

Sarcomere length in wrist extensor muscles

Changes may provide insights into the etiology of chronic lateral epicondylitis

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Since the etiology of tennis elbow (lateral epicondylitis) is poorly understood, we studied the anatomical changes in the extensor carpi radialis brevis (ECRB) muscle during elbow joint rotation. Specifically, we measured ECRB sarcomere length, using an intraoperative laser diffraction procedure that measures muscle sarcomere length with an accuracy of $\pm 0.05 \mu\text{m}$. We found an unexpected biphasic response in ECRB sarcomere length as the elbow was rotated from full extension to full flexion. The initial sarcomere length of $3.49 \mu\text{m}$, with the elbow extended,

was gradually changed to $3.68 \mu\text{m}$, $3.34 \mu\text{m}$, $3.81 \mu\text{m}$, and $3.45 \mu\text{m}$ with progressive elbow flexion. Based on the very nonlinear mechanical properties of skeletal muscle, this "double lengthening" of the ECRB during progressive flexion would impose intense eccentric contractions on the muscle itself. Given that eccentric contractions cause muscle injury and subsequent inflammation, these findings may provide insights into the etiology of lateral epicondylitis.

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There is general agreement that the extensor carpi radialis brevis (ECRB) muscle plays a central role in the etiology of lateral epicondylitis (tennis elbow). Microrupture of fibrous origin (Garden 1961), inflammation of ECRB origin (Hohmann 1933), muscular circulatory compromise (Boyd and McLeod 1973), excessive intramuscular pressure (Werner 1979), and excessive muscle passive tension (Fridén and Lieber 1994) have been thought to cause lateral epicondylitis. Predictably, since the etiology of tennis elbow is not well understood, various treatments have been proposed, but without much success.

We recently studied the sarcomere length changes accompanying normal wrist joint rotation (Lieber et al. 1994) which occur subsequent to surgical lengthening of the ECRB muscle-tendon junction (Fridén and Lieber 1994). We demonstrated that the ECRB normally can operate on the descending limb of its length-tension curve and that a $0.3 \mu\text{m}$ decrease in length of the sarcomere accompanies the lengthening of the ECRB muscle-tendon unit when using the Garden procedure (Garden 1961). These measurements were made with the elbow fully extended and we were concerned that the measured sarcomere lengths might actually be inappropriately long, since the

ECRB is reported to have a small flexor moment arm (Amis et al. 1979, An et al. 1981). The purpose of this study was to measure the ECRB change in length of the sarcomere accompanying elbow joint rotation.

Patients and methods

The 13 patients in this study were all undergoing lengthening of the ECRB muscle-tendon junction for treatment of tennis elbow. The median age was 53 ± 8 years and 8 were men. All procedures performed were approved by the Committee on the Use of Human Subjects at the University of California, San Diego and the University of Umeå.

Intraoperative measurements of length of sarcomere

After induction of intravenous regional anesthesia, a 7 mW He-Ne laser beam was inserted into the distal portion of the ECRB muscle, as previously described (Lieber et al. 1994a). With the wrist in the neutral position and the forearm pronated, ECRB sarcomere length was measured from 0° to 90° of elbow flexion inclusively at approximately 30° increments, estimat-

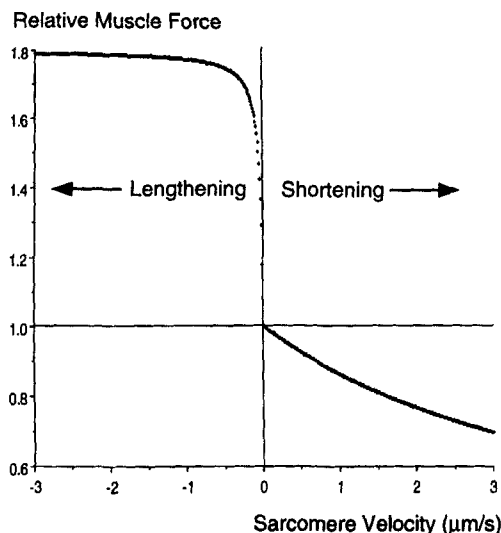


Figure 1. Force-velocity relationship used in the experimental model based on experimental data of Hill (1938) for muscle shortening and Katz for muscle lengthening (Katz 1939). Data are presented for muscle shortening (positive velocities) and lengthening (negative velocities). Horizontal line represents maximum isometric muscle tension (1.0), while vertical line represents isometric condition (velocity 0).

ed with a goniometer. Then, the ECRB muscle-tendon junction was lengthened by the procedure suggested by Garden (1961).

