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Validation of a simplified method for muscle volume assessment

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ABSTRACT

The present study investigated the validity of a simplified muscle volume assessment that uses only the maximum anatomical cross-sectional area ($ACSA_{max}$), the muscle length (L_M) and a muscle-specific shape factor for muscle volume calculation (Albracht et al., 2008, J Biomech 41, 2211–2218). The validation on the example of the triceps surae (TS) muscles was conducted in two steps. First L_M, $ACSA_{max}$, muscle volume and shape factor were calculated from magnet resonance image muscle reconstructions of the soleus (SO), gastrocnemius medialis (GM) and lateralis (GL) of a group of untrained individuals ($n=13$), endurance ($n=9$) and strength trained ($n=10$) athletes. Though there were significant differences in the muscle dimensions, the shape factors were similar across groups and were in average 0.497 ± 0.026, 0.596 ± 0.030, and 0.556 ± 0.041 for the SO, GM and GL respectively. In a second step, the shape factors were applied to an independent recreationally active group ($n=21$) to compare the muscle volume assessed by the simplified method to the results from whole muscle reconstructions. There were no significant differences between the volumes assessed by the two methods. In conclusion, assessing TS muscle volume on the basis of the reported shape factors is valid across populations and the root mean square differences to whole muscle reconstruction of 7.9%, 4.8% and 8.3% for SO, GM and GL show that the simplified method is sensitive enough to detect changes in muscle volume in the context of degeneration, atrophy or hypertrophy.

1. Introduction

Muscle volume is a major determinant of the mechanical power of the muscle (O'Brien et al., 2009; Sleivert et al., 1995), which has important implications for athletic performance (Chelly and Denis, 2001; Cronin and Sleivert, 2005; Sleivert and Taingahue, 2004) and functional abilities during daily activities. (Bassey et al., 1992; Rantanen and Avela, 1997). Regarding the latter, it has been reported that important mobility functions show closer associations to muscle power than to muscle force, especially in the elderly population (Cuoco et al., 2004; Suzuki et al., 2001). Further, it is well documented that plastic processes in response to mechanical loading (Folland and Williams, 2007) as well as degenerative processes following immobilization (Oates et al., 2010), unloading (Adams et al., 2003) or ageing (Morse et al., 2005a) involve changes in muscle volume and power output. Therefore, it is evident that muscle volume assessment is an important tool to evaluate the effectiveness of interventions aiming to induce anabolic muscle adaptation or mitigate degenerative processes.

Another major determinant of athletic performance (Delecluse et al., 1995) and key factor regarding the prevention and rehabilitation of injuries (Alentorn-Geli et al., 2009; Aune et al., 1997; Shelbourne and Nitz, 1992) as well as locomotor safety in the elderly (Carter et al., 2001; Karamanidis and Arampatzis, 2007) is muscle strength. The maximum force generating capacity of a muscle is predominantly determined by the number of parallel sarcomeres, which is reflected in the physiological cross-sectional area (PCSA) (Haxton, 1944). In pennate muscles it is not possible to measure the PCSA in vivo, however, the indirect calculation by dividing the muscle volume by fascicle length as proposed by Powell et al. (1984) as well as Lieber and Fridén (2000) is well accepted, yet also reliant on muscle volume assessment.

The measurement of muscle volume currently involves the reconstruction of the muscle from magnetic resonance imaging (MRI) recordings (Mitsiopoulos et al., 1998), which is a time-consuming procedure. Albracht et al. (2008) presented an approach to assess muscle volume of the triceps surae muscles by easily measurable parameters. Based on the theoretical consideration that the muscle volume is a fraction of the product of the maximal anatomical cross-sectional area (ACSA) and the muscle length, this

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fraction (or *shape factor*) describes the shape of a given muscle, which is assumed to be constant within a population. Indeed it has been shown that the coefficient of variance of both the shape factor of the triceps suare muscles as well as the standard deviation of the location of the maximum ACSA along the length of the shank is considerably low (about 4–7% and 4% respectively) (Albracht et al., 2008) and it was concluded that the product of maximum ACSA, the muscle length and the shape factor provides a valid assessment of muscle volume. However, the shape factors of the triceps surae muscles reported by Albracht et al. (2008) were not cross-validated on a subject collective other than the one the shape factors were originally obtained from. Furthermore, the data of Albracht et al. (2008) were obtained from recreationally active individuals. Yet, there is evidence of non-uniform muscle hypertrophy in response to mechanical loading (Hedayatpour and Falla, 2012). Although, to our knowledge, there are no reports of non-uniform hypertrophy in the triceps surae muscles, these findings might be in conflict with the reported low variability of the shape factors in the triceps surae muscles (Albracht et al., 2008). However, the regional differences of thigh muscle cross-sectional area increases reported earlier (Housh et al., 1992; Narici et al., 1989) can be attributed mainly to great relative changes in the peripheral muscle regions with small absolute cross-sectional areas, with only a minor effect on muscle shape to be assumed. Nevertheless, the generalizability of the reported triceps surae shape factors of untrained muscles to muscles that underwent hypertrophic changes induced by athletic training cannot be assumed a priori and, thus, needs to be supported by scientific evidence.

