Table 1 Comparison of parameters between men with and without metabolic syndrome

	Metabolic syndrome (+)	Metabolic syndrome (−)	*p* Unpaired t test	*p* Adjusting for age	*p* Adjusting for BMI	*p* Adjusting for age and BMI
Number of subjects	169	398				
Age	49.9 ± 10.6	48.6 ± 12.4	0.2262			
Height (cm)	168.8 ± 6.0	167.9 ± 6.1	0.1060			
Body weight (kg)	79.1 ± 13.5	66.5 ± 9.7	<0.0001			
Body mass index (kg/m^2)	27.7 ± 4.0	23.5 ± 2.9	<0.0001			
Whole body reaction time (sec)	0.400 ± 0.072	0.390 ± 0.076		0.0022	0.0498	0.1267
	Waist circumference (+)	Waist circumference (−)				
Number of subjects	274	293				
Age	48.9 ± 11.0	49.0 ± 12.6	0.9200			
Whole body reaction time (sec)	0.398 ± 0.077	0.388 ± 0.072		0.1014	0.1966	0.0816
	Impaired glucose tolerance (+)	Impaired glucose tolerance (−)				
Number of subjects	155	412				
Age	53.2 ± 10.1	47.4 ± 12.1	<0.0001			
Whole body reaction time (sec)	0.413 ± 0.083	0.385 ± 0.070		0.7112	0.8371	0.4658
	Dyslipidemia (+)	Dyslipidemia (−)				
Number of subjects	284	283				
Age	48.8 ± 11.1	49.2 ± 12.6	0.7239			
Whole body reaction time (sec)	0.396 ± 0.071	0.390 ± 0.078		0.0032	0.2653	0.1691
	High blood pressure (+)	High blood pressure (−)				
Number of subjects	344	223				
Age	50.4 ± 11.5	46.8 ± 12.1	0.0003			
Whole body reaction time (sec)	0.397 ± 0.077	0.386 ± 0.071		0.7563	0.2893	0.0801

Mean ± SD
BMI: body mass index

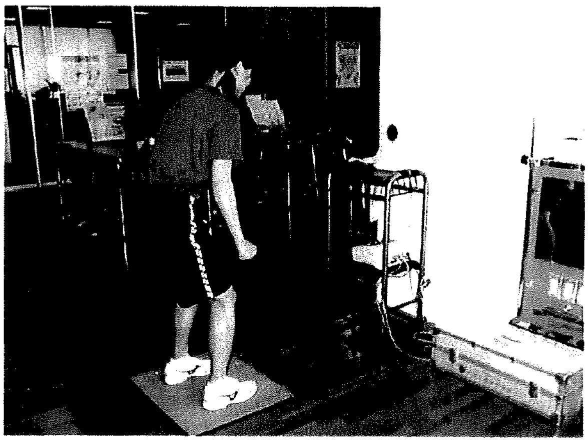

Figure 1 Measurement of whole body reaction time photographed at Okayama Southern Institute of Health, Okayama, Japan

time of five times that both legs completely left the floor was employed to be whole body reaction time.

Data were expressed as mean ± standard deviation. Unpaired *t* test and covariance analysis were performed; $p<0.05$ was statistically significant.

3. Results

Whole body reaction time in subjects with metabolic syndrome (0.400±0.072 sec) was significantly longer than those without the syndrome (0.390±0.076 sec) after adjusting for age ($p=0.0022$) and BMI ($p=0.0498$) by covariance analysis (**Table 1**). However, after adjusting for both age and BMI, whole body reaction time in subjects with metabolic syndrome was similar to those without the syndrome.

We then analyzed the groups with and without each component of metabolic syndrome *i.e.* waist circumference, dyslipidemia, high blood pressure and impaired glucose tolerance (**Table 1**). Based on the comparison of whole body reaction time adjusting for age, in subjects with dyslipidemia (n=284), whole body reaction time was significantly longer (0.396±0.071 sec) than those without dyslipidemia (n=283) (0.390±0.078 sec) ($p=0.0032$). In turn, after adjusting for BMI or after adjusting for both age and BMI, the difference of whole body reaction time between men with and without dyslipidemia was not at a significant level. In addition, there was no significant difference between men with and without each component, *i.e.* abdominal obesity, high blood pressure and impaired glucose tolerance after adjusting for age, BMI, and both age and BMI.

4. Discussion

This is the first report of the relation between whole body reaction time and metabolic syndrome using criteria in Japan and longer whole body reaction time was noted in subjects with the syndrome. Drory, et al., (1999) reported that they evaluated subjects with hyper triglyceridemia without other causes of neuropathy and found mild signs of an asymptomatic motor and/or sensory and/or autonomic axonal polyneuropathy. Kassem, et al., (2005) also reported that hypertriglyceridemia is associated with early peripheral neuropathy. In addition, we previously reported on lower leg strength per body weight and higher BMI in men with metabolic syndrome than in those without the syndrome. In this study, longer whole body reaction time was observed in subjects with metabolic syndrome and clinical significance of dyslipidemia and BMI on whole body reaction time in subjects with metabolic syndrome was also noted. Neuropathy caused by dyslipidemia and lower leg strength per body weight may be one of the possible mechanisms. Kassem, et al., (2005) investigated the correlation between hypertriglyceridemia and peripheral neuropathy by using an electroneurographic study. They reported that abnormalities in longer nerves of the lower extremities were observed and alterations of myelin sheaths in the sural nerve might affect parameters.

Potential limitations still remain in this study. First, our study was cross sectional, not longitudinal. Second, we could not accurately prove the mechanism of the relationship between whole body reaction time and metabolic syndrome. Third, although increased reaction time was reported in subjects with type 2 diabetes (Richerson, et al., 2005), we could not find the difference of whole body reaction time between men with and without impaired glucose tolerance. The difference between the definition of impaired glucose tolerance in metabolic syndrome (fasting plasma glucose≧110 mg/dl) and that of type 2 diabetes mellitus (fasting plasma glucose≧126 mg/dl) may affect the results. In conclusion, longer whole body reaction time was noted in Japanese men with metabolic syndrome. Further studies are needed to prove the clinical significance of longer whole body reaction time on metabolic syndrome.

Acknowledgement

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References

Definition and the diagnostic standard for metabolic syndrome-Committee to evaluate diagnostic standards for metabolic syndrome. (2005). Nippon Naika Gakkai Zasshi. 94: 794-809. (Japanese)

Drory, V.E., Groozman, G.B., Rubinstein, A., & Korczyn, A.D. (1999). Hypergriglyceridemia may cause a subclinical peripheral neuropaghy. Electromyogr Clin Nurophysiol, 39: 39-41.

Kassem, H.S., Azar, S.T., Zantout, M.S., & Sawaya, R.A. (2005). Hypertriglyceridemia and peripheral neuropathy in neurologically asymptomatic patients, Neuro Endocrinol Lett, 26: 775-779.

Miyatake, N., Saito, T., Wada, J., Miyachi, M., Tabata, I., Matsumoto, S., Nishikawa, H., Makino, H., & Numata, T. (2007). Comparison of ventilatory threshold and exercise habits between Japanese men with and without metabolic syndrome. Diabetes Res Clin Prac, 77: 314-319.

Miyatake, N., Wada, J., Saito, T., Nishikawa, H., Matsumoto, S., Miyachi, M., Makino, H., & Numata, T. (2007). Comparison of muscle strength between Japanese men with and without metabolic syndrome. Acta Med Okayama, 66: 99-102.

Richerson, S.J., Robinson, C.J., & Shum, J. (2005). A comparative study of reaction times between type II diabetics and non-diabetics. Biomed Eng Online, 4: 12.

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MUSCLE FORCE PER CROSS-SECTIONAL AREA IS INVERSELY RELATED WITH PENNATION ANGLE IN STRENGTH TRAINED ATHLETES

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ABSTRACT

The present study aimed to examine the effect of pennation angle on the force per cross-sectional area for elbow extensor muscles in strength-trained athletes. A total of 52 male bodybuilders ($n = 32$) and Olympic weightlifters ($n = 20$) did maximal isometric elbow extension on an isokinetic dynamometer. Muscle cross-sectional area (CSA) and muscle-fiber pennation angle (PA) of the triceps brachii muscles were measured by ultrasonography. Bodybuilders had significantly greater isometric elbow extension force (F), CSA and PA than weightlifters. The ratio of force to CSA (F/CSA) of bodybuilders was significantly lower than that of weightlifters. A significant positive correlation was observed between CSA and PA in both groups ($r = 0.832$, $P < 0.001$, and $r = 0.682$, $P < 0.001$, for bodybuilders and weightlifters, respectively). The F/CSA was negatively correlated to PA both for bodybuilders ($r = -0.408$, $P < 0.05$) and weightlifters ($r = -0.465$, $P < 0.05$). Thus present study indicates that the larger pennation angle is associated with the lower force relative to muscle CSA in strength-trained athletes.

KEY WORDS muscle force and cross-sectional area, pennation angle, triceps brachii

INTRODUCTION

Force exerted by muscle is closely related to its cross-sectional area (2,3,11,18). However, the ratio of force to cross-sectional area (F/CSA) shows quite a few individual variation, the reason for which has been a matter of debate (1,4,6,7,13,17).

The F/CSA of elbow flexor muscles is negatively correlated with muscle force (1,12) and CSA (16). Bodybuilders show smaller F/CSA as compared with less trained individuals (1). Bodybuilders have larger muscle fiber pennation angles (PA) than untrained individuals (5), and Kawakami et al. (7) found a decrease of F/CSA of the triceps brachii with increasing PA after resistance training. These findings hint to the notion that the pennation angle is inversely related with F/CSA, which results in substantially small F/CSA in athletes with hypertrophied muscles, such as bodybuilders. This possibility has been proposed in a previous study (5,7,13), but not has been confirmed so far.

Bodybuilders train to acquire muscles to their dimensional limit, and weightlifters focus to increase muscle force production in their own weight-categorized classes. We expected that any difference in these strength-trained athletes' F/CSA is related with interindividual differences in PA, and we tested this hypothesis by measuring muscle force, cross-sectional area and muscle fiber pennation angles in elite bodybuilders and weightlifters.

METHODS

Experimental Approach to the Problem

To test the above hypothesis, we carried out measurements of muscle size, pennation angles, and muscle force in highly-trained bodybuilders and weightlifters and investigated any differences between subjects. The latter athletes perform Olympic lifting which consists of "snatch" and "jerk." Both of these actions involve extension of the elbow joint in a ballistic manner by a high-velocity contraction of the triceps muscle. Consequently, Olympic lifting mainly focuses on explosive power. On the contrary, bodybuilders repeat single joint actions such as elbow extension (French press) with much slower movements, aiming to gain muscle hypertrophy. We therefore tested differences between them with respect to muscle architecture and force-producing capability.

Subjects

Thirty-two male bodybuilders (age, 29 ± 9.2 years; height, 170.1 ± 6.1 cm; mass, 76.6 ± 15.6 kg; means ± *SD*) and 20 male weightlifters (18.1 ± 3.6 yr, 167.3 ± 7.0 cm, 70.2 ± 19.7 kg)

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served as subjects. There is no significant difference in body weight and height between two groups. All bodybuilders were ranked at an elite level by their successful performance in domestic competitions, and all weightlifters were highly ranked at an intercollegiate level. Prior to experiment, written informed consent to participate in the study was obtained from each subject. This study was approved by the Department of Life Sciences ethics committee at the University of Tokyo.

