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3 authors, including:

Hans Chaudhry
New Jersey Institute of Technology

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FASCIA SCIENCE AND CLINICAL APPLICATIONS: FORCE TRANSMISSION RESEARCH

Transmission of muscle force to fascia during exercise

Thomas Findley, M.D, Ph.D [a], Hans Chaudhry, Ph.D [b,*], Sunil Dhar, Ph.D [c]

[a] *Rutgers University and V.A. Medical Center, East Orange, NJ, USA*
[b] *Department of Biomedical Engineering, New Jersey Institute of Technology, Newark, NJ, USA*
[c] *Department of Mathematical Sciences, New Jersey Institute of Technology, Newark, NJ, USA*

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Summary *Objective:* As the muscle contracts, fibers get thicker, forcing the fascial tubular layers surrounding the muscle (endomysium, perimysium and epimysium) to expand in diameter and hence to shorten in length. We develop a mathematical model to determine the fraction of force generated by extremity muscles during contraction that is transmitted to the surrounding tubes of fascia.
Methods: Theory of elasticity is used to determine the modulus of elasticity, radial strain and the radial stress transmitted to the fascia.
Results: Starting with published data on dimensions of muscle and muscle force, we find radial stress is 50% of longitudinal stress in the soleus, medial gastrocnemius, and elbow flexor and extensor muscles.
Conclusion: Substantial stress is transmitted to fascia during muscular exercise, which has implications for exercise therapies if they are designed for fascial as well as muscular stress. This adds additional perspective to myofascial force transmission research.
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Introduction

There is a substantial literature finding that as much as 30–50% of the longitudinal stress exerted by the muscle on the proximal tendon may be transmitted to other structures besides the distal tendon (Huijing, 2009). This has been termed myofascial force transmission. This force also causes major sarcomere length heterogeneity in human lower leg muscles (Yucesoy, 2010) as forces are transmitted from fascia to muscle and this has been addressed with mathematical and finite element modeling. But our study in this paper is in the reverse direction, i.e. we want to know what fraction of muscle force generated by muscle contraction is

* Corresponding author. 176 Prestwick Way, Edison, NJ 08820, USA. Tel.: +1 973 642 7835; fax: +1 973 596 5222.
E-mail address: Chaudhry@njit.edu (H. Chaudhry).

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transmitted to the myofascial layer wrapping the muscle. There has been some work identifying fascial and vascular structures outside the muscle which can conduct these myofascial forces to both agonistic and antagonistic muscles (Huijing, 2009) but a comprehensive model of forces in the fascia is lacking. This paper will looks specifically at the tubular layers of fascia which by necessity must expand outward as the muscle shortens and increases in diameter. This outward force in the radial direction will occur along the entire shortened length of the muscle. While muscle fiber expansion is greater in the mid-muscle, our initial modeling assumes that the entire muscle expands uniformly for simplicity of calculations.

Understanding how epimuscular myofascial force transmission affects fascial mechanics provides a theoretical framework to address the structures outside the muscle/tendon unit itself which in turn may suggest modifications of traditional exercise protocols. These protocols have been designed primarily on the basis of how they affect the muscle (strength, endurance, fiber type, etc.) rather than on their effects on the muscle/fascia structure.

As a secondary and entirely different approach, in addition to the structural support of the body by muscle and fascia forces, we also explore implications at the cellular level. The importance of force on extra cellular matrix (ECM) is described by (Guang-Kui Xu, 2014). They report that *'Cells sense and respond to the elasticity of extracellular matrix (ECM) via integrin-mediated adhesion. Integrins switch among inactive, bound, and dissociated states, depending upon the variation of forces acting on them. A soft ECM can increase the activation level of integrins while a stiff ECM has a tendency to prevent the dissociation and internalization of bound integrins. In addition, more stable focal adhesions can form on stiffer and thinner ECMs*'. Recent experimental findings demonstrate that a stiff extracellular matrix is conducive to metastasis of cancer (Lu, 2012). Fascia is one such matrix. Heavy resistance muscular exercise has been found to reduce cancer mortality across many types of cancers (Allison, 2013), but there is as yet no understanding of why this happens and which types of exercise are most beneficial, except for some differences between aerobic and resistance training. Since resistance training generates much higher forces within the muscle, we are interested in how much of these forces are transmitted to the fascia, as this may possibly be transmitted to and affect the extracellular matrix.

In this paper we develop a mathematical model to determine the fraction of force generated by extremity muscles assumed to be of cylindrical shape under contraction. For this purpose we use simple formulas of theory of elasticity valid for isotropic material to determine longitudinal and radial stresses and strains as well as modulus of elasticity. For simplicity of calculation we assume the modulus of elasticity in radial direction is the same as that along the longitudinal direction.

