles in
cadaveric specimens and to mathematically model the
posterior deltoid to triceps tendon transfer. This was
done to provide a quantitative evaluation of the struc-
tural basis of the transfer.

Materials and Methods

Specimen Preparation

Muscles from fresh cadaver specimens were fixed
by high-pressure perfusion of 10% buffered formal-
dehyde via the carotid artery. This method was de-
veloped, as opposed to using previously described immers-
ion techniques, because the large size of the triceps and
deltoid muscles precluded excellent fixation by immersion. To achieve adequate pressure
50-L containers filled with fixative were placed at a
height of approximately 3 m above the cadaver. The
infusion tubing had a diameter of approximately 5
mm. The carotid artery was cannulated and fixative
introduced under pressure over a period of approxi-
mately 3 days. This method produced the best fixa-
tion of muscle tissue from cadaver specimens that we
have observed during 10 years of this type of exper-
imentation. Fixation quality was ascertained based
on the sharpness and intensity of the lines within the
sarcomere matrix was excellent using this fixation method.

Specimen Dissection

After skinning the upper extremity the entire del-
toid (n = 10) was removed from its origin on the
scapula and clavicle and its insertion onto the hu-
erus. Similarly, the 3 heads of the triceps (n = 10)
were dissected free of their origin and their insertion
onto the olecranon. At the time of dissection the
elbow extension moment arm of the triceps was
estimated by measuring the excursion of the triceps
tendon while rotating the elbow joint through an arc
of 1 radian (approximately 60°). This moment arm
value was used in subsequent modeling.

Architectural Determination

Muscle architecture was determined according to
the methods developed by Sacks and Roy as previ-
ously implemented. Muscle mass was recorded
immediately after dissection. Muscle length (Lm)
was measured as the distance from the origin of the
most proximal muscle fibers to the insertion site of
the most distal muscle fibers. For the triangular del-
toid, Lm along the anterior, posterior, and midline
were recorded. The muscle fiber surface pennation
angle was determined using a goniometer. Three
separate muscle fiber bundles (consisting of 5–50
muscle fibers) were isolated from the proximal, mid-
dle, and distal muscle regions under magnification
and fiber bundle length (Lb) was measured using
dial calipers (Mitutoyo Corporation, Tokyo, Japan;
accuracy, 0.01 mm). Sarcomere length (Ls) of the
isolated fiber bundles was determined by laser dif-
fraction according to the method previously described using the 0 to 1st order diffraction angle. Briefly, small muscle fiber bundles on glass slides were transilluminated by a helium–neon laser (λ = 632.8 nm; Melles Griot model LHR-007, Irvine, CA) and the resulting diffraction pattern was imaged onto a solid-state photodiode array. Diffraction peaks were digitized and converted to real distances, enabling diffraction angle (θ) calculation. This angle was then used in the grating equation, \( nλ = d \sin(θ) \), where \( n = \text{order}, \ λ = \text{wavelength}, d = \text{sarcomere length}, \) and \( θ = \text{diffraction angle} \), to solve for sarcomere length. In all cases, the first order diffraction peak was used (\( n = ±1 \)).

In addition to the measured parameters \( L_f / L_m \) ratio was calculated as a measure of the relative pennation of the muscle and physiologic cross-sectional area (PCSA) was determined according to the following equation:

\[
\text{PCSA (cm}^2\text{)} = \frac{\text{Muscle mass (g) } \cdot \cos(θ)}{\rho (g/cm^3) \cdot L_t (cm)}
\]

where \( ρ = \text{muscle density (1.056 g/cm}^3\text{)} \) and \( θ = \text{surface pennation angle} \). Proximal, middle, and distal \( L_r \) and \( L_s \) values were averaged for each dissected fiber specimen and then averaged across the 3 specimens from each muscle. \( L_m \) and \( L_t \) values were normalized to \( L_s = 2.5 \mu m \) to compensate for variations between specimens in muscle length during fixation.

