Validity of estimating limb muscle volume by bioelectrical impedance

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Masae, Hiroaki Kanehisa, Yoshihisa Masuo, Masamitsu Ito, and Tetsu Fukunaga. Validity of estimating limb muscle volume by bioelectrical impedance analysis. J Appl Physiol 91: 386–394, 2001.—The present study aimed to investigate the validity of estimating muscle volume by bioelectrical impedance analysis. Bioelectrical impedance and series cross-sectional images of the forearm, upper arm, lower leg, and thigh on the right side were determined in 22 healthy young adult men using a specially designed bioelectrical impedance acquisition system and magnetic resonance imaging (MRI) method, respectively. The impedance index \((L^2/Z)\) for every segment, calculated as the ratio of segment length squared to the impedance, was significantly correlated to the muscle volume measured by MRI, with \(r = 0.902–0.976 (P < 0.05)\). In these relationships, the SE of estimation was 38.4 cm\(^3\) for the forearm, 40.9 cm\(^3\) for the upper arm, 107.2 cm\(^3\) for the lower leg, and 362.3 cm\(^3\) for the thigh. Moreover, isometric torque developed in elbow flexion or extension and knee flexion or extension was significantly correlated to the \(L^2/Z\) values of the upper arm and thigh, respectively, with correlation coefficients of \(0.770–0.937 (P < 0.05)\), which differed insignificantly from those \((0.799–0.958; P < 0.05)\) in the corresponding relationships with the muscle volume measured by MRI of elbow flexors or extensors and knee flexors or extensors. Thus the present study indicates that bioelectrical impedance analysis may be useful to predict the muscle volume and to investigate possible relations between muscle size and strength capability in a limited segment of the upper and lower limbs.

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niquest, respectively. In addition, maximum voluntary isometric torque was determined in elbow flexion or extension and knee flexion or extension. The purposes of this study were to investigate the validity of BIA for predicting skeletal muscle volume of limb segments compared with the data obtained by MRI measurement and to document the relation between bioelectric impedance and muscle strength.

**METHODS**

**Subjects.** Twenty-two healthy adult men participated voluntarily in this study. The subjects were physically active but had not performed in any organized program of regular exercise for at least 1 yr before testing. The physical characteristics of the subjects are shown in Table 1. The subjects were fully informed about the procedures to be used as well as the purpose of the study. Written informed consent was obtained from all subjects.

**MRI measurement.** Series cross-sectional images of the upper and lower limbs on the right side were obtained by MRI scans with a body coil (Airis, Hitachi Medco). All the subjects participated in the MRI measurement for the lower limb, but only 17 of the 22 subjects participated for the upper limb due to scheduling limitations. Spin-echo, multislice sequences with a slice thickness of 10 mm were used with a repetition time of 200 ms and an echo time of 20 ms. Each subject lay supine with their arms and legs extended and relaxed during MRI measurement. Transverse scans were performed with an interslice gap of 0 mm from the head of humerus to the facies articularis carpea for the upper limb and from the caput femoris to the facies articularis inferior for the lower limb. From each cross-sectional image for the upper or lower limb, the fat-muscle and muscle-bone interfaces were traced. The anatomic muscle CSA, which was the area surrounded by the fat-muscle and muscle-bone interfaces, was then calculated by using a personal computer (Power Macintosh 7500/100, Apple). Adipose and tendinous tissues, which were imaged in different tones from the muscle tissue, were excluded when digitizing. Muscle length was defined as the distance between the most proximal and distal images in which the muscle was visible. By summing the anatomic CSA of the muscle along its length and then multiplying the sum by the interval of 10 mm, muscle volume was determined and is referred to as MRIv.

In addition, the CSA values of elbow or knee flexors and extensors were also determined to investigate the relation between the muscle volume and strength. The muscles analyzed were as follows: elbow flexors, which included the biceps brachii and brachialis; elbow extensors, which included the triceps brachii; knee flexors, which included the biceps femoris, semitendinosus, semimembranosus, gracilis, and sartorius; and knee extensors, which included the rectus femoris, vastus lateralis, vastus medialis, and vastus intermedius.

