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Technical note

Architecture of the rectus abdominis, quadratus lumborum, and erector spinae

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Abstract

Quantitative descriptions of muscle architecture are needed to characterize the force-generating capabilities of muscles. This study reports the architecture of three major trunk muscles: the rectus abdominis, quadratus lumborum, and three columns of the erector spinae (spinalis thoracis, longissimus thoracis and iliocostalis lumborum). Musculotendon lengths, muscle lengths, fascicle lengths, sarcomere lengths, pennation angles, and muscle masses were measured in five cadavers. Optimal fascicle lengths (the fascicle length at which the muscle generates maximum force) and physiologic cross-sectional areas (the ratio of muscle volume to optimal fascicle length) were computed from these measurements. The rectus abdominis had the longest fascicles of the muscles studied, with a mean (S.D.) optimal fascicle length of 28.3 (4.2) cm. The three columns of the erector spinae had mean optimal fascicle lengths that ranged from 6.4 (0.6) cm in the spinalis thoracis to 14.2 (2.1) cm in the iliocostalis lumborum. The proximal portion of the quadratus lumborum had a mean optimal fascicle length of 8.5 (1.5) cm and the distal segment of this muscle had a mean optimal fascicle length of 5.6 (0.9) cm. The physiologic cross-sectional area of the rectus abdominis was 2.6 (0.9) cm^2, the combined physiologic cross-sectional area of the erector spinae was 11.6 (1.8) cm^2, and the physiologic cross-sectional area of the quadratus lumborum was 2.8 (0.5) cm^2. These data provide the basis for estimation of the force-generating potential of these muscles.

Keywords: Muscle; Architecture; Erector spinae; Trunk

1. Introduction

The architecture of a muscle (i.e., the length and arrangement of its fibers) is an important determinant of its function (Gans, 1982; Lieber and Shoemaker, 1992). For example, optimal fiber length determines the range of lengths over which a muscle can generate active force (Zajac, 1989). Physiologic cross-sectional area provides a measure of a muscle's maximum force-generating capacity (Gans, 1982; Sacks and Roy, 1982). Measurements of muscle architecture (Friederich and Brand, 1990; Lieber et al., 1990; Kamibayashi and Richmond, 1998) have provided the basis for development of models that estimate forces generated by muscles of the neck (Vasavada et al., 1998), wrist (Gonzalez et al., 1997), and lower limb (Delp et al., 1990).

Radiographs, computed tomography, and magnetic resonance imaging have been used to visualize torso muscle geometry and estimate muscle cross-sectional areas (Reid and Costigan, 1985; McGill et al., 1988; Tracy et al., 1989; Chaffin, 1990; Han et al., 1992; Moga et al., 1993; Tsuang et al., 1993; Stokes and Gardner-Morse, 1999). While these studies have provided valuable data, medical imaging techniques have some important limitations. For instance, muscle cross-sectional area estimated from a two-dimensional medical image may not represent the force-generating capacity of a muscle accurately if the cross-sectional area varies along the length of the muscle or if the muscle path is not perpendicular to the image plane. Often an entire muscle cannot be imaged due to the complexity of the muscle geometry or the limits of the

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imaging device. Muscles such as the erector spinae have subdivisions that may not be distinguished in medical images, and it is frequently difficult to visualize the length and orientation of muscle fascicles in medical images.

Measurements from cadavers provide a valuable complement to medical images. McGill et al. (1988) performed anatomical studies to correct the cross-sectional areas of torso muscles measured with computed tomography. Macintosh and Bogduk (1987, 1991) performed extensive anatomical studies that provided the basis for a model of the lumbar muscles (Bogduk et al., 1992). However, no previous studies have reported sarcomere lengths or optimal fascicle lengths for torso muscles. Measurements of these architectural features are needed to determine where trunk muscles operate on their length–tension curves and how changes in trunk orientation affect muscle force-generating capacities (Vasavada et al., 1998).

