Intracellular-to-total water ratio explains the variability of muscle strength dependence on the size of the lower leg in the elderly

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A B S T R A C T

Bioelectrical impedance spectroscopy (BIS) can assess intracellular water (ICW) and total water (TW) in limbs. This study aimed to examine whether BIS can explain a part of the inter-individual variation of the muscle size-strength relationship in older adults. We analyzed the data of 79 participants aged 64–86 years. The maximal voluntary isometric torques of dorsiflexion and plantar ﬂexion on the right side were measured. The anterior and posterior muscle thickness (MT) in the right lower leg was assessed using ultrasonography. The length of the right lower leg (L) was measured, and the ICW-to-TW ratio (ICW/TW) in the right lower leg was obtained using BIS. The MT was multiplied by L to represent an index of muscle volume (MV). Correlation and stepwise regression analyses were performed. The anterior and posterior MT × L signiﬁcantly and positively correlated with the muscle torque of dorsiflexion and plantar ﬂexion (r = 0.710 and 0.649, respectively, P < 0.001). In the stepwise regression analyses, ICW/TW was selected as a signiﬁcant predictor of muscle torque independent of MT × L (P < 0.05) for both dorsiflexion and plantar ﬂexion. Electrical parameters of BIS (membrane capacitance, characteristics frequency, and phase angle) in the lower leg also signiﬁcantly correlated with muscle torques. In addition, the skeletal muscle mass index (appendicular lean mass/height<sup>2</sup>) was also associated with ICW/TW (P < 0.001). The present results suggest that ICW/TW explains the interindividual variations of the muscle size-strength relationship.

1. Introduction

The term sarcopenia was originally created and deﬁned by Rosenberg as the age-related loss of muscle or lean mass (Rosenberg, 1989). Mitchell et al. (2012) reviewed the literature and found that the skeletal muscle mass (SMM) in the elderly decreased by approximately 0.4% per year in comparison with that in young adults. The rate of decrease declined more steeply at a certain older age (range, 50–65 years) than at a younger age, but the longitudinal study that assessed this in older adults (≥65 years) aged 5 to 12.2 years showed that the decrease rate was still up to approximately 1% (Mitchell et al., 2012).

Conversely, longitudinal studies with the elderly showed that muscle strength decreased by approximately 3% every year (Mitchell et al., 2012). In the cohorts where muscle size and strength were measured at the same time (e.g., the Baltimore Longitudinal Study and Health ABC study), the rate of decrease in muscle strength was two to four times as high as that in muscle size (Ferrucci et al., 2012a; Goodpaster et al., 2006). Muscle size, determined using either mid-thigh muscle cross-sectional area (CSA) measured on computed tomography (CT) or leg and arm lean soft tissue mass measured on dual-energy X-ray absorptiometry, did not explain the strong association of muscle strength with mortality (Newman et al., 2006). In the INCHIANTI study, calf skeletal muscle CSA was also not a signiﬁcant risk factor of mortality in community-dwelling older adults after adjustment for potential confounders, although physical function (e.g., gait speed) was conﬁrmed to be a powerful predictor of mortality (Cesari et al., 2009).

Although the ratio of skeletal muscle strength to mass is relatively constant during development from childhood to adulthood, the strength-to-mass ratios have great heterogeneity between individuals in older adults (Ferrucci et al., 2012b). Moritani and deVries’s studies

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revealed that muscle strength is not solely dependent on muscle size (Moritani and DeVries, 1979; Moritani and DeVries, 1980). Clark and Manini, therefore, coined the term “dynapenia,” defined as the age-related loss of muscle strength (Clark and Manini, 2008). On the basis of many studies in the late 1990s and through the 2000s, international working groups have re-defined sarcopenia as an age-related loss of muscle mass and loss of strength and/or physical function to connect a diagnostic condition to a subject’s future health outcomes (Cruz-Jentoft et al., 2010; Fielding et al., 2011; Studenski et al., 2014; Chen et al., 2014).