Biomechanical simulation

To predict the force experienced by the activated ECRB during elbow extension based on sarcomere length measurements, we generated a biomechanical model (Mathematica Version 2.2, Wolfram Research, Inc., Champaign, IL, USA) that predicted muscle force using the known properties of the ECRB muscle and tendon (Lieber et al. 1990, Loren and Lieber 1995, Loren et al. 1996). The model was validated by comparing predicted sarcomere lengths with those measured intraoperatively using laser light diffraction. ECRB muscle force was then calculated for elbow angular velocities of 30°, 60°, and 120°/sec over a 90° range of motion. For modeling purposes, we assumed that each patient had ECRB muscles with muscle architecture and tendon, as previously reported (Lieber et al. 1990, Loren and Lieber 1995), i.e., a fiber length:muscle length ratio of 0.38, a fiber length:tendon length ratio of 2.9, and a tendon of compliance such that it strained 2.0% at maximum muscle tetanic tension. The ECRB muscle itself was given a force-velocity relation described by:

$$F = \frac{V_{\max} - V}{V_{\max} + 4V}$$

for shortening, while during lengthening, the relation was given by:

$$F = 1.8 - 0.8 \frac{V_{\max} + V}{V_{\max} - 7.6 V}$$

$V_{\max}$ was taken to be 17.6 µm/s for lengthening and shortening (Figure 1). This force-velocity relationship illustrates the fact that muscle force increases sharply when forced to lengthen, but is only slightly depressed when shortening is allowed. Muscle length-tension properties were assumed to be as described by Gordon et al. (1966), but adjusted for the longer actin filament lengths observed in humans (2.6 µm vs. 2.0 µm; (Lieber et al. 1994a)). Tendon compliance was also explicitly included in the model, using a modulus and strain at maximum muscle tetanic tension of 726 MPa and 2.0%, respectively (Loren and Lieber 1995). Sarcomere length as a function of joint angle was obtained by fitting the raw data to a curve of the form: sarcomere length (µm) = 3.56 - 0.23 * sin(0.16 - 4.91 * x), where x represents joint angle in radians. The precise form of the equation was arbitrary, since the physical phenomenon was relatively insensitive to absolute sarcomere length changes. The sin function was chosen to reproduce only the salient features of the relationship shown in Results.

Statistics

Sarcomere lengths were compared between joint angles, using one-way ANOVA with repeated measures. Post hoc comparisons between the various angles were made, using linear contrasts. Significance level (α) was chosen as 0.05 and statistical power (1-β) was calculated using the equation provided by Sokal and Rohlf (1981).

Results

A most unexpected finding in this study was that, in all subjects, sarcomere length demonstrated a biphasic response as the elbow was moved from full extension to 90° of flexion. Interestingly, the actual form of the sarcomere length-joint angle curves obtained fell into two categories: those which had a minimum at 30° of elbow flexion and those which had a minimum at 60° of flexion (Figure 2). Despite maintenance of the wrist in a roughly neutral position, our explanation for the two different "groups" was that the wrist joint angle was not carefully checked. This assertion was based on the observations that the curve shapes

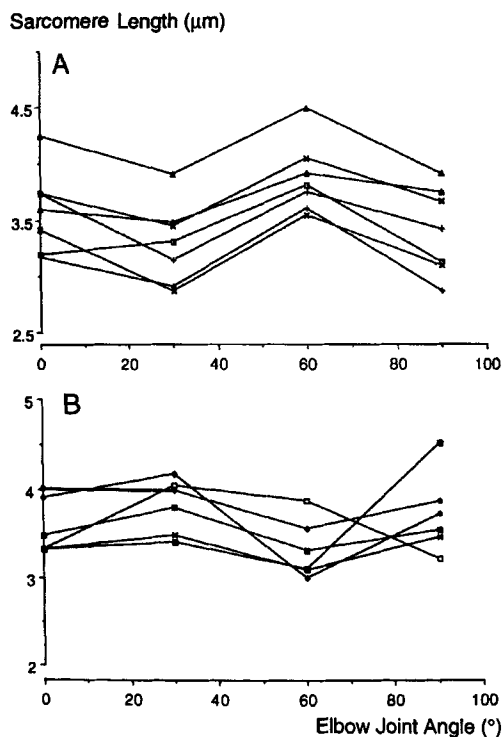


Figure 2. Raw ECRB data concerning sarcomere length obtained intraoperatively for 13 subjects. Data were obtained with the wrist in the neutral position and the forearm pronated. (A) Subjects with a minimum sarcomere length at 30°. (B) Subjects with a minimum sarcomere length at 60°.

