The validity of anthropometric leg muscle volume estimation across a wide spectrum: From able-bodied adults to individuals with a spinal cord injury

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1Department of Medicine, Division of Geriatrics, University of Utah, Salt Lake City, Utah; 2Geriatric Research, Education, and Clinical Center, George E. Whalen VA Medical Center, Salt Lake City, Utah; 3Department of Neurological, Neuropsychological, Morphological and Movement Sciences, University of Verona, Verona, Italy; 4Department of Radiology and Utah Center for Advanced Imaging Research, University of Utah, Salt Lake City, Utah; 5Department of Exercise and Sport Science, University of Utah, Salt Lake City, Utah

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Layec G, Venturelli M, Jeong EK, Richardson RS. The validity of anthropometric leg muscle volume estimation across a wide spectrum: From able-bodied adults to individuals with a spinal cord injury. J Appl Physiol 116: 1142–1147, 2014. First published January 23, 2014; doi:10.1152/japplphysiol.01120.2013.—The assessment of muscle volume, and changes over time, have significant clinical and research-related implications. Methods to assess muscle volume vary from simple and inexpensive to complex and expensive. Therefore this study sought to examine the validity of muscle volume estimated simply by anthropometry compared with the more complex proton magnetic resonance imaging (1H-MRI) across a wide spectrum of individuals including those with a spinal cord injury (SCI), a group recognized to exhibit significant muscle atrophy. Accordingly, muscle volume of the thigh and lower leg of eight subjects with a SCI and eight able-bodied subjects (controls) was determined by anthropometry and 1H-MRI. With either method, muscle volumes were significantly lower in the SCI compared with the controls (P < 0.05) and, using pooled data from both groups, anthropometric measurements of muscle volume were strongly correlated to the values assessed by 1H-MRI in both the thigh (r² = 0.89; P < 0.05) and lower leg (r² = 0.98; P < 0.05). However, the anthropometric approach systematically overestimated muscle volume compared with 1H-MRI in both the thigh (mean bias = 2407 cm³) and the lower (mean bias = 170 cm³) leg. Thus with an appropriate correction for this systemic overestimation, muscle volume estimated from anthropometric measurements is a valid approach and provides acceptable accuracy across a spectrum of adults with normal muscle mass to a SCI and severe muscle atrophy. In practical terms this study provides the formulas that add validity to the already simple and inexpensive anthropometric approach to assess muscle volume in clinical and research settings.

skeletal muscle; imaging; magnetic resonance; muscle mass; atrophy

IN HEALTHY ADULT INDIVIDUALS, skeletal muscle usually represents ~40–50% of the nonadipose tissue component in the body (4). In many debilitating conditions, such as advanced age and chronic disease, a decrement in muscle mass has been directly related to mobility limitation (12), cognitive decline (2), lower health-related quality of life (18), and higher mortality (13). Therefore the use of analytical methods with adequate validity are essential to identify and follow high-risk groups for age- or disease-related muscle mass loss and to monitor the efficacy of potential muscle mass sparing interventions.

Over the past 30–40 years, several technology-dependent methods of quantifying total body and regional skeletal muscle volume have been developed. In particular, proton magnetic resonance imaging (1H-MRI), dual-energy X-ray absorptiometry (DEXA), and quantitative computed tomography have been documented to provide accurate and reliable measurements of skeletal muscle volume (11, 16). However, these methods are both complex and expensive, requiring sophisticated equipment in a purpose-designed setting, and so are not widely available. In this context the anthropometrically based method could be valuable as it is simple and inexpensive (9). Indeed, previous studies have demonstrated the validity of this approach to estimate muscle volume in young (10, 20, 21) and older subjects (3, 5). However, these studies were primarily conducted in normal, healthy individuals. It is therefore still unclear whether the accuracy of skeletal muscle estimated from anthropometric measurements would be compromised in aging and disease conditions associated with extreme inactivity and muscle atrophy, such as exhibited by individuals with a spinal cord injury (SCI). Certainly, the expected changes in the proportion of skeletal muscle to adipose tissue could bias the anthropometric method; however, this potential issue has yet to be assessed. Given the feasibility of the anthropometric assessment of body composition in clinical practice and in large population-based studies, it is paramount to determine the validity of this method across a spectrum of individuals including those with a SCI, who exhibit significant fat infiltration due to disuse.