The mechanisms of the interindividual variations of muscle size-strength relationships are diverse, from “neural factors” and “neuromuscular factors” to “factors in muscle tissues” (Manini and Clark, 2012).

In terms of “factors in muscle tissues,” about three-quarters of muscle tissue is water in vivo. Azazbou et al. used nuclear magnetic resonance (NMR) imaging with water T2 maps and fat fraction quantified using the three-point Dixon technique and found that water T2 mean values and the heterogeneity index, as well as fat fractions, were significantly higher in the elderly than in young adults (Azazbou et al., 2015). NMR is, however, difficult to apply in a large-scale study or in a clinical setting for sarcopenia screening. Water in muscle tissues is divided into intracellular water (ICW) and extracellular water (ECW) fractions. The muscle cell membrane acts as a capacitor in bioelectrical impedance spectroscopy (BIS) (Giaever and Keese, 1993); thus, BIS can obtain information on the ratio of intracellular water (ICW) to total water (TW) in the limbs (Bartok and Schoeller, 2004). Recent studies (electrical impedance myography by Rutkove et al.) that used rodent models found that bioelectrical impedance can estimate information on myofibers in vivo (Arnold et al., 2017; Kapur et al., 2018). In addition, previous studies indicated that electrical parameters measured using BIS are good biomarkers of muscle mass or function (Yamada et al., 2017a; Yamada et al., 2010; Yamada et al., 2014; Siglinsky et al., 2018; Taniguchi et al., 2017; Yamada et al., 2013; Yamada et al., 2017b).

Ultrasoundography is widely available and easily operated at bedside or at regular health checkups, without any radiation exposure, and can be used to assess the muscle thickness (MT) in each site (Abe et al., 2011; Kawakami et al., 1998). The first research on assessing the size-strength relationship of human muscle in vivo was also conducted using ultrasonography by Ikai and Fukunaga (1968). Ultrasonography has the advantage of being able to take pictures not obtainable using BIS. We hypothesized that the combination of BIS and ultrasonography may be a good solution for assessing muscle quantity and quality in the clinical setting, and the ratio of ICW/TW, measured using BIS, can partly explain the heterogeneity of the size-strength relationship in older adults. The primary aim of the present study was to examine whether BIS can explain a part of the interindividual variation of the muscle size-strength relationship in older adults. In addition, the secondary aim was to confirm that the electrical parameters (membrane capacitance [Cm], characteristic frequency [fc], and phase angle [φ]) obtained with BIS correlated with single-joint muscle strength in the older adult population, which have been examined in a recent previous study with the complex multi-joint task of jumping muscle power in adults aged 26–76 years (Yamada et al., 2017b).

2. Methods

2.1. Subjects

For this study, 82 community-dwelling older adults were recruited. One potential participant had a chronic nerve injury to his right leg, and two participants had joint instability; these three were excluded from the study. Therefore, the present study included 79 subjects aged 64–86 years (40 women and 39 men). Height was measured without shoes. Body weight and composition were assessed using a standing-posture 8-electrode multi-frequency bioelectrical impedance analysis (MC-980, TANIA, Tokyo, Japan) with the subjects dressed in light clothing. The appendicular lean mass (ALM) was obtained using a previously developed and cross-validated equation (Yamada et al., 2017c). The skeletal muscle mass index was calculated as ALM divided by height squared (ALM/Ht², kg/m²). A previous study in Japan indicated that for sarcopenia, the skeletal muscle mass index cutoffs were 6.8 and 5.7 kg/m² from the dataset of 1624 men and 1368 women aged 18–40 years, respectively (Yamada et al., 2017c). This study protocol was approved by the ethics committee of Waseda University and conducted in laboratories at Waseda University (2016-311).