Muscle Force

Maximal voluntary isometric muscle force of elbow extension was measured with a specially designed isokinetic dynamometer (DTM, SAKAI medical electronics, Tokyo). Maximal isometric force of elbow extension was measured with the elbow angle flexed by 80 degrees. The subject was seated on an experimental chair with his trunk and thigh secured by strap belts, and the upper arm rested and fixed with a strap belt on a horizontal table with the wrist attached to the lever arm of the dynamometer. The force was measured at the wrist for three to five exertions, and the maximal score was converted to muscle force, by multiplying the ratio of the ulna length to the triceps brachii moment arm, derived from a previous study (14).

Muscle CSA

The CSA of the triceps brachii muscles was measured by an ultrasonic apparatus (ALOKA SSD-120 with a circular compound scanner). This ultrasonic system was specially designed for measuring only the cross-section of limb. The ultrasonic transducer could move automatically around the limb without touching it. The frequency of the ultrasonic wave was 5MHz. Each subject placed the limb perpendicularly along the central axis of a water tank. The scanner, circulated around the tank for 30s and made an image of cross-section of upper arm. The scanning point was at a site 60% of the upper arm length, distal from the acromion process of the scapula. The ultrasonic cross-sectional image of the upper arm was photographed by a 35 mm camera. From the printed image, boundaries of subcutaneous fat and muscles and those of muscles and a bone were manually traced, and CSA of the triceps brachii was calculated by planimetry. The accuracy and validity of measurements have been confirmed in a prior study (3).

Muscle Fiber Pennation Angles

The muscle fiber pennation angle (PA) was defined as the angle between the fascicle and the aponeurosis, i.e., the vertical inclination of fibers from the long axis of muscle. The pennation angle of the long head of triceps brachii was measured by a B-mode ultrasonic apparatus (ALOKA SSD-500) at the same site as that of the CSA measurement. The subjects stood with their arms relaxed in extended position. The center of probe of ultrasonic apparatus was set at the dermal surface of scanning point with water-soluble transmission gel. Before the measurement, the subject extended his elbow and exerted slight isometric force. The tester visually confirmed the muscle belly of the long head of triceps brachii. The angle between the echoes of the aponeulosis of the triceps and the echoes from interspaces among the fascicles were measured and defined as the muscle fiber pennation angle (PA). The reason for the same relative position over subjects was to obtain PA from the same relative position of the muscle, to exclude intra-muscle variability of PA (8,19). The accuracy and validity of measurements have been confirmed elsewhere (5).

Statistical Analyses

Values are presented by means ± *SD*. Differences between bodybuilders and weightlifters were tested by a student's *t*-test. When there was a significant relationship between parameters, a simple linear regression was calculated by using the least squares method, and a Pearson correlation coefficient was calculated. The probability level accepted for statistical significance was set at $P \leq 0.05$.

RESULTS

The CSA was significantly greater in bodybuilders (36.8 ± 10.3 cm^2) than in weightlifters (23.6 ± 5.9 cm^2). The mean maximal isometric muscle force of bodybuilders was 4499 (±1157) N, which was significantly greater than 3553 (±725) N of weightlifters. The ratio of maximal isometric muscle force to CSA (F/CSA) of bodybuilders (127.7 ± 34.1 N/cm^2) was, on the other hand, significantly smaller than weightlifters (153.5 ± 22.4 N/cm^2). The mean PA of bodybuilders was significantly larger than that of weightlifters (Table 1).

There was a significant positive correlation between muscle force and CSA both for bodybuilders ($r = 0.580$, $P < 0.001$) and weightlifters ($r = 0.823$, $P < 0.001$) (Figure 1). Also, muscle CSA positively correlated with PA in both groups ($r = 0.832$, $P < 0.001$, and $r = 0.682$, $P < 0.001$, for bodybuilders and weightlifters respectively) (Figure 2). Furthermore, F/CSA was negatively correlated with PA in both groups (Figure 3).

DISCUSSION

In the present study, we measured muscle force, CSA, and fiber pennation angles in bodybuilders and weightlifters. Bodybuilders had larger force, CSA, and pennation angles, and smaller F/CSA compared with weightlifters. The F/CSA

TABLE 1. Group mean data for CSA, F, PA and F/CSA.

	Bodybuilders	Weightlifters
CSA (cm^2)	36.8 (10.3)	23.6 (5.86)†
F (N)	4499 (1157)	3554 (725)†
PA (deg)	34.4 (11.7)	21.7 (6.22)*
F/CSA (N/cm^2)	127.7 (34.0)	153.5 (22.4)*
		Mean (*SD*)

*$P < 0.01$.
†$P < 0.001$.

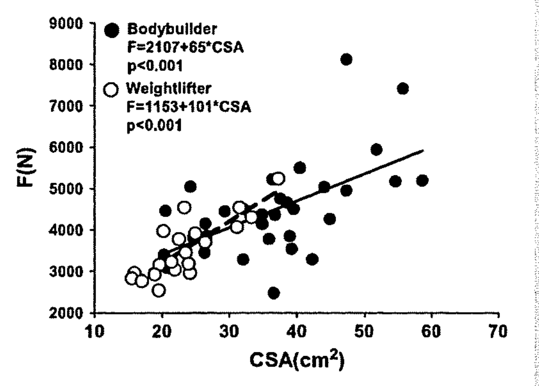

Figure 1. The relationship between elbow extension force (F) and cross-sectional areas (CSA) of the triceps brachii muscles. Individual values are plotted for bodybuilders (●) and weightlifters (○). There are significant positive relationships between these variables in both groups.

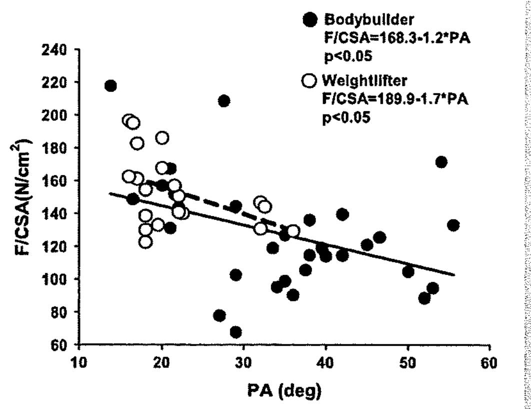

Figure 3. The relationship between F/CSA and PA. Individual values are plotted for bodybuilders (●) and weightlifters (○). There are significant negative relationships between these variables in both groups.

was negatively correlated to PA both in bodybuilders and weightlifters. The results strongly suggest that the larger pennation angle is associated with lower force generating capacity in strength trained athletes. But in the weightlifters, the ranges of both pennation angles and F/CSA were smaller in weightlifters, thus this negative effect is less pronounced in these athletes.

In the present study, PA of the triceps brachii was closely related to CSA. This is in agreement with previous studies that measured PA of the quadriceps femoris muscles (15) and triceps brachii muscles (5). Moreover, the present result is not consistent with the study of Rutherford and Jones (15) that reported no correlation between PA and CSA for the quardriceps femoris muscles. This might be due to a small variation in pennation angles in the vastus lateralis and intermedius (6–16°) in the their study compared with those of triceps brachii (13–55°) determined in the present study.

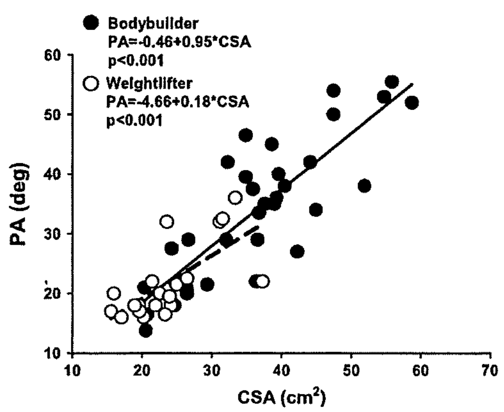

Figure 2. The relationship between the pennation angle (PA) and muscle CSA. Individual values are plotted for bodybuilders (●) and weightlifters (○). There are significant positive relationships between these variables in both groups.

The physiological cross-sectional area (PCSA), which is the sum of CSA of all muscle fibers at right angles to their long axes, represents the number of sarcomeres in parallel, and accordingly, is related directly to the amount of tension that the muscle can generate (5,7). The PCSA of a pennate muscle is given by the following equation, i.e.,

$$\text{PCSA} = (\text{MV}/\text{FL}) \cos \text{PA},$$

where MV is muscle volume and FL is muscle-fiber length. Cosine of PA translates the line of action of each muscle fiber to the direction of tendon. If a muscle has greater PA, this would be disadvantageous for force transmission from muscle fibers to tendon. Therefore, it is quite possible that greater PA results in lower F/CSA, and in fact, Kawakami et al. (7) found a decreased F/CSA in the triceps brachii as a result of resistance training. Significant negative correlations between PA and F/CSA in both groups, and significantly larger PA in bodybuilders than in weightlifters strongly suggest the negative impact of larger PA on the observed difference in F/CSA. Maughan et al. (13) found a negative correlation between muscle CSA and F/CSA, and suggested architectural factors as a candidate of their finding. The present results provide experimental evidence for their speculation. We speculate that weightlifters train their muscles to the level at which muscle force is effectively produced, unlike bodybuilders whose primary objective is to increase muscle size. It is possible that inter-group difference was eminent for the triceps brachii muscles which are highly responsive to training with respect to muscle size and architecture (9).

In the present study, the ratio of muscle force to CSA of weightlifters was significantly higher than that of bodybuilders. Apart with the fact of a significant difference in F/CSA between the two groups (weightlifters higher than bodybuilders) which might be related to the explosive type training of weightlifters, both groups demonstrated negative correlations between F/CSA and PA. This result strongly suggests that higher pennation angles are associated with lower F/CSA in the present strength-trained athletes. Of the other contributors to the divergent F/CSA ratios, differences in the fiber type composition have been proposed. However, it has been reported that there is no effect of fiber type composition on F/CSA when isometric muscle force is used (10). An increase in the non-contractile connective tissues by training might be the source of possible explanations for a decreased F/CSA in bodybuilders. However, MacDougall et al. (10) reported that the proportion of connective and other noncontractile tissues was similar between bodybuilders and untrained subjects. Thus, the contribution of noncontractile tissues to the increase in muscle CSA, if any, would be of a minor effect.

It should be noted that only the long head of the triceps brachii muscles was tested for PA, neglecting architecture of the other two (medial and lateral) heads. It has been shown that PA of the medial head increases similarly to that of the long head in hypertrophied muscles (5). Although no information is available for the architectural feature of the lateral head, by considering the fact that the long and medial heads occupy most of the triceps volume (20), we feel it justified to conclude that PA significantly affects F/CSA for the triceps muscles. Another issue to note is that in this study, only isometric, single joint action was tested. Future study is warranted to clarify the relationship between muscle size, architecture and dynamic force- and power-producing capability.

In summary, we found greater isometric muscle force, CSA and PA in bodybuilders than in weightlifters. However, muscle force per CSA was smaller for bodybuilders, and it negatively correlated with CSA and PA in both groups. It was suggested that isometric muscle force per CSA is significantly influenced by muscle fiber pennation angles.

