RELIABILITY AND VALIDITY OF A DEVICE TO MEASURE MUSCLE HARDNESS

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Although clinicians judge muscle tenseness by palpation, methods to quantify this have not become established. We examined the reliability and validity of a commercially available myotonometer to assess the biceps brachii and brachioradialis. Torques ranging from 0–72% of maximum effort were isometrically resisted in five men and five women, all healthy and 21–23 years of age. Root-mean-square of surface electromyographic response was also measured. Intraclass correlations were 0.80 or higher within sessions but decreased to 0.57 between sessions except for myotonometry of the biceps brachii. Correlation with isometric load was 0.79 or higher for both myotonometry and electromyography, but these relations were consistently curvilinear. The myotonometer is more useful for fleshy muscles like the biceps brachii than for thin muscles like the brachioradialis. Because hardness has a curvilinear relation with tension in the muscle, hardness cannot be considered strictly equivalent to tension.

Keywords: Myotonometer; muscle tension; muscle hardness; surface electromyography; biceps brachii; brachioradialis.

1. Introduction

Muscle hardness has been a topic of interest among clinicians for decades, if not centuries. Attempts to quantify changes in the hardness of a human muscle *in vivo* began at least as far back as 1911.[1] Failure to simultaneously satisfy the demands of validity, objectivity, and clinical applicability has prevented development of a universally recognized "gold standard" for defining or measuring muscle hardness in clinical settings.

From an intuitive point of view, muscle hardness is something perceived when an examiner pokes the skin overlying the muscle of interest. Although chronic disuse may induce physical changes in the tissue of the muscle that could make it feel firmer to the touch, in general elevated hardness is clinically associated with neural activation of the muscle. In either case, a palpable *change* in muscle hardness within a day, a week, or a month would generally be judged to reflect a corresponding change in the amount of tension that the muscle is continuously exerting.

In the investigation reported in this paper, we examined the reliability and validity of judging changes in muscle hardness by an electromechanical device that mimics the clinician's subjective approach of poking at the muscle to judge its hardness. Under the assumption that changes in muscle tension produce changes in muscle hardness, we studied the validity of this device (to be called a *myotonometer* in the remainder of this paper). Although we began this investigation simply to examine validity of the myotonometer, the results prompted us to focus also on the broader issue of what a clinician actually perceives when palpating a muscle.

The myotonometer, commercially available in Japan, is both safe and easy to use in clinical settings. In performing this study, we used a unit purchased through ordinary channels and received no incentive from the manufacturer, financially or otherwise, to perform this investigation.

A forerunner of the myotonometer used in this study was developed half a century ago.[2] The original instrument operated entirely with mechanical parts and was slightly larger than the device used in this study, but the basic principle for measuring hardness of the surface overlying the muscle remains unchanged.

Other devices have recently been described that are designed for clinical purposes to measure the hardness of tissue beneath a probe.[3–6] We do not know how these other devices compare to the one that we have adopted for this study. Validity of the other devices has been described in terms of detecting hardness or stiffness of a clinically identifiable state, but not in terms of quantitative change of tension in the substrate tissue.

We measured hardness over the biceps brachii and over the brachioradialis while isometric flexion torque was produced at the elbow by external loading. We expected to see surface hardness increase as the load on the elbow flexors was augmented, so we considered the nature of this relation to serve as a criterion for judging validity of the myotonometer. For purposes of comparison, we simultaneously measured electromyographic activity of the same muscles.

2. Methods

2.1. *Subjects*

Five men and five women, 21–23 years of age, volunteered to participate in the study. They were healthy physical therapy students, 160–173 cm tall, weighing 50–71 kg.

Each subject consented to participate in the experiment after being duly informed about the procedures.

