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Correlation Between Isometric Force and Intramuscular Pressure in Rabbit Tibialis Anterior Muscle with an Intact Anterior Compartment

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Abstract

To determine the degree to which intramuscular pressure (IMP) and muscle force are correlated in an intact compartment, a custom pressure transducer was inserted into the rabbit tibialis anterior (TA) while activating the muscle via the peroneal nerve and measuring TA muscle force distal to the ankle retinaculum. In general, IMP was more variable compared to muscle force throughout the entire isometric length-tension relationship. In contrast to results obtained on isolated TA muscles, IMP-force relations with the compartment intact were not significantly different between the ascending and descending limbs of the length-tension curve. Specifically, average relative pressure-force coefficients of determination (r^2) were 0.76 ± 0.11 for the active ascending limb and 0.98 ± 0.01 for the active descending limb. These data demonstrate that muscle force and IMP are fairly well correlated under isometric conditions and that this relationship is not improved by measuring IMP in an intact environment.

Keywords

Intramuscular pressure; Length-tension relationship; Isometric contraction; Fluid pressure; Fluid mechanics

1. Introduction

Human skeletal muscle functional studies are notable for the variety of methodological approaches used. Functional evaluation of human muscle may range in scale from the highly invasive direct measurement of active^{8,18} or passive¹³ muscle force to noninvasive or minimally invasive inference of function based on the electromyogram (EMG^{9,23}) or a muscle image (Ultrasound^{15,3} and MRI^{25,12}). For the purposes of assigning cause-effect

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Conflict of Interest: Patrick Cottler is employed by Luna Innovations who manufactures the pressure transducer.

relationships between muscle function and individual performance, it is desirable to obtain direct muscle function measurements in a clinically acceptable manner. The most promising approach for obtaining such unambiguous information (absent modeling assumptions) is direct measurement of intramuscular pressure (IMP) during voluntary movement. Muscle IMP measurements have enjoyed great popularity in the clinical and applied physiological literature where descriptive studies have correlated IMP with ground reaction force², isometric joint torque²⁶ and the onset of compartment syndrome¹¹. In these situations, it has been assumed that IMP serves as an accurate surrogate of muscle force. Yet only recently has IMP been directly compared to muscle force⁶. In that study, it was found that muscle force and IMP were reasonably correlated but that the IMP measurements were much more variable than force measurements with coefficients of variations approaching 100%. However, this study was performed with the anterior compartment muscles of the leg exposed. IMP has been shown previously in clinical and cadaveric studies to correlate with tissue depth and muscle position¹⁰ and with transducer movement in basic science studies.²⁸ We suspected that retaining the myofascial boundaries may help anchor the transducer and minimize transducer movement, thereby improving the muscle stress-IMP correlation. The importance of this approach is to reflect the clinical use of the device, since one of the intended applications of IMP measurement in humans is to understand movement and aid in the surgical decision-making process^{27,5}. Thus, the purpose of this study was to measure the muscle force-IMP correlation under conditions of intact skin and fascia to quantify the degree to which IMP serves as a surrogate for active and passive force.

2. Materials and Methods

Experiments performed in this report were similar to previously described methods⁶ but the anterior compartment of the leg remained intact. The tibialis anterior (TA) muscle of the New Zealand White rabbit (mass = 2.6 ± 0.3 kg; $n=9$) was chosen for force and pressure measurements based on its accessibility, parallel fiber arrangement (pennation angle of 3 degrees²⁰), and predominantly fast fiber type percentage (95% fast fiber type^{19,1,24}). Control experiments demonstrated that the small transducer tip, representing only 0.2% of the muscle's physiological cross-sectional area (PCSA)⁶ did not affect isometric force production after 40 isometric contractions. The protocol was approved by the Department of Veterans Affairs, San Diego Committee on the Use of Animal Subjects in Research. All experimental procedures were performed in accordance with the guidelines set forth by the National Institutes of Health "Guide for the Care and Use of Animals."

