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MUSCLE PHYSIOLOGY

Muscle strength and stiffness in resistance exercise: Force transmission in tissues

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Summary Physical therapists and osteopaths want to know the quantitative force transmitted in the tissues during resistance exercise and also the relationship between tissue strength and the specific type of resistance exercise of the skeletal muscles.

This paper uses the strain energy function for large deformations associated with the active and passive response of transversely isotropic skeletal muscle tissue to evaluate muscle strength and force transmitted in tissues during resistance exercises for the quadriceps muscle at the knee during isometric training exercise at different knee angles in vivo.

It is found that after an exercise program, the muscle stiffness is halved when the bending angle of the knee increases from 50° to 100°. The muscle strength generated is marginally greater at 100° than at 50°. The stress transmitted in the lateral direction for 100° bending is double that for 50°.

Introduction

Health care providers and physical fitness professionals have long touted the benefits of resistance exercise for improving functional and athletic performance. Different approaches of resistance training have been investigated for the purposes of improving strength, endurance and power. Thomas L. Delorme, an early researcher in the area of resistance exercise, promoted and observed resistance training exercises with hundreds of injured soldiers. He

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advanced the work of resistance training and recommended a protocol using a 10-repetition maximum (RM) to determine the load or weight to be lifted or moved. The protocol called for one set of 10 repetitions to be performed with half the 10-RM, followed by a 2nd set of 10 repetitions with $^3/_4$ the 10-RM, followed by a 3rd set of 10 repetitions with the full 10RM. The weight was to be progressed once the person was able to complete more than 15 repetitions during the third set.

Delorme observed remarkable improvements in strength and muscle hypertrophy as a result of the progressive resistance exercise (PRE) protocol (Delorme and Watkins, 1948; Delorme, 1945). In particular, he reported on hundreds of cases of femur fractures, cruciate ligament injuries and post-meniscectomies for which a high resistance, low repetition resistance program was successful in treating muscular atrophy, joint instability, pain and swelling.

What has frequently been overlooked in Delorme's research however, are the observations he made of muscle as a connective tissue. Delorme noted that immobilized muscles, especially the quadriceps, would become very hard in consistency, reflective of fibrotic changes. Soon after strenuous PRE were begun, the tissue began to soften and the muscle returned to a normal consistency. While he provided data on joint range, with $p < 0.05$ for PRE compared to standard physical therapy, his observations on fibrosis and scars are only comments in the text of his papers.

Another feature of Delorme's protocol of PRE are the recommended positions and techniques for performing exercise. Delorme believed that in order to achieve maximum hypertrophy, the heaviest load should be imposed on a muscle as it approaches its most shortened length. He theorized that when the muscle fibers are contracted, a greater numbers of fibers are recruited to move the load compared to the type of contraction that occurs when the muscle is in an elongated position. Thus, more fibers are exercised and hypertrophy can occur quickly. In patients with limited range of motion because of scarring around the knee joint, Delorme observed that his protocol of high load and at short muscle length not only produced strength and muscle girth gains, it also resulted in a remarkable softening of the scar tissue and a considerable improvement in joint range of motion.

Delorme's (Delorme and Watkins, 1948; Delorme, 1945) observations could be based on local changes from muscle forces being transmitted to surrounding lateral connective tissues (Huijing, 2009) or to local carryover to muscles crossing adjacent joints noted from quadriceps exercise to the plantar flexor muscles and tendons (Onambele et al., 2008). These findings may also be from the systemic release of myokines or other hormonal factors with muscle contraction (Pedersen and Febbraio, 2008). Knowing the effect of muscle resistance training on the surrounding connective tissue and fascia can influence recommendations for an exercise that will improve strength and flexibility.

Previous studies of exercise have looked at different aspects of the muscle-tendon unit. Tipton et al. (1975) found increased strength of the tendon-bone junction. Stiffness of the muscle-tendon as a unit increased in response to isometric exercise (Klinge et al., 1997) but adding flexibility exercises did not change this increase in stiffness. Exploring further, Kubo et al. (2001) found similar increases in tendon stiffness with quadriceps exercise with/without flexibility exercise, but the stretching reduced hysteresis of the tendon, leading him to conclude that stretching changed tissue velocity but not elasticity. While both 1 s and 20 s isometric contractions of plantar flexors increased muscle strength, only the 20 s training increased tendon stiffness (Kubo et al., 2001). Quadriceps training at 40% or 80% of 1 RM both increased strength in elderly adults, but only the 80% loading increased patellar tendon stiffness (Grosset et al., 2014). Training of the quadriceps with either flywheel or resistance exercises affected the plantar muscle-tendon unit with moderate increase in plantar flexion force and a large increase in achilles tendon stiffness, particularly in the flywheel training (136%) (Onambele et al., 2008). Seynnes et al. (2009) specifically noted that changes in muscle strength are independent of changes in tendon stiffness, modulus or cross sectional area.