Furthermore, the percentage of each of fat, muscle, and bone tissue CSA to the whole CSA of limb at a given site was proposed to investigate the influences of tissue constituent of limb on BIA measurement. The selection of sites for the analyses and the procedure for CSA determinations were in accordance with those described in a prior study (17). Four sites were selected: at 30% of the distance from the head of radius to the processus styloides for the forearm, at 60% of the distance from the acromion process of the scapula to the lateral epicondyle of the humerus for the upper arm, at 70% of the distance from the malleolus lateralis to the articular cleft between the femur- and tibiacondyles for the lower leg, and at 50% of the distance from the greater trochanter of the femur to the articular cleft between the femur- and tibiacondyle for the thigh. Bone CSA was measured in the area surrounded by the bone-muscle boundary. Fat CSA was calculated by subtracting lean tissue (muscle + bone) CSA from the whole CSA of the limb.

**BIA measurement.** A bioelectrical impedance data acquisition system (Art Haven 9, Kyoto, Japan) was used to determine the bioelectrical impedance of the right upper and lower limbs (Fig. 1). This system applies a constant current of 800 µA at 50 kHz through the body. The equipment for the measurement of the BIA in the upper limb included specially made handgrip electrodes, which consisted of two separate plastic engineering rods in which current-introducing (source) and voltage-sensing (detector) electrodes are mounted at a distance of 15 mm. The four electrodes are wired and connected to a measurement unit and computer. Of the two pairs of wires, the one connected to the detector electrodes in the two rods is detachable; thus we could change the electrode combinations by connecting to detector electrodes placed at given sites on the upper limb. For example, the combination with detector electrodes placed on the elbow and shoulder makes it possible to determine the BIA of the upper arm. For the measurement of BIA in the lower limb, specially made footplate electrodes were used. Two footplate electrodes, implemented with current electrodes at the distal end (toe side) and detector electrodes at the proximal end (heel side) at a distance of 7 cm, were set on the board at an interval of 16 cm. The four electrodes were wired and connected to an impedance generator and computer. Similar to the handgrip electrodes, because one pair of electrodes that is connected to the detector electrodes in the footplate is detachable, we can determine the BIA of either the thigh or the lower leg by changing the combinations of the sites where the detector electrodes are placed.

Before the test, calibration of the system was checked against a precision resistor of 500 Ω provided by the manufacturer. All measurements were performed in the morning after the subjects fasted for at least 12 h. All subjects abstained from vigorous exercise before the bioelectrical impedance measurement and were tested after voiding and after 15 min of rest. The skin where the detector electrodes were positioned was cleaned with a 75% alcohol solution. Figures 2 and 3 show the schemas of the electrode combination for the impedance measurements of the upper arm and thigh, respectively. During the BIA measurement of the upper limb, the subject sat at a desk with his arms extended and softly grasped the two rods that were placed on the desk. After the completion of the BIA measurement for the upper limb, that of the lower limb was performed. The subjects stood properly on the footplate electrodes, so as to equalize weight on the right and left legs, and kept an upright posture with the
muscles of the whole body as relaxed as possible. The positions of the detector electrodes were as follows: on the lateral surface of the shoulder at the midpoint of a line joining the tip of acromion to processus coracoideus and lateral epicondyle of the humerus for the upper arm, at the lateral epicondyle of the humerus and the middorsum of the wrist centered on a line joining the bony prominences of radius and ulna for the forearm, at the greater trochanter of the femur and articular cleft between the femur- and tibiacondyles for the thigh, and at the articular cleft between the femur- and...
tibiacondyles and the midanterior ankle centered on a line joining the malleolus lateralis and malleolus medialis for the lower leg. The distance between the two electrodes was measured with a steel roller tape to the nearest 0.5 cm and was then used as segment length to calculate the impedance index. The impedance value obtained with each combination of detector electrodes was determined as the impedance value of the corresponding segment and was referred to as \( Z \).

The repeatability for measurement of \( Z \) was assessed on 2 separate days in a pilot study with 10 young adult subjects (3 women and 7 men). The intraclass correlation coefficient for the test-retest of \( Z \) in every segment ranged from 0.960 to 0.989, and the coefficient of repeatability (3) ranged from 2.8 to 9.6 \( \Omega \). These values were 5.1–7.1% of the corresponding impedance for each of the segments examined.

The impedance index of the examined segment was calculated with the following equation

\[
\text{Impedance index} = \frac{L^2}{Z}
\]

where \( L \) is the segment length in centimeters, which is the distance between the two detector electrodes, and \( Z \) is in ohms.