2.2. *Myotonometer*

The myotonometer (Muscle Meter PEK-1, Imoto Machinery Co. Ltd., Kyoto, Japan) used in this study was purchased from the manufacturer. The manufacturer subsequently provided technical information about the device upon request, but cooperated in no other way in the performance or funding of this study. The myotonometer had two parts to apply to the skin over the target muscle, an outer hollow cylinder with an inner diameter of 11.7 mm and an inner cylindrical shaft with a diameter of 5 mm, located concentrically within the outer cylinder (Fig. 1). The end of the outer cylinder flanged into a flat ring with an outer diameter of 25 mm. The end of the inner shaft lay flush with the plane of the flat surface of the ring. The ring could be pushed 10.75 mm toward the body of the myotonometer, but was loaded by a spring to remain fully extended. The spring had a constant of 0.18 N/mm. The shaft likewise was loaded to remain displaced away from the body of the myotonometer, but with a stiffer spring constant of 0.41 N/mm.

When the myotonometer was pressed on the skin overlying the target muscle, both the ring and the shaft would be displaced toward the body of the myotonometer, but the shaft would be displaced less than the ring because of the stiffer spring. At the instant when the ring was being displaced past 10 mm, the displacement of the shaft was registered on the digital display of the myotonometer as a percentage of 10 mm. The myotonometer was used on both the short head and the long head of the biceps brachii and on the brachioradialis. The two heads of the biceps were identified by palpating the furrow between them and then marking the skin overlying the midportion of each head. The skin overlying the brachioradialis was marked, while the muscle was contracting, about 40 mm distal to the cubital fossa. During the experimental session the myotonometer was applied in succession at the locations of these three marks.

Fig. 1. The device used in this study (myotonometer) for measuring hardness of the surface overlying the muscle of interest. The examiner holds the device by the large part with the digital display (DD) and pushes the projecting outer cylinder (OC) with inner shaft (IS) into the surface overlying the muscle of interest.

2.3. *Electromyography*

The skin was additionally marked for locations of electrodes for surface electromyography. One pair of electrodes straddled the myotonometer's mark for the short head of the biceps brachii and another pair of electrodes straddled the myotonometer's mark for the brachioradialis. The distance between electrodes was 35 mm, just slightly greater than the 25 mm outer diameter of the ring of the myotonometer.

Electromyograms were made by placing silver-silver chloride electrodes on their designated loci, previously prepared by lightly scratching the skin,[7] running the signals through custom-made differential amplifiers into an analog-to-digital converter (MacLab/8s, ADInstruments Pty Ltd, Castle Hill, NSW, Australia), which recorded the data at 1000 samples/s. The software enabled simultaneous recordings of the raw signals and of their root-mean-square values with a moving window of 50 ms. The raw signals were also visible on an oscilloscope so that a clean and stable baseline with a clear myoelectric signal could be ascertained and monitored during data collection.

2.4. *Procedure*

During an experimental session the subject sat with both right shoulder and right elbow flexed 90° and the arm resting comfortably on a platform (Fig. 2). The forearm was positioned midway between pronation and supination. A load attached

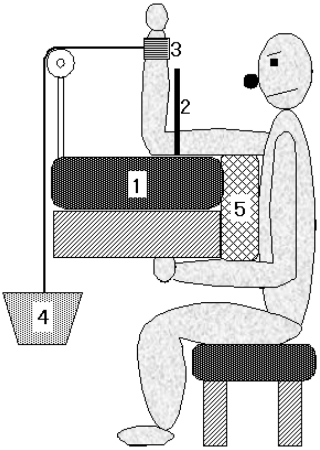

Fig. 2. Diagram of the loading condition. The subject sat at a table on which a wooden platform (1) was placed so that the arm would rest comfortably on it with the shoulder at 90° of flexion. The subject was instructed to maintain the forearm at 90° of elbow flexion and a vertical bar (2) was set near the forearm as a visual reference so that the subject could keep the forearm consistently in the desired position. With the forearm midway between pronation and supination, a cuff (3) was attached to the wrist. A rope was connected to the wrist cuff that went horizontally to a pulley and then downward to a load (4). A foam pad (5) was placed between the subject's trunk and the table because without the pad the higher loads would cause the thorax to uncomfortably abut against the table.

to a cuff at the wrist via a rope and pulley exerted an extension moment about the elbow. The magnitude of the load was set according to the subject's maximal isometric flexion moment, determined in a preliminary session as explained in the next section. Measurements during the experimental session were taken at ten levels of loading, ranging from 0 to 72% of the subject's maximal isometric flexion moment, with the intermediate values at multiples of 8% of the isometric maximum. For the sake of convenience, the actual loads were only approximately at the intended percentages, because the load consisted of weights, calibrated in kilograms, placed in a basket attached to the end of the rope. The exact actual percentages were recorded for each subject and used in the subsequent analysis.