Methods

To understand the mechanism of the force transmitted to the fascia during muscle contraction, we need to know the variables such as the muscle force, the fiber length, the volume of the muscle, its radius and cross section area. For this paper, we take these values from existing publications. Maganaris (2001) estimated the in vivo force-length characteristics of the human soleus and tibialis anterior (TA) muscles for six healthy males (age 24–32 years, height 167–183 cm, body mass 70–82 kg) at ankles angles from 30° of dorsiflexion to 45° of plantar flexion in steps of 15°. Barber et al. (2013) compared the voluntary and involuntary force generating capacity of the triceps surae muscles in 16 older adults and 18 young adults during isometric and isokinetic contractions at five ankle angles. Albracht et al. (2008) assessed the muscle volume and physiological cross sectional area of the human triceps surae muscle in vivo for thirteen male adults. Wright et al. (1984) studied the elastic properties of plantar fascia in vivo. Kawakami et al. (1994) determined all the above variables for extensor and flexor muscles at the elbow. We use these variables in evaluating the stress/force transmitted to the fascia enveloping the peripheral length of the muscles.

Results

A. We first examine the soleus muscle at the ankle to calculate the magnitude of force transmitted by soleus muscle to fascia during dorsiflexion and plantar flexion (see Fig. 1).

We assume the muscle as cylinder with length l and radius r. The variables given as a function of ankle angles in the Soleus muscle (Maganaris, 2001) are given in Table 1 below:

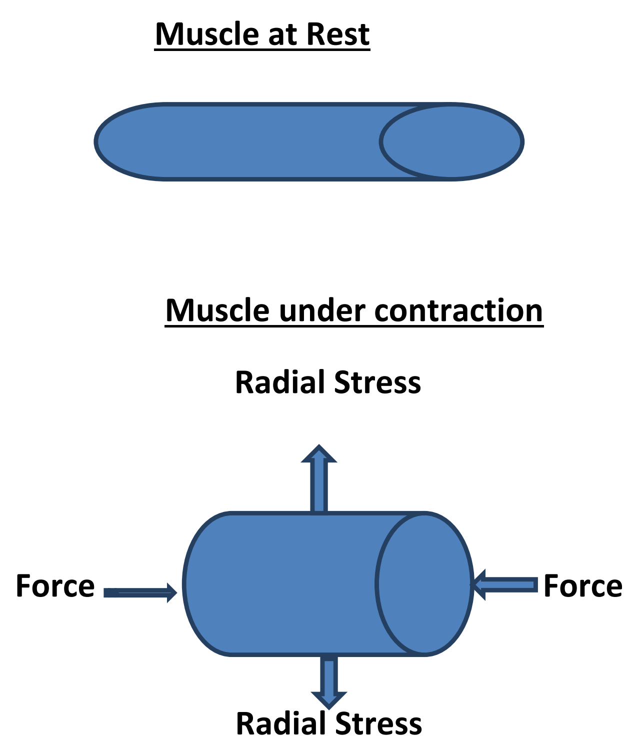

Figure. 1 In the un-deformed state, muscle is at rest. In the deformed state, muscle is under contraction. The length shortens and the radius becomes larger for constant volume of the muscle. The radial stress is produced which is transmitted to the fascia wrapping the muscle.

Table 1 Published values for soleus (Maganaris, 2001).

Ankle angles (degrees)	−30	−15	0	+15	+30	+45
Fiber length (cm)	3.8	3.5	3.0	2.8	2.6	2.4
Muscle force (N)	3330	3370	2330	1460	711	290

We use the variables for different ankle angles in the Soleus muscle given in Table 1 to find the values given in Table 2 below, using the Poisson's ratio of - 0.49 for muscle (Ozkaya and Nordin, 1998)

Calculation procedure

1. Effective Longitudinal Force is the difference between the forces of 3330 N at −30° and 290 N at 45°.
2. Mean Length is the mean of lengths of 3.8 cm at −30 and 2.4 cm at 45°.
3. Area of Cross-section is taken Volume/Mean Length.
4. Longitudinal Stress is calculated as Effective Force/Area of Cross-section.
5. Longitudinal Strain is calculated as change in length/original length at −30 and 45°.
6. Longitudinal Modulus of Elasticity is given by Longitudinal Stress/Longitudinal strain.
7. Radial Strain is calculated as Poisson's Ratio of −0.49 multiplied by longitudinal Strain.
8. Radial Stress is calculated as Longitudinal Modulus of elasticity multiplied by Radial strain for isotropic material.

B. The magnitude of force transmitted to fascia during dorsiflexion and plantar flexion combined (−30°–20°) for MEDIAL GASTROCNEMIUS (MG) muscles. The variables for MEDIAL GASTROCNEMIUS muscle at the ankle (Barber et al., 2013) are given in Table 3 below:

Using the rationale given above for Table 2, the values calculated for MG Muscle are given in Table 4 below.