Animal preparation and measurement of isometric contractile properties were performed essentially as described previously^{22,21}, but they were modified to ensure that the anterior compartment remained intact. Briefly, rabbits were anesthetized with 5% isoflurane and a subcutaneous injection of a ketamine-xylazine cocktail (50 and 5 mg/kg body mass, respectively) and maintained on 2% isoflurane anesthesia. Heart rate and oxygen saturation were monitored (VetOx, Heska Co., Fort Collins, CO) throughout the test duration, and anesthesia level was adjusted as needed. Two cm incisions made at the medial and lateral femoral condyles and just proximal to the medial and lateral malleoli of the leg, allowed 3.2 mm Steinmann pins to be drilled through the femur and tibia. The pins were used to secure the leg to a custom-made jig for muscle testing. The lateral femoral condyle incision was extended, and the biceps femoris was split to expose the peroneal nerve. A cuff electrode was placed around the peroneal nerve for direct muscle activation (Pulsar 6Bp Stimulator; FHC, Bowdoinham, ME). A fifth incision was made distal to the extensor retinaculum. The distal TA tendon was transected and clamped to a servomotor (Cambridge Model 310B; Aurora Scientific, Aurora, ON, Canada), which controls muscle length and measures force. It was located at the muscle-tendon junction, and it was aligned with the force-generating axis of the motor (Fig. 1). Muscle temperature was maintained at 37°C with radiant heat,

mineral oil, and a servo-temperature controller (Model 73A; YSI, Yellow Springs, OH). A 250 μm diameter fiber optic pressure sensor (Luna Innovations, Blacksburg, VA) was inserted via a 20-gauge angiocatheter needle at approximately 10 degrees in the sagittal plane in line with the force-generating axis of the fibers in the mid-belly of the muscle (Fig. 2). The pressure performance characteristics of the force transducer¹⁶ showed a mean accuracy of $1.45 \pm 0.32\%$ and a mean repeatability of $1.5 \pm 0.81\%$ ($n = 5$ different transducers tested in vitro).

The length-tension protocol consisted of a series of 100 Hz tetanic contractions (pulse width 0.3 ms; amplitude 10 V) over a 640 ms period. Two minute rest intervals were interposed between contractions to minimize fatigue effects. Measurements began at a zeroed motor length and ranged from -30% muscle length (L_m) to 30% L_m in increments of 5% L_m . L_m was assumed to be 56.84 mm—the literature optimal muscle length for the TA20. This length was chosen, as muscle length could not be measured directly with the compartment intact. Passive muscle force was defined as the resting muscle force at each length and measured for each contraction bout during the 100 ms time period prior to muscle stimulation. Length, force, and pressure were recorded for each contraction using a data acquisition board (610E series; National Instruments, Austin, TX) and a custom-written LabView program (National Instruments) acquiring data at 4 kHz per channel.

Upon completion of testing, animals were euthanized with pentobarbital (Euthasol; Virbac AH, Fort Worth, TX). The skin and fascia surrounding the TA were excised to validate the position of the intramuscular pressure sensor, and the sensor was gently removed. The muscle was pinned to a corkboard at a length of ~ 56 mm and fixed in 10% phosphate-buffered formalin for 48 hours. After rinsing in isotonic phosphate-buffered saline and digestion in 15% H_2SO_4 for 20 minutes, three muscle fiber bundles were microdissected from the proximal, middle, and distal regions of the muscle to yield representative sarcomere lengths (L_s) across the entire muscle. Fiber bundle length was measured under a dissecting microscope to the nearest micron from 2 different fiber bundles in each of the 3 regions, providing 6 measurements of bundle length across the entire muscle. The L_s of each bundle was measured by laser diffraction in 3 regions of each muscle; thus, the whole-muscle sarcomere length was calculated as the average of 18 L_s measurements obtained from the entire muscle. This permitted muscle length normalization to a sarcomere length of $2.27 \mu\text{m}$ ⁴, yielding an experimentally measured optimal muscle length (L_0) for each animal⁷.

Active and passive force and IMP records were converted to relative tension and relative IMP by dividing by peak force (P_0) and peak IMP (I_0), respectively, for the purpose of comparing the two measurements. The experimentally measured absolute muscle lengths were divided by the animal-specific normalized muscle lengths (L_0) to obtain relative muscle lengths. Since L_0 was not determined until experiments were completed, relative lengths were not identical among trials. Thus, active data were fit with a second order polynomial (Force: $r^2 = 0.93 \pm 0.02$; IMP: $r^2 = 0.70 \pm 0.07$), and passive data were fitted with a third order polynomial (Force: $r^2 = 0.95 \pm 0.02$; IMP: $r^2 = 0.81 \pm 0.05$), to facilitate interpolation in 5% muscle length increments. To characterize the relative agreement between the relative tension and relative IMP data, the coefficient of determination (r^2) was quantified using the statistical package SPSS (SPSS, Chicago, IL). Likewise, the intraclass correlation coefficient (ICC) was employed to quantify absolute agreement between the data sets. The r^2 and ICC values were calculated for the ascending limb (defined as lengths less than or equal to L_0), the descending limb (defined as lengths greater than L_0), and both limbs (all data) for the purpose of examining the underlying contributions of each limb to the active IMP signal. In investigating the passive IMP signal, relative tension and IMP data for the entire curve was analyzed. Differences in ascending and descending limbs and

differences in active and passive relationships were compared with paired t-tests. All data are presented as mean $\pm$ SEM unless otherwise stated. Significance is set to $p < 0.05$ and presented as a range when depicting significance across trials.