**Tendon Transfer Mathematical Model**

To predict the function of the transferred posterior deltoid, we modified the mathematical model previously developed by Loren et al. Briefly, each muscle was modeled as half parallelogram, with sides of fiber length (\( L_f \)), muscle length (\( L_m \)), and aponeurosis length (\( L_a \)). The area of this triangle was held independent of muscle length, which requires the pennation angle, the angle between aponeurosis and fiber, to change as a function of muscle length. The normalized force–length property was based on the relationship described by Cutts, with a force–length relationship plateau extending from sarcomere lengths of 2.5 to 2.8 \( \mu m \). To account for tendon lengthening due to muscle force generation, tendon force was iteratively matched to muscle force while muscle–tendon unit length was held constant. Because the material properties of the triceps tendon have not been reported in the literature, the properties of the human extensor carpi radialis longus tendon were used as an approximation of the triceps tendon. This conservative choice was made because the extensor carpi radialis longus tendon was the stiffest of the 5 prime movers of the wrist previously measured and would thus have the smallest influence on the calculations performed. This assumption is not expected to have a significant impact on the findings reported here (see Zajac for a discussion of the effect of tendon material properties on muscle–tendon unit function).

**Results**

**Quantitative Gross Anatomy**

A number of interesting anatomic features of the deltoid were quantified along with the detailed properties of the muscle itself. For example, the axillary nerve traveled along the deep aspect of the deltoid in a straight medial–lateral course. It entered the deltoid in a consistent position, 50.1 \( ± \) 9.3 mm (mean \( ± \) SD, \( n = 10 \)) from the posterior border and 100.9 \( ± \) 15.6 mm proximal to the distal deltoid apex (Fig. 1). The axillary nerve branched 2 to 3 times after entering into the deltoid muscle itself (Table 1). As deltoid mobilization is an important part of the tendon transfer and the axillary nerve must be spared, these dimensions provide the surgeon with guidelines for safe mobilization of the posterior deltoid.

The radial nerve was located 12.5 \( ± \) 1.1 mm posterolateral to the apex of the distal deltoid. At the apex level the nerve was still in the lateral triceps muscle compartment and continued distally at a 35° \( ± \) 5° angle in the anteroposterior plane relative to the long axis of the humerus. It reached the immediate lateral aspect of the humerus, ie, it crossed the extrapolated line of deltoid force generation 23.8 \( ± \) 2.3 mm distal to the deltoid apex.

The deltoid muscle could be easily divided into 3 or 4 units based on septa that were placed 10 to 12 mm apart starting 90 mm proximal to the apex. The 2 most posterior units merged into the distal aponeurosis while the most anterior unit inserted directly into the deltoid tuberosity. In this study, we defined the “posterior deltoid” as the posterior, approximately 25% of the muscle that naturally separated from the remainder of the deltoid using blunt dissection. The aponeurosis ended distally 16.6 \( ± \) 2.3 mm proximal to the apex, whereafter the insertion tissue continued as part of the humeral periosteum. The enclosed area of the quadrilateral-shaped aponeurosis was 11.0 \( ± \) 1.5 cm\(^2\), calculated based on the length and angle of each aponeurosis border.
Triceps and Deltoid Architecture

The most important architectural property, fiber bundle length, varied significantly among the deltoid and the 3 heads of the triceps (p < .05; Table 2). Fibers could be isolated from the distal regions of each triceps head, but the heads themselves could not be separated due to their complete fusion at the insertion site. Thus, fiber lengths are reported for each head, but the triceps muscle mass and physiologic cross-sectional area are considered a single value. The fiber bundles of the posterior deltoid were 50% to 100% longer than any of the 3 heads of the triceps. Translated to the functional realm, these data indicate that the excursion of the posterior deltoid greatly exceeds that of any of the triceps heads. The second important architectural property, cross-sectional area, is a good predictor of maximum muscle force generation.²⁰ The relevant comparison to be made was between the posterior deltoid portion and the sum of the 3 triceps heads since the transferred

Figure 1. Deep aspect of dissected deltoid muscle. The location of the axillary nerve (circle in upper area) and the average dimensions of the deltoid insertion aponeurosis (trapezoid in the distal deltoid) can be seen. Calibration bar = 2 cm.
Deltoid is being used for total elbow extension. Of course, this comparison assumes that all 3 of the triceps heads are used for normal elbow extension. Since the neuromuscular control of the triceps is complex and may not involve complete simultaneous activation of all 3 heads, this comparison could tend to underestimate the relative force-producing ability of the transferred posterior deltoid.