Accordingly, the purpose of this study was to examine the validity of the anthropometric approach assessing the leg skeletal muscle volume by the comparison to 1H-MRI as a gold standard method across a wide spectrum of individuals including those with a SCI. On the basis of a previous study conducted in healthy children and adults, with large differences in terms of muscle volume (20), we hypothesized that anthropometric measurements will, compared with 1H-MRI, lead to a systematic, but proportional, overestimation of muscle volume in able-bodied individuals. We also hypothesized that this overestimation will be of similar proportion in individuals with a SCI, despite being a clinical population characterized by extreme muscle atrophy and greater fat content. Thus a combination of data from able-bodied individuals and those with a SCI could generate regression equations that would add validity to the anthropometric assessments of muscle volume across a wide scope of people.
METHODS

Subjects. Eight people with a SCI (six men and two women) and eight able-bodied subjects (controls) (six men and two women) participated in this study. All SCI subjects had clinically confirmed paraplegia with complete lesions between the 6th (T-6) and 12th (T-12) thoracic vertebrae (American Spinal Injury Association class A) (15). This was also confirmed in the laboratory by neurological tests (cutaneous pinprick and cold perception), which documented the absence of feedback in the lumbar region and legs, but the maintenance of such sensations in the upper torso and arms. Time postinjury was 9 ± 3 yrs (4–16 yrs), and, based on the Ashworth test (1), at the time of evaluation none of the SCI subjects exhibited muscle spasticity. None of the study participants were smokers and most were physically active. Descriptive characteristics of the subjects are reported in Table 1. All procedures conformed to the standards set by the Declaration of Helsinki and were approved by the Institutional Review Boards of the University of Utah and the Salt Lake City VA Medical Center. Subjects gave written informed consent prior to their participation.

Volume anthropometry measurement. Thigh and lower leg volume were calculated based on leg circumferences (three sites: distal, middle, and proximal), thigh and lower leg length, and skinfold measurements using the following formula (9, 19):

\[
V = (L/12\pi) \cdot (C1^2 + C2^2 + C3^2) - \left(\frac{(S - 0.4)}{2}\right) \cdot L \cdot [(C1 + C2 + C3)/3]
\]

where L refers to the length; C1, C2, and C3 refer to the proximal, middle, and distal circumferences, respectively; and S is skinfold thickness of either the thigh or the lower leg. The length of the leg was measured from the greater trochanter to the lateral femoral epicondyle (thigh) and from the head of the fibula to the lateral malleolus (lower leg). The length and circumference were measured to the nearest 1 mm using a flexible standard measuring tape. Skinfold thickness was measured using skinfold calipers (Beta Technology Incorporated, Cambridge, MD) at three sites at the midpoint of each limb segment. Specifically, for the thigh these sites were medial, anterior, and lateral, while for the lower leg, medial, posterior, and lateral sites were used.