For a given load, for example 36% of the isometric maximum, the weight required to exert such a moment about the elbow from the distance of the wrist cuff was calculated and then weights were put in the basket so that the combined load of the inserted weights and that of the basket itself would be close to 36% of the isometric maximum. The subject was then instructed to be ready for the load and the basket was hung on the rope. In quick succession, the analog-to-digital converter was turned on and the myotonometer was applied to the short head of the biceps brachii, long head of the biceps brachii, and brachioradialis, in that order. The load was then lifted from the rope and the analog-to-digital converter was shut off. The electromyogram was monitored during and after the measurements to confirm that no extraneous noise contaminated the recording. Between successive loads, the subject had at least 30 seconds of rest. For the 0% load an experimenter supported the unloaded subject's forearm in 90 degrees of elbow flexion so that the subject could relax the elbow flexors while the data were being taken.

2.5. *Determining maximal tension*

Prior to the experimental sessions, maximal isometric flexion moment at the elbow was measured with the subject in the same position as in Fig. 2, but with a Cybex 770 isokinetic dynamometer (Cybex International, Inc., Ronkonkoma, NY) providing the isometric resistance instead of a weight and pulley. The subject was instructed to take one or two seconds to reach maximal effort and was given strong verbal encouragement as he or she was attempting to exert such effort. Two trials of ten seconds each were recorded and the highest value reached during either recording was taken to be the subject's maximal isometric flexion moment.

2.6. *Organization of data*

Each subject participated in two experimental sessions, approximately a week apart. In the first session the ten loads were applied in random order and then one of those loads, randomly chosen, was applied a second time. In the second session the ten loads were applied in the reverse order of the first session and the eleventh load was a different repetition of one of the ten. Among the five women and likewise among the five men, each of the ten levels of load was used once as the eleventh load.

From the electromyograms for a given trial, one second of stable activity early in the trial was excerpted and the mean value of root-mean-square activity over that one second was calculated for both biceps brachii and brachioradialis.

2.7. *Curvilinearity*

Deviation of the myotonometer reading or of the root-mean-square electromyographic activity from a straight linear response to the load was assessed by the following procedure. First, the response of the myotonometer or electromyographic activity to the percentage load L applied to the elbow flexors was characterized by a quadratic curve $f(L)$ determined by least-squares approximation:

$$f(L) = aL^2 + bL + c \qquad (0 < L < 72).$$

Next, a straight line $g(L)$ was calculated that would intersect the quadratic curve at its endpoints:

$$g(L) = (72a + b)L + c \qquad (0 < L < 72).$$

Finally, the area between the quadratic curve and the straight line was divided by the range of response to yield a normalized deviation of the response from a straight line:

$$\frac{\int_0^{72} [f(L) - g(L)]dL}{g(72) - g(0)} = \frac{-864a}{72a + b}.$$

This value is referred to hereinafter as an *index of curvature*. See Fig. 3 for a graphic characterization of this method.

2.8. *Statistical treatment of data*

Reliability of the myotonometer was assessed by calculating an intraclass correlation coefficient [ICC (2,1)][8] and a standard error of measurement in an analysis of variance with repeated measures. Reliability *within* sessions was based on the degree of consistency in response between the eleventh trial and the prior trial of the same load. Reliability *between* sessions was based on consistency of response between corresponding loads of the two sessions that the subject underwent. The redundant eleventh trial of each session was ignored in the analysis of reliability between sessions.

For purposes of comparison, reliability of the one-second averaged electromyograms was assessed in the same way as for the myotonometer.