2.2. Bioelectrical impedance spectroscopy

Bioelectrical impedance was measured using a logarithmic distribution of 256 frequencies ranging from 4 to 1000 kHz (SF77, ImpediMed, Pinkenba, QLD, Australia) with a disposible tab-type monitoring electrodes (2 × 2 cm; Red Dot, 3 M, St. Paul, MN) (Yamada et al., 2017a; Siglinsky et al., 2018; Yamada et al., 2013). Before the test, the system was checked with a series of precision resistors provided by the manufacturer. Current injection electrodes were placed on the dorsal surface of the right hand, proximal to the second and third metacarpal-phalangeal joints, and on the dorsal surface of the right foot, proximal to the second and third metatarsal-phalangeal joints. Sensing electrodes were placed on the right articular cleft between the femoral and tibial condyles (“knee”) and on the anterior surface of the ankle between the protruding portions of the tibial and fibular bones (“ankle”; Fig. 1) (Yamada et al., 2010). “Impedance measurements were obtained with the subjects in a relaxed supine position on a padded bed, arms slightly abducted from the body, forearms pronated, and legs slightly apart. Room temperature was adjusted to maintain a thermo-neutral environment. The BIS measurement was taken after 5–10 min of rest to avoid the immediate (1–2 min) effect of the transition from a standing to a supine position on the shift in body fluid from the extremities to the thorax, as well as the slow phase of this shift that continues for up to 3–12 h” (Yamada et al., 2013). The resistance of the extracellular water compartment (Rₑ) and that of the total water compartment (Rₜ) for the lower leg were determined by extrapolation after fitting the spectrum of bioimpedance data to the Cole-Cole model using the supplied software. The resistance of the intracellular water compartment (RᵢCₑ) was calculated as 1/(1/(1/Rₑ) − (1/Rᵢ)). The segmental ECW and ICW in the lower leg were calculated using the following equations (Bartok and Schoeller, 2004): ECW = ρₑCₑ × L²/Rₑ and ICW = ρᵢCᵢCₑ × L²/RᵢCₑ, where ρᵢ represents factors for extracellular (ρₑCₑ = 47 Ωcm) and intracellular resistivities (ρᵢCₑ = 273.9 Ωcm), respectively; L is the segmental length, Rᵢ is the segmental extracellular resistance, and RᵢCₑ is segmental intracellular resistance. The volume of TW was calculated as the sum of ECW and ICW, and the ratio of ICW divided by TW (ICW/TW) was calculated for the right lower leg. According to a previous study, the electrical parameters (Cm, fc, and φ) in the lower leg were also obtained from the Cole-Cole model (Yamada et al., 2017b).
2.3. Muscle thickness measurements

The following measurements were conducted while a subject was in a standing position. The length (L) of the right lower leg was measured using a metal tape measure, as the distance between the popliteal cleft and lateral malleolus. The measurement sites were precisely located and marked at the anterior and posterior surfaces in the proximal 30% of the lower leg length by using a cloth tape that was tightly looped around the lower leg to measure its circumference in the transverse plane. The MTs at the anterior and posterior right lower leg were determined using real-time B-mode ultrasonography (SSD-900, Aloka, Japan). The overall brightness of the ultrasonography images was adjusted individually to obtain the clearest images. The sites selected for the cross-sectional images and MT measurements were the same as those in previous studies (Abe et al., 2011; Miyatani et al., 2004). The MT multiplied by L (MT × L cm²) was obtained to represent an index of muscle volume (MV cm³) (Takai et al., 2013).

2.4. Dorsiflexion and plantar flexion torque measurements

The right foot of each subject was firmly attached to an electric dynamometer (VTK-002, VINE, Tokyo, Japan) (Miyamoto et al., 2012), and the lower leg was fixed to a test bench. The knee joint was fixed at 0° (extended position), and the ankle joint was fixed at 30° for dorsiflexion and 0° for plantar flexion. After relaxing, the participants were instructed to perform maximal voluntary isometric dorsiflexion or plantar flexion, and the torque outputs were recorded using PowerLab 16/35 and LabChart (ADInstruments Pty Ltd., New South Wales, Australia). After the participants practiced dorsiflexion and plantar flexion with approximately 30%, 50%, and 80% of their maximum effort, they conducted the maximum voluntary contraction (MVC) of dorsiflexion and plantar flexion for at least two times each. If the difference between the two MVC values was >10%, a third or fourth trial(s) was conducted to obtain stable data. The maximal value was recorded as their MVC.

