Analysis of Posterior Deltoid Function One Year After Surgical Restoration of Elbow Extension

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Purpose: The purpose of this study was to measure the extent and timing of elbow extension torque recovery after posterior deltoid-to-triceps tendon transfer.

Methods: Elbow extension moment was measured in 40 limbs from 23 patients who underwent surgical restoration using the posterior deltoid-to-triceps tendon transfer at times ranging from 8 weeks to 1 year after surgery. For comparison purposes, elbow extension moment also was measured in healthy controls and persons with C7 spinal cord injuries.

Results: Maximum extension moment was 5.89 ± 0.24 Nm (mean ± standard error of mean, n = 40), which corresponds to approximately 65% of the predicted posterior deltoid force and provided an adequate moment to oppose gravity. Based on the shape of the moment-joint angle curve and using a biomechanical model, it was predicted that posterior deltoid was inserted at a relatively short muscle length of 123.1 mm and thus operated exclusively on the ascending limb of the length-tension relationship.

Conclusions: These observations support an evolving model of muscle architecture in which connective tissue septa restrict muscle fiber elongation during surgical tensioning of the tendon transfer. This relatively short length would result in a significant force loss should any of the repair sites slip or stretch during rehabilitation. These data have implications for the reconstruction and rehabilitation of this patient population. (J Hand Surg 2003;28A:288–293. Copyright © 2003 by the American Society for Surgery of the Hand.)

Key words: Tetraplegia surgery, tendon transfer, muscle physiology, anastomosis, rehabilitation.

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For tetraplegic persons active elbow extension against gravity is necessary to position the hand correctly for a wide range of activities of daily living.1,2 Restoration of elbow extension after spinal cord injury can be accomplished by transferring the posterior aspect of the deltoid muscle into the insertion of the triceps tendon. Because the deltoid is too short to reach the triceps tendon a free tendon graft often is used to span the interface, but other methods including the use of alloplastic materials are available.3 Deltoid-to-triceps tendon transfer has been reported by a number of investigators to provide adequate strength and excursion for elbow extension.1,3,4

We recently reported the architectural properties of both the posterior deltoid muscle and the 3 heads
of the triceps. The main findings of this architectural study were that: (1) muscle fibers of the posterior deltoid are extremely long relative to the moment arm of the elbow rendering this transfer very forgiving in terms of setting muscle length, and (2) after transfer it is only possible for the posterior deltoid to generate a maximum of 20% of the combined force of the triceps musculature. We also developed a quantitative model of triceps extension based on measured muscle and joint properties that enabled prediction of both the shape and the magnitude of the moment-joint angle curve for the posterior deltoid muscle after transfer into the triceps tendon. At that time, however, we had no information regarding the length of the posterior deltoid during transfer and thus simulated extension moment over a wide range of possible lengths.

In light of our theoretical understanding of this muscle-joint system as well as the success and prevalence of deltoid-to-triceps transfers we have now measured directly the moment-joint angle relationship in 40 limbs of 23 patients. The majority of these patients underwent simultaneous bilateral deltoid-to-triceps transfer 21 months to 20 years after traumatic spinal cord injury using the tibialis anterior distal tendon as the graft. We found an excellent correlation between the predicted and measured moment-joint angle relationships when the computer model set muscle length to 123.1 mm and scaled maximum posterior deltoid force to 65% of its theoretical maximum. The excellent fit between experiment and theory provides support for the theoretical model used. These data reinforce the continued use of this tendon transfer in tetraplegia surgery and may even suggest improved methods for reconstruction and rehabilitation of these patients.

