MECHANICAL BEHAVIOR OF SKELETAL MUSCLE DURING STRETCH: INFLUENCE OF MUSCLE ATROPHY

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INTRODUCTION

From a clinical perspective, muscles are believed to act as dynamic stabilizers of joints, and their stiffness during lengthening contractions may play a significant role in protecting joint ligaments from injury/re-injury. One approach that has been used to study the stiffness of muscles/muscle fibers during lengthening contractions is shown in Figure 1. This approach involves fully activating a muscle/muscle fiber, and then imposing a ramp stretch. As shown in Figure 1, the mechanical behavior of the muscle to a ramp stretch is quite complex. During the initial phase of stretch, force rises very rapidly. However, once the muscle/muscle fiber has undergone a strain of approximately 1-2%, the force quickly yields such that force continues to rise but at a slower rate. Currently, the effects of muscle atrophy on the pre-yield modulus (*E;* see Figure 1) remain poorly defined. Accumulating evidence suggests that muscle atrophy does influence the specific-tension of skeletal muscle, and on this basis we hypothesized that *E* would be decreased in proportion to the loss in specific-tension.

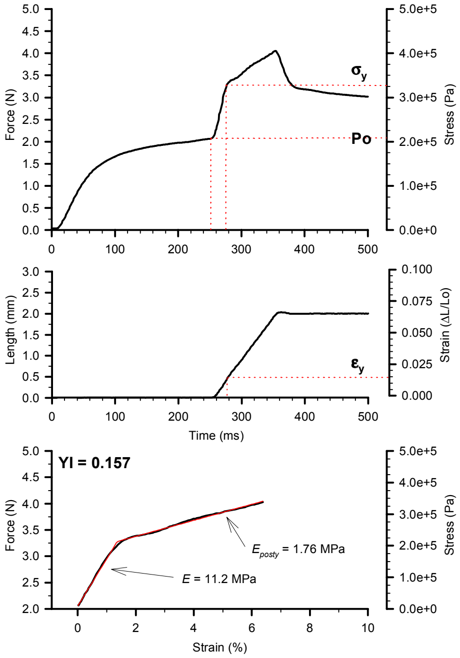

Figure 1.

MATERIALS AND METHODS

Animal Model. All treatment paradigms utilized in this study were approved by the university's Institutional Review Board prior to experimentation. Adult female Sprague-Dawley rats (~250 g body weight) were obtained from Charles River (Wilmington, MA). Animals were randomly assigned to two groups: 1) control (CON; *n* = 8;); and 2) 4 wks of hindlimb suspension (HS; *n*=6) . Hindlimb suspension was used as an intervention to induce muscle atrophy of the soleus muscle.

In situ measurement of force development during ramp stretches of the soleus muscle. Soleus muscle length was set to L_o. Maximal unloaded shortening velocity was determined using the slack test. Muscles were then required to perform ramp stretches that varied in both amplitude (0.5, 1, and 2 mm) and rate. The amplitude of ramps used in this study corresponded to strains of ~1.5 to ~6 % of L_o. Collectively, the ramp velocities spanned a spectrum of strain rates equivalent to 5-40% of V_o. Muscles were also passively stretched under each condition. The active force generated by the muscle during the stretch was simply the difference between total force minus passive force.

Determination of E, E_{posty}, σ_y, and S_Y. Stress (σ) was defined as the force per cross-sectional area, and was expressed in units of Pascals (Pa; 1 Pa = $1 N/m^2$). Strain (ε) was defined as:

$$\varepsilon = (\Delta L - L_o)/L_o$$

To avoid subjective bias in determining E, E_{posty}, σ_y, and ε_y, the stress-strain records obtained from the ramp stretches were analyzed using a non-linear regression model.

Statistical analyses. Data are reported as means ± SEMs. Muscle weight and specific-tension were analyzed using a one-way ANOVA. The stretch data (e.g., *E*) were analyzed using a two-way ANOVA (group, ramp velocity). Statistical significance was defined as $P<0.05$.

RESULTS

Muscle weights and specific-tension. The mean soleus muscle weight of the CON group was 124 ± 4 mg. In contrast, the mean soleus mucle weight of the HS group was much less than that of the CON group (49 ± 4 mg; $P<0.001$). Specific-tension of the CON group was 27.6 ± 1.1 N/cm^2, whereas that of the HS group was 22.4 ± 2.5 N/cm^2 ($P<0.01$).

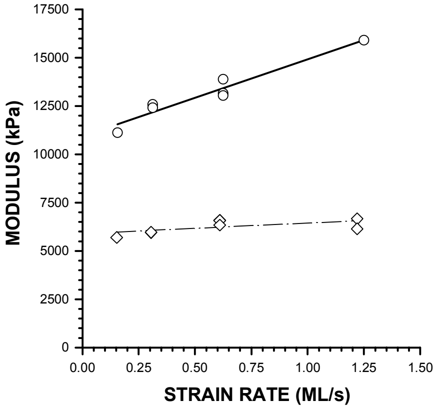

Figure 2

Pre-yield modulus. The data for *E* is shown in Figure 2. Each data point represents the mean value at a given strain rate. In some instances, there is more than one value per group at each strain rate due to the combination of amplitudes and rates of stretch used in this study. Results of the two-way ANOVA demonstrated that there were significant group effects ($P<0.001$), ramp velocity effects ($P<0.05$), and interaction effects ($P<0.01$). Note that the difference in *E* between the CON and HS groups is a function of strain rate, with the difference increasing as a function of strain rate.

DISCUSSION

The stiffness of a muscle is dependent on the number of crossbridges attached and the unitary stiffness of each crossbridge. Theoretically, the normalization of force to cross-sectional area accounts for differences in the density of crossbridges. The findings shown in Figure 2 demonstrate that muscle atrophy markedly effects the *E* of skeletal muscle to an extent greater than that predicted by the loss in specific-tension. Within this context, the findings of this study suggest that muscle atrophy may effect the unitary stiffness of crossbridges.

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