3. Results

The raw intramuscular pressure-time traces mimicked the general shape of the raw isometric force-time traces but exhibited a drop in pressure over the course of activation (Fig. 3) as previously reported⁶. As expected, the muscle length-isometric tension curve was characterized by an ascending limb at lengths less than L_0 and a descending limb with passive tension rising exponentially at lengths greater than L_0 (Fig. 4A). Stress at optimal length was 298.2 ± 3.7 kPa. Similarly, the length-intramuscular pressure relationship was also characterized by an ascending and descending limb for most individual trials (Fig. 4B), despite the difference in length at which optimal force and pressure occurred. This yielded high variability and an irregular shape of the length-intramuscular pressure relationship in comparison to tension. As seen previously⁶, pressure declined more rapidly than tension at long lengths. The passive relative pressure curve had a similar shape to the passive relative tension, and it also had a higher degree of variability.

A positive linear correlation was found between relative tension and relative intramuscular pressure for both the ascending and descending limbs (Table 1). Relative pressure-force coefficient of determination (r^2) averaged 0.76 ± 0.11 ($p < 0.001 - 0.114$) for the active ascending limb and 0.98 ± 0.01 ($p < 0.001$) for the active descending limb. The passive coefficient of determination averaged 0.77 ± 0.05 ($p < 0.001 - 0.003$) for both limbs combined. In contrast to our previous report on the isolated TA6, pressure-stress correlations for the ascending limb of the length-tension curve and descending limb were not significantly different ($p = .091$). However, correlations for active tension ($r^2 = 0.61 \pm 0.13$) were generally lower than those for passive tension ($r^2 = 0.77 \pm 0.05$). An overall significant absolute agreement was found between intramuscular pressure and tension. Average ICC value was 0.60 ± 0.11 ($p < 0.001 - 0.946$) for the active ascending limb and 0.49 ± 0.11 ($p < 0.001 - 0.275$) for the active descending limb. The passive pressure-tension relation yielded an ICC of 0.80 ± 0.03 ($p < 0.001 - 0.034$).

Linear regression of relative tension and intramuscular pressure yielded a slope of 1.57 ± 0.22 with an intercept of -63.91 ± 28.13 . Decomposing this into ascending and descending limbs resulted in slopes of 1.48 ± 0.28 and 1.58 ± 0.31 , respectively, which were not significantly different from each other ($p = 0.827$). Intercepts were also not significantly different from each other ($p = 0.906$) with values of -87.18 ± 52.57 and -93.32 ± 30.57 for the ascending and descending limbs, respectively. The passive tension-IMP regression yielded a slope of 0.94 ± 0.07 and intercept of 6.72 ± 1.70 . A comparison of the active and passive regressions resulted in a significant difference between both the slope ($p = 0.042$) and intercept ($p = 0.034$).

4. Discussion

The purpose of this study was to define the relationship between isometric force generation and intramuscular pressure (IMP) under conditions where the myofascial compartment was intact. Our main finding was that the previous demonstration of good correlations between these two parameters remained true but did not improve in spite of the system remaining intact. These data suggest that continuity of the myofascial compartment does not change the IMP-force relationship observed in isolated muscle systems. Thus, these data provide support for the ability of IMP to predict muscle force in a clinical setting.

In contrast to previous studies, no difference between the pressure-force correlations were observed on the ascending compared to the descending limb of the length-tension curve. Previously, based on a higher correlation observed between pressure and force on the descending limb, we hypothesized that, at longer lengths, the pressure transducer was held more securely in the muscle tissue, thus minimizing movement artifact⁶. Indeed, direct high-speed video recordings of muscle contractions subsequently demonstrated the critical effect of transducer movement on the fidelity of the pressure signal. When transducer movement occurred, the pressure curve was almost completely dissociated from the force curve, even after transducer movement ceased²⁸. Based on this finding, we suspected that an intact myofascial compartment might secure the transducer more firmly compared to the case of an isolated muscle and improve the pressure-force correlation. However, this was not the case.