C. The magnitude of force transmitted to fascia during contraction for elbow muscles.

For this we use the variables given below:

The variables for Elbow Muscles (Kawakami et al., 1994).

Extensor: Stress at the eccentric end is S_0 = 820 (10^3 m^{-2}).

Table 4 Values calculated for the MG Muscle at the Ankle.

Longitudinal strain	Longitudinal stress	Modulus of elasticity	Radial strain	Radial stress
−0.29	−(0.035)10^5P_a	(0.121)10^5P_a	0.142	(0.017)10^5P_a

Stress at the concentric end is S_1 = 470 (10^3 m^{-2}).

PCSA (Physical Cross Sectional Area) = $4.68 \cdot 10^{-3}$ m^2; radius = 0.04 m; Muscle length = 0.24 m.

Constant volume = 0.0012 m^3

Using the variables given above, the values for Extensor Muscle at the Elbow are given in Table 5 below.

The variables for the Flexor Muscle at the elbow are given below:

Flexor: Stress at the eccentric end, S_0 = 870 (10^3).

Stress at the concentric end, S_1 = 440 (103 m^{-2}).

PCSA (Physical Cross Sectional Area) = $2.50 \cdot 10^{-3}$ m^2; radius = 0.03 m; Muscle length = 0.22 m.

Constant volume = 0.00064 m^3.

Using the variables given above, the values for Extensor Muscle at the Elbow are given in Table 6 below.

Summarizing the above findings, we find very similar values for each muscle.

Desired Ratio = Radial Stress/Longitudinal Stress = (E1 × Radial Strain)/(E1 × Longitudinal Strain) (for isotropic material, as assumed in this paper for simplification of calculations) = Radial Strain/Longitudinal Strain = Poisson's ratio of −0.49, which is a constant value. Thus there is no possibility of finding the Confidence interval.

This ratio could be immediately determined without using the calculations as in the Methods section, but these calculations give us the additional information such as the values of modulus of elasticity, longitudinal strain and the radial strain. It may be noted that the results of calculations using the variables given in the references are similar to the ratio determined above taking into considerations the rounding off errors.

Discussion and conclusions

Limitations

1. For Soleus muscle at the ankle, the raw data were given in the reference paper by Magnaris (2001) which enabled

Table 2 Values calculated for Soleus Muscle at the Ankle.

Effective longitudinal force	Constant volume	Mean length	Area of cross-section	Longitudinal stress	Longitudinal strain	Longitudinal modulus of elasticity	Radial strain	Radial stress
−3040 N	477 cm^3	3.1 cm	154 cm^2	−(2.1)10^5P_a	−0.37	(5.4)10^5P_a	0.18	10^5P_a

Table 3 Published values for medial gastrocnemius (Barber et al., 2013).

Ankle angles (degrees)	−30	−20	0	8	10	15	20
Muscle force (N)	20	74	50	254	242	238	228
Muscle length (cm)	0.40	0.41	0.48	0.51	0.52	0.54	0.56

Table 5 Values calculated for the Extensor Muscle at the Elbow.

Longitudinal strain	Longitudinal stress	Modulus of elasticity	Radial strain	Radial stress
−0.049	$-(3.50)10^5P_a$	$(35)10^5P_a$	0.049	$(1.715)10^5P_a$

Table 6 Values calculated for the Flexor Muscle at the Elbow.

Longitudinal strain	Longitudinal stress	Modulus of elasticity	Radial strain	Radial stress
−0.014	$-(5.8)10^5P_a$	$(414)10^5P_a$	0.007	$(2.89)10^5P$

us to find the variables needed for mathematical analysis. However for elbow and Medial gastrocnemius muscles, the raw data were not given in the paper and we had to estimate the variables from individual points on the plots presented, which limits the precision of our calculations.

2. The Poisson's ratio used is − 0.49 (Ozkay and Nordin, 1998). However, it may vary slightly for each muscle. Therefore the results are approximate.
3. For simplicity of initial calculations, the fascia and muscle are assumed to be in a cylindrical shape. Both muscle and fascia are also assumed to be isotropic. However, the ratio of radial to longitudinal stress determined in our analysis is found to be independent of whether tissues are anisotropic or isotropic.
4. These calculations are not experimentally verified. However, the magnitude of the radial stress is similar enough in magnitude to longitudinal stress and therefore can be measured using experimental methods similar to those for determining proximal and distal tendon forces in studies of myofascial force transmission (Huijing, 2009).