Validity of the myotonometer for measuring change of muscle tension in a given subject was assessed by calculating the Pearson product moment correlation between the value registered on the myotonometer and the load applied to the subject's elbow flexors. Failure of the myotonometer readings to correspond to muscle tension in a rectilinear manner was assessed by the index of curvature described above.

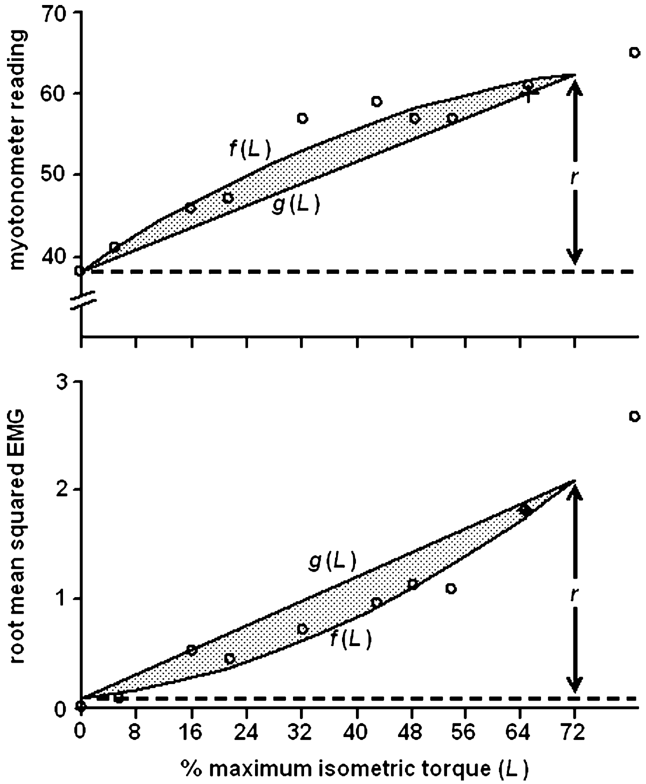

Fig. 3. Index of curvature. The degree to which a quadratic curve $f(L)$ deviated from a straight line $g(L)$ was assessed by calculating the area between the curve and the line (shaded area) and dividing that value by the range r of the response to the load L applied to the muscle. Maximum load for the quadratic curve was set at 72% of full isometric effort, but the actual loads were set approximately rather than precisely at ten levels between 0 and 72%. Open circles indicate actual values for the first ten trials, and crosses the values of an eleventh trial to replicate one of the first ten loads (in this instance, the second highest load). If the quadratic curve bowed upward, as shown in the upper graph for the myotonometer, the enclosed area was assigned a positive value. If instead the quadratic curve bowed downward, as usually happened for electromyographic (EMG) activity as in the lower graph, the area was given a negative value. The graphs shown here are for the brachioradialis in the subject whose indices of curvature were closest to the mean values of all ten subjects for that muscle.

Again, for purposes of comparison, the one-second averaged electromyograms were subjected to a corresponding analysis to assess their validity for measuring change in muscle tension.

Post hoc analyses of variance were done to check whether index of curvature differed between myotonometry and electromyography. Analogous analyses of variance were performed concerning the *magnitudes* (absolute values) of the index of curvature. Still more analyses of variance were done to check for differences between men and women in myotonometric readings, electromyograms, and indices of curvature.

3. Results

3.1. *Reliability*

Table 1 shows statistics related to reliability of the data. The myotonometer yielded reproducible values for the biceps brachii, with standard errors of measurement less than one per cent of the full scale of the instrument. For the brachioradialis, on the other hand, the standard errors of measurement exceeded 6% of the full scale. Standard error of measurement was not greater between sessions than within sessions, but one must note that the estimates for between sessions were based on 200 measurements per estimate, whereas the estimates for within sessions were based on 40 measurements per estimate. Although myotonometry of the biceps brachii was clearly more precise than that of the brachioradialis, dispersion of averaged root-mean-square values in electromyograms was only slightly greater in the brachioradialis than in the biceps brachii.