Our research team has primarily focused on the proximal muscle portion of the muscle tendon unit. We (Findley et al., 2015) have studied the transmission of muscle force to fascia during exercise and found that substantial forces are experienced laterally through connective tissues when muscle shortens. Researchers have found that skeletal muscle is transversely isotropic and experiences large deformations when subjected to forces (Morrow et al., 2010; Papazoglou et al., 2005; Odegard et al., 2008). As an indication that modeling these tissues as isotropic in all directions is not appropriate, we note that the Young's modulus in the axial direction of the skeletal muscle is about 15 times that in the lateral direction (Papazoglou et al., 2005). Kubo et al. (2006) determined the effects of isometric training at different knee angles (50 and 100° angles) on the muscle—tendon complex in nine males who participated in a 12-week unilateral training program. When the knee is flexed at 50°, the quadriceps is at a shorter length (ST) than when the knee is flexed at 100° (LT). They concluded based on their calculations that tendon stiffness does not significantly change at a 50° knee angle ($p = 0.18$) whereas it significantly increases at 100° ($p = 0.014$) and the difference in stiffness change for the two angles was significant ($p = 0.033$). They also concluded that isometric training at longer muscle length may be beneficial in sports training, through mechanisms which remain unclear, However, they did not investigate the changes in muscle stiffness at these angles.

In this paper, we use data obtained from Kubo via email (2015) that was not reported in his 2006 paper (Kubo et al., 2006) and evaluate the transmission of forces across the tissue based on the assumption that the muscle is transversely isotropic. In addition, we calculate both the longitudinal and lateral stresses. We suggest that including an analysis of muscle as well as tendon stiffness may help clarify potential clinical applications beyond sport specific ones. We report the changes in muscle strength and stiffness and also the stress transmitted in tissues at the angles studied by Kubo et al. (2006).

In 2015, Bohm et al. (2015) performed a systematic review of human tendon adaptation in response to mechanical loading during longitudinal exercise interventions on healthy humans. The review included 27 studies with 37 separate interventions on either the Achilles or patellar tendon, located through PubMed, Web of Knowledge, Scopus, and reference lists of articles retrieved. The authors of the review reported that tendons are highly responsive to diverse loading regimens and that in particular, the loading magnitude plays a key role for tendon adaptation in contrast to muscle contraction type. The observed exercise-induced changes in tendon stiffness were due to adaptation of the material properties rather than the morphological properties.

Of note, the change in stiffness/Young's modulus reported was determined in the longitudinal direction only, not in the lateral direction. We hypothesize that changes in these mechanical properties will take place in both the longitudinal as well as lateral directions. For evaluation of stresses in the muscle and surrounding fascia and not just the tendon, we need to employ a constitutive model valid for large deformation for transversely isotropic skeletal muscles in three dimensions. Odegard et al. (2008) determined the Explicit Strain Energy Function of skeletal muscles and quantified their material constants, (their measurement properties are given in the Methods section after equation (4)) taking into account their transverse material properties as well as the finite deformation in passive as well as active responses. In this paper, we use their Strain Energy Function to examine the effects of isometric training on muscle stiffness and muscle strength as well as on the stresses transmitted in the quadriceps muscle at different knee angles in vivo.

Methods

The strain energy function valid for small and large deformations associated with the active and passive response of transversely isotropic skeletal tissues (Odegard) is used to evaluate the stress components and subsequently the stiffness and muscle strength when the quadriceps muscle is bent 50°(short length) and 100°(long length). To find the stress components, we use the equation (equation 28 of Odegard (2008)):

$$\mathrm{S}=\frac{\mu}{2}\left[(L_1^{\alpha}-1)\boldsymbol{M}-(L_2^{\beta}-1)\boldsymbol{C}^{-1}\boldsymbol{M}\ \boldsymbol{C}^{-1}\right]+\frac{\boldsymbol{p}}{3}\mathbf{C}^{-1}+\mathrm{q}\ \gamma)\ \phi\ \boldsymbol{M}_1 \tag{1}$$

which in component form reduces to:

Longitudinal stress:

$$\mathrm{S}_{11}=\frac{\mu}{2}\left[w_1\left(w_1\lambda_1^2+\frac{2w_2}{\lambda_1}\right)^{\alpha-1}-w_1\lambda_1^{-4}\left(\frac{w_1}{\lambda_1^2}+2w_2\lambda_1\right)^{\beta-1}\right]+\mathrm{q}\gamma)\phi \tag{2}$$

and lateral stresses:

$$\mathrm{S}_{22}=\frac{\mu}{2}\left[w_2\left(w_1\lambda_1^2+\frac{2w_2}{\lambda_1}\right)^{\alpha-1}-w_2\lambda_1^2\left(\frac{w_1}{\lambda_1^2}+2w_2\lambda_1\right)^{\beta-1}\right] \tag{3}$$

$$\mathrm{S}_{33}=\mathrm{S}_{22} \tag{4}$$

where $\mu = 300$ kPa, $\alpha = 11.1$, $\beta = 5.3$, $w_1 = 0.5$, $w_2 = 0.25$, $\gamma = 232$ kPa, $q = 1$, $\phi = 1$ (Odegard et al., 2008). We use the value of extension ratio, $\lambda_1 = 1.013$ for the 50° case and $\lambda_1 = 1.026$ for the 100° case (Kubo, 2015). See Table 3.

In all the above equations μ, α, β are material constants ($\mu \geq 0$, $\alpha > 0$, $\beta > 0$).

p is an indeterminate Lagrange multiplier for enforcement of the incompressibility constraint, C^{-1} is the inverse of C, the right Cauchy–Green deformation tensor.

q is the activation level (q = 1 for fully activated muscle and q = 0 for completely relaxed muscle).

ϕ is the actin/myosin overlap parameter dependent on the deformation of the muscle.

$\boldsymbol{M}$ are the structural tensors that describe the material symmetry, and.

L_1 and L_2 are the dyadic products of C and M, and C^{-1} and $\boldsymbol{M}$ respectively.

w_i are the weighting factors that dictate the relative difference between properties parallel and orthogonal to the fiber asxis and are restricted by $w_1+w_2+w_3=1$ and $w_2=w_3$ for transverse isotropy, γ is a material parameter ($\gamma \geq 0$) and λ_1 is the extension ratio.

Nine males (Kubo et al., 2006) participated in 12-week training program on the knee extensors. One leg was trained at 50° (ST) and the other leg at 100° angles (LT). The data for the mean values of the of nine males' muscle volumes at these angles is given below (Table 1), with the p-value equal to 0.017 (Kubo et al., 2006) found using Tukey's post-hoc test. We are using the data collected and published in Kubo et al. (2006) for the analysis in this paper. The descriptive statistics were provided in (Kubo et al., 2006).

For CSA (Cross Section Area), the mean values of nine males' CSA is given in Table 2 (Kubo, 2015).

The quadriceps muscle is assumed to be of cylindrical shape so that the muscle length at any time is calculated as muscle volume divided by CSA. The extension ratio is determined as muscle length (after) divided by muscle length (before) at any angle. The strain is calculated as extension ratio minus 1 as the extension ratio is very small. The Young's Modulus is defined as stress divided by strain. The stiffness is calculated as Young's Modulus multiplied by CSA and divided by muscle length at any instant. The derivation is given below.

$$\mathrm{Stiffness}=\frac{F}{d}, \tag{5}$$

Table 1 Muscle volume before and after exercise with standard deviation (SD).

Muscle volume (50°) mean (SD)	Muscle volume (100°) mean (SD)
Before: 1858 (242) cm^3 After: 2049 (224) cm^3	Before: 1913 (224) cm^3 After: 2152 (213) cm^3

Table 2 Cross sectional area (CSA) before and after exercise with standard deviation (SD).

CSA (50°) mean (SD)	CSA (100°) mean (SD)
Before: 74.1 (9.2) cm^2 After: 80.7 (10.5) cm^2	Before: 75.5 (8.8) cm^2 After: 82.8 (6.8) cm^2

Table 3 Muscle length, extension ratio and strain.

Muscle length 50°	Muscle length 100°	Extension ratio, λ_1 50°	Extension ratio, λ_1 100°	Strain 50°	Strain 100°
Before: 25.07 cm After: 25.39 cm	Before: 25.34 cm After: 25.99 cm	1.013	1.026	0.013	0.026

where F is the force applied and d is the distance produced.

$$\text{Youngs modulus} = \frac{\text{Stress}}{\text{Strain}} = \frac{\frac{F}{A}}{\frac{d}{l}} = \frac{Fl}{Ad} \tag{6}$$

where A is the cross-section area (CSA) and l is the length of the muscle. Using (5) and (60, we get.

Youngs modulus $= \frac{\text{Stiffness}}{A} \cdot l$ or Stiffness = Young's modulus. $\cdot \frac{A}{l}$

The muscle strength is the stress generated along the longitudinal direction.

Results

Using the data in Tables 1 and 2 we find muscle length, extension ratio and strain, see Table 3.

Using the results in Table 3 along with the stress equations given above we find the stresses, Young's modulus and stiffness, see Table 4.