Practical Applications

Athletes who wish to gain muscle strength normally perform resistance training, often aiming muscle hypertrophy. Based on our findings, we suggested that the possibility of a decrease in isometric force per muscle mass due to excessive muscle hypertrophy such that observed in bodybuilders. For the athletes of sport events in which force exertion is an important issue, training regimens should be cautiously organized to optimally increase muscle strength.

References

1. Alway, SE, Stray-Gundersen, J, Grumbt, WH, and Gonyea, WJ. Muscle cross-sectional area and torque in resistance-trained subjects. *Eur J Appl Physiol* 60: 86–90, 1990.
2. Fukunaga, T, Miyatani, M, Tachi, M, Kouzaki, M, Kawakami, Y, and Kanehisa, H. Muscle volume is a major determinant of joint torque in humans. *Acta Physiol Scand* 172: 249–255, 2001.
3. Ikai, M and Fukunaga, T. A study on training effect on strength per unit cross-sectional area of human muscle by means of ultrasonic measurement. *Int Z Angew Phusiol* 28: 173–180, 1970.
4. Häkkinen, K and Keskinen, KL. Muscle cross-sectional area and voluntary force production characteristics in elite strength- and endurance-trained athletes and sprinters. *Eur J Appl Physiol* 59: 215–220, 1989.
5. Kawakami, Y, Abe, T, and Fukunaga, T. Muscle-fiber pennation angles are greater in hypertrophied than in normal muscles. *J Appl Physiol* 74: 2740–2744, 1993.
6. Kawakami, Y, Nakazawa, K, Fujimoto, T, Nozaki, D, Miyashita, M, and Fukunaga, T. Specific tension of elbow flexor and extensor muscles based on magnetic resonance imaging. *Eur J Appl Physiol* 68: 139–147, 1994.
7. Kawakami, Y, Abe, T, Kuno, S, and Fukunaga, T. Training-induced changes in muscle architecture and specific tension. *Eur J Appl Physiol* 72: 37–43, 1995.
8. Kawakami, Y, Ichinose, Y, Kubo, K, Ito, M, and Fukunaga, T. Architecture of contracting human muscles and its functional significance. *J Appl Biomech* 16: 88–98, 2000.
9. Kawakami, Y, Abe, T, Kanehisa, H, and Fukunaga, T. Human skeletal muscle size and architecture: variability and interdependence. *Am Human Biol* 18: 845–848, 2006.
10. MacDougall, JD, Sale, DG, Alway, SE, and Sutton, JR. Muscle fiber number in biceps brachii in bodybuilders and control subjects. *J Appl Physiol* 57: 1399–1403, 1984.
11. Maughan, RJ, Watson, JS, and Weir, J. Relationship between muscle strength and muscle cross-sectional area in male sprinters and endurance runners. *Eur J Appl Physiol* 50: 309–318, 1983.
12. Maughan, RJ and Nimmo, MA. The influence of variations in muscle fibre composition on strength and cross-sectional area in untrained males. *J Physiol* 351: 299–311, 1984.
13. Maughan, RJ, Watson, JS, and Weir, J. Muscle strength and cross-sectional area in man: a comparison of strength-trained and untrained subjects. *Br J Sports Med* 18: 149–157, 1984.
14. Murray, WM, Buchanan, TS, Delp, S, and Scott, L. The isometric functional capacity of muscles that cross the elbow. *J Biomech* 33: 943–952, 2000.
15. Rutherford, OM and Jones, DA. Measurement of fibre pennation using ultrasound in the human quadriceps in vivo. *Eur J Appl Physiol* 65: 433–437, 1992.
16. Sale, DG, MacDougall, JD, Alway, SE, and Sutton, JR. Voluntary strength and muscle characteristics in untrained men and women and male bodybuilders. *J Appl Physiol* 62: 1786–1793, 1987.
17. Sale, DG, Martin, JE, and Moroz, DE. Hypertrophy without increased isometric strength after weight training. *Eur J Appl Physiol* 64: 51–55, 1992.
18. Schanz, P, Randall-Fox, E, Hutchinson, W, Tyden, A, and Astrand, PO. Muscle fiber type distribution, muscle cross-sectional area and maximal voluntary strength in humans. *Acta Physiol Scand* 117: 219–226, 1983.
19. Scott, SH, Engstrom, CM, and Loeb, GE. Morphometry of human thigh muscles. Determination of fascicle architecture by magnetic resonance imaging. *J Anat* 182: 249–257, 1993.
20. Yamaguchi, GT, Sawa, AGU, Moran, DW, Fessler, MJ, and Winters, JM. A survey of human musculotendon actuator parameters. In: Multiple Muscle Systems. Biomechanics and Movement Organization, Winters, JM, and Woo, SL-Y, eds. New York: Springer-Verlag, 1990, pp. 717–773.

ESTABLISHING A NEW INDEX OF MUSCLE CROSS-SECTIONAL AREA AND ITS RELATIONSHIP WITH ISOMETRIC MUSCLE STRENGTH

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ABSTRACT

The present study aimed i) to establish an index of muscle cross-sectional area (CSA) based on muscle thickness and circumference through a comparison with muscle CSA determined by magnetic resonance imaging (MRI), and ii) to examine the relationships between muscle strength and the index determined at rest and during the maximal isometric contraction. The muscle CSA of elbow flexors at 60% of the upper arm length (CSA_{60}) and the maximal CSA of elbow flexors (CSA_{max}) were measured using MRI in 26 men and 8 women. The muscle thickness (MT) of elbow flexors and the circumference (C) of upper arm at 60% of the upper arm length were measured using ultrasonography and anthropometry, respectively, in 29 men and 9 women. The measurements of MT and C were performed in the resting (MT_r and C_r) and contracted condition (MT_m and C_m), where the subjects performed maximal voluntary contraction (MVC) of isometric elbow joint flexion. The torque developed during MVC was converted into the muscle force (F) of elbow flexors. The $MT_r \times C_r$ was significantly correlated both with CSA_{60} and CSA_{max} ($P < 0.001$). The F was significantly correlated with $MT_m \times C_m$ ($r = 0.847$, $P < 0.001$) and $MT_r \times C_r$ ($r = 0.839$, $P < 0.001$). However, stepwise multiple regression analysis selected only $MT_m \times C_m$ as a significant contributor for estimating F. The present study indicates that MT × C reflects muscle CSA, and can be an index for assessing muscle CSA. In addition, the findings obtained here showed a possibility that MT × C during MVC is more closely related to F than that at rest.

KEY WORDS elbow flexors, muscle thickness, circumference, maximal isometric contraction, ultrasonography

INTRODUCTION

The force generation capability of a muscle is related to its cross-sectional area (CSA) (13). Many studies have examined this subject through CSA measurements and/or estimates using imaging techniques such as computerized tomography (CT) (17,18,22), ultrasonography (13) and magnetic resonance imaging (MRI) (3,8,21), or using anthropometry (7). Among these techniques, MRI and CT provide precise muscle dimensions, but have poor applicability to practical use in filed studies. On the other hand, ultrasonography and anthropometry are more easily applicable in field studies on a large number of subjects. In particular, ultrasonography has the same merit as those of MRI or CT in directly visualizing fat and muscle tissues, but the major drawback of this technique is the limitation to image size which in many cases cannot cover the whole section of the muscle of interest. Anthropometry overcomes the latter concern, but it cannot evaluate distributions of tissues under the skin.

The forte of ultrasonography and anthropometry is that they make it possible to evaluate muscle dimensional changes during contraction owing to their real-time measurement. Hodges et al. (12) reported that an isometric contraction resulted in an increase in muscle thickness of parallel-fibered muscles such as the biceps brachii and brachialis. This implies that the CSA of parallel-fibered muscles increases during contraction and that it might affect muscle force production. One would therefore expect that if proper methodology is developed by combining ultrasonography and anthropometry to estimate muscle dimensions, it is valuable for not only quantitative assessment of muscle size in field studies, but also for examination on the relationship between muscle dimensions and force under a contracted condition. However, little attention has been paid to contraction-induced changes in muscle dimensions and their relations to the force exerted.

Muscle thickness (MT) measured by ultrasonography correlates closely with muscle CSA (1,25) and its squared value has been used as an index of muscle CSA (8,19,20). This index was derived from the idea that the cross-section of the

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whole skeletal muscle can be approximated by a circle and its diameter is equal to MT. But in reality, it is not the case, and muscle thickness is not always equal to width (the length of the distance between peripheries of the muscle perpendicular to MT). This has not been taken into consideration. On the other hand, the squared value of circumference (C) of a limb has been used to estimate muscle and bone CSA (5,7,11,23). Although C involves other tissues besides the muscle, it should reflect muscle dimensions including both muscle thickness and width. Because the muscle CSA is a function of length to the second power, we hypothesized that the product of MT and C (MT × C) can be an index for estimating muscle dimensions both at rest and in a contracted condition. We tested this hypothesis in the case of the elbow flexors in young adults. The main purposes of the present study were to investigate i) validity of MT × C through a comparison with muscle CSA determined by MRI and ii) the relationships between muscle strength and MT × C determined at rest and during the maximal isometric contraction.

METHODS

Experimental Approach to the Problem

The present study involved two experiments in relation to its purposes. To develop the index of muscle CSA, the MT of elbow flexors (biceps brachii and brachialis) and the C of upper arm were determined at the level of 60% of the upper arm length (the distance from the acromial process of the scapula to the lateral epicondyle of the humerus) as described in a prior study (2). This measurement site was almost the maximal CSA in the upper arm (14). MT × C was calculated and defined as an index of muscle CSA. In the first experiment, the relationship between MT × C and muscle CSA measured by MRI at rest condition was tested to examine the validity of the index. In the second experiment, the relationships between muscle strength and MT × C not only at rest but also during maximal voluntary contraction (MVC) were examined. Some prior studies (13,18,24) found no significant difference in the force-area relationship between men and women. Hence, its relationship was examined with no distinction between men and women in the present study.

Subjects

A total of 38 healthy men (n = 29) and women (n = 9) volunteered as subjects. Their means (±standard deviations, SDs) in age, body height, and mass were 24.8 (±3.1) yr, 170.1 (±6.6) cm and 64.0 (±9.0) kg, respectively. Two of the subjects were university officials, 8 of them were university students and the remainders were graduate students. This study was approved by the ethical committee of the Faculty of Sport Sciences at Waseda University, and was consistent with their requirement for human experimentation. Each subject was informed of the purpose and procedures of this study and possible risks of the measurements beforehand. Written informed consent was obtained from each subject.

Procedures

Examination for the Validity of MT × C as Muscle CSA Index. Of the subjects, 26 men and 8 women participated in the experiment for examining the validity of MT × C. All measurements were performed for the subjects' right arms. They had no orthopedic abnormality in their right arms. In the measurements of the upper arm length and the forearm length (the distance from the head of radius to the processus styloideus), the elbow joint was kept in an extended position. After these measurements were made using a steel measure, the measurement site was marked with a pen. A B-mode ultrasonic apparatus (SSD-900, Aloka, Tokyo, Japan) was used for the MT measurements. An electronic linear array probe (UST-579T, 7.5 MHz wave frequency, Aloka, Tokyo, Japan) was prepared with water-soluble transmission gel and applied on the anterior skin surface. The obtained ultrasonographic images were printed out by echo copier (SSZ-309, Aloka, Tokyo, Japan). The MT was determined as the distance from the adipose tissue-muscle interface to the muscle-bone interface in 0.5 mm (Figure 1). The C was measured in 0.1 cm by a cloth measure.