Methods

Patient Population

Patients entered into this study were all relatively young individuals who were tetraplegic secondary to cervical spine injuries primarily caused by motor vehicle and rugby accidents. After informed consent was obtained patients received posterior deltoid-to-triceps tendon transfers as previously described. Ultimately 23 patients were enrolled in the study and 17 received simultaneous bilateral transfers with the remaining 6 receiving a unilateral transfer, resulting in a data set consisting of 40 limbs. Analysis of the moment data revealed as much or more variability between limbs within a single patient as between patients and, thus, each limb was treated as a separate data point. Covariance among moment levels between patients was similar to the covariance between limbs within patients, which supports the use of each limb as a separate experimental entity. We did not explicitly investigate the basis for the high intraindividual variability between sides but did note that maximum extension moment did not correlate with handedness (p > .6). Anecdotally we believe that differences between sides within patients were caused by the differential nerve root sparing that occurs during spinal cord injury itself. For example we observed that one side of a patient may have a grade 5 posterior deltoid while the other side of the same patient may have only a grade 3+. As further support for pooling time-course data across individuals linear regression was applied to each individual patient’s data set and none of the regression relationships were statistically significant (p > .5) as observed with the pooled data set (see Results section). All surgeries were performed by 2 upper-limb surgeons associated with the spinal injuries unit at Burwood Hospital.

Elbow Extension Moment Measurement

Elbow extension moment was measured 8 weeks, 9 weeks, 11 weeks, 13 weeks, and 1 year after surgery. The measuring device used a force transducer custom-designed by the Engineering Department of the University of Canterbury in Christchurch, New Zealand, that measured force at a fixed lever arm distance to calculate isometric extension moment generated for each 20° of elbow rotation with an accuracy of ±4%. The subject was seated with the arm abducted 90° at neutral humeral rotation with the chest and upper arm secured with adjustable clamps (this position was chosen for logistical reasons because patients were bound to a wheelchair and this position did not result in maximum joint moment, which could affect measured strength values; see Discussion section). Elbow extension moment was defined based on the axis of elbow rotation being coincident with medial epicondyle. Before surgery patients were trained on the testing device. For postsurgical measurements the greater reading of 2 maximum voluntary isometric efforts was defined as the maximal extension moment for that angle. At least 2 minutes were permitted between trials to avoid complications of muscle fatigue. The range over which the moment was measured was limited to 0° to 40° 8 weeks after surgery, 0° to 60° 9 weeks after surgery, and 0° to 90° 11 weeks after surgery. Elbow extension moment was measured over the full range from...
0° (full extension) to 120° of flexion thereafter. For comparative purposes this device also was used to measure maximum elbow extension moment in a cohort of young male volunteers (age range, 17–33 y, n = 10) as well as persons with injuries at the level of C7 (age range, = 30–34 years, n = 18).

Theoretical Modeling

The biomechanical model used was based on the muscle architectural properties previously reported and the theoretical model previously developed to describe the interaction between muscle, joint, and tendon using an analytical software package (Mathematica version 4.1; Wolfram, Inc, Champaign, IL). The posterior deltoid 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 constant independent of muscle length, which permitted pennation angle, the angle between aponeurosis and fiber, to change as a function of muscle length. Although fiber rotation is not necessarily typical in musculoskeletal modeling, such rotation has been reported to occur during voluntary contractions in humans as measured by ultrasonography. The deltoid force-length property was based on the relation presented by Cutts with a force-length relation plateau extending from sarcomere lengths of 2.5 to 2.8 μm and a maximum sarcomere length for force generation of 4.25 μm. To account for tendon lengthening owing to muscle force generation tendon force was matched iteratively to muscle force while muscle-tendon unit length was held constant.

The model was able to predict elbow extension moment for any muscle length or sarcomere length chosen. Because the actual muscle length of our patients was chosen intraoperatively based on the surgeon’s experience we used the model to calculate retrospectively what the muscle length must have been at the time of surgery. This calculation was performed for every muscle length ranging from 100 mm, at which the muscle was predicted to operate exclusively on the ascending limb of the force-length relationship, to 225 mm, at which the muscle was predicted to operate exclusively on the descending limb of the force-length relationship. The goodness of fit between each predicted and measured moment-angle relationship was assessed by using the coefficient of determination, for each muscle length chosen. To attempt to account for differences in absolute moment between measured and predicted data, goodness-of-fit statistics were calculated with and without scaling of the predicted moment maximum to the measured moment maximum. This scaling did not affect the result obtained with the length corresponding to the best fit of the data easily determined (see later). Thus scaling was implemented only to reproduce the shape of the curve without regard to magnitude and did not affect the results reported here. Muscle fiber length corresponding to each muscle length was calculated based on the measured fiber length:muscle length ratio of 0.67. Data are presented in the text as mean ± standard error of mean.