Discussion

Reeves (Reeves et al., 2003, 2004) reported the effect of strength training on human patella tendon mechanical properties of older individuals. Leg-extension and leg—-press exercises increased the muscle-specific force by 19% and increased the stiffness and Young's modulus of the tendons, suggesting the effectiveness of strength training for increasing the intrinsic muscle-force producing capacity of skeletal muscle in old age (mean age 74.3 years with standard deviation 3.5 years). This is of clinical importance since the increased stiffness of tendons results may reduce tendon injuries in old age through faster contractile force production and more rapid execution of motor tasks.

Reeves (2003, 2004), similar to Kubo et al. (2006), investigated the effects of strengthening exercises on the patella tendon, but not on the quadriceps and the surrounding fascia. Delorme's observations (1946) suggest that loading the quadriceps in the shortened range will reduce fibrosis and stiffness in the muscle thereby improving knee range of motion. Together, the findings of Reeves (2003, 2004), Kubo et al. (2006), Bohm et al. (2015) and now this study, suggest that resistance exercise of the quadriceps may benefit healthy persons as well as those with a variety of lower extremity conditions such as femur fracture, knee meniscectomies, ligamentous injuries and knee instability Delorme (1946). Furthermore, the hypertrophy and reduction of swelling and pain without muscle stiffness has implications for the restoration of functional mobility including gait and stair climbing in a patient population.

In other medical conditions, resistance exercise has been found to have benefits over aerobic exercise for cancer patients in general and prostate cancer in particular. Exercise is being promoted for all individuals whether to help prevent the occurrence of cancer or post treatment. In the new field of Exercise Oncology (Jones and Alfano, 2013; Courneya and Friedenreich, 2011) with specific exploration of exercise for prostate cancer (Newton and Galvao, 2013; Santa et al., 2013; Segal et al., 2009).

While our team has modeled forces going laterally from muscle to surrounding tissue (Findley, 2015), applying external compression in the other direction has been a topic of investigation. It is well documented that compression garments worn during or after exercise have beneficial effects for performance recovery and delayed-onset muscle soreness (Beliard et al., 2015; Hill et al., 2014; Friedstat and Hultman, 2014; Burden and Glaister, 2010) although there are some conflicting opinions regarding such beneficial effects. Realizing that compression garments have been widely used in treating burning scars, Leung (Leung et al., 2010) proposed an analytical pressure prediction model for compression garments using Laplace's law.

In this study we found evidence that the observations documented by Delorme (1946) may be due to short muscle length loading and the resultant forces across the contractile tissue and surrounding fascia. We found that that the ratio of lateral stress to longitudinal stress is about 1% when the quadriceps is bent 50° whereas it is about 2% for bending of 100°. This implies that the stress transmitted in the lateral direction for 100° bending (although insignificant relative to longitudinal direction) is about double that for 50° bending. Young's modulus for a 50° angle is almost double that for a 100° angle. The stiffness at 50° is almost double that at 100°. Therefore the stiffness as measured at these two angles generally depends on the knee angle and is reduced by about 50% as the knee angle is doubled. Muscle bent at 100° (252 kPa) generates slightly more stress compared to when bent at 50° (243 kPa). That is, muscle becomes slightly (9 kPa or 4%) stronger at 100° than at 50° after performing exercises.

The influence of specific exercises on muscle strength and tension stiffness has been well studied and applications

Table 4 Stresses, Young's modulus and stiffness.

Stress 50°	Stress 100°	Young's modulus 50°	Young's Modulus 100°	Stiffness 50°	Stiffness 100°
Longitudinal 243 kPa Lateral 3 kPa	Longitudinal 252 kPa Lateral 5 kPa	19 MPa	10 MPa	600 N/mm	320 N/mm

have been made in the context of sports. Resistance training however, has not been well investigated for tissue pliability, including fascial changes and range of motion, issues that have a direct impact on functional mobility. We believe the results for the quadriceps muscle presented in this paper has the potential to be applied to other skeletal muscles and is an avenue for future research. In this paper for simplicity in calculations we have assumed the quadriceps muscle to be cylindrical in shape. More accurate anatomic assumptions and more complex models may be required.

Conclusions

We find that the muscle strength for the quadriceps is slightly greater after exercise at 100° compared to 50° while muscle stiffness becomes almost half at 100° compared to that at 50°. The stress transmitted in the lateral direction at 100° is twice that at 50°. Our paper may be useful in establishing specificity of resistance training for persons with medical conditions such as knee and femur injuries, for which DeLorme exercises were originally developed. While DeLorme then applied his methods to treatment of persons with polio, we think that exploration of these findings beyond knee injuries may lead to insights in rehabilitation and treatment of other injuries and conditions commonly seen today.

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