The measurements of MT and C at rest condition (MT_r and C_r) were performed while the subjects seated on a test chair and their right arms were secured to a torque meter (VTE-002R, VINE, Tokyo, Japan) by using an unelastic belt (Figure 2). The subjects kept 90° of shoulder joint flexion angle and elbow joint angle, and their wrists were fixed in a position halfway between supination and pronation.

The measurement CSA of elbow flexors was performed as stated below. A series of cross-sectional images of the right arm were obtained using MRI (Signa 1.5T, GE, Milwaukee, Wisc.) with a 3 inch and a 5 inch round GP coils. Transverse scans were performed with a conventional T1-weighted Spin-echo technique (a repetition time: 950 ms, an echo time: 9 ms, a slice thickness: 5 mm, an interspaced distance: 0 mm). Imaging was carried out on a field view of 16 × 16 cm with a 256 × 192 matrix. A marker was applied on the subjects' skin

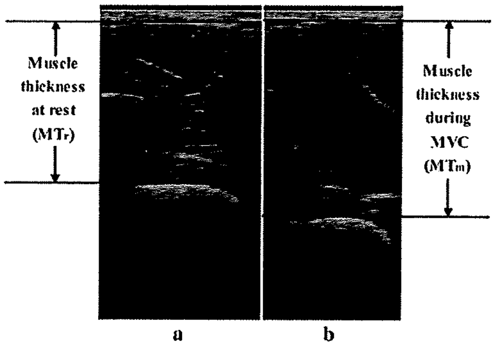

Figure 1. Ultrasonographic images of elbow flexors (a) at rest and (b) during maximal voluntary contraction (MVC).

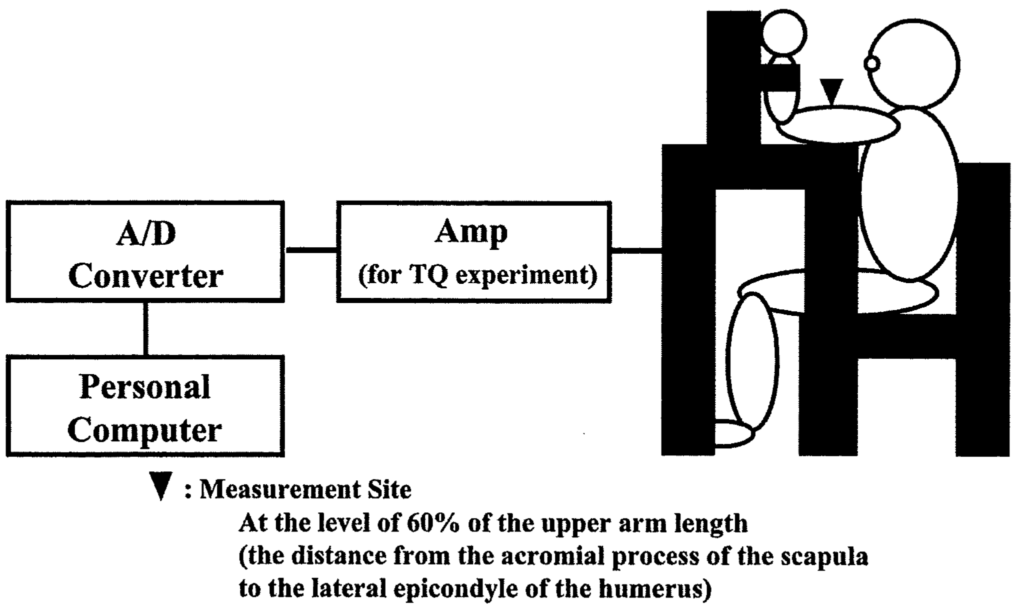

Figure 2. Schematic presentation on the experimental setup.

surface at the level of 60% of the upper arm length. Within the device, the subjects lay in the supine position and their right arms were relaxed on a handmade wooden armrest. Their wrists were fixed in a position halfway between supination and pronation by using an unelastic belt. Since the armrest had slight list, their elbows were slight bent (10° of elbow joint angle). From scanned images, outlines of elbow flexors were digitized and each cross-sectional image was measured using a personal computer (LaVie LL350/8, NEC, Tokyo, Japan). The measurement was carried out 2 times and the averaged values at the level of 60% of the upper arm length and the maximal averaged values were adopted as CSA$_{60}$ and CSA$_{max}$, respectively. The CVs of the two measured values were less than 2% and the intraclass correlation coefficients for them in CSA$_{60}$ and CSA$_{max}$ were more than 0.999.

Examination for the Relationship Between Muscle Strength and MT × C. All of the subjects participated in the examination for the relationships between muscle strength and MT × C. First, the measurements of MT$_r$ and C$_r$ were performed as stated above. Second, MT and C were determined in the contracted condition, in which the subjects performed MVC of isometric elbow joint flexion for 3 seconds at 90° of elbow joint angle, and referred to as MT$_m$ and C$_m$, respectively. The torque (TQ) data during the elbow joint flexion was recorded through an A/D converter (PowerLab/16SP, ADinstruments, Bella Vista, Australia) into the aforementioned personal computer (LaVie LL350/8, NEC, Tokyo, Japan) at 100 Hz sampling frequency and processed with a low-pass filter (cutoff frequency: 20 Hz). The TQ measurements were performed two times with at least a 5 minute interval. If the difference between two values of TQ was more than 5% of the higher one, the TQ was measured 1 more time. In 2 or 3 TQ measurements, the highest value was adopted. The MT was measured on the first trial and the C was measured on the second one. In the case of performing the third trial, the MT or C was measured once again according to the following conditions. If the first measured TQ was lower, the MT was measured on the third trial. If not so, the C was measured on the third trial. The MT and C were measured while TQ output peaked and was stable. According to a prior study (14), TQ was converted to muscle strength (F) by dividing by the forearm length of each subject.

Reproducibility of Measurement Variables. The measurements of MT, C and TQ were repeated on another day to ensure the reproducibility of them. Of the subjects, 14 men and 2 women participated in these measurements.

Statistical Analyses

Descriptive data were presented as means ± SDs. The reproducibility of MT, C and TQ was assessed by using a coefficient of variance (CV) and an intraclass correlation coefficient. To assess the validity of MT × C, a simple regression analysis was performed to calculate Pearson's product-moment correlation coefficients between MT$_r$ × C$_r$ and CSA measured by MRI (CSA$_{60}$ and CSA$_{max}$) and to confirm whether each regression intercept for each regression line differs from zero. A Student's paired t-test was used to test the differences in MT, C and MT × C between at rest and during MVC. According to prior studies (3,6,10), the following statistical processing was performed to test which MT × C was more closely related to F, that at rest or during MVC. First, Pearson's product-moment correlation coefficients were calculated between F and MT × C both at rest and during MVC. Second, a stepwise multiple regression analysis was performed, including $MT_r \times C_r$ and $MT_m \times C_m$ as the independent variables and F as the dependent variable. Third, a simple regression analysis was performed to confirm whether the regression intercepts for the relationships between either $MT_r \times C_r$ or $MT_m \times C_m$ and F differ from zero. Lastly, the CVs of F per MT × C at rest and during MVC were calculated to compare between the interindividual variations of the two variables. Statistical significance was set at $P \leq 0.05$.

RESULTS

Reproducibility of Measurement Variables. Table 1 summarizes the CVs and intraclass correlation coefficients of MT, C and TQ. The CVs of the two measured values were less than 2.6% and the intraclass correlation coefficient in each of them was more than 0.985.

Validity of MT × C for Estimating Muscle CSA. Figure 3 shows the relationship between $MT_r \times C_r$ and CSA measured by MRI. $MT_r \times C_r$ was significantly correlated to both CSA_{60} and CSA_{max} ($P < 0.001$) and both intercepts of their regression lines were not significantly different from zero.

Relationship Between MT × C and F. Descriptive data on MT, C and MT × C at rest and during MVC are shown in Table 2. Each of the variables during MVC was significantly ($P < 0.001$) higher than that at rest. The CV of $MT_m \times C_m$ (23.6%) was lower than that of $MT_r \times C_r$ (26.2%).

Figure 4 shows the relationships between MT × C and F. Both $MT_m \times C_m$ and $MT_r \times C_r$ were significantly correlated to F ($P < 0.001$), with similar correlation coefficients in them. As a result of the stepwise multiple regression analysis, however, only $MT_m \times C_m$ was selected as a significant contributor for estimating F. The intercept of the regression line for the relationship between $MT_r \times C_r$ and F was significantly different from zero ($P < 0.05$). In addition, the CV of F per MT × C during MVC (12.8%) was lower than that at rest (14.5%) (Table 2).

DISCUSSION

The main findings of this study were that i) $MT_r \times C_r$ was significantly correlated with both CSA_{60} and CSA_{max}, ii) the MT, C and MT × C during MVC were significantly higher than those at rest, and iii) although both $MT_m \times C_m$ and $MT_r \times C_r$ were significantly correlated with F, the stepwise multiple regression analysis selected only $MT_m \times C_m$ as a significant contributor for estimating F.

Some researchers pointed out that anthropometry overestimates muscle and bone CSA due to an underestimation of skin and subcutaneous tissue (5,7,11,23). To take the arm muscle area as an example, this has been attributed to the assumption that the shape of the arm is circular (11). To resolve this problem, the MT and C were adopted as the variables in the present study. On the other hand, the C includes not only elbow flexors but also elbow extensors. Hence, MT × C may include the error in evaluating muscle CSA attributed to it. However, $MT_r \times C_r$ was highly correlated with both CSA_{60} and CSA_{max} and each intercept of each regression line was not significantly different from zero (Figure 3). This result indicates that MT × C can be the index of the muscle CSA.

The MT_m and C_m were significantly higher than MT_r and C_r. Consequently, the $MT_m \times C_m$ was significantly higher than $MT_r \times C_r$ (Table 1). When a joint is fixed at a given joint angle, a muscle-tendon complex is constant in length. However, a tendon is stretched during isometric contraction (16) and consequently muscle length is shortened. Since muscle volume hardly changes by contraction (4), the shortening of muscle length results in an increase of muscle thickness and CSA. Thus, it is reasonable to assume that the greater MT × C during MVC as compared to that at rest is attributed to the elongation of a tendon during contraction. Another possibility is the effect of gravity on muscle geometry. A relaxed muscle is deformed by gravity due to its slackness. During contraction, stiffened muscle might resist gravity by maintaining its shape, which could also influence different MT, C and MT × C at rest and during MVC.

Bruce et al. (6) have reported that the regression line for the relationship between muscle CSA and force cannot have a true intercept because if there

TABLE 1. Reproducibility of MT, C and TQ (n = 16).

	MT		C		
	Rest	MVC	Rest	MVC	TQ
CV %	2.0 ± 1.3	1.8 ± 1.2	0.9 ± 0.5	0.8 ± 0.7	2.6 ± 1.8
Intraclass correlation coefficient	0.985	0.990	0.997	0.997	0.990

Values are mean ± SD.
MT = muscle thickness; C = circumference; TQ = torque; CV = coefficient of variance; MVC = maximal voluntary contraction.