2.5. Statistical analysis

Results are presented as mean ± SD. Pearson correlation coefficients were calculated, and scatter plots were obtained for the simple relationship between muscle force and MT × L or ICW/TW. The residuals were obtained on the scatter plots with muscle size indexes on the x-axis and muscle strength on the y-axis. Pearson correlation coefficients were calculated, and scatter plots were obtained for the relationship between the residuals and ICW/TW. Pearson correlation coefficients were calculated, and scatter plots were also obtained for the relationship between muscle force and Cm, fc, and φ in the same manner as that in a previous study (Yamada et al., 2017b). Multiple linear regression analyses were conducted with dorsiflexion or plantar flexion as a dependent variable, and anterior or posterior MT × L or PFMV and ICW/TW were entered as independent variables. All analyses were performed using the SPSS Version 22.0 software for Windows (IBM Corp. Armonk, NY).

3. Results

The physical characteristics of the study subjects are presented in Table 1. The anterior MT × L significantly, positively, and strongly correlated with the muscle torque of dorsiflexion (r = 0.710, P < 0.001; Fig. 2A). This correlation is significantly higher (P = 0.018) than the correlation between anterior MT and dorsiflexion torque (r = 0.578). Moreover, the posterior MT × L significantly correlated positively with the muscle torque of plantar flexion (r = 0.649, P < 0.001, Fig. 2B). This correlation is significantly higher than the correlation between posterior MT and plantar flexion torque (r = 0.487).

The ICW/TW significantly correlated positively with the muscle torque of dorsiflexion and plantar flexion (P < 0.001, Fig. 2C and D). ICW/TW significantly and positively correlated with the ratio of dorsiflexion or plantar flexion muscle torque divided by the MT × L of the anterior (r = 0.434, P < 0.001; Fig. 3A) or posterior lower leg (r = 0.380, P < 0.001; Fig. 3B).

The results of the multiple linear regression analyses are shown in Tables 2 and 3. ICW/TW was a significant predictor of dorsiflexion independent from anterior MT × L and plantar flexion independent from posterior MT × L (P < 0.05). Dorsiflexion and plantar flexion both significantly and positively correlated with Cm and φ, and negatively correlated with fc (P < 0.001; Fig. 4).

4. Discussion

We found that ICW/TW significantly positively correlated with muscle function and positively correlated with the ratio of muscle torque divided by MV, an indicator of muscle quality (i.e., specific strength). The results derived that the ratio of ICW/TW assessed with BIS in the lower legs partly explained the interindividual variation of muscle size-strength relationship assessed using ultrasonography both in dorsiflexion and plantar flexion in older adults. In addition, we confirmed a previous finding that the electrical parameters obtained by BIS significantly correlated with muscle function (positively with Cm and fc, and negatively with φ), which was the secondary purpose of the present study. A previous study examined the correlation between these electrical parameters measured using BIS and a complex multi-joint