As expected, the cross-sectional area of the posterior deltoid was significantly less than the total triceps area (p < .001; Table 2) and would be expected to provide only approximately 20% of the maximum isometric tension of the combined triceps heads. From the point of view of “architectural difference,” quantitative calculation of the architectural difference index between the muscles was 2.20.21 Briefly, this number represents the relative difference between 2 muscles using an equation that includes fiber length, fiber length–muscle length ratio, pennation angle, muscle mass, and muscle length. The smaller the number, the more similar the muscles from an architectural point of view. Since the maximum difference between muscles is 2.25, from an architectural point of view, the muscles would be viewed as highly different.

### Table 1. Descriptive Properties of Deltoid Muscle

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measurement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deltoid muscle length</td>
<td></td>
</tr>
<tr>
<td>Posterior</td>
<td>184.4 ± 6.6</td>
</tr>
<tr>
<td>Anterior</td>
<td>180.4 ± 10.1</td>
</tr>
<tr>
<td>Deltoid muscle width</td>
<td></td>
</tr>
<tr>
<td>Proximal</td>
<td>163.3 ± 7.6</td>
</tr>
<tr>
<td>Middle</td>
<td>122.1 ± 9.2</td>
</tr>
<tr>
<td>Distal</td>
<td>34.1 ± 3.0</td>
</tr>
<tr>
<td>Deltoid aponeurosis</td>
<td></td>
</tr>
<tr>
<td>Width</td>
<td>24.7 ± 2.8</td>
</tr>
<tr>
<td>Length</td>
<td>44.2 ± 1.7</td>
</tr>
<tr>
<td>Area</td>
<td>11.0 ± 1.5 cm²</td>
</tr>
<tr>
<td>Position*</td>
<td>16.6 ± 2.3</td>
</tr>
<tr>
<td>No. of septa</td>
<td>3.3 ± 0.2</td>
</tr>
<tr>
<td>Humerus length</td>
<td>319.0 ± 14.0</td>
</tr>
<tr>
<td>Axillary nerve</td>
<td></td>
</tr>
<tr>
<td>X-position†</td>
<td>48.4 ± 3.1</td>
</tr>
<tr>
<td>Y-position†</td>
<td>98.0 ± 4.8</td>
</tr>
</tbody>
</table>

Data are presented as mean values ± SEM, n = 10.
* Distance from the most distal end of the aponeurosis to apex.
† X-axis represents medial–lateral axis; y-axis represents proximal–distal axis.

### Table 2. Architectural Properties of the Deltoid and Triceps Muscles*

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Muscle Mass (g)</th>
<th>Pennation Angle (°)</th>
<th>Muscle Length (mm)</th>
<th>Fiber Length (mm)</th>
<th>Cross-Sectional Area (cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Posterior deltoid</td>
<td>65.0 ± 5.4</td>
<td>0 ± 0</td>
<td>184.4 ± 6.6</td>
<td>123.1 ± 7.8</td>
<td>5.1 ± 0.5</td>
</tr>
<tr>
<td>Medial triceps</td>
<td>14.5 ± 1.7</td>
<td>8.3 ± 0.9</td>
<td>207.4 ± 6.3</td>
<td>64.5 ± 3.8</td>
<td></td>
</tr>
<tr>
<td>Lateral triceps</td>
<td>294.1 ± 58.3†</td>
<td>6.3 ± 1.4</td>
<td>228.2 ± 5.2</td>
<td>66.5 ± 5.4</td>
<td>39.2 ± 2.4†</td>
</tr>
<tr>
<td>Long triceps</td>
<td>183.4 ± 58.3†</td>
<td>8.3 ± 0.9</td>
<td>268.7 ± 9.9</td>
<td>85.3 ± 9.5</td>
<td></td>
</tr>
</tbody>
</table>