Results

Twenty-three patients (40 limbs) were enrolled in the study. For 7 of the patients data were acquired at every time interval. For the remaining 16 patients, however, measurements were not performed at 1 or 2 time periods throughout the experimental periods. These time periods were arranged randomly throughout the test period of 8 weeks to 1 year and missing values did not affect the results shown here. There was no clear trend in mean extension moment as a function of time from 8 weeks to 1 year (Fig. 1). Mean extension moment was initially 6.05 ± 0.64 Nm and did not change markedly after 1 year when mean extension moment was 5.89 ± 0.24 Nm (p > .7). The small fluctuations in extension moment means are believed to result from the fact that not all patients were examined at every time point.
Extension moment as a function of elbow joint angle measured 1 year after surgery showed a slight but significant increase with elbow flexion (Fig. 2) and was described by the equation

\[ y \, (\text{Nm}) = 0.0245 \, (\text{Nm/degree}) \times x \, (\text{degrees}) + 4.303 \, \text{Nm} \, (r^2 = .89, \ p < .001). \]

Assuming that the shape of the curve was a direct result of muscle force change with joint angle and the elbow joint moment arm given by the equation

\[ r(\theta) \, [\text{cm}] = 11.6 \, [\text{cm/rad}] \times \sin(\theta) \, [\text{rad}] \]

where \( r(\theta) \) is the moment arm and \( \theta \) is the joint angle as measured previously,\(^5\) the best fit of the biomechanical model to the experimental data indicated that the muscle length at the time of the surgery was only 123.1 mm, which corresponds to a fiber length of 82.5 mm \((r^2 = .93 \text{ between predicted and model data, } p < .01)\), thus placing the transferred muscle exclusively on the ascending limb of the length-tension relationship.

Mean cross-sectional area of posterior deltoid muscles studied previously in cadaveric specimens\(^5\) was 5.1 ± 0.5 cm²,\(^2\) which, if muscle length is 123.1 mm, is predicted to generate a peak moment of 7.06 Nm with the elbow in full extension. Based on our measurements of the mean patient’s elbow extension moment at 0° of 4.59 Nm these data indicate that the muscle force generated was only 65% of the theoretical maximum force that this transfer could achieve. For comparative purposes mean elbow extension strength measured in tetraplegic persons with an injury level of C7 (which preserves triceps function) was 25.6 ± 4.5 Nm \( (n = 18) \), whereas that for young men was 83.2 ± 12.4 Nm \( (n = 10) \).

**Discussion**

The purpose of this study was to quantify elbow extension strength in patients after posterior deltoid-to-triceps tendon transfer and to compare experimentally measured values with those predicted using a previously developed biomechanical model.\(^8\) We found that mean elbow extension moment did not vary significantly over the 1-year follow-up period, that the transferred muscle generated only ~65% of its predicted maximum, and that the transferred posterior deltoid was predicted to operate exclusively on the ascending limb of the length-tension curve.

Our follow-up moment data were confounded by the fact that each patient was not examined at each time period. We do not believe, however, that there is physiologic importance to the slight statistically insignificant variations observed in moment values as a function of follow-up time \( (p > .5, \ \text{Fig. 1}) \). It was a bit surprising that we noted little or no moment increase over the 1-year period because these patients had been immobilized after surgery for 5 weeks and might have been expected to begin the study with significant immobilization-induced atrophy. Additionally based on the neural retraining that might be expected to occur during the 1-year postoperative period, as the patient relearned elbow extension, one might expect a steady and significant improvement in elbow function. This was not the case, however, because the data indicated that elbow extension moment measured at the end of the rehabilitation phase was unlikely to change significantly in the long term.

The posterior deltoid muscle has a cross-sectional area that is only 20% of the combined triceps muscles.\(^5\) Thus it was not surprising that measured extension moment after tendon transfer was relatively low. It should be noted that this moment magnitude is sufficient to oppose gravity and therefore provide elbow control when the arm is used against gravity.\(^7\) That the measured moment was 65% of the theoretical maximum of the posterior deltoid may have a neural or a muscular basis or may result from a combination of the 2 factors. Muscle fiber atrophy results from immobilization\(^13\) and also can result from chronic muscle shortening.\(^14\) If muscle fibers were atrophied secondary to the immobilization used to protect the repair site it is
unlikely that such atrophy would persist 1 year later. Based on the relatively shortened position in which the muscle was apparently placed (see later) it might not be surprising to observe a persistent level of fiber atrophy secondary to chronic shortening as has been observed in animal models. Direct measurement of the average muscle fiber area within normal and transferred posterior deltoid muscles would address this question directly.