| Table 1: Physical characteristics of the subjects and muscle force, size, and water distribution in the right lower leg (men = 39, women = 40). |
|---------------------|---------------------|---------------------|
|                      | Men                 | Women               |
|---------------------|---------------------|---------------------|
| Age (years)         | 72.8 ± 5.0          | (64–83)             |
| Height (cm)         | 166.5 ± 4.8         | (157.4–179.3)       |
| Weight (kg)         | 65.2 ± 11.1         | (53.8–119.6)        |
| BMI                 | 23.5 ± 3.8          | (18.2–41.5)         |
| Percent body fat (%)| 20.4 ± 7.2          | (9.2–44.9)          |
| ALM (kg)            | 22.1 ± 2.6          | (18.0–31.5)         |
| ALM/Ht² (kg/m²)     | 7.98 ± 0.69         | (6.67–10.9)         |
| Dorsi flexion (Nm)  | 31.8 ± 5.2          | (23.6–45.1)         |
| Plantar flexion (Nm)| 127.7 ± 25.9        | (72.8–167.0)        |
| Anterior MV index (cm²) by MT × L | 110.8 ± 16.4 | (82.5–167.2) |
| Posterior MV index (cm²) by MT × L | 243.8 ± 24.9 | (208.8–327.6) |
| PF MV (cm³)         | 847 ± 143           | (646–1327)          |
| ICW (mL)            | 630 ± 96            | (478–800)           |
| ECW (mL)            | 435 ± 77            | (311–735)           |
| TW (mL)             | 1065 ± 132          | (789–1403)          |
| ICW/TW              | 0.59 ± 0.05         | (0.48–0.66)         |
The task of jumping power in adults aged 26–76 years (Yamada et al., 2017b). Our present study examined single-joint muscle strength in an older adult population, which is a simpler and more homogeneous task than that in a previous report (Yamada et al., 2017b). The relationship between the electrical parameters measured using BIS and voluntary maximum muscle force production was confirmed in the present study.

Water makes up nearly three-quarters of SMM in vivo. Imaging methods such as ultrasonography or dual-energy X-ray absorptiometry cannot differentiate the contractile component of SMM from other components. A previous research found that the relationships between age and estimated SMM vary between estimating methods of SMM (Proctor et al., 1999). Therefore, attention has focused on the assessment of muscle quality. Several studies have demonstrated changes in muscle composition with aging. Kent-Braun et al. (2000) reported that the intramuscular fat in the tibialis anterior muscle as estimated using magnetic resonance imaging (MRI) increased, and Galban et al. (2007)...

Fig. 2. The relationship between voluntary maximal torque and indexes of muscle size and composition in the right lower leg. (A) Correlation between dorsiflexion and anterior muscle thicknesses (MT) multiplied to the right lower leg length (L). (B) Correlation between plantar flexion and posterior MT × L in the right lower leg. (C) Correlation between dorsiflexion and the ratio of intracellular water (ICW) to total water (TW) in the right lower leg (ICW/TW). (D) Correlation between plantar flexion and ICW/TW. Triangles and circles represent women and men respectively.

(A)

(B)

(C)

(D)

Fig. 3. The relationship between the ratio of muscle torque divided by muscle thickness (MT) multiplied by right lower leg length (L). (A) Correlation between the ratio of dorsiflexion muscle torque [Nm] divided by anterior MT × L, an index of muscle volume (MV) [cm³], and ICW/TW. (B) Correlation between the ratio of plantar flexion muscle torque [Nm] divided by posterior MT × L, an index of MV [cm³] and ICW/TW. Triangles and circles represent women and men respectively.
lower extremity function (Goodpaster et al., 2006; Sipila et al., 2004; de Vree et al., 2015) decreases in muscle density, estimated using CT, with aging, related to lower leg muscles with aging. Other studies have found significant differences in muscle density, as measured using CT, with aging (Yamada et al., 2017a; Yamada et al., 2017b). In addition, another study reported that the water distribution in the lower legs assessed using BIS explained the inter-individual variation of muscle force independently from ultrasonography measurements for both dorsiflexion and plantar flexion. A previous study (Yamada et al., 2017a) reported that the water distribution in the upper legs is related positively to knee extension strength and maximal gait speed in older adults. Another study reported that the water distribution in the lower limbs is related positively to power production during maximal voluntary jump (Yamada et al., 2017b). In addition, another study reported that the water distribution in the lower limbs is related positively to power production during maximal voluntary jump (Yamada et al., 2017b). In addition, another study reported that the water distribution in the lower limbs is related positively to power production during maximal voluntary jump (Yamada et al., 2017b). In addition, another study reported that the water distribution in the lower limbs is related positively to power production during maximal voluntary jump (Yamada et al., 2017b).