Data are presented as mean values ± SEM; n = 10.
* While 10 specimens were obtained, 3 were eliminated for fiber length measurements due to poor fixation quality resulting in an inability to measure sarcomere lengths.
† Average value for entire triceps complex since individual muscle masses could not be reliably determined (see text for details).
where the negative sign indicates muscle lengthening with flexion. The posterior deltoid muscle was predicted to have a minimum length of approximately 150 mm and a maximum length of approximately 175 mm during elbow joint rotation from full flexion to full extension (Fig. 3). (Note that this is not the same range as the lengths that are physiologically possible; see Fig. 4.) While the overall excursion of approximately 25 mm predicted for this muscle transfer should be considered accurate, the absolute range over which the muscle acts is questionable as there are no direct measurements of this parameter. Similarly, the sarcomere length range over which these muscles act is unknown; therefore, for the purposes of this report, the deltoid was considered to be at optimal length with the elbow at 90°. If this is true, the range over which the posterior deltoid would operate is shown as the solid bar in Figure 2. It should be emphasized that while this assumption is questionable, it does not affect the main result of this study.

The functional effects of this tendon transfer surgery are simulated by plotting posterior deltoid force as a function of elbow joint angle at a number of different absolute lengths ranging from 100 to 225 mm (Fig. 4). It can be seen, as expected, that at very short muscle lengths, force would increase as elbow angle and muscle length increase. Functionally, the muscle would be lengthening up the ascending limb of the length–tension curve (Fig. 2). Once the muscle length reaches approximately 150 mm it operates primarily on the plateau of the length–tension curve; by the time this transferred muscle reaches approximately 200 mm, it is completely on the descending limb of the curve and would be predicted to sustain relatively high passive tensions. Based on the assumption that the muscle was reattached at a near-optimal muscle length of approximately 160 mm, the effect of the previously observed 23-mm tendon slippage was predicted. The main effect of tendon slippage was to permit the muscle to shorten onto the ascending limb of the length–tension curve, thus decreasing muscle force by approximately 20% (from approximately 12 N to approximately 10 N). The 23-mm slippage corresponded to 18% of the posterior deltoid fiber length (Fig. 5). The assumption that the muscle was reattached at the optimal length of 160 mm was arbitrary to place it on the plateau of the length–tension curve (see Discussion).

**Discussion**

The purpose of this study was to measure the architectural properties of the posterior deltoid and triceps muscles to quantify the structural properties of the muscles involved in this reconstructive procedure. In addition, we wanted to understand the functional significance of tendon slippage at the graft, site which we recently reported to be up to 23 mm. We
acknowledge the well-documented functional results that have been reported using this tendon transfer.\textsuperscript{1,2}

Based on the observation that posterior deltoid fiber length is very long (Table 2) and would be predicted to have a large excursion (Fig. 2), we provide an anatomic explanation for the fact that this transfer is an excellent choice to restore lost elbow extension function. Because the elbow joint moment arm is only approximately 12 mm and thus muscle excursion is only approximately 25 mm, it would be difficult to imagine surgically placing this muscle in a position where it would result in an insufficient active range of motion. In other words, this transfer is technically forgiving. A possible limitation of this transfer is that the transferred portion of the deltoid would only generate approximately 20\% of the force of the normal triceps. Thus, while the transfer might be adequate to power antigravity movements and placing of the hand in space, it would not suffice for such high force elbow extension maneuvers, such as wheelchair transfer. In principle, this transfer represents the opposite extreme of architectural matching between donor and recipient muscle properties compared with the tendon transfer we recently studied, the FCU to EDC transfer.\textsuperscript{7} In that transfer, the short fibers of the single joint FCU (42 mm) could not provide adequate excursion to provide adequate wrist, metacarpophalangeal, and digital extension. Specifically, the sarcomere length of the transferred FCU was 4.96 ± 43.00 $\mu$m with the wrist and digits.
flexed, indicating that the FCU would only develop significant forces during movements involving synergistic wrist flexion and finger extension where the actual length change of the muscle was minimal. No such excursion restriction was seen for the transferred posterior deltoid. If it had been the case that the posterior deltoid muscle fibers were too short to provide adequate excursion, elbow extension would have to have been coupled simultaneously to shoulder flexion, which is obviously an undesirable situation.

