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Validation of a simplified method for muscle volume assessment

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A B S T R A C T

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 $n=10$	Recreationally 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):

$$p = \frac{V}{ACSA_{max} \cdot L_M} \tag{1}$$

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)).

$$V_E = p \cdot ACSA_{max} \cdot L_M \tag{2}$$

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 length and the maximum ACSAs with significantly greater values of the strength trained athletes compared to the untrained individuals and endurance athletes, with no significant differences between the latter two groups (Table 2). Further, the greatest values were measured on the soleus muscle, followed by those of the gastrocnemius medialis and then gastrocnemius lateralis, with each significant differences in-between ($p < 0.05$, Table 2). The maximum ACSA was located at $67.1 \pm 2.6\%$, $80.6 \pm 4.4\%$ and $84.1 \pm 4.4\%$ of the shank length (measured from the tuberositas calcanei to the tibial plateau) for the soleus, the medial and the lateral gastrocnemius respectively. Though there was an effect of investigated muscle on the shape factors ($p < 0.05$), there was no effect of activity group ($p > 0.05$), indicating similar muscle shape between the untrained, endurance and strength trained group independent of the investigated muscle (Table 3). Further, the shape factors showed a low inter-individual variability, expressed in a coefficient of variation of 5.2%, 5.0% and 7.3% for the soleus, gastrocnemius medialis and lateralis respectively.

3.2. Muscle volume assessment

There was no significant difference ($p > 0.05$) between the muscle volume assessed using the measured muscle length and maximum ACSA of the independent subject sample (Table 4) and the shape factors calculated in the first step of the evaluation (see Eq. (2)) compared to the values measured following whole-muscle reconstruction in all three muscles of the triceps surae (Table 4). Furthermore the coefficients of determination for the assessed muscle volume were quiet high (≥ 0.85) in all three muscles (Table 4). The agreement of the assessed and measured muscle volumes of all participants and the relative RMS differences between the two methods are depicted in Fig. 1. The absolute RMS differences were 39.4, 13.9 and 16.1 cm^3 for the muscle SO, GM and GL respectively.

Table 2
Mean values ± standard deviations of muscle length, maximum anatomical cross-sectional area (ACSA$_{max}$) and muscle volume of the soleus (SO), gastrocnemius medialis (GM) and gastrocnemius lateralis muscle (GL) of untrained individuals, endurance and strength athletes.

Parameter	Muscle	Untrained (*n*=13)	Endurance athletes (*n*=9)	Strength athletes (*n*=10)
Muscle length (cm)	SO	33.8 ± 2.9	33.8 ± 3.1	$35.3 \pm 2.1^{*,\circ}$
	GM†	27.8 ± 1.7	27.9 ± 1.8	$30.1 \pm 2.8^{*,\circ}$
	GL†,‡	23.9 ± 1.6	23.3 ± 2.2	$26.6 \pm 2.4^{*,\circ}$
ACSA$_{max}$ (cm^2)	SO	28.6 ± 3.7	29.3 ± 4.1	$34.2 \pm 4.9^{*,\circ}$
	GM†	17.9 ± 3.1	16.9 ± 2.6	$19.3 \pm 2.7^{*,\circ}$
	GL†,‡	11.2 ± 2.3	12.4 ± 1.8	$14.8 \pm 2.1^{*,\circ}$
Muscle volume (cm^3)	SO	477.2 ± 65.8	493.6 ± 60.6	$597.3 \pm 86.5^{*,\circ}$
	GM†	294.5 ± 55.6	282.5 ± 40.1	$345.0 \pm 54.8^{*,\circ}$
	GL†,‡	151.5 ± 30.6	159.4 ± 26.1	$211.4 \pm 30.7^{*,\circ}$

* Significant difference to untrained individuals.
$^{\circ}$ Significant difference to endurance athletes.
† Significant difference to SO.
‡ Significant difference to GM, $p < 0.05$.

4. Discussion

The purpose of the present study was to examine the validity of the muscle volume assessment proposed by Albracht et al. (2008), using muscle length, maximum ACSA and a muscle shape specific factor. The validation was performed in two steps. First, the shape factors of the triceps surae muscles of three subject samples with different habitual mechanical loading profiles were calculated and compared. It was found that, despite significant differences in muscle dimensions, the shape factors did not differ significantly between untrained individuals, endurance runners and strength athletes. In a second step, the calculated shape factors were used on an independent, recreationally active subject collective within the simplified volume assessment described by Albracht et al. (2008) and the calculated muscle volumes were then compared to those measured following traditional full-muscle reconstruction. It was found that there were no significant differences between the two methods and a generally good agreement with RMS differences of ~5–8% depending on the muscle of the triceps surae group.

