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Muscle size-strength relationship including ultrasonographic echo intensity and voluntary activation level of a muscle group

Ryota Akagi[a,b,*], Momoka Suzuki[a], Emi Kawaguchi[a,c], Naokazu Miyamoto[d], Yosuke Yamada[e], Ryoichi Ema[b,f]

[a] College of Systems Engineering and Science, Shibaura Institute of Technology, 307 Fukasaku, Minuma-ku, Saitama-shi, Saitama, 337-8570, Japan
[b] Graduate School of Engineering and Science, Shibaura Institute of Technology, 307 Fukasaku, Minuma-ku, Saitama-shi, Saitama, 337-8570, Japan
[c] Graduate School of Human Sciences, Waseda University, 2-579-15 Mikajima, Tokorozawa-shi, Saitama, 359-1192, Japan
[d] National Institute of Fitness and Sports in Kanoya, 1 Shiromizu, Kanoya-shi, Kagoshima, 891-2393, Japan
[e] Department of Nutritional Science, National Institute of Health and Nutrition, 1-23-1 Toyama, Shinjuku-ku, Tokyo 162-8636, Japan
[f] Research Fellow of Japan Society for the Promotion of Science, 5-3-1 Kojimachi, Chiyoda-ku, Tokyo 102-0083, Japan

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ABSTRACT

This study aimed to investigate the relationship between muscle volume (MV) and joint torque for the plantar flexors (PF) in 40 young (20 men and 20 women) and 33 elderly (19 men and 14 women) individuals in consideration of the voluntary activation (VA) of PF and ratio of intramuscular adipose tissue within PF assessed by ultrasonographic echo intensity (EI). MV was estimated from the thickness of PF on ultrasonography and the lower leg length using a prediction equation previously reported. The maximal voluntary contraction torque of isometric plantar flexion was measured as TQ_{MVC}. VA (%) was assessed using the twitch interpolation technique, and maximal joint torque calculated by $TQ_{MVC}/VA \times 100$ was adopted as $TQ_{100\%}$. The correlation coefficients between MV and TQ_{MVC} ($r = 0.518$) and between MV and $TQ_{100\%}$ ($r = 0.602$) were both significant, with the latter being significantly higher than the former. When a stepwise multiple regression analysis using MV and EI as independent variables and $TQ_{100\%}$ as the dependent variable was performed, MV ($\beta = 0.554$) and EI ($\beta = -0.203$) were both selected as significant contributors for estimating $TQ_{100\%}$. Additionally, the residual errors of $TQ_{100\%}$ using the multiple regression equation (independent variables: MV and EI; 18.6 ± 14.4 Nm) were significantly lower than those using the simple regression equation (independent variable: MV; 36.6 ± 28.0 Nm). These results suggest that the consideration of VA and EI with muscle size results in a closer muscle size-strength relationship than previously achieved.

1. Introduction

Muscle strength is one of the fundamental parameters in the production of human movement. Muscle strength is theoretically proportional to muscle size (Akagi et al., 2009; Bamman, Newcomer, Larson-Meyer, Weinsier, & Hunter, 2000; Bruce, Phillips, & Woledge, 1997). Based on this concept, the ratio of muscle strength to size has been evaluated as specific tension and/or its index. Specific tension values are nearly equal among a number of mammalian muscles (Close 1972; Powell, Roy, Kanim, Bello, & Edgerton, 1984; Spector, Gardiner, Zernicke, Roy, & Edgerton, 1980; Witzmann, Kim, & Fitts, 1983), whereas the corresponding ratio markedly varies among human individuals *in vivo* (Maughan, Watson, & Weir, 1983; Maughan & Nimmo 1984). Therefore, the size-strength relationship of human skeletal muscle may be affected by factors such as muscle fiber composition (Nygaard, Houston, Suzuki, Jorgensen, & Saltin, 1983; Thorstensson, Grimby, & Karlsson, 1976), the voluntary activation level (VA) of the agonist (Jakobi & Rice 2002; Klein, Rice, & Marsh, 2001; O' Brien et al., 2010), coactivation level of the antagonist (Klein et al., 2001; Macaluso et al., 2002; O' Brien et al., 2010), and ratio of non-contractile tissue volume within a muscle (Kent-Braun & Ng 1999; Klein et al., 2001; O' Brien et al., 2010). The consideration of these factors has been limited to investigating age and/or sex differences in specific tension and/or its index (Jakobi & Rice 2002; Kent-Braun & Ng 1999, Klein et al., 2001; Macaluso et al., 2002; O' Brien et al., 2010), and the effects of these factors on the muscle size-strength relationship have not yet been investigated. The effects of factors other than muscle size on muscle strength need to be clarified in order to more precisely understand the