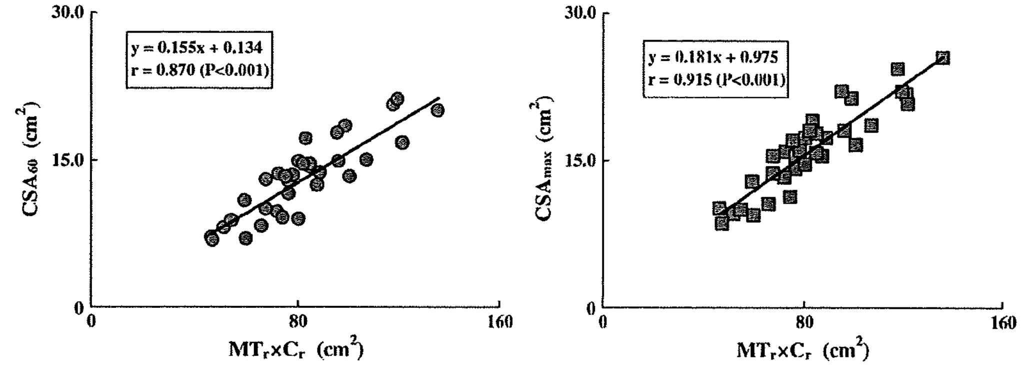

Figure 3. Relationship between $MT_r \times C_r$ and CSA measured by MRI (n = 34). MT_r = muscle thickness at rest; C_r = circumference at rest; CSA_{60} = cross-sectional area of elbow flexors at the level of 60% of the upper arm length measured by MRI; CSA_{max} = the maximal cross-sectional area of elbow flexors measured by MRI.

is no muscle (i.e., independent variable equals zero), there must be no force (i.e., dependent variable must equal zero). Moreover, when each data is plotted closer to this regression line, the CV of force per CSA (i.e., dependent variable per independent variable) will probably come close to zero. In the present result, the regression intercept for the relationship between $MT_r \times C_r$ and F was significantly different from zero unlike that during MVC (Figure 4), and the CV of F per $MT_m \times C_m$ (12.8%) was lower than that of F per $MT_r \times C_r$ (14.5%) (Table 2). Considering the results of the Pearson's product-moment correlation coefficients and the stepwise multiple regression analysis, these results suggest that MT × C during MVC is similarly or more closely related to F than that at rest. In the relationship between muscle strength and MT × C, the observed difference between at rest and during MVC is probably attributed to the difference of the interindividual variation in muscle CSA. In the present study, the CV of $MT_m \times C_m$ (23.6%) was lower than that of $MT_r \times C_r$ (26.2%) (Table 2). As mentioned above, a relaxed muscle is deformed by gravity that could lead to greater interindividual variation in the muscle CSA in the relaxed condition. Further investigation is needed to clear the difference between the relationship of MT × C and F at rest and that during MVC by examining other populations such as strength trained athletes and elderly individuals.

Table 2. Descriptive data on MT, C, MT × C and F per MT × C at rest and during MVC (n = 38).

	Rest	MVC
MT cm	3.0 ± 0.5	3.7 ± 0.5*
C cm	27.9 ± 2.9	28.8 ± 3.0*
MT × C cm^2	85 ± 22	108 ± 25*
CV %	26.2	23.6
F per MT × C N/cm^2	2.8 ± 0.4	2.2 ± 0.3*
CV %	14.5	12.8

Values are mean ± *SD.*

MT, muscle thickness; C, circumference; F, muscle strength; CV, coefficient of variance; MVC, maximal voluntary contraction.

*Significant difference between at rest and during MVC, $P < 0.001$.

PRACTICAL APPLICATIONS

The present study indicates that MT × C is highly correlated with muscle CSA determined by MRI and it can be an index for assessing muscle CSA not only at rest but also during contracted conditions. In addition, the findings obtained here showed a possibility that MT × C during MVC is more closely related to F than that at rest. This suggests the importance of determining muscle dimensions during contracted conditions

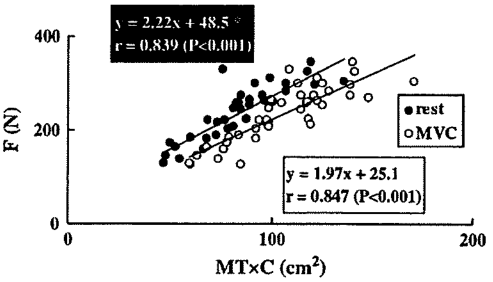

Figure 4. Relationship between F and MT × C at rest and during MVC (n = 38). MT = muscle thickness; C = circumference; F = muscle strength; MVC = maximal voluntary contraction. *Significant difference from zero, $P < 0.05$.

to examine the relationship between muscle CSA and strength. As described in the earlier part, ultrasonography and anthropometry make it possible to determine muscle dimensional changes during contraction. The MT × C developed using ultrasonography and anthropometry may be useful for evaluating the relationship between muscle CSA and strength in individuals whose muscle dimensions during contracted conditions largely differ from those at rest.

REFERENCES

1. Abe, T, Kawakami, Y, Suzuki, Y, Gunji, A, and Fukunaga, T. Effects of 20 days bed rest on muscle morphology. *J Gravit Physiol* 4: S10–S14, 1997.
2. Abe, T, Kondo, M, Kawakami, Y, and Fukunaga, T. Prediction equations for body composition of Japanese adults by B-mode ultrasound. *Am J Hum Biol* 6: 161–170, 1994.
3. Bamman, MM, Newcomer, BR, Larson-Meyer, DE, Weinsier, RL, and Hunter, GR. Evaluation of the strength-size relationship in vivo using various muscle size indices. *Med Sci Sports Exerc* 32: 1307–1313, 2000.
4. Baskin, RJ and Paolini, PJ. Volume change and pressure development in muscle during contraction. *Am J Physiol* 213: 1025–1030, 1967.
5. Baumgartner, RN, Rhyne, RL, Troup, C, Wayne, S, and Garry, PJ. Appendicular skeletal muscle areas assessed by magnetic resonance imaging in older persons. *J Gerontol* 47: M67–M72, 1992.
6. Bruce, SA, Phillips, SK, and Woledge, RC. Interpreting the relation between force and cross-sectional area in human muscle. *Med Sci Sports Exerc* 29: 677–683, 1997.
7. De Koning, FL, Binkhorst, RA, Kauer, JM, and Thijissen, HO. Accuracy of an anthropometric estimate of the muscle and bone area in a transversal cross-section of the arm. *Int J Sports Med* 7: 246–249, 1986.
8. Fukunaga, T, Miyatani, M, Tachi, M, Kouzaki, M, Kawakami, Y, and Kanehisa, H. Muscle volume is a major determinant of joint torque in humans. *Acta Physiol Scand* 172: 249–255, 2001.
9. Fukunaga, T, Roy, RR, Shellock, FG, Hodgson, JA, and Edgerton, VR. Specific tension of human plantar flexors and dorsiflexors. *J Appl Physiol* 80: 158–165. 1996.
10. Gadeberg, P, Andersen, H, and Jakobsen, J. Volume of ankle dorsiflexors and plantar flexors determined with stereological techniques. *J Appl Physiol* 86: 1670–1675, 1999.
11. Heymsfield, SB, McManus, C, Smith, J, Stevens, V, and Nixon, DW. Anthropometric measurement of muscle mass: revised equations for calculating bone-free arm muscle area. *Am J Clin Nutr* 36: 680–690, 1982.
12. Hodges, PW, Pengel, LH, Herbert, RD, and Gandevia, SC. Measurement of muscle contraction with ultrasound imaging. *Muscle Nerve* 27: 682–692, 2003.
13. Ikai, M, and Fukunaga, T. Calculation of muscle strength per unit cross-sectional area of human muscle by means of ultrasonic measurement. *Int Z Angew Physiol* 26: 26–32, 1968.
14. Kanehisa, H, and Fukunaga, T. Velocity associated characteristics of force production in college weight lifters. *Br J Sports Med* 33: 113–116, 1999.
15. Kanehisa, H, Ikegawa, S, Tsunoda, N, and Fukunaga, T. Cross-sectional areas of fat and muscle in limbs during growth and middle age. *Int J Sports Med* 15: 420–425, 1994.
16. Kubo, K, Kawakami, Y, and Fukunaga, T. Influence of elastic properties of tendon structures on jump performance in humans. *J Appl Physiol* 87: 2090–2096, 1999.
17. Maughan, RJ and Nimmo, MA. The influence of variations in muscle fibre composition on muscle strength and cross-sectional area in untrained males. *J Physiol* 351: 299–311, 1984.
18. Maughan, RJ, Watson, JS, and Weir, J. Strength and cross-sectional area of human skeletal muscle. *J Physiol* 338: 37–49, 1983.
19. Miyatani, M, Kanehisa, H, and Fukunaga, T. Validity of bioelectrical impedance and ultrasonographic methods for estimating the muscle volume of the upper arm. *Eur J Appl Physiol* 82: 391–396, 2000.
20. Miyatani, M, Kanehisa, H, Kuno, S, Nishijima, T, and Fukunaga, T. Validity of ultrasonograph muscle thickness measurements for estimating muscle volume of knee extensors in humans. *Eur J Appl Physiol* 86: 203–208, 2002.
21. Narici, MV, Landoni, L, and Minetti, AE. Assessment of human knee extensor muscles stress from in vivo physiological cross-sectional area and strength measurements. *Eur J Appl Physiol Occup Physiol* 65: 438–444, 1992.
22. Nygaard, E, Houston, M, Suzuki, Y, Jorgensen, K, and Saltin, B. Morphology of the brachial biceps muscle and elbow flexion in man. *Acta Physiol Scand* 117: 287–292, 1983.
23. Rice, CL, Cunningham, DA, Paterson, DH, and Lefcoe, MS. A comparison of anthropometry with computed tomography in limbs of young and aged men. *J Gerontol* 45: M175–M179, 1990.
24. Schantz, P, Randall-Fox, E, Hutchison, W, Tyden, A, and Astrand, PO, Muscle fibre type distribution, muscle cross-sectional area and maximal voluntary strength in humans. *Acta Physiol Scand* 117: 219–226, 1983.
25. Sipila, S and Suominen, H. Ultrasound imaging of the quadriceps muscle in elderly athletes and untrained men. *Muscle Nerve* 14: 527–533, 1991.

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Difference in Abdominal Muscularity at the Umbilicus Level between Young and Middle-aged Men

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Abstract This study aimed to examine how the muscularity of the abdomen at the umbilicus level differs between sedentary middle-aged and young men. Magnetic resonance imaging was applied to determine the cross-sectional areas of skeletal muscle, subcutaneous fat, and interperitoneal tissue in 43 middle-aged (40–58 yrs) and 38 young (21–29 yrs) men. The cross-sectional area of the skeletal muscle was analyzed as the sum of those of the rectus abdominis, abdominal oblique, lower back, and iliopsoas skeletal muscle groups. The middle-aged men showed greater waist circumference and whole abdominal cross-sectional area than the young men. In addition, the cross-sectional areas of subcutaneous fat and interperitoneal tissue were greater in the middle-aged men than in the young men. However, the total cross-sectional area of the skeletal muscle was similar between the two groups, although its percentage to the whole abdominal cross-sectional area was higher in the young men compared to the middle-aged men. Among the four skeletal muscle groups analyzed, the percentage of the cross-sectional areas in abdominal oblique muscles to that of total skeletal muscle was higher in the middle-aged men than in the young men and that of the lower back muscles was the reverse. These results were similar even when cross-sectional area data were analyzed using a sub-sample (33 middle-aged and 23 young men) matched for body height and mass. Thus, the present study indicated that the total muscularity of the abdomen at the umbilicus level was similar between the middle-aged and young men, but the relative distributions of lower back and abdominal oblique muscles varied between the two generations. *J Physiol Anthropol 26(5): 527–532, 2007* http://www.jstage.jst.go.jp/browse/jpa2
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Keywords: skeletal muscle, subcutaneous fat, interperitoneal tissue, waist circumference, aging

Introduction

For men, the circumference of the waist starts to increase dramatically during and after the 40 s (Wang et al., 2000) as a result of increments in visceral fat deposits (Enzi et al., 1986). However, available information on the profile of abdominal muscularity in middle-aged men is scarce. Skeletal muscle groups located in the trunk regions play an important role in transferring and/or stabilizing the body in various human movements (Krebs et al., 1992; MacKinnon and Winter, 1993; Sakurai and Miyashita, 1985). In addition to the quantification of the fat tissue, therefore, to determine the muscularity in the abdomen of middle-aged men may provide useful information for discussing not only the health conditions but also physical functions of individuals in this generation.