We confirmed a previous finding that the electrical parameters obtained with BIS significantly correlated with muscle function (positively with Cm and fc, and negatively with ϕ) (Yamada et al., 2017a; Esposito et al., 2013).

Table 2

Multivariate analysis: linear model with dorsiflexion or plantar flexion as a dependent variable (n = 79).

| Dependent variable, dorsiflexion (Nm); R² | β (95% CI) | P value | VIF |
|-----------------------------------------|------------|---------|-----|
| (Constant)                              | 0.026      | 0.691   | 1.4 |
| Anterior MT × L                         | 0.276      | < 0.001 | 1.03|
| ICW/TW                                  | 0.274      | < 0.001 | 1.03|
| R² = 0.577                              |            |         |     |
| (Constant)                              | 0.001      | 0.982   | 1.03|
| Anterior MT × L                         | 0.352      | < 0.001 | 1.11|
| ICW/TW                                  | 0.162      | 0.01    | 1.00|
| Sex                                     | 0.535      | < 0.001 | 1.72|
| R² = 0.743                              |            |         |     |
| (Constant)                              | 0.002      | 0.998   | 1.00|
| Anterior MT × L                         | 0.591      | < 0.001 | 1.07|
| ICW/TW                                  | 0.229      | 0.01    | 1.00|
| R² = 0.471                              |            |         |     |
| (Constant)                              | 0.565      | 0.056   | 1.00|
| Anterior MT × L                         | 0.254      | 0.026   | 1.18|
| ICW/TW                                  | 0.165      | 0.041   | 1.10|
| Sex                                     | 0.48       | < 0.001 | 2.26|
| R² = 0.572                              |            |         |     |

CI, confidence interval; VIF, variance inflation factor; MT, muscle thickness; ICW, intracellular water; TW, total water. Bold numbers show statistically significant P value.

Table 3

Multivariate analysis: linear model with dorsiflexion or plantar flexion as a dependent variable and/or sex as a covariate (n = 79).

| Dependent variable, plantar flexion (Nm); R² | β (95% CI) | P value | VIF |
|---------------------------------------------|------------|---------|-----|
| (Constant)                                  | 0.040      | 0.606   | 1.00|
| Anterior MT × L                            | 0.510      | < 0.001 | 1.00|
| ICW/TW                                     | 0.229      | 0.01    | 1.00|
| R² = 0.471                                 |            |         |     |
| (Constant)                                  | 0.565      | 0.056   | 1.00|
| Anterior MT × L                            | 0.254      | 0.026   | 1.18|
| ICW/TW                                     | 0.165      | 0.041   | 1.10|
| Sex                                        | 0.48       | < 0.001 | 2.26|
| R² = 0.572                                 |            |         |     |

CI, confidence interval; VIF, variance inflation factor; MT, muscle thickness; L, length of right lower leg; ICW, intracellular water; TW, total water. Bold numbers show statistically significant P value.

reported that the diffusion tensor MRI signal intensity decreased in the lower leg muscles with aging. Other studies have found significant decreases in muscle density, estimated using CT, with aging, related to lower extremity function (Goodpaster et al., 2006; Sipila et al., 2004; Visser et al., 2002). The ICW/TW ratio has been used to differentiate the contractile component of SMM from other components. In the present study, combination of ultrasonography and BIS allowed us to evaluate both muscle mass and quality. In addition, BIS-related electrical parameters such as Cm, fc, and ϕ further add to this study as discussed later in detail.