Previous studies of intramuscular pressure have described factors that affect the magnitude of measured pressure. For example, depth, proximity to bone and muscle curvature have been isolated as important factors that define absolute muscle pressure levels^{10,26}. In several pilot studies in which multiple pressure transducers were inserted into a single muscle, we found qualitative and quantitative differences among the absolute pressure records recorded. It thus appears that the pressure records obtained here may represent a relatively local phenomenon.

The data may provide some insights into the mechanism of pressure generation in skeletal muscle. Specifically, we observed that IMP declines more rapidly than active force as muscle length increases on the descending limb (Fig. 4). This observation is consistent with the idea that contractions at longer lengths may disrupt parallel passive structures in the tissue such as connective tissue, intermediate filament meshes, and even muscle cell-extracellular matrix interactions¹⁷. If disruption occurs, it might be expected that the muscle contractile force would be dissipated throughout the tissue, and the pressure rise would not scale directly with myofilament overlap. Of course, this assertion must be tested experimentally. Since finite element models suggest that muscle tissue strain and pressure are causally related¹⁴, the data suggest that muscle strains are not dramatically affected by superficial fascia and skin.

In summary, these experiments demonstrate that IMP and muscle force are roughly correlated in both the passive and active conditions. This correlation is not superior to that observed for the isolated TA suggesting that anterior compartment patency does not affect the fundamental nature of pressure generation in skeletal muscle.

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Abbreviations

EMG	Electromyogram
I₀	Peak Intramuscular Pressure
ICC	Intraclass Correlation Coefficient
IMP	Intramuscular Pressure
L₀	Experimentally Measured Optimal Muscle Length for the Tibialis Anterior
L_m	Literature Optimal Muscle Length for the Tibialis Anterior
P₀	Peak Tension
r²	Coefficient of Determination
TA	Tibialis Anterior

Figure 1.

Experimental apparatus used to measure isometric force-intramuscular pressure relationship with an intact anterior compartment. The rabbit hindlimb is immobilized in a custom jig via Steinmann pins securing the distal femur and ankle joint. A cuff electrode is placed around the peroneal nerve to activate the TA. Arrows mark the path of the pressure sensor with the star depicting the insertion position. Inset: Close-up view of the pressure sensor insertion.

Figure 2. Lateral X-ray of the rabbit hindlimb with sensor. Left: Placement of the sensor in the mid-belly of the TA muscle. Right: Sensor tip placed mid-muscle with approximately 5 mm of the sensor entering the muscle.

Figure 3. Sample record of muscle force (N) and intramuscular pressure (mmHg) recordings from an isometric contraction. Average force and intramuscular pressure values on the plateau were used to construct the length-tension and length-IMP relations. The period of muscle activation is denoted by the solid bar at the bottom and vertical dotted lines.

Figure 4. Relationship between relative change in length and (A) average isometric force or (B) average intramuscular pressure for the rabbit tibialis anterior. Filled symbols represent measurements from activated muscles while open symbols represent measurements from passive muscles. Force and pressure correlations did not differ between limbs and passive stretch generally maintained higher correlations (see Table 1 for details). Data are plotted as mean $\pm$ SEM.

Table 1

Summary of relative isometric tension-pressure correlations*

Activation State	Limb of the Length-Tension Curve	Coefficient of Determination (r^2)			Intraclass Correlation Coefficient (ICC)		
		Mean $\pm$ SEM	Range (Min - Max)	Mean $\pm$ SEM	Range (Min - Max)	Mean $\pm$ SEM	Range (Min - Max)
Active	Ascending Limb	0.76 $\pm$ 0.11	0.16 - 0.99	0.60 $\pm$ 0.11	0.16 - 0.99		
	Descending Limb	0.98 $\pm$ 0.01	0.90 - 0.99	0.49 $\pm$ 0.11	0.09 - 0.99		
	Ascending + Descending Limb	0.61 $\pm$ 0.13	0.10 - 0.99	0.48 $\pm$ 0.12	0.18 - 0.99		
Passive	Ascending + Descending Limb	0.77 $\pm$ 0.05	0.51 - 0.93	0.80 $\pm$ 0.03	0.66 - 0.93		

* Values represent mean $\pm$ standard error for $n = 9$ animal subjects