We have begun development of a biomechanical model of the trunk muscles to study the control of trunk posture with functional electrical stimulation. The major muscles available for electrical stimulation are the erector spinae, the quadratus lumborum, and the rectus abdominis. Architectural measurements of these muscles are needed to estimate their force-generating potential. The objective of this study was to measure the muscle parameters that would allow calculation of physiologic cross-sectional areas (PCSAs) and optimal fascicle lengths for these three muscles. This study augments the existing data for PCSA of torso muscles and provides the first report of sarcomere lengths and optimal fascicle lengths of these muscles.

2. Methods

Four unembalmed specimens and one embalmed specimen were studied (Table 1). Careful dissection was used to identify three components of the erector spinae: the spinalis thoracis, the longissimus thoracis, and the iliocostalis lumborum. The quadratus lumborum was divided into proximal and distal components. The proximal component represented the average of the fibers attached to the 12th rib and the L1 vertebra; the distal component represented the average of the fibers attached to the L2–L4 vertebrae. Only muscles on the right side of the body were studied.

Table 1
Characteristics of the anatomical specimens

	Age (yr)	Sex	Height (cm)	Weight (kg)
Specimen 1	[a]	F	169	69.1
Specimen 2	[a]	F	169	95.5
Specimen 3	68	M	177	68.2
Specimen 4	57	M	172	74.1
Specimen 5[b]	75	F	166	65.9
Mean (S.D.)	67 (9.1)		170.6 (4.2)	76.2 (13.3)

[a] Unknown age at death.

[b] Specimen 5 was an embalmed specimen; the rest were unembalmed.

Musculotendon length (the length of the entire muscle–tendon unit from origin to insertion) and muscle length (the distance from the most proximal fibers to the most distal fibers) were measured while each muscle was attached to the skeleton. Each muscle or muscle compartment was then removed and fixed in formalin for measurement of pennation angle (the acute angle between the line of action of the tendon and the line of action of the muscle fibers), fascicle length (the length of a small bundle of muscle fibers from the tendon of origin to the tendon of insertion), and sarcomere length. We measured fascicle lengths rather than fiber lengths because it is very difficult to isolate individual muscle fibers.

After fixation, each muscle was treated with phosphate buffer and placed in 15% sulfuric acid for 24–48 h to help remove fat and fascia. Each muscle was then rinsed in phosphate buffer to neutralize the acid (Sacks and Roy, 1982). Consistent with previous studies (Cutts, 1988), we found only a small amount shrinkage due to fixation of the tissue.

Ten fascicles were teased out of each muscle or muscle component. The length of each fascicle was measured and the mean of the 10 fascicles was determined. Sarcomere lengths were estimated using laser diffraction (Yeh et al., 1980; Baskin et al., 1981; Lieber et al., 1990) and the protocol described by Murray et al. (2000). Each fascicle was divided into three regions: proximal, middle, and distal. A small piece of muscle tissue was taken from each region and mounted on a microscope slide. A 5 mW He–Ne laser was passed through the muscle tissue and the width of the resulting diffraction pattern was measured. Three diffraction patterns were recorded for the proximal and distal regions, and six patterns were recorded for the middle region; this was done for each of the 10 fascicles from each muscle studied. The width of the diffraction pattern was measured with a micrometer. Sarcomere lengths (ℓ^{S}) were calculated as follows:

$$\ell^{S} = \frac{\lambda}{\sin\,\theta}, \tag{1}$$

$$\tan\,\theta = \frac{y}{L}, \tag{2}$$

where λ is the wavelength of the laser (0.6327 μm), y is the distance between the undiffracted laser beam and the first-order band, and L is the distance between the microscope slide and the plane on which the micrometer measured the width of the diffraction pattern (Murray et al., 2000). Optimal fascicle lengths (ℓ_{o}^{M}) were calculated by normalizing measured fascicle lengths (ℓ^{F}) to a sarcomere length of 2.8 μm, the optimal sarcomere length in human muscle (Walker and Schrodt, 1974). That is,

$$\ell_o^M = \ell^F \times \frac{2.8}{\ell^S}. \tag{3}$$

The physiologic cross-sectional area (PCSA) was calculated as the ratio of the muscle fiber volume and optimal fascicle length. The muscle fiber volume was estimated as the ratio of the muscle fiber mass and a muscle density of 1.06 g/cm^3 (Mendez and Keys, 1960). PCSA is reported for one side of the body and does not include the effects of pennation angle.