More recently, Azzabou et al. (2015) examined the differences in NMR T2 imaging between younger and older adults and found that aside from fat fraction, elevated water T2 and increased T2 heterogeneities in the quadriceps muscles were observed in the elderly. An age-related increase in T2 in the calf muscles was further reported by Hatakenaka et al. (2001) and Schwenzer et al. (2009); and in the tibialis anterior muscles in humans and mice; by Esposito et al. (2013). Hatakenaka et al. (2001) stated that the T2 relaxation time of fast-twitch muscles increases with aging and that this is mainly attributable to increased extracellular space, reflecting age-related type II fiber atrophy. Lexell et al. (1988) examined the cross sections of autopsied whole vastus lateralis muscle from 43 previously physically healthy men between 15 and 83 years of age. Yamada et al. (2017a) previously recalculated, using data from the study of Lexell et al., and reported that the whole muscle cross-sectional area (CSA) of the vastus lateralis was approximately 26% lower in subjects in their 70s than in those in their 20s. This value is consistent with a previous study by Janssen et al. (2000) that measured SM in 468 men and women aged between 18 and 88 years by using MRI and found an approximately 26% difference in lower body SM as compared with that in men in the same age brackets as those used by Lexell et al. (1988). Yamada et al. (2017a) furthermore calculated the “total muscle cell CSA” based on the study by Lexell et al. (1988), using the total number of fibers, proportion of type I fibers, and mean fiber size of types I and II. The total muscle cell CSA was approximately 48% lower in subjects in their 70s despite the fact that a difference of just approximately 26% was observed in whole muscle CSA between the two age groups. This calculation suggests that the extracellular space in skeletal muscle tissue increases with age. The inter-dependence of muscle morphology, fiber types and aging is worth further investigation in future studies.
The reduction in Cm may be linked to fiber shrinkage and fiber loss, both of which would lead to a relative reduction in membrane content. Increase of fc may be related to fat infiltration or increased fibrosis in the muscle. Previous studies suggest that φ is linked to ECW/ICW ratio and fat-free mass, but not fat mass, and a previous study in patients with cancer showed that whole-body φ is linked to handgrip strength and peak expiratory flow. The data shown here emphasize the importance of muscle tissue quantity and quality in muscle force generation during aging.

The equations of segmental ECW = \( \rho_{ECW} \times \frac{L^2}{R_0} \) (\( \rho_{ECW} = 47 \Omega \text{cm} \)) and ICW = \( \rho_{ICW} \times \frac{L^2}{R_{ICW}} \) (\( \rho_{ICW} = 237.9 \Omega \text{cm} \)) were used in the present study. The specific resistivities were determined empirically. \( \rho_{ECW} \) and \( \rho_{ICW} \) were determined by Kaysen et al. (2005) and also from a study by Zhu et al. (1998). Zhu et al. (2006) reported that segment-specific resistivity improves the body fluid measurement for the whole leg (\( \rho_{ECW} = 99 \Omega \text{cm} \) and \( \rho_{ICW} = 281 \Omega \text{cm} \)) in patients on hemodialysis. We, however, assessed only lower leg segments in the present study, and the specific resistivity may be different from it. Theoretically, the correlation coefficients and standardized regression coefficients between ICW/TW and muscle strength are independent of the specific resistivity so that our conclusion will not be influenced much, although further studies are needed to determine the specific resistivity of the segments.

A cross-sectional study design is another limitation, and longitudinal or intervention studies will further reveal the utility of ultrasonography and BIS for assessment of aging on skeletal muscles.
5. Conclusion

The ratio of ICW/TW in the lower leg, assessed with BIS, is positively associated with both dorsiﬂexion and plantar ﬂexion independently of the index of muscle size assessed using ultrasonography. The index of ICW/TW can be easily obtained as a proportion of \( R_{ICW} \) and \( R_{TW} \) without the need for any undisclosed equations dependent on a manufacturer. As BIS and ultrasonography are portable, noninvasive, and rapid methodologies that can be used daily in the clinical setting, assessment of water distribution in the limbs is an appealing method for assessing both muscle quality and quantity. Increased extracellular water in skeletal muscle tissue is one contributor toward decreased muscle quality during aging. The combination of ultrasonography and BIS is a useful technique for the assessment of sarcopenia in older adults in vivo in clinical settings.

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