Table 1. Subject characteristics

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Controls</th>
<th>SCI</th>
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</thead>
<tbody>
<tr>
<td>Age, yrs</td>
<td>40 ± 7</td>
<td>42 ± 8</td>
</tr>
<tr>
<td>Mass, kg</td>
<td>68 ± 6</td>
<td>74 ± 10</td>
</tr>
<tr>
<td>Height, m</td>
<td>1.8 ± 0.1</td>
<td>1.8 ± 0.12</td>
</tr>
<tr>
<td>ASIA grade</td>
<td>–</td>
<td>A</td>
</tr>
<tr>
<td>Years postinjury</td>
<td>–</td>
<td>9 ± 3</td>
</tr>
<tr>
<td>Quadriceps spasticity Ashworth scale (0–4)</td>
<td>–</td>
<td>0–2</td>
</tr>
<tr>
<td>Glucose, mg/dL</td>
<td>62 ± 10</td>
<td>97 ± 11</td>
</tr>
<tr>
<td>Cholesterol, mg/dL</td>
<td>184 ± 6</td>
<td>160 ± 8*</td>
</tr>
<tr>
<td>HDL, mg/dL</td>
<td>65 ± 2</td>
<td>43 ± 5*</td>
</tr>
<tr>
<td>LDL, mg/dL</td>
<td>108 ± 6</td>
<td>98 ± 5</td>
</tr>
<tr>
<td>Triglycerides, mg/dL</td>
<td>78 ± 19</td>
<td>96 ± 15</td>
</tr>
<tr>
<td>Hemoglobin, g/dL</td>
<td>14.8 ± 0.8</td>
<td>14.6 ± 0.3</td>
</tr>
<tr>
<td>Hematocrit, %</td>
<td>46 ± 3</td>
<td>47 ± 2</td>
</tr>
<tr>
<td>WBC, K/µL</td>
<td>5.1 ± 0.6</td>
<td>4.4 ± 0.7</td>
</tr>
<tr>
<td>Neutrophil, K/µL</td>
<td>2.9 ± 0.4</td>
<td>2.6 ± 0.3</td>
</tr>
<tr>
<td>Lymphocyte, K/µL</td>
<td>1.6 ± 0.2</td>
<td>1.7 ± 0.2</td>
</tr>
<tr>
<td>Monocyte, K/µL</td>
<td>0.41 ± 0.03</td>
<td>0.43 ± 0.2</td>
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</table>

Data are presented as mean ± SD. All SCI subjects had a spinal lesion between T-6 and T12. American Spinal Injury Association (ASIA) score was used to classify the severity of the lesion: A = complete sensory and motor. The quadriceps spasticity Ashworth scale is used to classify the severity of muscular spasms in SCI subjects: 0 = no spasms. HDL = high-density lipoprotein; LDL = low-density lipoprotein; WBC = white blood cells. * P < 0.05; significantly different from Controls.

DISCUSSION

The purpose of this study was to examine the validity of anthropometrically assessed thigh and lower leg muscle volume in able-bodied individuals and those with a SCI compared with 1H-MRI, as a gold standard method. With both methods, muscle volume was determined to be significantly lower in the SCI compared with able-bodied subjects. Consistent with our hypothesis, the anthropometric assessment led to a systematic overestimation of muscle volume compared with 1H-MRI measurements in able-bodied subjects and individuals with SCI in both the thigh and lower legs. However, this overestimation was proportional to the volume determined by 1H-MRI and did not vary between controls and SCI as there was a close correlation between muscle volume estimated by anthropometry and 1H-MRI with the pooled dataset. Together,
these findings document that the anthropometric measurements provide a valid index of muscle volume and, with appropriate correction, the method yields acceptable accuracy even in individuals exhibiting severe muscle atrophy such as SCI.

Comparison among methods. The principal finding of this study was the close correlation ($r^2 = 0.89$ and 0.98 in the thigh and lower leg, respectively) between muscle volume estimated by anthropometry and $^1$H-MRI in controls and SCI individuals (Fig. 2). In agreement with these results, correlation coefficients akin to the present values have previously been reported for these two methods in the upper (20) (5) and lower limb (6, 10, 21) of healthy subjects.