Previous studies using magnetic resonance imaging (MRI) or computerized tomography (CT) have provided substantial data on the age-related loss of the skeletal muscles in the whole body or certain limbs (e.g., Janssen et al., 2000). As a result of a cross-sectional observation, Janssen et al. (2000) observed a reduction in whole body skeletal muscle mass after the middle 40 s. In addition, cross-sectional observations on muscle thickness (Ishida et al., 1997; Miyatani et al., 2003; Kanehisa et al., 2004) have shown that the rectus abdominus is susceptible to aging as compared to those in other parts of the body. Considering these findings, it may be assumed that an increase in the abdominal fat in middle-aged men will be followed by a reduction of muscularity in this region. On the other hand, previous studies performing the muscle thickness measurements have examined only the rectus abdominis muscles among the skeletal muscles located in the lower trunk. The skeletal muscles located in the lower trunk are divided broadly into four groups in relation to their locations: the rectus abdominis, the abdominal oblique, the lower back, and the iliopsoas muscle groups. These skeletal muscle groups differ structurally and functionally from each other. Assuming that a reduction in abdominal muscularity occurs in middle-aged men, therefore, the magnitude of the aging effect might be assumed to be different among the individual skeletal muscle groups.

In the present study, the cross-sectional areas (CSAs) of the skeletal muscle, as well as the subcutaneous fat and interperitoneal tissue at the umbilicus level, were determined using MRI in sedentary middle-aged men and young men. The present study aimed to examine the differences in the muscularity of the abdomen between the two generations, with relation to muscle locations.

Method

Subjects

Forty-three middle-aged (46.0±5.3 yrs, mean±SD) and 38 sedentary young men (24.5±2.2 yrs) voluntarily participated in the present study. All subjects were healthy and had no functional disorder such as low-back pain. The subjects had not participated in any organized program of regular physical exercise (≥30 min per day, ≥2 days per week) for at least 1 year prior to being tested. The physical characteristics of the subjects are shown in Table 1. The average value in the body mass for the middle-aged group was greater than that for the young group, although the difference was not significant. The young group was significantly (p=0.0157) taller than the middle-aged group, so the body mass index (BMI) was significantly higher (p=0.0145) in the middle-aged men (26.3±2.2 kg/m^2) than in the young men (24.7±3.4 kg/m^2). For the comparison of CSA measurements between the two age groups, therefore, analyses of a sample matched for body height and mass were also performed to diminish the influence of the difference in body size. First, subjects were selected in accordance with a range of the shortest height in the young group and the tallest one in the middle-aged group, i.e., from 162.7 cm to 181.1 cm. Secondly, the subjects whose body mass were within the range of the lightest in the middle-aged group and the heaviest in the young group, i.e., from 57.7 kg to 96.3 kg, were selected from the height-matched subjects. This sample consisted of 33 middle-aged (age, 40–54 yrs, 45.4±4.9 yrs) and 23 young (21–29 yrs, 24.5±2.4 yrs) men. There were no significant differences between the two age groups of the sub-sample in morphological variables, with the exception that waist circumference was significantly greater in the middle-aged men than in the young men (Table 1). All descriptive data were presented using the sub-sample data. This study was approved by the Office of the Department of Life Sciences, University of Tokyo, and was consistent with their requirements for human experimentation. The subjects were fully informed about the procedures and the purpose of this study. Written informed consent was obtained from all subjects.

Table 1 Physical characteristics of subjects

Variables	All subjects		
	Middle-aged men, n=43	Young men, n=33	p values*
Body height, cm	170.2±9.4	173.8±5.1	0.0157
Body mass, kg	76.4±9.4	74.6±10.6	0.4187
BMI, kg/m^2	26.3±2.2	24.7±3.4	0.0145
Chest, cm	98.3±5.9	98.8±6.8	0.6795
Waist, cm	91.9±7.2	82.3±7.3	<0.0001
Hip, cm	101.7±4.7	99.2±6.2	0.0493

Variables	Sub sample data		
	Middle-aged men, n=33	Young men, n=23	p values*
Body height, cm	171.4±4.7	173.5±4.1	0.0903
Body mass, kg	77.1±7.2	76.8±9.4	0.9116
BMI, kg/m^2	26.2±2.1	25.6±3.3	0.3749
Chest, cm	98.4±5.5	100.4±3.3	0.2049
Waist, cm	92.2±6.0	83.9±7.0	<0.0001
Hip, cm	102.0±3.9	100.6±5.8	0.2764

Values are means±SDs.
* Student's t-test

MRI measurements

Using MRI scans with a body coil (Sierra 1.5 tesla, GE Yokokawa Medical Systems, USA), a transverse image at the height of the umbilicus (Ashwell et al., 1985) was obtained. The image condition was T-1 weighted, spin-echo, multi-slice sequences with a slice thickness of 10 mm, with a repetition time of 200 ms and an echo time of 20 ms. Each subject lay supine in the body coil with his arms and legs extended and relaxed. During the scan, the subjects were asked to hold their breath for about 20 seconds at the top of the inhalation to reduce the respiratory-motion artifact. From the cross-sectional image, outlines of the tissue (skeletal muscle, subcutaneous fat, interperitoneal, bone, and others) were traced (Fig. 1) and digitized using a personal computer (Power Macintosh G4, Apple) to calculate their CSAs. Within the skeletal muscle compartment, the adipose fat tissue imaged in different tones from the skeletal muscle tissue was excluded when digitizing. The CSA of the skeletal muscle was analyzed by separating it into four skeletal muscle groups: rectus abdominis (CSA_{RA}), abdominal oblique (CSA_{AO}, the sum of the internal oblique, external oblique, and transversus abdominis muscles), lower back (CSA_{LB}, the sum of the iliocostal, longissimus dorsi, semispinal, and quadratus lumborum muscles), and iliopsoas (CSA_{Ip}, the sum of the psoas major and minor muscles) muscles. The total CSA of the skeletal muscle compartment,

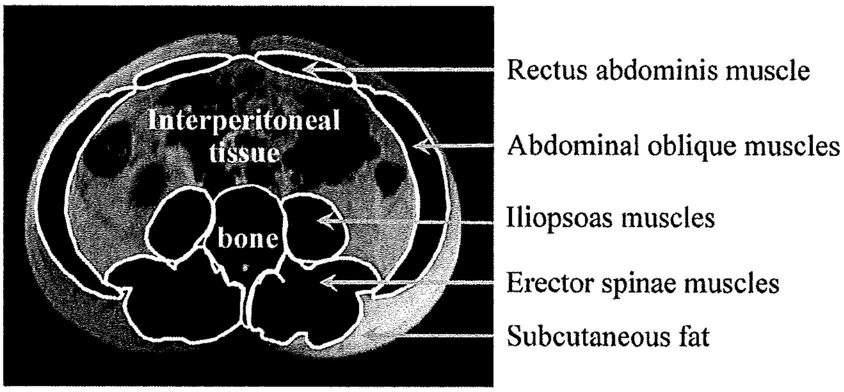

Fig. 1 Abdominal MRI image obtained from the umbilicus level.

Table 2 Descriptive data of CSA measurements: cm^2

Variables	Middle-aged men, n=33	Young men, n=23	*p* values*
Abdominal whole	600.7±79.7	389.9±96.2	<0.0001
Total skeletal muscle	137.3±15.4	140.7±19.6	0.4684
RA	12.1±3.3	13.4±3.8	0.1654
AO	42.0±7.7	42.0±6.6	0.3353
LB	54.8±6.9	59.8±8.3	0.0177
Ip	28.3±4.4	27.3±6.4	0.4843
Subcutaneous fat	172.8±43.5	106.6±55.3	<0.0001
Interperitoneal tissue	265.0±46.1	123.6±47.1	<0.0001

Values are means±SDs.
* Student's t-test
RA, AO, LB, and Ip indicate the rectus abdominins, abdominal oblique, lower back, and iliopsoas muscle groups, respectively.

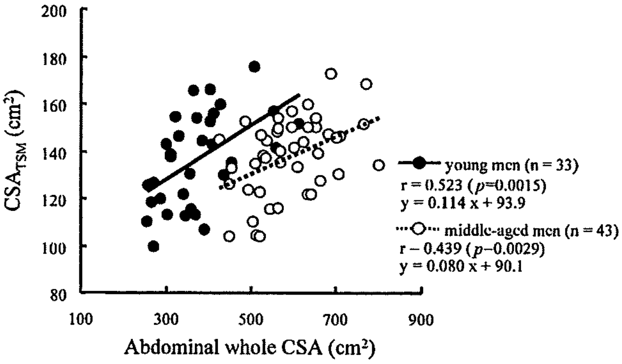

Fig. 2 Relationship between the whole abdominal CSA and the total skeletal muscle CSA (CSA_{TSM}).

Table 3 Descriptive data on the percentages of the CSAs of skeletal muscle (SM), subcutaneous fat (SF), and interperitoneal (IP) tissue to the abdominal whole CSA: %

Variables	Middle-aged men, n=33	Young men, n=23	*p* values*
Total skeletal muscle	23.1±2.7	37.5±7.4	<0.0001
Subcutaneous fat	28.6±5.0	26.1±9.0	0.1812
Interperitoneal tissue	44.0±4.6	31.4±6.6	<0.0001

Values are means±SDs.
* Student's t-test.

that is, the sum of the CSAs of the four skeletal muscle groups, was referred to as CSA_{TSM}. In addition to the absolute term, the CSA of every skeletal muscle group analyzed was expressed as a percentage of the CSA_{TSM} and referred to as $\%CSA_{RA}$, $\%CSA_{AO}$, $\%CSA_{LB}$, and $\%CSA_{Ip}$.

Statistics

Descriptive data were presented as the means and SDs for each subject group. The Student's t-test was used to test the significance of the difference between the means of the middle-aged and young men. A simple linear regression analysis was used to calculate the correlation coefficients between CSA_{TSM} and each of CSA_{RA}, CSA_{AO}, CSA_{LB}, and CSA_{Ip}. Statistical significance was set at $p<0.05$.

Results

Table 2 indicates the descriptive data on CSA measurements. The middle-aged men showed significantly greater whole abdominal CSA than the young men. In addition, the CSAs of the subcutaneous fat and interperitoneal tissue were also significantly greater in the middle-aged men than in the young men. The CSA_{TSM} and CSAs of the four skeletal muscle groups were similar between the two age groups, with the exception that the young men showed significantly greater CSA_{LB} than the middle-aged men.