**Muscle strength measurement.** The torque output during maximal voluntary isometric elbow or knee extension and flexion was recorded using a specially designed dynamometer. The torque measurement was made for only 13 of the 22 subjects due to scheduling limitations. To standardize the measurements and localize the action to the appropriate muscle group, the subjects sat in an adjustable chair with support for the back, elbow, shoulders, and hips. During torque measurements, the hips and back of the subject were held tightly in the seat using adjustable lap belts. The rota-

### Table 2. Descriptive data on magnetic resonance imaging and bioelectrical impedance measurements

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean ± SD</th>
<th>Maximum</th>
<th>Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRI( \text{MV} ), cm(^3)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forearm</td>
<td>485.7 ± 108.92</td>
<td>627.0</td>
<td>288.6</td>
</tr>
<tr>
<td>Upper arm</td>
<td>669.1 ± 199.83</td>
<td>1,116.0</td>
<td>349.0</td>
</tr>
<tr>
<td>Lower leg</td>
<td>1,317.6 ± 262.50</td>
<td>1,829.6</td>
<td>847.7</td>
</tr>
<tr>
<td>Thigh</td>
<td>3,498.2 ± 840.30</td>
<td>5,582.0</td>
<td>2,137.1</td>
</tr>
<tr>
<td>( Z ), ( \Omega )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forearm</td>
<td>137.5 ± 30.10</td>
<td>205.1</td>
<td>106.1</td>
</tr>
<tr>
<td>Upper arm</td>
<td>100.4 ± 24.28</td>
<td>143.5</td>
<td>71.5</td>
</tr>
<tr>
<td>Lower leg</td>
<td>148.6 ± 21.14</td>
<td>201.1</td>
<td>117.4</td>
</tr>
<tr>
<td>Thigh</td>
<td>56.4 ± 8.25</td>
<td>77.2</td>
<td>41.3</td>
</tr>
<tr>
<td>( L^2/Z ), cm(^2)/( \Omega )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forearm</td>
<td>3.9 ± 0.92</td>
<td>5.2</td>
<td>2.3</td>
</tr>
<tr>
<td>Upper arm</td>
<td>10.9 ± 2.76</td>
<td>16.2</td>
<td>6.3</td>
</tr>
<tr>
<td>Lower leg</td>
<td>10.2 ± 1.94</td>
<td>14.9</td>
<td>6.4</td>
</tr>
<tr>
<td>Thigh</td>
<td>28.0 ± 5.84</td>
<td>42.7</td>
<td>19.7</td>
</tr>
</tbody>
</table>

MRI\( \text{MV} \), muscle volume determined by magnetic resonance imaging method; \( Z \), impedance; \( L^2/Z \), segment length\(^2/\)impedance.

**Fig. 4.** Relationship between impedance index \((L^2/Z)\) and muscle volume determined by magnetic resonance imaging (MRI; MRI\( \text{MV} \)). A: forearm; B: upper arm; C: lower leg; D: thigh. SEE, SE of estimation.
tion axis of the elbow or knee joint aligned with that of the lever arm of the dynamometer.

During elbow extension and flexion measurements, the subject’s right upper arm with a semipronated forearm was supported in the horizontal plane on an adjustable padded table, and the wrist was fixed with a strap at the end of an adjustable lever arm. During knee extension and flexion measurements, the subject sat in a chair designed for such experiments with the right ankle attached to the lever arm of the dynamometer. The upper arm and thigh were fixed with an adjustable lap belt to avoid any upward movement while muscle force was developed during elbow extension and knee flexion, respectively. Each movement task was performed with the elbow or knee joint angles at a 90° flexed position.

Calibration of the dynamometer was performed using known weights placed on the lever arm before every test. Before maximal testing, the subjects were asked to perform a series of isometric muscle actions with ~50% maximal voluntary effort to familiarize themselves with the apparatus. After a 5-min rest after the submaximal isometric force exertion, the subjects were encouraged to perform three to five maximal voluntary isometric muscle actions for 3 s with a rest period of 1 min between each trial. The peak torque produced was measured continuously on a recorder. The relative accuracy of the estimate of muscle mass in the total limb, not in the limb muscle mass determined by dual X-ray absorptiometry (DXA). The observed correlation coefficients, which were calculated as the difference between muscle volume estimated from the regression equation between L2/Z and the muscle volume estimated from the regression equation between L2/Z and MRI1 were highly significant (r = 0.799–0.958; P < 0.05). Similarly, the L2/Z of the upper arm (Fig. 5) and thigh (Fig. 6) was also significantly correlated to the torque value, with correlation coefficients of 0.770–0.937, which differed insignificantly from those obtained for the corresponding relations using MRI1.