However, the present results extend these findings by confirming the validity of anthropometric measurements of muscle volume in individuals with SCI, a population characterized by an extreme level of muscle atrophy. Indeed, on average muscle volume measured by $^1$H-MRI was reduced by $\sim 70\%$ in the thigh and lower leg of SCI, reaching values as low as $\sim 100–200 \text{ cm}^3$ in some individuals. These differences are large compared with previous research documenting a reduction of only $\sim 15\%$ in men with long-term, complete SCI (17). However, it should be kept in mind that, by design, while matching SCI subjects for height and weight, able-bodied controls subjects in the present study were recruited to reflect a large spectrum of values for

Fig. 1. Representative T1-weighted image from the midpoint of the lower leg of a healthy control (left) and an individual with a spinal cord injury (right). Muscle (grey) is separated from fat (green) and other tissues such as bone and connective tissues (blue) using the signal-intensity threshold method and then muscle cross-sectional area is calculated.
muscle volume, which might have exaggerated the differences between groups. In addition, the time postinjury when the assessment was performed (≈9 years) and muscle spasticity (all but two subjects had no muscle spasticity, and one of the two was pharmacologically treated to prevent muscle spasms), which affects muscle atrophy associated with SCI (7), should also be taken into account when comparing SCI with able-bodied individuals. Therefore one should be cautious about drawing from the present study any quantitative inference regarding the general decrement in muscle volume associated SCI. Instead, given the strong relationship between the two techniques (anthropometry and 1H-MRI) indicating a high level of qualitative agreement, this study supports the use of the anthropometric method to provide an index of muscle volume. In addition, with appropriate corrections (see below), this simple, inexpensive, and widely available method can provide a valid measurement of muscle volume for clinical and research settings where advanced and expensive technique to assess body composition are not available.

Table 2. Muscle volume measurements

<table>
<thead>
<tr>
<th></th>
<th>Controls</th>
<th>SCI</th>
</tr>
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<tbody>
<tr>
<td><strong>Thigh</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anthropometric muscle volume, cm³</td>
<td>6488 ± 1112</td>
<td>3943 ± 1864*</td>
</tr>
<tr>
<td>MRI muscle volume, cm³</td>
<td>3855 ± 1183</td>
<td>1160 ± 1077*</td>
</tr>
<tr>
<td><strong>Lower leg</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anthropometric muscle volume, cm³</td>
<td>1472 ± 332</td>
<td>625 ± 310*</td>
</tr>
<tr>
<td>MRI muscle volume, cm³</td>
<td>1356 ± 370</td>
<td>403 ± 275*</td>
</tr>
</tbody>
</table>

Values expressed as mean ± SD. *, P < 0.05; significantly different from Controls.

Absolute quantification of muscle volume. Anthropometric assessment led to a systematic overestimation of muscle volume compared with 1H-MRI measurements in both able-bodied and SCI subjects in thigh and lower legs (Table 2, Fig. 3). This documentation of an overestimation of muscle volume by anthropometry, although far greater, is in agreement with previous reports conducted in the limbs of healthy subjects (6, 10, 20, 21). Quantitative differences between the present results and previous studies investigating the lower limb (6, 10, 21) likely stem from the higher magnetic field employed in the present study (3 Tesla compared with 0.5–1.4 Tesla in previous investigations), thus allowing a greater number of slices (10), faster acquisition time, and far superior spatial resolution [voxel size = 0.6 mm² compared with 7.6 mm² (21) and 3.5 mm² (6)], which results in more accurate tissue segmentation and improved quantification. The difference between the anthropometric method and the 1H-MRI measurements of muscle volume is also larger than a recent study investigating the validity of the anthropometric estimation of the midtigh cross-sectional area (CSA) in older adults and patients with lung disease (14). This discrepancy between studies likely originates from the anthropometric method used and the mathematics related to the calculation of cross-sectional area (CSA) rather than volume. Indeed, in the current study we used the equation initially proposed by Jones and Pearson (9), which was based on the concept that the volume of the leg could be partitioned into segments, each similar in shape to a truncated cone. In contrast, the study from Mathur et al. (14) utilized different equations (8), which were actually derived from MRI measurements and therefore already contained corrections to more accurately estimate the anatomical CSA of the quadriceps, hamstrings, and total CSA of the thigh muscles (not the anatomical volume of the thigh and lower legs, as in the present study). It should also be kept in mind that, compared with the simple estimation of muscle CSA, the calculation of muscle volume requires multiple calculations, and according to the theory of error propagation, limb muscle volume estimation should mathematically result in greater error compared with the estimation of muscle CSA of a specific muscle group (quadriceps and hamstrings), as in the study by Mathur et al. (14). Together, the use of MRI-corrected
algorithms and the estimation of muscle CSA rather than volume probably contributed to the smaller differences between muscle volume assessments reported by Mathur et al. (14) and those in the current study.