Intraclass correlations within sessions were on the order of 0.8, indicating that for a given session both the myotonometer and electromyography were reproducible enough to effectively discriminate one subject from another. Intraclass correlation of electromyography for the biceps brachii was conspicuously (and inexplicably) high. Intraclass correlations between sessions, however, remained favorable only for myotonometry of the biceps brachii, dropping to 0.57 in all other cases.

3.2. *Validity*

Table 2 presents statistics related to validity of the data. Correlation of measurements from the myotonometer with loads imposed on the forearm flexors was on the order of 0.8, as was correlation of measurements from electromyography with

Table 1. Reliability of myotonometer and of electromyograms.

		Intraclass correlation		Standard error of measurement[1]	
		Within sessions[2]	Between sessions[3]	Within sessions[2]	Between sessions[3]
Myotonometer	Biceps brachii, short head	0.81	0.79	0.28	0.30
	Biceps brachii, long head	0.89	0.82	0.73	0.65
	Brachioradialis	0.82	0.57	6.67	6.10
Electromyogram	Biceps brachii	0.97	0.57	6.15	5.45
	Brachioradialis	0.80	0.57	8.41	6.63

[1] Expressed in arbitrary units dependent on method of measurement. Values from myotonometer should not be compared directly to values from electromyograms.

[2] $n = 200$ (10 loads per session, 2 sessions per subject, 10 subjects).

[3] $n = 40$ (2 times per load, 1 load per session, 2 sessions per subject, 10 subjects).

Table 2. Correlations with muscle tension and deviations from rectilinearity.

	Correlation[1]	Index of curvature[2]	
Myotonometer	Biceps brachii, short head	0.85	10.61 ± 6.51
	Biceps brachii, long head	0.83	10.98 ± 8.00
	Brachioradialis	0.82	10.11 ± 8.78
Electromyogram	Biceps brachii	0.79	-8.25 ± 3.77
	Brachioradialis	0.82	-4.73 ± 4.63

[1] $n = 200$ (10 loads per session, 2 sessions per subject, 10 subjects).
[2] $n = 20$ (2 sessions per subject, 10 subjects), mean ± standard deviation.

the imposed loads. Deviation of a quadratic fit from an ideal rectilinear relation was consistently positive for myotonometry and negative for electromyography, meaning that the curve bowed upward in myotonometry and downward in electromyography (Fig. 3).

In either the biceps brachii or the brachioradialis, the index of curvature for myotonometry was significantly higher than the index of curvature for electromyography ($p < 0.00001$), indicating that the upward bowing of the myotonometric curves was clearly distinguishable from the downward bending of the electromyograhic curves. When the *absolute values* of index of curvature were compared, no significant differences were found, meaning that the myotonometric curves could not be characterized as deviating more or less from straight lines than their corresponding electromyographic curves.

Mean (± standard deviation) value of hardness determined by the myotonometer among the subjects was, at no load, 43.6 ± 3.6 for the short head and 45.8 ± 4.8 for the long head of the biceps brachii and 40.1 ± 3.9 for the brachioradialis and, at full load (approximately 72% maximal isometric effort), 67.5 ± 5.4 for the short head and 66.5 ± 5.9 for the long head of the biceps brachii and 67.1 ± 3.5 for the brachioradialis. Electromyograms were measured in uncalibrated units and thus representative values need not be reported here.

No significant differences in either myotonometric or electromyographic measurements were found between men and women. Indices of curvature for both myotonometric and electromyographic data likewise exhibited no significant differences between men and women.

4. Discussion

The myotonometer used in this study appears to be most useful when applied to a fleshy area. Measurements over the large biceps brachii, cushioned from the humerus by the brachialis, were much more consistent than measurements over the belly of the long but thin brachioradialis, which lay immediately above the radius. The greater consistency of measurement over the biceps brachii than over the brachioradialis was seen between sessions (about a week apart) as well as within sessions. The myotonometer thus appears to be useful for serial measurement of hardness over large muscle masses.