**RESULTS**

The descriptive data on MRI and BIA measurements are shown in Table 2. The L2/Z for every segment was significantly correlated to the related MRI1, with correlation coefficients of 0.902–0.976 (Fig. 4). In these relationships, the SE of estimation value was 38.4 cm3 for the forearm, 40.9 cm3 for the upper arm, 107.2 cm3 for the lower leg, and 362.3 cm3 for the thigh.

For all segments examined, the muscle volume estimated from the regression equation between L2/Z and MRI1 did not significantly differ with the MRI1. The error of estimates, which was calculated as the difference between the MRI1 and muscle volume estimate, was −0.01 (±38.43) cm3 for the forearm, −0.01 (±43.88) cm3 for the upper arm, 4.83 (±107.40) cm3 for the lower leg, and 15.45 (±363.66) cm3 for the thigh. The error of the muscle volume estimate for each segment was not significantly correlated to the related MRI1 (r = 0.069–0.430; P > 0.05) or body mass relative to height squared, i.e., body mass index (r = 0.014–0.192; P > 0.05).

Table 3 shows the descriptive data on the CSA measurements. The percentage of fat CSA to whole CSA of limb for all sites was not significantly correlated with the error of muscle volume estimates for all segments (r = 0.172–0.397; P > 0.05). Similarly, the corresponding relations of the percentages of muscle and bone CSA values to the whole CSA were also insignificant: r = 0.142–0.415 (P > 0.05) for muscle tissue and r = 0.032–0.304 (P > 0.05) for bone tissue.

Isometric torque developed in elbow flexion and extension (Fig. 5) and knee flexion and extension (Fig. 6) was significantly correlated to the MRI1 of the related muscle group (r = 0.799–0.958; P < 0.05). Similarly, the L2/Z of the upper arm (Fig. 5) and thigh (Fig. 6) was also significantly correlated to the torque value, with correlation coefficients of 0.770–0.937, which differed insignificantly from those obtained for the corresponding relations using MRI1.

**DISCUSSION**

The L2/Z for every segment examined was highly correlated to the muscle volume determined by MRI. The observed correlation coefficients, r = 0.902–0.976, are comparable to those reported in previous studies that investigated the relationship between the ratio of limb length or height squared to the impedance and limb muscle mass determined by dual X-ray absorptiometry (r = 0.88–0.95) (13, 24, 30, 32). However, it should be noted that most of the prior research focused on the estimate of muscle mass in the total limb, not in...
a limited segment of the limb. To our knowledge, only two studies (7, 11) using MRI as a reference method have attempt to ascertain the precision of BIA for estimating muscle volumes of a limited part of the thigh (20-cm sections) and lower leg (10-cm sections). In addition to these findings, the present result indicates that BIA is useful for predicting the total muscle volume of limb segment, regardless of the location of the limb.

The estimation of limb muscle volume by BIA is based on the assumption that models the limb as a set of concentric cylindrical conductors consisting of subcutaneous adipose tissue, muscle, and bone (2). However, the CSA of a limb shows nonuniformity along its length. Moreover, the changes induced by weight reduction (18) or resistance training (28, 29) in the CSA of a muscle vary from site to site. Again, the muscle-fiber arrangement in a pennate muscle differs from the magnitude of muscle size (19, 20). Because skeletal muscle fiber can have anisotropic effects on bioelectrical resistance (2), it is likely that morphological and/or architectural profiles of individual muscles, related to the size, influence the accuracy in the estimates of muscle volume by BIA. In the present results, however, the error in the estimate of muscle volume for each site was not significantly correlated to MRI\textsubscript{MV}. This excludes the above-mentioned influences on the impedance measurements for predicting the muscle volume, at least within an individual segment.

As a noninvasive way to estimate the CSA or volume of lean or muscle tissue in a limited part of the limb, the anthropometric method has been used. The anthropometric estimates of lean tissue (muscle + bone) CSA and/or volume of limbs are highly correlated to those determined by CT (5, 6, 8, 31, 34), dual X-ray absorptiometry (15), or MRI (1, 22), with correlation coefficients of 0.84–0.99. However, it has been documented that the anthropometric approach significantly overestimates the actual lean tissue value (1, 6, 7, 11, 22). On the other hand, Elia et al. (7) and Fuller et al. (11) indicated that the BIA technique gave group mean values that were closer than anthropometric results to the MRI values. Because no anthropometric estimation was made in the present study, we cannot elucidate whether the BIA method used in this study is superior to the anthropometric approach for predicting limb muscle volume. In addition to the insignificant correlation between the error of estimate and MRI\textsubscript{MV}, however, the estimated muscle volume did not significantly differ from the MRI\textsubscript{MV}. These points suggest that the
BIA method used in this study has a greater validity for predicting muscle volume than do anthropometric methods.