appear to be identical, except for a 30° shift in angle and that a relatively small amount of wrist rotation can cause a sarcomere length shift of this magnitude (18° using the data of Lieber et al. (1994a) who reported sarcomere length changes of 0.08 μm/° wrist joint rotation). Alternatively, these differences may represent true variations between individuals. This difference would not affect our results but only the angles at which they occur. For the purposes of this study, we therefore replaced the absolute angles, 0°–90°, with 5 relative elbow joint positions, A–E (Figure 3). The two groups of data were pooled to yield this general curve by shifting the group that showed a minimum at 30° of elbow flexion by 30°, so that the minima coincided. These pooled data demonstrate an initial sarcomere length of 3.49 μm and successive average lengths of 3.68 μm, 3.34 μm, 3.81 μm, and 3.45 μm with progressive elbow flexion.

The functional significance of this biphasic change in sarcomere length is appreciated when one predicts muscle force from sarcomere length, using the model

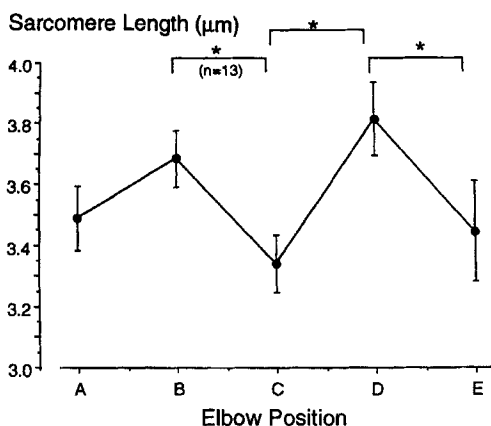


Figure 3. Average change in sarcomere length for all subjects grouped so that minimum value occurs in position C (n=13). Note that during joint rotation, the muscle has two phases of increasing length. Asterisks denote significant differences between adjacent angles.

described in Methods. Since it is well-known that active muscle lengthening results in muscle tension that is significantly higher than isometric (Katz 1939), large force spikes are seen as the muscle enters its lengthening phases (Figure 4). Results were calculated for elbow angular velocities ranging from 30°–120°/sec and were all qualitatively similar to the example shown in Figure 4 (30°/sec). These values are well within normal ranges of movement achieved during activities of daily living and athletic events.

The dramatic discontinuity of muscle mechanical function is appreciated as one follows force and sarcomere velocity for a slow movement. Note that, as the muscle shortens during the first 0.7 s of the movement, sarcomere velocity decreases from about 0.6 μm/s to 0 (Figure 4). This decrease in velocity results in a slight increase (8%) in muscle force during the same period. However, as the muscle begins to lengthen, force spikes rapidly due to the basic biophysical properties of muscle (Figure 1). Since muscle force is relatively insensitive to velocity during lengthening, the force remains at almost 1.8 times maximum isometric muscle force throughout this period (0.7 s–2.0 s), after which it begins the shortening cycle again. Thus, under these conditions, force during the shortening phase decreases by about 8% whereas, for lengthening, muscle force increases by almost 80% or a tenfold asymmetry. If muscle force and injury are related, as has been demonstrated in animal models (Warren et al. 1993, Lieber and Fridén 1993), these maneuvers would be expected to damage muscle.