3. Results

The rectus abdominis had the longest fascicles of the muscles studied, with a mean fascicle length of 28.3 cm (Table 2). The erector spinae had fascicles that ranged in length from 5.2 cm in the spinalis thoracis to 12 cm in the iliocostalis lumborum. The proximal component of the quadratus lumborum had fascicles with an average length of 7.3 cm, while the distal component had an average fascicle length of 4.7 cm.

The rectus abdominis had sarcomeres that were close to optimal length (2.8 μm) in the supine position. By contrast, the components of the erector spinae and the quadratus lumborum had sarcomeres that were shorter than optimal length, on average. The proximal and distal segments of the quadratus lumborum had average sarcomere lengths of approximately 2.38 μm. The average sarcomere length for the three components of the erector spinae was 2.31 μm. This suggests that the quadratus lumborum and erector spinae develop greater forces at body positions that elongate the muscles relative to the supine position.

The PCSA of the rectus abdominis was 2.6 cm^2. The total PCSA of the quadratus lumborum was 2.8 cm^2; the proximal segment had a PCSA of 1.6 cm^2 and the distal segment had a PCSA of 1.2 cm^2. The total PCSA of the erector spinae was 11.6 cm^2; the individual components had PCSAs of 1.6 cm^2 for spinalis thoracis, 5.9 cm^2 for longissimus thoracis, and 4.1 cm^2 for iliocostalis lumborum.

The length parameters varied less across specimens than muscle mass and PCSA. For example, the standard deviation of musculotendon length was less than 15% of the mean length for each muscle. The standard deviation of muscle length was less than 27% of the mean length for each muscle. By contrast, the standard deviations of muscle mass and PCSA were as high as 62% of the mean values for some muscles.

4. Discussion

This study provides the first measurements of optimal fascicle length and sarcomere length for three important trunk muscles. These data characterize the range of lengths over which a muscle can develop force and are required for understanding and modeling the behavior of these muscles.

One should consider the limitations of this study before utilization of these data. First, we have reported the muscle parameters from only five specimens; thus, we were not able to study the variation of muscle architecture across a wide range of body sizes. Also, while we observed that overall muscle geometry did not change substantially after fixation (e.g., the musculotendon length of the rectus abdominis decreased 3%), we did not study the effects of fixation on sarcomere length. While this study provides new architectural data for three important muscles, optimal fascicle lengths for other muscles, such as the obliquus, multifidus, and psoas, are also needed.

One should also realize the limitations of estimating the force-generating properties of muscles from the anatomical data. PCSA provides only an estimate of the maximum force-generating potential of a muscle. It does not account for the effects of different muscle fiber types and the variation of non-contractile tissue between

Table 2
Summary of muscle parameters from five specimens[a]

	Musculotendon length (cm)	Muscle length (cm)	Fascicle length (cm)	Pennation angle (°)	Sarcomere length (μm)	Optimal fascicle length (cm)	Muscle Fiber Mass (g)	PCSA (cm^2)
Rectus Abdominis	35.9 (1.9)	34.3 (2.7)	28.3 (3.6)	0.0 (0.0)	2.83 (0.28)	28.0 (4.2)	92.5 (30.5)	2.6 (0.9)
Quadratus Lumborum (proximal)	11.7 (1.7)	10.7 (1.3)	7.3 (1.3)	7.4 (2.9)	2.39 (0.21)	8.5 (1.5)	13.3 (5.2)	1.6 (0.6)
Quadratus Lumborum (distal)	9.3 (1.3)	8.1 (1.2)	4.7 (0.5)	7.4 (6.2)	2.37 (0.20)	5.6 (0.9)	7.3 (2.4)	1.2 (0.4)
Spinalis Thoracis	24.7 (1.5)	18.2 (3.2)	5.2 (0.4)	16.0 (3.8)	2.26 (0.17)	6.4 (0.6)	10.2 (6.0)	1.6 (0.9)
Longissimus Thoracis	42.6 (5.5)	34.7 (4.8)	9.6 (1.2)	12.6 (5.8)	2.31 (0.17)	11.7 (2.1)	73.4 (31.0)	5.9 (2.5)
Iliocostalis Lumborum	43.8 (4.3)	33.1 (9.0)	12.0 (1.7)	13.8 (4.5)	2.37 (0.17)	14.2 (2.1)	60.9 (29.9)	4.1 (1.9)