According to the instructions that come with the myotonometer, the user should push the myotonometer into the muscle slowly enough that three seconds elapse before the tone is sounded indicating completion of the measurement. We could not take so much time measuring each location at the higher loads, in deference to the comfort of the subject, and we needed to perform the measurement in a consistent manner across all loads, so we never observed the three-second rule. In pilot studies, we found that the speed of application had no discernible effect on reproducibility as long as care was taken to apply the myotonometer perpendicularly to the surface of the locus. Because application to the brachioradialis was performed in the same manner as to the biceps brachii, differences in reproducibility between the muscles are more likely due to characteristics of the loci examined than to the manner of examination. Nevertheless, further investigation of the myotonometer might include a study on the effect of manner of application over thin muscles such as the brachioradialis.

One point of interest is the pattern of response afforded by the myotonometer. Because the response was consistently a curve that bowed upward, changes in values of the myotonometer did not reflect changes in muscle tension in a strictly proportional manner. Since the slope of the response curve is greater at low tension than at high tension of the muscle, the myotonometer is more sensitive to changes in the lower range of muscle tension. This characteristic is favorable for clinical application, in which problems of muscle hardness are typically encountered in patients with paralysis or paresis. Detecting early subtle changes in the low muscle hardness of a weak patient is more likely to be interesting than quantifying grossly conspicuous hardness.

The myotonometer contains ordinary linear springs, so it simply reflects change in hardness of the surface in a linear manner (Fig. 4). Thus an upwardly bowing curvilinear response like that illustrated in the upper graph of Fig. 3 suggests that hardness detected at the surface of a muscle increases or decreases more dramatically at low tensions than at high tensions. We are aware of only two other studies[1,9] that present data relating hardness measured from the surface over a human muscle to mechanical load borne isometrically by the muscle. In both studies, just as in ours, the increment in hardness increased at a greater rate per increment of muscle tension at low loads than at high loads, but the curvilinear nature of the relation was not discussed in either paper. The reason for this curvilinear relation between hardness measured at a given locus on the surface of a muscle and the tension generated by that muscle is not obvious. This relation does not appear to have been studied in the recent literature, either, as far as we have been able to determine.

One might rationalize the curvilinear response of the myotonometer on geometrical grounds. The reading on the myotonometer would likely reflect the amount of activated muscle directly beneath the inner shaft of the device, but tension in