* Corresponding author at: College of Systems Engineering and Science, Shibaura Institute of Technology, 307 Fukasaku, Minuma-ku, Saitama-shi, Saitama 337-8570, Japan.
E-mail addresses: rakagi12@sic.shibaura-it.ac.jp (R. Akagi), bn13240@shibaura-it.ac.jp (M. Suzuki), bn13217@shibaura-it.ac.jp (E. Kawaguchi), miyamoto@nifs-k.ac.jp (N. Miyamoto), yamaday@nibiohn.go.jp (Y. Yamada), i039491@sic.shibaura-it.ac.jp (R. Ema).

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muscle size-strength relationship.

Ultrasonographic echo intensity (EI) may provide information on the ratio of intramuscular adipose tissue, one of the non-contractile tissues influencing muscle strength, within a muscle (Akima et al., 2016). Previous studies found that the EI value is negatively related to muscle strength (Cadore et al., 2012; Fukumoto et al., 2012; Rech et al., 2014; Watanabe et al., 2013) and muscle thickness (MT) assessed by ultrasonography (Akima et al., 2017; Fukumoto et al., 2012) in middle-aged and/or elderly individuals. Therefore, the use of EI may contribute to a clearer understanding of the muscle size-strength relationship. Moreover, MT assessed by ultrasonography may be used to estimate muscle volume (MV) (Miyatani, Kanehisa, Ito, Kawakami, & Fukunaga, 2004; Akagi et al., 2010). Due to the difficulties associated with evaluating the precise physiological cross-sectional area of a muscle, MV and joint torque have often been used to investigate the muscle size-strength relationship (Akagi et al., 2009; Fukunaga et al., 2001; Macaluso et al., 2002). Ultrasonography may also be useful for investigating the muscle size-strength relationship.

In addition to the ratio of intramuscular adipose tissue evaluated by EI, we need to consider how to apply the VA of agonist muscles to examinations of the muscle size-strength relationship. A previous study (O'Brien, Reeves, Baltzopoulos, Jones, & Maganaris, 2010) estimated the maximal joint torque produced by an examined muscle group if it was fully activated based on the assumption of a linear relationship between joint torque and VA. To the best of our knowledge, the muscle size-strength relationship has not yet to be investigated using estimated maximal joint torque. Among skeletal muscles, the plantar flexors (PF) are used in many daily activities such as walking (Ishikawa, Komi, Grey, Lepola, & Bruggemann, 2005) and postural stability (Ema et al., 2016; Ushiyama & Masani 2011). Therefore, the present study calculated maximal plantar flexion torque using the VA of PF, and investigated the relationship between MV and the maximal joint torque of PF in young and elderly individuals in consideration of the ratio of intramuscular adipose tissue within PF assessed by EI. The hypothesis of the present study was that the muscle size-strength relationship may become closer when considering EI and VA.

2. Materials and methods

2.1. Subjects

After providing written informed consent, 20 young men (22 ± 2 yr, 170.6 ± 5.0 cm, 62.6 ± 6.5 kg, means ± standard deviations [SDs]) and 20 young women (22 ± 1 yr, 157.4 ± 4.1 cm, 51.7 ± 6.5 kg) in their early 20s, and 19 elderly men (73 ± 5 yr, 165.4 ± 6.5 cm, 67.6 ± 10.3 kg) and 14 elderly women (72 ± 7 yr, 154.5 ± 4.7 cm, 56.0 ± 5.9 kg) older than 65 years voluntarily participated in this study. A two-way analysis of variance (ANOVA) with between-group factors (age [young and elderly individuals] and sex [men and women]) revealed the significant main effect of age for age, body height, and body mass and the significant main effect of sex for body height and body mass, without a significant interaction between age and sex. All subjects were functionally independent in daily living, and their amounts of physical activity during daily living were estimated using the long version of International Physical Activity Questionnaire (IPAQ) (Craig et al., 2003), the validation of which was confirmed in Japanese (Murase, Katsumura, Ueda, Inoue, & Shimomitsu, 2002). This study was approved by the Ethics Committee of the Shibaura Institute of Technology.