Therefore, the purpose of the present study was to investigate, if the volume assessment suggested by Albracht et al. (2008) using the muscle length and the maximum muscle ACSA is valid in its entirety. To address that issue, we first compared the shape factors of the triceps surae muscles of untrained individuals with those of athletes engaging in disciplines featuring different loading profiles (i.e. endurance and strength athletes). In a second step, we compared the muscle volume values of an independent group of participants assessed using the examined shape factors of the triceps surae muscles with the volume values from the whole muscle reconstruction. We hypothesized that the triceps surae shape factors of untrained, endurance and strength athletes would be similar, regarding the considerably low variability of the muscle shape factors in relation to the high variability of muscle volumes in the sample of Albracht et al. (2008). We further hypothesized that the assessment of muscle volume using the maximum ACSA, muscle length and the examined shape factors would provide acceptable results for an independent cohort of participants.

2. Methods

2.1. Participants

In the first step 32 participants were recruited and divided into three groups, namely untrained persons ($n=13$, no sportive training), long distance runners ($n=9$, engaging in endurance training at least three times a week) and strength athletes ($n=10$, jumpers and sprinters engaging in athletic training at least three times a week). On these subjects, we investigated differences in the shape factors of the triceps surae muscles and, thus, the specificity of muscle shape in dependence of habitual mechanical loading. For the second step of the validation an additional group of 21 recreationally active males were recruited. The anthropometric data of all groups are shown in Table 1. The study has been approved by the university ethics committee and all participants signed informed consent to the experimental procedure.

2.2. Data acquisition

Transversal plane MRI images were obtained from the right leg of every participant between the femur condyles and the calcaneal tuberosity (T1 vibe scan, slice thickness 1.8 mm, no inter-slice spacing, echo time 1.18 ms, repetition time 3.11 ms, field of view 244×449 mm^2) lying supine with the knee fully extended in a 1.5 T Magnetom Avanto scanner (Siemens, Erlangen, Germany). To measure the volume of the triceps surae muscle (i.e. soleus, SO; gastrocnemius medialis, GM; gastrocnemius lateralis, GL) the boundaries of the muscles were tracked manually in every image using Osirix (Version 4.0, 64bit, Pixmeo SARL, Bernex, CH). From the resulting muscle contours the muscle volume V was calculated as the integral of the cross-sectional area of the contours along the muscle length M_L, which in turn was measured on the longitudinal axis of the coordinate system (along which the transversal images were obtained) as the distance between the two marginal slices contributing to the muscle reconstruction.

Table 1
Mean values ± standard deviations of age, body height and mass of the untrained individuals, endurance and strength athletes as well as the recreationally active group.

Parameter	Untrained individuals $n=13$	Endurance athletes $n=9$	Strength athletes $n=10$	Recreation-ally active $n=21$
Age	30 ± 6	25 ± 3	26 ± 6	25 ± 8
Body height (cm)	180 ± 4	178 ± 4	188 ± 7	177 ± 7
Body mass (kg)	76 ± 6	69 ± 5	85 ± 8	73 ± 10

2.3. Investigation of muscle-specific shape

Based on the theoretical consideration that the volume V of a muscle is the product of the mean anatomical cross-sectional area (ACSA) and the muscle length (L_M) and the mean ACSA can be described as the fraction p (i.e. shape factor) of the maximum ACSA ($ACSA_{max}$), the triceps surae shape factors of the untrained, endurance and strength trained group were obtained from the whole muscle reconstructions by dividing the measured volume by the product of the $ACSA_{max}$ and the muscle length for each muscle (Eq. (1)) (Albracht et al., 2008):

$$p = \frac{V}{ACSA_{max} \cdot L_M} \quad (1)$$

2.4. Muscle volume assessment

For the second step of the validation, the muscle volumes, muscle lengths and maximal ACSAs of the recreationally active group were measured from MRI analysis by full-muscle reconstruction (as described in the section *Data acquisition*). The measured volumes were then compared to the volumes estimated (V_E) based on Eq. (2), using the measured $ACSA_{max}$ and L_M from the present data set and the average shape factors for each investigated muscle calculated from the three groups of untrained, endurance and strength trained athletes (Eq. (1)).

$$V_E = p \cdot ACSA_{max} \cdot L_M \quad (2)$$

2.5. Statistics

A two-way analysis of variances (ANOVA) with the fixed factors activity group (i.e. untrained, long-distance runners and strength athletes) and investigated muscle (i.e. soleus, gastrocnemius medialis and lateralis) was performed to examine the specificity of muscle shape. A Bonferroni *post hoc* test was applied to identify differences between the groups of untrained individuals, endurance and strength athletes respectively regarding the shape factor of the muscle, muscle volume, $ACSA_{max}$ and muscle length.

For the second step of the validation, the estimated muscle volume and the one measured from the whole muscle MRI analysis were compared by means of a paired samples t-test after checking for normal distribution with a Kolmogorov–Smirnov-Test. For accuracy evaluation, the root mean squares (RMS) of the differences between estimated and measured volume as well as the coefficients of determination (R^2) were calculated.

All statistical procedures were performed in SPSS (IBM Corp., Version 19.0, NY, USA) and the level of significance for the t-test as well as the ANOVA was set to $\alpha=0.05$.

3. Results

3.1. Investigation of muscle-specific shape

There was a significant effect of activity group as well as investigated muscle ($p < 0.05$) on the muscle volume, the muscle