The approach of calculating muscle volume on the basis of easily assessable parameters (i.e. muscle length and maximum ACSA) presented by Albracht et al. (2008) has the potential to circumvent the time-consuming procedure of whole-muscle reconstruction and greatly reduce the length of the required MRI sequences. However, the reported assessment method and shape factors for the triceps surae muscles have not been validated with respect to generalizability thus far. Reports of non-uniform muscle adaptation in response to mechanical loading are numerous (see Hedayatpour and Falla, 2012, for review) and is attributed to heterogeneous fiber type distribution (Lexell and Taylor, 1991), regional differences in muscle activation (Löscher et al., 1994), local expressions of growth-mediating messengers (Borst et al.,

Table 4
Mean values ± standard deviations of measured muscle length (L_M) and maximal anatomical cross-sectional area (ACSA$_{max}$) of the recreationally active group (n=21), the estimated and measured volumes of the soleus (SO), gastrocnemius medialis (GM) and gastrocnemius lateralis muscle (GL) and the associated coefficients of determination (R^2).

Muscle	L_M (cm)	ASCA$_{max}$ (cm^2)	Estimated volume (cm^3)	Measured volume (cm^3)	R^2
SO	34.6 ± 3.4	29.8 ± 4.6	513.6 ± 103.4	501.6 ± 100.1	0.864
GM	26.6 ± 3.0	18.5 ± 3.5	292.3 ± 63.2	290.3 ± 58.3	0.953
GL	23.7 ± 2.4	14.8 ± 3.4	193.5 ± 41.5	194.6 ± 41.4	0.849

Table 3
Mean values ± standard deviations of the shape factors (see Eq. (1)) of the soleus (SO), gastrocnemius medialis (GM) and gastrocnemius lateralis muscle (GL) obtained from untrained individuals, endurance and strength athletes.

Muscle	Untrained (*n*=13)	Endurance athletes (*n*=9)	Strength athletes (*n*=10)	Total (*n*=32)
SO	0.496 ± 0.029	0.502 ± 0.029	0.495 ± 0.022	0.497 ± 0.026
GM	$0.592 \pm 0.025^{\dagger}$	0.604 ± 0.041	$0.593 \pm 0.025^{\dagger}$	$0.596 \pm 0.030^{\dagger}$
GL	$0.568 \pm 0.038^{\dagger,\ddagger}$	$0.555 \pm 0.046^{\dagger,\ddagger}$	$0.540 \pm 0.040^{\dagger,\ddagger}$	$0.556 \pm 0.041^{\dagger,\ddagger}$

† Statistically significant difference to SO ($p < 0.05$).
‡ Statistically significant difference to GM ($p < 0.05$).

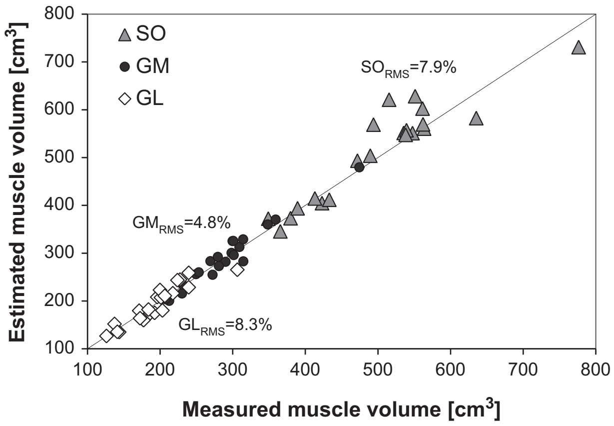

Fig. 1. Estimated and measured muscle volumes of soleus (SO), gastrocnemius medialis (GM) and lateralis (GL) of the recreationally active group ($n=21$), as well as the corresponding root mean square differences (RMS) between the two assessment methods. The solid diagonal line represents the identity line.