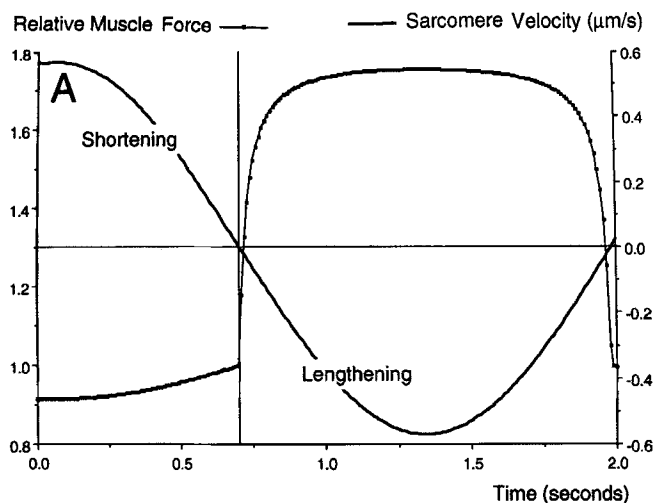
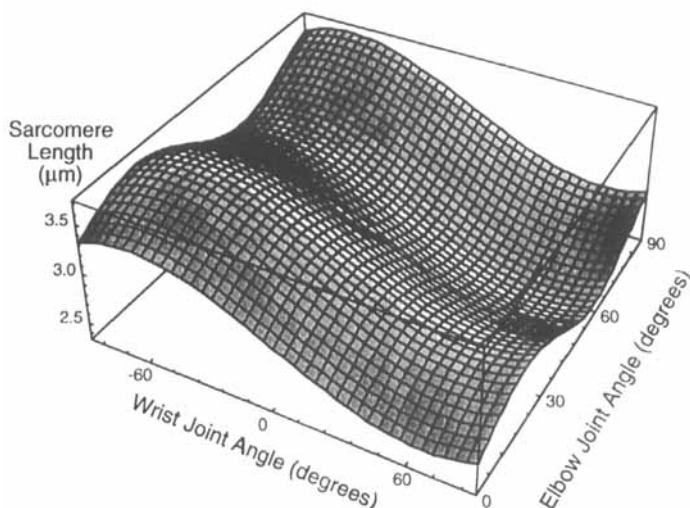


Figure 4. Muscle force predicted using the model described in Methods. Note that during eccentric contraction, large force spikes are observed at this elbow angular velocity (30°/sec). Horizontal and vertical lines denote transition from shortening to lengthening. Relative force values are noted on trace.

Figure 5. Sarcomere length vs. wrist and elbow joint angle predicted using equations obtained independently for the wrist and elbow joint. Data were obtained by applying the constraint that the elbow equation and wrist equation simultaneously satisfy the condition that sarcomere length = 3.0 μm , with the wrist and elbow at 0° (i.e., wrist in the neutral position and elbow fully extended). Equation used for the elbow: sarcomere length (μm) = $3.56 \mu\text{m} - 0.23 \cdot (\sin[0.16 - 4.91\theta])$, where θ is elbow joint angle measured from full extension. Equation used for the wrist: sarcomere length (μm) = $3.033 \mu\text{m} - 0.6\phi - 0.01\phi^2 + 0.17\phi^3$, where ϕ is wrist joint angle measured relative to neutral. Negative angles represent wrist flexion. For both equations, angles are measured in radians.



Discussion

Operating range of ECRB sarcomere length

The goal of this study was to quantify the change in the length of ECRB sarcomeres that occurs during elbow flexion. Previous studies demonstrated that the ECRB operated at sarcomere lengths on the descending limb of the length-tension relationship, even after correction for tendon compliance (Lieber et al. 1994a). We found that this operating range of from 2.44 μm to 3.33 μm can be shifted by elbow rotation. On the basis of the measured actin and myosin filament lengths of 2.6 μm and 1.66 μm , respectively (Lieber et al. 1994a), ECRB muscle would have an optimal sarcomere length of 2.6–2.8 μm and a maximum sarcomere length for active force production of

4.26 μm . Elbow joint rotation can increase these sarcomere lengths by approximately 0.3 μm (with the elbow in position D; Figure 3) or can reduce sarcomere length by approximately 0.2 μm (with the elbow in position C; Figure 3). Given the sarcomere length vs. elbow joint angle relationship defined in this study, along with the sarcomere length vs. wrist joint angle designed in our previous study (Lieber et al. 1994a), one can calculate all possible sarcomere lengths that occur upon elbow and wrist joint rotation (Figure 5). Note that the majority of these sarcomere lengths are on the descending limb of the length-tension relationship (i.e., sarcomere lengths greater than 2.8 μm), a finding that supports our previous contention that this muscle can operate at sarcomere lengths well above the optimum. Thus, changes in sarcomere length are