[a] Mean values and S.D.s.

Table 3
Comparison of PCSA (cm^2) from the present study with cross-sectional areas from other studies

	Present study[a]	Bogduk et al. (1992)[a]	Reid and Costigan (1985)[b]	McGill et al. (1988)[b]	Tracy et al. (1989)[b]	Chaffin et al. (1990)[b]	Han et al. (1992)[b]	Tsuang et al. (1993)[b]
Rectus Abdominis	2.6	—	10.5	7.9	6.8	3.8	4.9	6.9
Quadratus Lumborum	2.8	—	—	6.1	6.4	4.2	2.6	5.0
Erector Spinae	11.6	16.5	15.9	—	20.0	18.0	12.9	16.5

[a] Physiologic cross-sectional area (PCSA) values estimated from anatomical studies.
[b] Average cross-sectional areas estimated from radiographs, CT, or MRI.

muscles. Optimal fascicle length provides an estimate of the range of lengths over which a muscle develops active force, but there may be significant variations in fascicle and sarcomere lengths within a muscle.

The PCSAs calculated from our anatomical study are consistently lower than values estimated from imaging studies (Table 3). The average PCSA of the rectus abdominis reported here (2.6 cm^2) is lower than PCSA values (3.8–10.5 cm^2) estimated using imaging techniques (Reid and Costigan, 1985; McGill et al., 1988; Tracy et al., 1989; Chaffin et al., 1990; Han et al., 1992; Tsuang et al., 1993; Stokes and Gardner-Morse, 1999). We computed the total PCSA of the erector spinae to be 11.6 cm^2. In vivo studies using imaging report PCSA values of the erector spinae that range from 12.9 to 20.0 cm^2 (Reid and Costigan, 1985; Tracy et al., 1989; Chaffin et al., 1990; Han et al., 1992; Tsuang et al., 1993). We computed the total PCSA for quadratus lumborum to be 2.8 cm^2, while previous studies have reported 2.6–6.4 cm^2 (McGill et al., 1988; Tracy et al., 1989; Chaffin et al., 1990; Tsuang et al., 1993; Han et al., 1992).

These differences may arise from bias introduced by anatomical techniques. All the specimens used in this anatomical study were elderly subjects, compared to younger volunteers used in some imaging studies. Estimation of PCSA from elderly cadavers, a limitation of most anatomical studies, may lead to underestimation of PCSA. While the absolute values we report for PCSA are at the low end of the ranges reported by others, the relative PCSAs are within 10% of the results reported by Tracy et al. (1989), Chaffin et al. (1990), Han et al. (1992)and Tsuang et al. (1993), and provide a useful basis for intermuscular comparisons.

The differences in PCSA also may arise from a basic limitation of imaging techniques. It is not generally possible to determine a true physiologic cross-sectional area (the ratio of muscle volume to optimal fiber length) from imaging studies because optimal fiber lengths cannot be measured with current in vivo imaging techniques. This limitation exists even when geometric cross-sectional areas are adjusted to accommodate imaging planes that are not orthogonal to the muscle line of action, and cross-sectional areas are averaged over multiple muscle levels to account for the variation in muscle cross-sectional area with muscle length.

A hybrid approach that utilizes accurate in vivo muscle volume measurements derived from medical images and the detailed measurements of fascicle and sarcomere lengths reported here may provide the most accurate estimates of muscle force-generating potentials.

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