There are several explanations for the bias toward a greater muscle volume assessed by anthropology compared with MRI. For instance, the anthropology-based approach provides an estimate of the lean limb volume, thus including both muscle and bone. Interestingly, however, this factor alone did not fully explain the systematic bias of anthropometric measurements (20), implying other factors contribute to this overestimation. It is noteworthy that the truncated cone model assumes that the limb is circular and that subcutaneous fat is homogeneously distributed around the limb, which oversimplifies the limb anatomy as confirmed by the MR images reported herein. Along the same lines, the use of only three circumferential measurements with the anthropology-based approach compared with 15–20 axial images with the MRI method likely further contributes to the systematic overestimation of muscle volume with anthropometric measurements.

Interestingly, despite the above-described sources of bias and variability between populations, our statistical analysis did not reveal any interaction between the groups and the slope of the relationship between the muscle volumes estimated with both methods in either the thigh or the lower legs. This finding supports the use of the same equation in both populations to correct muscle volume estimated anthropometrically:

\[
\text{Thigh muscle volume from MRI} = 0.866 \cdot \text{Vol_{anthropo}} - 1,750 \\
\text{Lower Leg muscle volume from MRI} = 1.077 \cdot \text{Vol_{anthropo}} - 250
\]

Of note, in the lower leg only, the anthropometric method tended to overestimate muscle volume to a greater extent in subjects with smaller leg volume and this occurred to a lesser extent in subjects with a larger muscle volume (Fig. 3). However, this effect appears relatively minimal and would likely not account for an error of more than \( \sim 50–100 \text{ cm}^3 \) with the correction equation.

CONCLUSION

In summary, this study has documented that although the anthropometric approach systematically overestimated muscle volume compared with \(^1\text{H-MRI}\), these two techniques exhibited a high level of agreement in the thigh and lower legs across a spectrum of able-bodied adults to those with a SCI. Overall, these findings illustrate that anthropometric measurements provide a good index of muscle volume in adults. In addition, with appropriate correction, using the equations presented in this study, anthropometry is a valid, simple, inexpensive, and practical approach to estimate muscle volume in a clinical or research setting, even in individuals exhibiting severe muscle atrophy such as SCI.

ACKNOWLEDGMENTS

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GRANTS

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

AUTHOR CONTRIBUTIONS

Author contributions: G.L., M.V., E.-K.J., and R.S.R. conception and design of research; G.L., M.V., and E.-K.J. performed experiments; G.L. and M.V. analyzed data; G.L. interpreted results of experiments; G.L. prepared figures; G.L., drafted manuscript; G.L., M.V., E.-K.J., and R.S.R. edited and revised manuscript; G.L., M.V., E.-K.J., and R.S.R. approved final version of manuscript.

Fig. 3. Bland-Altman plot between anthropology and \(^1\text{H-MRI}\) muscle volume in controls (●) and SCI (○). There was a systematic overestimation of muscle volume using anthropology compared with MRI measurements in both thigh and lower leg. The continuous and dashed lines represent the mean bias and \( \pm 2 \) SD of the difference between anthropology and MRI muscle volume measurements, respectively.
REFERENCES