2001) and selective increases of muscle fiber cross-sectional area (Häkkinen et al., 2001). Consequently, it would have been quite possible that the reported shape factors for the triceps surae muscle group obtained from recreationally active individuals would not be applicable on muscles that underwent hypertrophic changes. However, the present study demonstrated that the triceps surae shape factors do not differ between untrained individuals, endurance and strength athletes. This indicates a relative independency of muscle shape from muscle dimensions. The present findings do not contradict the reports of non-uniform muscle adaptations, as regional differences in cross-sectional area changes were described mainly following exercise interventions. It may be possible that early changes of muscle cross-sectional area occur regionally in an early phase of adaptation, but spread more globally during long-term mechanical loading. Furthermore, regional differences in the adaptation of muscles have mainly been examined on upper-extremity and thigh muscles (Hedayatpour and Falla, 2012) and can in part be explained by the great relative increases of peripheral muscle regions with small absolute cross-sectional areas (Housh et al., 1992; Narici et al., 1989). Then again, information about site-specific changes in the triceps surae muscles in humans is reduced to observations of regional differences in muscle activation during isometric contractions (Löscher et al., 1994) and regional hypertrophy that significantly affects muscle shape is not to be assumed on the basis of the data of the present study or the results of Albracht et al. (2008). The data of Morse et al. (2005a) further provide a strong argument for the relative consistency of muscle shape during sarcopenia. However, the generalizability of the reported triceps surae shape factors especially with regard to muscle volume changes that are associated with specific pathologies need further investigation.

The present findings of similar muscle shapes across groups with different muscle dimensions (i.e. validation step one) and the good agreement between the muscle volumes assessed on the bases of the consideration of Albracht et al. (2008) and the whole-muscle reconstruction (i.e. validation step two) provide strong evidence in favor of the generalizability of the calculated shape factors as well as their application in muscle volume assessment. The independent variables muscle length and maximal ACSA are easily measurable, with the latter being located at 67.1 ± 2.6%, 80.6 ± 4.4% and 84.1 ± 4.4% of the shank length (measured from the tuberositas calcanei to the tibial plateau) for the soleus, the medial and the lateral gastrocnemius respectively. The respective locations as well as the low inter-individual variability of the maximal ACSA position (showing a standard deviation of 3–4%) are in accordance with the values reported by Albracht et al. (2008) and could be used in the future as landmarks for muscle segmentations. For example, in 95% per cent of the cases (i.e. 95% confidence interval) a segmentation of ~10% and 17% of the shank length around the reported positions would be sufficient to identify the maximal ACSA of the soleus muscle and the two gastrocnemii respectively, which greatly reduces the required time with regard to a full muscle segmentation. Considering respective confidence margins, the reported locations of the maximal ACSAs may also be used to reduce the length of the MRI sequences during acquisition.

The RMS differences between the traditional and simplified assessment method of 4.8–8.3% values of the present study indicate that previously reported muscle volume changes of the triceps surae in response to environmental loading conditions or aging can be reliably detected with the simplified assessment method and the application of the triceps surae shape factors. For example, Berg et al. (2007) and Kubo et al. (2004) found decreases of triceps surae muscle volume of ~12% in young adults following five and three weeks of bed rest respectively. Alkner and Tesch (2004) even reported a decrease of 29% following 90 days of bed rest. Further, aging has been found to be associated with decreases of triceps surae muscle volume of 17–29% (Morse et al., 2005a; Thom et al., 2005). Information from longitudinal studies on the magnitude of hypertrophic responses of the triceps surae muscles to exercise on the other hand is sparse and less conclusive. Kubo et al. (2010) found an increase of triceps surae muscle volume of only 5% following resistance training in young men. However, Morse et al. (2005b) reported a 12% increase in elderly men, yet after a full year of training compared to twelve weeks in the study of Kubo et al. (2010). The cross-sectional comparison in the present study further demonstrated that differences between the muscle volume of strength-trained athletes and endurance athletes or untrained individuals are in the range of 21–25%. Clearly more research on the adaptive potential of the triceps surae in terms of short- and mid-term muscle hypertrophy in response to exercise is needed to draw final conclusions in this regard, yet the applicability of the simplified assessment method for detecting atrophic and long-term hypertrophic changes is strongly supported by scientific evidence and the results of the present study.

In conclusion, the results of the present study indicate that the muscle shape of the triceps surae muscles is similar across populations with different habitual mechanical loading and muscle dimensions (i.e. untrained individuals, endurance and strength athletes) and transferable on independent populations. Further, we conclude that a simplified assessment method, using the muscle shape factor, the muscle length and its maximum CSA for muscle volume calculation, is sensitive enough to detect atrophic responses of the plantar flexors due to unloading or aging as well as long-term muscle hypertrophy and, therefore, can serve as a valid method for volume assessment within these fields of research.

Conflict of interest statement

The authors disclose any financial and personal relationships with other people or organizations that could inappropriately influence (bias) their work.

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