Effects of Boundary Conditions on the Stress Relaxation of Passively Compressed Skeletal Muscle

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Introduction: Computational models of skeletal muscle are useful to study impact biomechanics and surgical-planning. However, the accuracy of these models comes into question as the behavior of muscle in compression is not well understood, specifically in regard to boundary conditions. In this study, we aim to understand how skeletal muscle behaves in different forms of compression (confined and unconfined) at different strain rates. Data from this study will help to develop physiologically accurate computational models of skeletal muscle.

Materials and Methods: Stress relaxation testing on porcine tibialis anterior was performed. Tissue was acquired from a local abattoir and dissected into transverse-oriented cuboids (thickness = 7.9 ± 0.5 mm) and cylindrical plugs (diameter = 6.6 mm). For unconfined compression, the samples were placed between compression plates and compressed to 40% axial strain. For confined compression, the plugs were placed into a well and compressed to 15% axial strain by a porous plunger. Samples were strained at fast rate (15%/s for confined and 40%/s for unconfined) and slow rate (1.5%/s for confined and 5%/s for unconfined). All samples were allowed to relax for 400s. A 10N static load cell was used for data collection. To characterize the stress relaxation behavior, three relaxation ratios (0-6s, 6-106s, 106-400s), total relaxation as a fraction of peak stress, and stress relaxation slope from 395 to 400s were calculated. Peak and equilibrium moduli were also determined. Two-tailed t-tests (significance set at $p < 0.05$) were performed to compare the aforementioned parameters with the form of compression between fast/slow strain rates.

Results and Discussion: Muscle was stiffer in confined compression as peak and equilibrium moduli were higher than unconfined compression at both strain rates. Relaxation ratio (RR) 1, 2 and 3 were different for confined and unconfined compression at the slow strain rates but only RR 1 and 3 were different with the form of compression for the fast strain rates. The total relaxation fraction was greater for the unconfined compression tests at both strain rates, which shows that greater relaxation occurred in muscles in unconfined compression. The slope of the relaxation curve from 395-400s was greater for confined compression than for unconfined at both strain rates, indicating that muscle continues relaxation in confined compression for longer than in unconfined compression. In summary, restricting lateral expansion of muscle shows to have great effects on passive compressive behavior of skeletal muscle. It still remains unclear what mechanism dictates these differences, although fluid pressurization is likely to play a key role.

Table 1: Parameters ($\pm$ standard error) characterizing stress relaxation behavior of muscle in the four testing configurations

Test type	Peak Modulus ($\times 10^5$ Pa)	Equilibrium Modulus ($\times 10^5$ Pa)	RR 1 (0-6s)	RR 2 (6-106s)	RR 3 (106-400s)	Relaxation Fraction	Slope for 395-400s ($\times 10^{-4}$ s ⁻¹)
Slow Confined (1.5%/s)	6.8 ± 1.3	1.4 ± 0.2	0.13 ± 0.01	0.23 ± 0.03	0.074 ± 0.007	0.43 ± 0.10	-2.8 ± 0.5
Slow Unconfined (5%/s)	0.4 ± 0.1	0.05 ± 0.01	0.49 ± 0.01	0.34 ± 0.01	0.038 ± 0.003	0.86 ± 0.02	-1.3 ± 0.3
p-value	0.003	<0.001	<0.001	0.047	0.002	<0.001	0.005
Fast Confined (15%/s)	16.7 ± 3.3	1.8 ± 0.5	0.34 ± 0.04	0.30 ± 0.02	0.031 ± 0.004	0.71 ± 0.05	-3.0 ± 0.4
Fast Unconfined (40%/s)	0.98 ± 0.27	0.07 ± 0.02	0.61 ± 0.02	0.25 ± 0.03	0.076 ± 0.007	0.90 ± 0.01	-0.90 ± 0.01
p-value	0.003	0.011	<0.001	0.296	0.001	0.013	0.002

Conclusions: Despite the higher peak moduli seen in confined compression, muscle in confined compression relaxed less than muscle in unconfined compression and also at a slower rate. This was true for confined compression even at lower strain levels and lower strain rates, suggesting boundary conditions can greatly affect observed passive muscle mechanics. Conclusions from this study suggest a mechanism in addition to viscoelasticity— possibly the biphasic nature of skeletal muscle— that gives rise to the observed behavior of muscle in compression. In the future, computational modelling could be used to study the nuances of the relaxation behavior of muscle in compression.