In a previous study the site between the tibialis anterior tendon graft and the proximal donor muscle was shown to slip by 23 mm in the absence of a specialized arm rest.\(^8\) We were concerned that this degree of slippage could result in extensive sarcomere shortening in the donor muscle and thus loss of force-generating capacity and/or excursion. Based on the long posterior deltoid fiber length measured in this study, however, we conclude that the slippage that can occur after this type of procedure should have little functional effect. It is impossible to predict the precise effect of this degree of slippage without a knowledge of the actual sarcomere length of the transferred muscle. In fact, slippage could result in force increase, force decrease, or no change whatsoever, depending on the sarcomere length at the time of transfer because skeletal muscles are extremely nonlinear in their force-generating properties. If the muscle were transferred at a relatively long length (>200 mm), tendon slippage would increase muscle strength as the muscle shortened up the descending limb of the length–tension curve (Figs. 2, 4). Conversely, if the muscle were transferred at a relatively short length (<150 mm), tendon slippage would decrease muscle strength as the muscle shortened down the ascending limb of the length–tension curve. It seems that the risk of slippage would be greater for longer lengths based on the passive tension that would be developed by the muscles at these lengths. Critical variables that must be measured to resolve this conundrum are the normal posterior deltoid operating range, the normal posterior deltoid passive tension-sarcomere length relationship, the posterior deltoid sarcomere length at the time of transfer, and the posterior deltoid passive tension at the time of transfer.

Posterior deltoid to triceps tendon transfers often result in an extension deficit. Reported deficits range from only 10° to over 30°. Using the results from this study such a deficit probably does not result from the inability of the donor muscle to provide adequate excursion for elbow extension. The only situation in which this would be true is if the muscle were attached at an extremely short length. Because the elbow extension moment arm is highly nonlinear (equation 2), very small muscle length changes transform to very large angular rotations (see leftmost portion of Fig. 3). At these very small angles, the terminal 30° of elbow extension are accompanied by only a 3-mm length change.

Limitations of the Study

This study is limited in a number of ways. First, there are no data available regarding the normal operating range of the deltoid or its length after tendon transfer; thus, precise consequences of the transfer remain speculative. We assumed that the deltoid was reattached at an optimal length of 160 mm (Fig. 5). In such a case, tendon slippage would cause muscle force to decrease. If the deltoid were attached at a very long length (ie, >175 mm), tendon slippage could actually result in increased deltoid force. Since no data are available to distinguish between these possibilities, definitive predictions are not yet possible. Second, the material properties of the triceps tendon and tibialis anterior tendon graft were not available to use in the model. Tendon compliance is known to cause a skewing and elongation of the muscle–tendon unit length-tension relationship.\(^{19,24}\) This would produce skewing the higher forces to the longer muscle lengths. Since none of these data were available, however, we chose not to speculate on their inclusion in the model. Another limitation is that functional properties were predicted based solely on architectural properties. While this assumption has been tested and shown to be valid for maximally activated mammalian skeletal muscle,\(^{20}\) it is not strictly true for submaximal activation levels.\(^{25}\) Submaximal length–tension curves generate optimal forces at longer lengths compared with maximal force generation. This would have the same effect as tendon compliance, namely, to shift the length–tension curves to longer lengths.

The long fibers of the posterior deltoid render it a very suitable transfer to provide elbow extension in tetraplegic patients. While the transferred muscle would probably generate only approximately 20% of normal triceps extension force, this should be adequate for antigravity and placement functions. Further studies of in vivo sarcomere length and passive tension are required to characterize the transfer definitively.
References