We have determined not only the radial stress transmitted to fascia, but also longitudinal strain, longitudinal stress, radial strain, and modulus of elasticity in the muscles at any ankle angle during dorsiflexion and plantar flexion. These variables are evaluated during isometric, concentric and eccentric contraction as this information may be useful in refining specific exercise protocols that have a fascial goal in addition to a muscular goal.

Almost half of the muscle longitudinal stress is transmitted to the fascia. This is similar to the Poisson's ratio, which for soft biological tissues is close to 0.5 regardless of tissue. Because it varies so little within a given tissue, Poisson's ratio is generally reported as a single constant number without confidence interval.

Table 7 Ratio of Radial stress to Longitudinal stress for different locations in the body.

Soleus muscle at the ankle	MG muscle at the ankle	Extensor muscle at the elbow	Flexor muscle At the elbow
50%	49%	49%	50%

There is therefore repeated stress transmitted to the fascia during activation and relaxation of the extremity muscles (Table 7). Fascia may remodel to accommodate the stresses produced and this may reduce the inherent stiffness of this tissue. The constant volume hypothesis suggests that radial expansion of the muscle results from its longitudinal contraction. Similarly, radial expansion of the fascial tube will result in longitudinal shortening. We also note that the perimysium is observed to be continuous with the muscle tendon, suggesting that there may be a force generation function of these fascial sheaths.

Fascia consists of a matrix layers of parallel fibers which cross each other at a certain angle which has been observed to be the same for the human elbow (Stecco et al., 2011), the neck of the cow (Purslow, 2010) and the fascia lata of the goat (Pancheri et al., 2014). Braided fibers around a rubber bladder have been used as McKibbin actuators to power artificial legs and robots; expansion of the bladder causes shortening of the braid (Tondu, 2012). The amount of the shortening depends on the angle of the fibers. We suggest the braided nature of fascia may similarly generate contraction forces when it expands radially.

There also has recently been development of flexible strain gauges for industry based on parallel fibers in a piezoelectric matrix (Cohen et al., 2012). As Fascia is a similarly piezoelectric matrix, and is highly innervated, the arrangement of fibers may also serve to sense forces generated by the muscles.

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List of abbreviations

- ECM: Extra Cellular Matrix
- MG: Medial Gastrocnemius
- PCSA: Physical Cross Sectional Area

References

Albracht, K., et al., 2008. Assessment of muscle volume and physiological cross sectional area of the human triceps surae muscle in vivo. J. Biomech. 41, 2211–2218.
Allison, S., et al., 2013. Effects and potential mechanisms of exercise training on cancer progression: a translational perspective. Brain Behav. Immun. 30, S75–S87.
Barber, et al., 2013. Neuromechanical properties of the triceps surae in young and older adults. Exp. Gerontol. 48, 1147–1155.
Cohen, D., et al., 2012. A highly elastic, capacitive strain gauge based on Percolating nanotube networks. Nano Lett. 12, 1821–1825.
Huijing, P.A., 2009. Epimuscular myofascial force transmission: a historical review and implications for new research. International society of Biomechanics Muybridge Award Lecture, Taipei, 2007. J. Biomech. 42 (1), 9–21.
Kawakami, Y., et al., 1994. Specific tension of elbow flexor and extensor muscles based on magnetic resonance imaging. Eur. J. Appl. Physiol. 68, 139–147.
Lu, P., 2012. The extracellular matrix: a dynamic niche in cancer progression. J. Cell. Biol. 196 (4), 395–406.

Maganaris, C., 2001. Force-length characteristics of in vivo human skeletal muscle. Acta Physiol. Scand. 172, 279—285.

Ozkaya, N., Nordin, M., 1998. Fundamental of Biomechanics, Equilibrium, Motion and Deformation, second ed. Springer, New York.

Pancheri, F., et al., 2014. A constitutive description of the anisotropic response of the fascia lata. J. Mech. Behav. Biomed. Mater. 30, 306—323.

Purslow, P., 2010. Muscle fascia and force transmission. J. Bodyw. Mov. Ther. 14 (4), 411—417.

Stecco, C., et al., 2011. The fascia: the forgotten structure. Ital. J. Anat. Embryol. 116 (3), 127—138.

Tondu, B., 2012. Modelling of the McKibben artificial muscle: a review. J. Intell. Mater. Syst. Struct. 23 (3), 225—253.

Wright, D., et al., April 1984. A study of the elastic properties of plantar fascia. J. Bone Jt. Surg. 46—A (3).

Xu, Guang-Kui, et al., 2014. Integrin activation and internalization mediated by extracellular matrix elasticity: a biomechanical model. J. Biomech. (in press).

Yucesoy, C., 2010. Epimuscular myofascial force transmission implies novel principles for Mmuscular mechanics. Exerc. Sport Sci. Rev. 38 (3), 128—134.