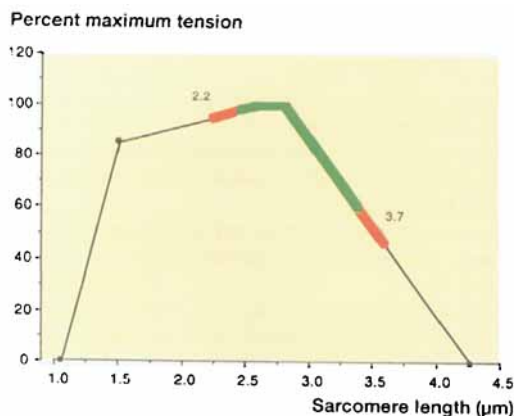


Figure 6. Sarcomere length-tension diagram for ECRB muscle as a function of wrist joint angle (green line) with potential modification by elbow joint rotation (red line). Overall operating range for ECRB is predicted to be from 2.3 μm to 3.7 μm . Data for ECRB sarcomere length as a function of wrist joint angle taken from Lieber et al. (1994) using filament length as measured in that study.

probably important in regulating normal ECRB muscle force in addition to muscle fiber recruitment and rate modulation.

Analysis of the sarcomere lengths shown in Figure 5 show a very abnormal distribution with a skew of -0.039 and kurtosis of -1.174 . These data indicate a preferential design for relatively long or relatively short lengths, without a high probability of intermediate values. In fact, the arithmetic mean of the data set (3.05 μm) is one of the least probable sarcomere lengths. The data, being highly platykurtotic, reinforce the preference for sarcomere lengths near the extremes.

In the context of the length-tension relationship, the operating range of the sarcomere length of the ECRB, including variation due to elbow joint rotation (Figure 6), could span the range from about 2.2 μm (with the wrist fully extended and the elbow in position C) to 3.7 μm (with the wrist fully flexed and the elbow in position D).

ECRB may be subjected to chronic eccentric contraction

The biphasic change in the length of the sarcomeres with elbow rotation results in eccentric muscle contraction during elbow joint flexion over a 90° range of motion. The corresponding force spikes result from the basic biophysical property of skeletal muscle which causes increased stiffness with lengthening (Katz 1939). Since it is known that eccentric muscle actions result in ultrastructural damage to the myofibrillar apparatus (Fridén et al. 1983) and subsequent

inflammation (Mishra et al. 1995), such cyclic motion could result in chronic muscle inflammation and decreased contractile performance, as observed in animal (Armstrong et al. 1983, Schwane and Armstrong 1983, McCully and Faulkner 1985, Lieber et al. 1994b) and human models (Clarkson et al. 1982, Evans et al. 1985, Cannon et al. 1990, 1991). Since the ECRB origin lies almost exactly on the elbow joint axis of rotation, the most likely explanation of the current finding is that, during joint rotation, the effective origin of the muscle slides back and forth across this axis during elbow joint rotation.

These data may also explain why the ECRL muscle is rarely involved in tennis elbow, although ECRL is activated synergistically with ECRB. Since the ECRL arises much more proximally on the humerus and has a much larger elbow flexion moment arm, it could not cross the elbow axis of rotation as the ECRB could. It is difficult to imagine any other muscle in the upper extremity which is so uniquely placed relative to the joint axis of rotation as is the ECRB.

Putative effect of intervention

The present finding may explain the reported beneficial effects of various tennis elbow treatments. For example, forearm bands which in many cases are placed on the forearm just distal to the lateral epicondyle, may prevent ECRB movement across the elbow axis of rotation, thus resulting in a purely concentric action with elbow extension. The resulting average force would be lower and there would be no high force spikes. Similarly, exploration and debridement of the ECRB origin may stimulate scar formation that would effectively “tack down” the muscle origin, preventing origin movement and resulting eccentric action.

Caution must be exercised regarding the present data. First, we have no evidence that this type of change in biphasic sarcomere length is typical for normal human ECRBs. Patients who complain of tennis elbow may do so because of this anomalous sarcomere behavior. The predisposition to tennis elbow may result from the ECRB origin being too close to the elbow axis of rotation. More studies on normal ECRB muscles are required to address this question.

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