A major source of error with the anthropometric method is measurement of the subcutaneous adipose tissue with skinfold calipers (1, 14, 22). The findings of de Koning et al. (6) revealed that the relative difference between the anthropometric estimate and the values measured by CT in the lean-tissue CSA of the upper arm increases as the subcutaneous fat layer becomes thicker. With the BIA technique too, the content of fat and nonmuscle tissues in the segment may influence the measured impedance because of their different conductivity. However, the error of muscle volume estimated for each segment did not correlate to the percentage of each of fat, muscle, and bone tissues to whole limb in CSA. This implies that the estimate is independent of limb composition, which consists of components with different conductivity. However, we must draw attention to the fact that this study examined a relatively small sample of subjects and no obese or female subjects. The findings of Baumgartner et al. (2) indicated that subcutaneous adipose tissue have a slight but significant effect on impedance measurements in obese women but not in obese men. In addition, Nunez et al. (30) found that age was also an independent variable in lower limb resistance-skeletal muscle associations and suggested the need to establish the underlying mechanisms of age-related resistance effects and to consider subject age when BIA prediction models are developed. It is known that aging increases the percentage of nonmuscle tissue in the muscle CSA or volume estimate (4, 21, 33, 34, 37). From the findings of previous studies using MRI or CT methods, the average percentages of nonmuscle tissue content for older men aged 65–90 yr range from 9 to 13% in the upper arm muscles (33, 34) and from 7 to 19% in the lower limb muscles (21, 33, 34). For younger men aged <40 yr, the corresponding values in the upper arm and lower limb muscles are 2–6 and 5–7%, respectively. In this study, although adipose and tendinous tissues, which were imaged in different tones from the muscle tissue, were excluded when digitizing, those in the muscle compartments were not quantified. To generalize the present findings for samples with wide ranges of body composition and/or age, therefore, further investigation is needed.

The other main finding of this study was that the $L^2/Z$ of the upper arm and thigh were significantly correlated to isometric torque, with similar correlation.
coefficients observed in the corresponding relationships using the MRI_{MV} of the elbow or knee extensors and elbow or knee flexors. Most previous studies that examined the relation between muscle function and muscle size used CSA at a given site as an index of the muscle size, which is the area of muscle cross section at right angles to the long axis of the limb, i.e., anatomical CSA. However, muscle force is more closely related to physiological CSA than to the greatest anatomical CSA among multislices (9, 35). In the case of muscles with a parallel fibre arrangement, the anatomical CSA corresponds to the physiological CSA (12). In pinnate muscles, however, the anatomical CSA cuts a limited number of fibers and is, therefore, smaller than the physiological CSA (10). There is presently no established method of directly determining physiological CSA in human skeletal muscle. However, the physiological CSA in vivo can be estimated by dividing the product of muscle volume and the cosine of the angles of pennation by the length of the muscle fibers (39), and it is linearly correlated to muscle volume (10). Hence, determination of the volume of a muscle is a way of approximating its physiological CSA. Furthermore, strength measured as torque is a function of muscular force (related to physiological CSA) and muscle moment arm length (36). Because the muscle volume can be expressed as a product of physiological CSA and muscle fibre length, torque relative to muscle volume may be theoretically considered as an index with the same dimension as that of muscle force relative to physiological CSA, i.e., specific tension. In other words, the significant correlation observed between $L_2IZ$ and torque, similar to that between $MRI_{MV}$ and torque, suggests that the use of BIA for measuring the impedance of a limb segment makes it possible to assess the force-generation capability in relation to the concept of specific tension.

In summary, the bioimpedance of a limited segment in the upper and lower limbs was highly correlated to the muscle volume determined by MRI and torque output. This indicates that, as an alternative to MRI, BIA may be useful for estimating the muscle volume and to investigate possible relations between muscle size and strength capability in a limited segment of the limb. However, there is a need for study examining subjects with a wide range of body compositions and/or ages to elucidate how the relative proportions of different tissues in limbs influence the muscle volume estimate.

REFERENCES