2.2. MT and EI measurements

MT and EI of the right PF were assessed using a B-mode ultrasound device (ACUSON S2000, Siemens Medical Solutions, USA). In MT measurements, the lateral gastrocnemius muscle (LG), soleus muscle (SOL), and tibialis posterior muscle were included as PF. In EI measurements, LG and SOL were included as PF. When subjects stood with their arms relaxed at their sides, the right lower leg length from the popliteal crease to the lateral malleolus was measured to the nearest 0.5 cm with a steel tape. At the proximal 30% of the lower leg length (Miyatani et al., 2004), a 45-mm electronic linear array probe (9L4 Transducer, 4–9 MHz, Siemens Medical Solutions, USA) attached to the ultrasound device was transversely placed perpendicular to the skin surface without compression of the tissues. Water-soluble transmission gel was applied to the contact surface. Before obtaining a transverse ultrasound image, acquisition parameters were set as follows: frequency 7 MHz; gain 0 dB; depth 7.5–10 cm. A focal point was set near the line approximately 1 cm below the lower end of subcutaneous adipose tissue. Three transverse ultrasound images of the right PF were obtained per subject (Fig. 1), and were stored on a personal computer. MT and EI were both analyzed once per image using ImageJ software (version 1.44; National Institutes of Health, USA). MT was defined as the distance from the subcutaneous adipose tissue-muscle interface to the muscle-bone interface, and was measured to the nearest 0.01 cm. EI was assessed in a computer-assisted 8-bit gray-scale analysis using the standard histogram function in ImageJ software. A region of interest as large as possible with exclusion of the surrounding fascia was selected for each muscle (Akima et al., 2017; Caresio, Molinari, Emanuel, & Minetto, 2015). The mean EI of the regions was expressed as a value between 0 (black) and 255 (white). The EI of PF was calculated as the mean of each EI value of LG and SOL. Regarding MT and EI, the mean values of the three measurements were used in further analyses. The coefficients of variation (CVs) for these measurements were 1.2% ± 1.0% for MT and 2.5% ± 1.7% for EI, with intraclass correlation coefficients type 1,3 (ICC(1,3)) of 0.992 ($P < 0.001$) for MT and

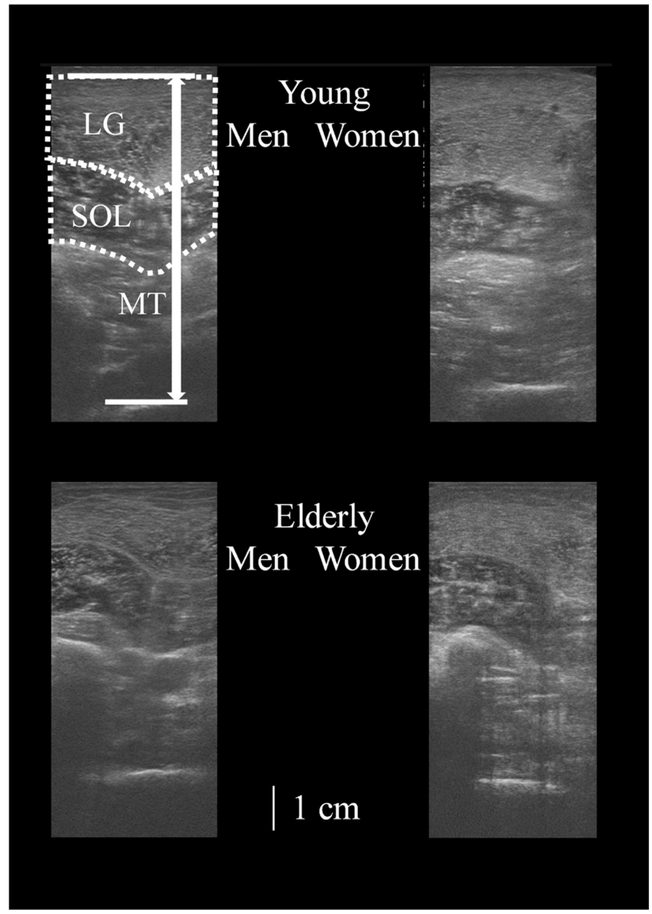

Fig. 1. Representative ultrasound images of plantar flexors. MG, medial gastrocnemius muscle; SOL, soleus muscle; MT, muscle thickness.