The position of these patients during elbow extension functional measurements was not explicitly designed to achieve maximum muscle force or maximum extension moment but rather for the convenience of the patient. Previous studies by Kirsch et al revealed that with the arm in 90° of abduction, as was used in this study, elbow extension moment was only about 75% of maximum. Thus during actual use when the arm was in approximately neutral abduction, day-to-day elbow extension moment could be even higher.

Finally other investigators have shown that true maximum muscle force is very difficult to achieve with voluntary activation even in the presence of extraordinary encouragement so that submaximal neural drive could explain the 65% maximal force measured. To show whether the lower than maximum moment was primarily neural or muscular in origin moment measurements combined with either electromyography, magnetic resonance imaging, or spike-triggered averaging of motor units could be used as reported by others. Additionally the posterior deltoid strength before transfer was often below Medical Research Council grade 5, so perhaps 65% underestimates the percentage strength these patients have achieved because the data were not compared explicitly with preoperative values rather they were compared with normative values from architectural measurements.

We were surprised at the relatively short length that was calculated in this study as the length at which the muscle was attached, namely 123.1 mm. The posterior deltoid muscle can generate force over a range of 73 to 192 mm based on its long muscle fibers. By using the moment arm equation listed earlier in the Methods section we calculated that muscle length changes by approximately 25 mm as the elbow rotates from full flexion to full extension. Based on the calculated muscle length of 123.1 mm and the associated moment arm the transferred posterior deltoid would be predicted to operate over the range of 110.6 to 135.6 mm (ie, 123.1 ± 12.5 mm), placing it exclusively on the ascending limb of the muscle length-tension curve (Fig. 3). The moment change measured as a function of joint angle is not as great as the muscle force change as a function of length because the extension moment arm decreases as the joint extends beyond 90° (see moment arm equation presented earlier). This provides the structural explanation for the increase in muscle force with increasing elbow flexion. Of course such an explanation assumes that musculoskeletal geometry and not selective neural activation provides the underlying explanation for moment change as a function of elbow joint angle. Whether this explanation is adequate requires direct testing as described earlier.

The short muscle length also would produce notable functional deficits should insertion site slippage occur. The patients involved in the current study were of course not the same patients who were enrolled in our study on tendon slippage and thus we could not correlate strength loss with repair site slippage directly. The rehabilitation program implemented was completely analogous to that used previously, with the exception of the special armrest that was developed. Based on the current results we are now in a position to predict the functional effect of the 23 mm of slippage previously reported. Because the transferred muscle apparently operates on
the ascending limb of the length-tension curve (Fig. 3) insertion site slippage and concomitant muscle shortening will result in loss of muscle force. In fact 23 mm of slippage would cause posterior deltoid strength to be near 0 at full extension at a muscle length of approximately 100 mm and thus repair site slippage could explain easily the extension deficit often observed in these patients.19

The short length at which the posterior deltoid was transferred also was surprising in light of our recent demonstration that during 22 tendon transfers about the wrist, sarcomere lengths chosen by surgeons were consistently much longer than optimal, even to the point of resulting in 0 active tension generation. In our previous report involving 22 patients the mean sarcomere length after tendon transfer was 3.78 ± 0.52 μm, which was predicted to result in only 28% of maximum active force generation.20 The assertion that the posterior deltoid was attached at such a short length either implies that the muscle cells of the posterior deltoid have a very short resting sarcomere length and are very stiff or, more likely, that the intraoperative feel of the muscle during tensioning is not an accurate reflection of the muscle fibers themselves but the associated connective tissue structures. Indeed in our previous architectural study we identified 3 to 4 connective tissue septa within this muscle that partitioned it into discrete regions.5 Based on these anatomic studies in combination with the current clinical study we suspect that these septa provide the majority of the resistance to elongation and are responsible for the fact that the muscle fibers are prevented from being stretched to or beyond optimum length. Such a constraint to elongation was reported recently for the brachioradialis muscle.21

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