The CSA_{TSM} was significantly correlated to the whole abdominal CSA in both middle-aged ($r=0.439, p=0.0029$) and young ($r=0.523, p=0.0015$) men (Fig. 2). In this relationship, most of the data for the young men were distributed above the regression line for the middle-aged men, so the percentage of CSA_{TSM} to the whole abdominal CSA was significantly lower in the middle-aged men than in the young men (Table 3). On the other hand, the corresponding value of the interperitoneal

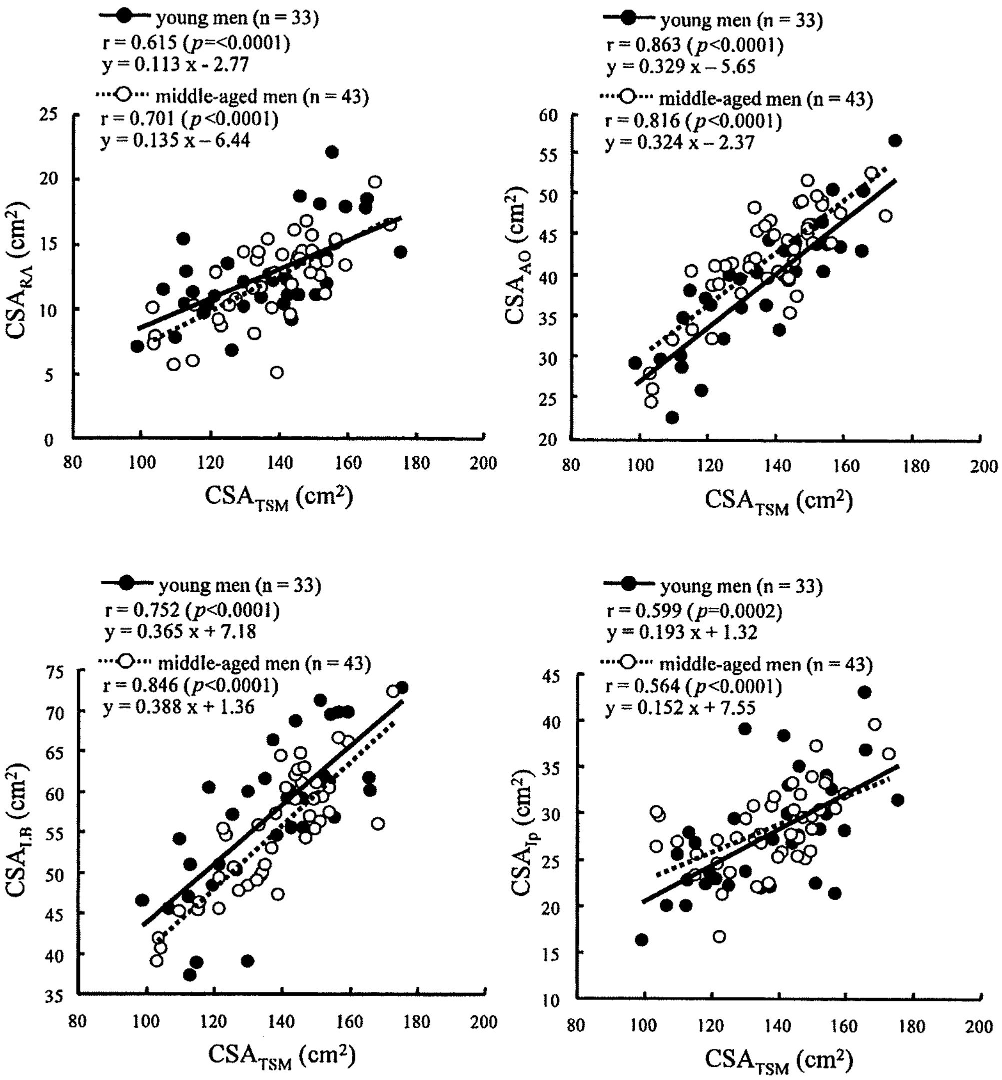

Fig. 3 Relationships between the total skeletal muscle CSA (CSA_{TSM}) and the CSA of each of the rectus abdominis (CSA_{RA}), abdominal oblique (CSA_{AO}), lower back (CSA_{LB}), and iliopsoas (CSA_{Ip}) skeletal muscle groups.

tissue was significantly higher in the middle-aged men compared to the young men, and that of the subcutaneous fat was similar between the two age groups.

Figure 3 indicates the relationship between CSA_{TSM} and the CSA of the each of the four skeletal muscle groups. In all relationships, significant correlations were found, with correlation coefficients of 0.564 ($p<0.0001$) to 0.846 ($p<0.0001$) in the middle-aged men, and 0.599 ($p=0.0002$) to 0.863 ($p<0.0001$) in the young men. There were the tendencies for the data for the middle-aged men to be plotted above the regression line for the young men in the relationship for CSA_{AO} and vice versa in that for CSA_{LB}. The differences were reflected in the comparison between the two age groups on the percentages of the CSA of every skeletal muscle group to CSA_{TSM} (Table 4). Namely, $\%CSA_{AO}$ was significantly higher in the middle-aged men than in the young men, and $\%CSA_{LB}$ in the young men than in the middle-aged men. On the other hand, there were no significant differences in $\%CSA_{RA}$ and $\%CSA_{Ip}$ between the two age groups.

Table 4 Descriptive data on the percentages of the CSAs of rectus abdominis (RA), abdominal oblique (AO), lower back (LB), and iliopasas (Ip) muscle groups to the total skeletal muscle CSA: %

Muscle groups	Middle-aged men, n=33	Young men, n=23	*p* values*
RA	8.7±1.9	9.5±2.3	0.1554
AO	30.5±2.7	28.4±2.8	0.0067
LB	40.0±3.0	42.7±3.9	0.0055
Ip	20.7±3.2	19.4±3.2	0.1221

Values are means±SDs.
* Student's t-test.

Discussion

The findings obtained here indicate that, at least at the umbilicus level, the middle-aged men can be characterized by greater CSAs of subcutaneous fat and interperitoneal tissue as compared to the young men, without a significant difference in the total skeletal muscle CSA. The present study did not quantify the intra-abdominal fat. In spite of the similarity of BMI, however, the CSA of the interperitoneal tissue was significantly greater in the middle-aged men than in the young men, in both the absolute value and the percentage to the whole abdominal CSA. Furthermore, the middle-aged men showed significantly greater waist circumference than the young men (Table 1). For men, the waist circumference has a strong potential for predicting the distribution of adipose tissue among several fat compartments in the abdominal region (Chan et al., 2003). In addition, a prior study using DEXA (Hunter et al., 2001) indicated that the trunk lean mass, which is largely representative of organ/visceral tissue mass (Piers et al., 1998), was relatively constant across ages. Hence, it is reasonable to assume that the observed difference in the CSA of the interperitoneal tissue between the two age groups can be attributed to the difference in the intra-abdominal fat CSA.

As described earlier, a reduction in whole body skeletal muscle mass occurs during and after the middle 40 s (Jansen et al., 2000). In addition, previous studies measuring the muscle thickness of the rectus abdominis have provided evidence indicating that abdominal muscularity is susceptible to aging (Ishida et al., 1997; Miyatani et al., 2003; Kanehisa et al., 2004). At the start of this study, therefore, it was expected that a significant difference in abdominal muscularity would be found between the middle-aged and young men. However, the CSA_{TSM} was similar in the two age groups. If an older group had been involved as the subjects, we would have had a greater chance for detecting a significant effect of age on muscularity. In the present study, however, we intended to clarify how abdominal muscularity in men of middle age, in which the waist circumference starts to increase dramatically (Wang et al., 2000), differs from that in young men. In terms of total skeletal muscle CSA at the umbilicus level, the present result denies our hypothesis and indicates a similarity of abdominal muscularity between young and middle-aged men. However, CSA_{LB} was significantly greater in the young men than in the middle-aged men. In addition, the $\%CSA_{AO}$ and $\%CSA_{LB}$ significantly differed between the two age groups. This implies that, although the total CSA of the skeletal muscle compartment in the abdomen is similar between the two generations, the relative distributions of the abdominal oblique and lower back muscles vary between young and middle-aged men.

The reasons for the observed differences in $\%CSA_{AO}$ and $\%CSA_{LB}$ between the two age groups are unknown but may be related to the functional characteristics of these muscle groups. A prior study (Arokoski et al., 2001) examining the muscular activities of the paraspinal and abdominal muscles in 16 different therapeutic exercises provided evidence suggesting that the activation level of the lower back skeletal muscles during daily life might be higher as compared to other skeletal muscle groups located in the abdomen. Again, Danneels et al. (2000) reported that, for the paravertebral muscles in chronic low back pain patients, stabilization exercises had no effect, but dynamic training induced a significant hypertrophic change. These findings tempt us to assume that the observed differences between the two age groups in lower back skeletal muscles can be attributed to the possible changes in the patterns of the loading to the lower back muscles and/or its activation levels during physical activities in daily life, associated with aging. Furthermore, the transversus abdominis is the abdominal skeletal muscle whose activity is consistently related to changes in intra-abdominal pressure and breathing (De Troyer et al., 1990; Cresswell et al., 1992). With regard to the higher $\%CSA_{AO}$ in the middle-aged men, therefore, it might be speculated that the greater CSA of the interperitoneal tissue itself would be a factor inducing a percentage of CSA_{AO} by becoming a load during breathing. In any case, we have no data on the functional properties of the skeletal muscle groups examined here. Further investigation is needed to clarify the assumptions mentioned above.

Before summarizing the present results, we should comment on a limitation of the procedure used for the CSA measurements. In a preliminary study using 27 adult men, we observed a high correlation between skeletal muscle CSA at the umbilicus level and the whole trunk skeletal muscle volume ($r=0.805$, $p<0.05$). This implies that the CSA of the skeletal muscles located at the umbilicus level can be considered a useful marker of the whole trunk skeletal muscle volume. However, the height of the umbilicus varies between individuals. In addition, the CSA determined at the umbilicus for every skeletal muscle group is not always the maximal anatomical CSA. Hence, we cannot exclude that, if the maximal CSA or volume for every skeletal muscle group is determined as a variable indicating the skeletal muscle size, the result on the age-related difference in muscularity would differ from that obtained here.

In summary, the present results indicate that the total muscularity of the abdomen at the umbilicus level was similar between the middle-aged and young men. However, the relative distribution of the abdominal oblique muscles was significantly higher in the middle-aged men than in the young men, and that of the lower back muscles was the reverse. To investigate the influences of aging on abdominal muscularity, further study examining elderly populations of both genders is warranted.