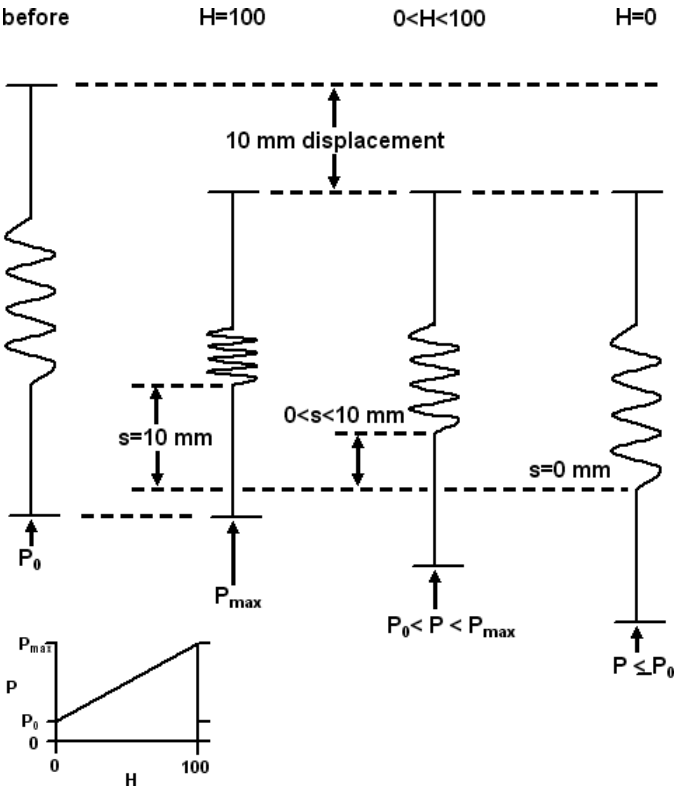

Fig. 4. Model of mechanical response of myotonometer. The wavy line represents the spring of the central shaft of the device. The portion above the spring is the part held by the examiner and the portion below the spring is the part applied to the skin over the muscle. The force P exerted by the myotometer on the subject (and vice versa) is proportional to the displacement s of the spring: $P = [(P_{\max} - P_0)/10\,\text{mm}]s + P_{0,}$, where the spring constant is 0.41 N/mm, $P_{\max}$ is the force exerted when the spring is displaced 10 mm, and P_0 is the threshold force required to begin displacing the preloaded spring. The reading of hardness H on the myotonometer is likewise proportional to displacement of the spring (by design), so the relation between H and P is linear as indicated in the graph in the lower left part of the figure: $H = [(P - P_0)/(P_{\max} - P_0)][100]$.

the muscle would be reflected more by its cross-sectional area (Fig. 5). Thus the myotonometer reading would be proportional to cross-sectional radius, whereas the muscle tension would be proportional to the square of the cross-sectional radius. Such a relationship would give rise to an upward-bowing curve like the one shown in the upper graph of Fig. 3.

The pattern of electromyographic response is better known and easier to explain. Although the monotonic increase of electromyographic activity to increase in the tension produced has traditionally been modeled as a rectilinear response,[10,11] the response over a large range of achievable tension has long been known to be curvilinear with a slope that increases as tension rises.[12] The greater increment

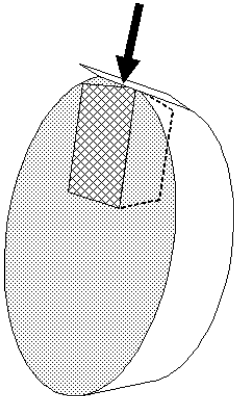

Fig. 5. Geometric conjecture to explain the curvilinear relation between the load borne by the muscle and the corresponding reading on the myotonometer. The myotonometer sampled hardness only of the column of muscle immediately below (cross-hatched area), proportional to the radius of the cross-section, whereas the entire cross-section of muscle (stippled area), proportional to the square of the radius, participated in bearing the load.

in myoelectric activity per increase in tension can be attributed partly to higher-threshold motor units producing larger action potentials and partly to greater synchronization of discharges among activated motor units.

The brachialis also contributed to the muscle tension produced in this study, but its hardness could not be assessed with the myotonometer because of its location beneath the biceps brachii. The pronator teres and many wrist and finger flexors could also have contributed to the flexor tension, although not likely very much. If the relative contributions of the various flexor muscles differed between high and low tensions in a consistent manner across subjects, our results would need to be interpreted in a different way, but such an idea is not likely because the relative contributions of elbow flexors vary across individuals.[13]

The results provoke a question concerning the extent to which a clinician can use palpation to judge changes in tension of a muscle. If, like the myotonometer, the clinician samples only a radial column of muscle tissue, as suggested in Fig. 5, changes in actual tension of the muscle will not be quite the same as changes detected by the clinician's fingers. This fundamentally physical phenomenon may be important to consider prior to psychophysiological issues of the sensory and perceptual processes involved in palpation. That is, the quadratic relation between tension and hardness found in this study (and others)[1,9] suggests that judging tension of a muscle by palpating part of it with the fingertips is fundamentally doomed to be approximate at best.

5. Conclusion

The myotonometer examined in this study is reliable within a measurement session, but measurement of the same muscle on different days is more variable if the muscle belly is thin. Hardness of a healthy surface muscle, as determined by the myotonometer, increases monotonically with isometric tension produced by the target muscle and synergists, but the relation is quadratic rather than linear and notably different from the relation between isometric tension and electromyographic activity. Insofar as the myotonometer samples muscle hardness in a manner similar to manual palpation, the results suggest that a palpator may have a physically fundamental difficulty in judging precise changes in muscle tension.

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