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References

Arokoski JP, Valta T, Airaksinen O, Kankaanpaa M (2001) Back and abdominal muscle function during stabilization exercises. Arch Phys Med Rehabil 82: 1089–1098

Ashwell M, Cole TJ, Dixon AK (1985) Obesity: new insight into the anthropometric classification of fat distribution shown by computed tomography. Br Med J (Clin Res Ed) 290 (6483): 1692–1694

Bjorntorp R (1992) Regional fat distribution–implications for type II diabetes. Int J Obes Relat Metab Disord 16: S19–S27

Chan DC, Watts GF, Barrett PH, Burke V (2003) Waist circumference, waist-to-hip ratio and body mass index as predictors of adipose tissue compartments in men. QJM 96: 441–447

Cresswell AG, Grundstrom H, Thorstensson A (1992) Observations on intra-abdominal pressure and patterns of abdominal intra-muscular activity in man. Acta Physiol Scand 144: 409–418

Danneels LA, Vanderstraeten GG, Cambier DC, Witvrouw EE, De Cuyper HJ (2000) CT imaging of trunk muscles in chronic low back pain patients and healthy control subjects. Eur Spine J 9: 266–272

De Troyer A, Estenne M, Ninane V, Van Gansbeke D, Gorini M (1990) Transversus abdominis muscle function in humans. J Appl Physiol 68: 1010–1016

Enzi G, Gasparo M, Biondetti PR, Fiore D, Semisa M, Zurlo F (1986) Subcutaneous and visceral fat distribution according to sex, age, and overweight, evaluated by computed tomography. Am J Clin Nutr 44: 739–746

Hunter GR, Weinsier RL, Gower BA, Wetzstein C (2001) Age-related decrease in resting energy expenditure in sedentary white women: effects of regional differences in lean and fat mass. Am J Clin Nutr 73: 333–337

Ishida Y, Kanehisa H, Carroll JF, Pollock ML, Graves JE, Ganzarella LG (1997) Distribution of subcutaneous fat and muscle thickness in young and middle-aged women. Am J Hum Biol 9: 247–255

Janssen I, Heymsfield SB, Wang ZM, Ross R (2000) Skeletal muscle mass and distribution in 468 men and women aged 18–88 yr. J Appl Physiol 89: 81–88

Kanehisa H, Miyatani M, Azuma K, Kuno S, Fukunaga T (2004) Influences of age and sex on abdominal muscle and subcutaneous fat thickness. Eur J Appl Physiol 91: 534–537

Kissebah AH, Krakower GR (1994) Regional adiposity and morbidity. Physiol Rev 74: 761–811

Krebs DE, Wong D, Jevsevar D, Riley PO, Hodge WA (1992) Trunk kinematics during locomotor activities. Phys Ther 72: 505–514

MacKinnon CD, Winter DA (1993) Control of whole body balance in the frontal plane during human walking. J Biomech 26: 633–644

Miyatani M, Kanehisa H, Azuma K, Kuno S, Fukunaga T (2003) Site-related differences in muscle loss with aging, "a cross-sectional survey on the muscle thickness in Japanese men aged 20 to 79 years". Int J Sports Health Sci 1: 34–40

Piers LS, Soares MJ, McCormack LM, O'Dea K (1998) Is there evidence for an age-related reduction in metabolic rate? J Appl Physiol 85: 2196–2204

Sakurai S, Miyashita M (1985) Mechanical energy changes during treadmill running. Med Sci Sports Exerc 17: 148–152

Wang J, Thornton JC, Kolesnik S, Pierson RN Jr (2000) Anthropometry in body composition. An overview. Ann NY Acad Sci 904: 317–326

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Age-Related Differences in the Force Generation Capabilities and Tendon Extensibilities of Knee Extensors and Plantar Flexors in Men

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Background. Recently, the number of elderly individuals who participate in sports has increased, thus injuries from overuse are now becoming recognized in the elderly population. Therefore, it is important to determine which muscle groups and tendons are most affected with aging to plan appropriate exercise interventions for elderly individuals. In particular, muscles and tendons in knee extensors and plantar flexors play an important role during locomotion. The purpose of this study was to compare the knee extensor and plantar flexor muscles and tendons.

Methods. Young ($n = 19$) and elderly ($n = 17$) men performed isometric voluntary knee extension and plantar flexion contractions. Muscle thickness and elongation of tendon structures in knee extensors and plantar flexors were measured by ultrasonography.

Results. Relative muscle thickness (to limb length) in the elderly group was significantly lower than that in the young group in knee extensors ($p < .001$), although no significant difference was found between the two groups in plantar flexors ($p = .063$). Relative muscle strength (to body mass) in the elderly group was significantly lower than that in the young group in both sites (all $p < .001$). Ratio of muscle strength to muscle thickness in the elderly group was significantly lower than that in the young group in plantar flexors, but not in knee extensors. The elderly group had significantly lower maximal elongation and strain of tendon structures in both sites than the young group had.

Conclusion. These results suggest that the age-related weakness in knee extensors may be attributed to muscle atrophy, whereas that in plantar flexors is not, and that elderly persons have less extensible tendon structures in both sites.

IT is well known that muscle strength declines with aging [e.g., (1)]. In particular, the age-related decline in muscle strength is greater in the lower than upper limbs (2). Although this age-related decline in muscle strength is largely due to muscle atrophy (3,4), it is also caused by a reduction in the neural activation level (5,6). Some previous studies indicated that the loss of muscle strength with aging exceeds the decrease in muscle size (2,4,7). However, previous findings concerning the influence of aging on the ratio of muscle strength to muscle size are conflicting (3,4). For example, Davies and colleagues (7) and Morse and coworkers (6) reported that the ratio of muscle strength to the cross-sectional area of plantar flexors was significantly lower in elderly individuals than in young individuals, whereas Overend and colleagues (3) and Young and coworkers (4) did not observe any effects of aging in the cross-sectional area knee extensors. Thus, previous reports on the existence of age-related change in muscle strength in relation to muscle size differ between the muscles examined. At present, however, few studies have simultaneously assessed these variables in knee extensors and plantar flexors (8).

Some previous studies using animal and human cadavers showed that the failure load and Young's modulus of tendons decreased with aging (9–11). Recently, we observed that the maximal strain of the human tendon structures in knee extensors decreased significantly with aging (12). On the contrary, Morse and colleagues (13) reported that the human gastrocnemius tendons of elderly participants were more compliant than those of young adults. Although the reasons for the discrepancy between the two reports are unknown, there is a possibility that age-related changes in the tendon properties would differ between the sites. However, no studies have so far been available regarding site differences in age-related changes in tendon properties.

Recently, the number of elderly individuals who participate in sports has increased, thus injuries from overuse are now becoming recognized in the elderly population (14). Therefore, it is important to determine which muscle groups and tendons are most affected with aging in order to plan appropriate exercise interventions for elderly individuals. In particular, muscles and tendons in knee extensors and plantar flexors play an important role during locomotion, that is, walking and running. The purpose of this study was to compare the mechanical and morphological properties of muscles and tendons in knee extensors and plantar flexors between two different age groups.

Table 1. Physical Characteristics and Step Numbers of Two Groups, Mean (SD)

	Young (N = 19)	Elderly (N = 17)
Age, y	26.4 (3.7)	70.4 (4.8)**
Stature, cm	171.0 (4.8)	159.7 (6.7)**
Body mass, kg	71.8 (11.8)	59.7 (8.7)*
Thigh length, cm	38.9 (1.5)	37.1 (2.2)*
Lower leg length, cm	39.2 (1.5)	35.3 (2.1)**
Step numbers, step · day^{-1}	7641 (2179)	7103 (2466)

Note: $*p < .01$; $**p < .001$, significantly different from young.

METHODS

Participants

Nineteen young (22–35 years) and 17 elderly (62–77 years) men participated in this study. All men were recruited from the community and were healthy and living independently. They were also free from cardiovascular and/or metabolic disorders according to a standardized interview. The procedures, purpose, and risks associated with the study were explained to all participants, and they gave their written informed consent to participate in this investigation before starting this project. This study was approved by the Local Ethics Committee of the Department of Sports Sciences, University of Tokyo, and complied with their requirements for human experimentation. The physical characteristics of the participants are shown in Table 1. All participants were sedentary or mildly active, with none currently involved in any type of exercise program (> 30 min/d, > 2 d/wk).

Number of Steps

For a 2-week period, the number of steps per day of each participant was measured to document the physical activity level during daily life. Each participant put a pedometer (FB-714; Tanita, Tokyo, Japan) on his belt or waistband as soon as he woke up each morning, removed it before going to bed every night, and recorded the number of steps per day. The total number of steps each day was recorded on daily log sheets. In the present study, the mean number of steps during 2 weeks was used as an index of the physical activity level during daily life (6).

Muscle Thickness

The muscle thickness values for knee extensors (three anatomic sites: on the anterior surface 30%, 50%, and 70% of the distance between the lateral condyle of the femur and greater trochanter) and plantar flexors (three anatomic sites: on the posterior surface 20%, 30%, and 40% of the distance between the lateral malleolus of fibula and the lateral condyle of the tibia) were measured with an ultrasonic apparatus (SSD-900; Aloka, Tokyo, Japan). The muscles involved in the measurement of muscle thickness were as follows: rectus femoris and vastus intermedius muscles for knee extensors; lateral gastrocnemius, soleus, and tibialis posterior muscles for plantar flexors. The participants remained in a supine position for the measurement of knee extensors and in a prone position for the measurement of plantar flexors with legs straight and the muscles relaxed. The anthropometric locations of the measurement sites were first precisely determined and marked by experienced technicians before the ultrasonic measurement. A transducer with a 7.5 MHz scanning head was coated with water-soluble transmission gel, which provided acoustic contact without depressing the dermal surface. The interfaces between subcutaneous adipose tissue and muscle and between muscle and bone were identified from the ultrasonic image, and the distance from the adipose tissue–muscle interface to muscle–bone interface was measured as a representative of muscle thickness. The thickness of each site was measured to the nearest 0.1 mm using a Vernier caliper. The mean values of the muscle thickness at all the measured sites were adopted as their representative of each part. Because the elderly participants were shorter than their younger counterparts (as shown in Table 1), it was considered that the age-related differences observed in muscle thickness could be attributed to differences in body size. Therefore, absolute and relative (to limb length) muscle thickness values were presented (15). Furthermore, some previous studies demonstrated that the ultrasonographic approach used in the present study was useful for examining muscle volume (16,17).

Muscle Strength

Maximal voluntary isometric torque (MVC) was measured by means of specially designed dynamometers (Vine, Tokyo, Japan) for knee extension and plantar flexion, respectively. All measurements were performed on the right lower limb. Participants had previously visited the laboratory on at least one occasion to become familiarized with the procedures involved. During each task, participants exerted isometric torque from 0 (relax) to MVC within 5 seconds. During the knee extension task, participants sat in an adjustable chair with support for the back and the hip joint flexed at an angle of 80° (full extension = 0°) to standardize the measurements and localize the action to the appropriate muscle group. During torque measurements, the hips and back were held tightly in the seat using adjustable lap belts. The axis of the knee joint was aligned with the axis of the lever arm of the dynamometer. The right ankle was firmly attached to the lever arm of the dynamometer with a strap and fixed with a knee joint flexed at an angle of 90° (full extension = 0°). During the plantar flexion task, participants sat on the chair of a dynamometer with their ankle at 90° (anatomic position) with the knee joint at full extension and the foot securely strapped to a foot plate. Prior to the test, participants performed a standardized warm-up and submaximal contractions to become accustomed to the test procedure. Each task was repeated two or three times per participant with at least 3 minutes between trials. The highest value among these trials was recorded as the muscle strength for each participant.

Elongation and Strain of Tendon Structures

Elongations of the tendon structures in knee extensors and plantar flexors were also assessed during ramp isometric knee extension and plantar flexion. An ultrasonic apparatus (SSD-2000; Aloka) with an electronic linear array probe (7.5-MHz wave frequency with 80 mm scanning length;