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Consistency and accuracy of measurement of lower-limb amputee anthropometrics

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Abstract—Lower-limb amputees often exhibit large fluctuation in residual-limb shape, necessitating careful observation and anthropometric measurement for prosthetists to ensure socket fit. Anthropometric measurement may become more important as an outcome measure indicating success in rehabilitation. This study investigated the accuracy and reliability of seven prosthetic anthropometric measurement devices as used by a group of eight prosthetic-orthotic practitioners and a group of five prosthetic-orthotic students to measure six common anthropometric dimensions on three foam positive models of transtibial amputee residual limbs. Two of the models were identical, enabling assessment of individual repeatability. Some clinically significant errors were noted in the results; however, the general variability in measurements was not clinically significant. Students were slightly more consistent than practitioners; students were more consistent with linear measurements, while practitioners were more consistent with circumferential measures. The results further demonstrated that the VAPC measurement device used in the study was both inaccurate and unreliable.

Key words: amputee, anthropometry, measurement, outcomes, prosthesis adjustment, prosthesis fitting, prosthetics, rehabilitation, residual limb, VAPC.

INTRODUCTION

One of the most important components of restoring limb function in the lower-limb amputee is the precise fitting of the prosthetic socket to the residual limb. Without proper fitting, overall function of the prosthesis as well as quality of life for the patient is diminished. In addition, repeated visits and in turn increased expense are incurred. Thus it is crucial that techniques used to produce limb sockets be accurate, repeatable, and cost-effective, and have high patient utility.

The residual limb is not only unique to each individual, but also dynamic, changing shape and volume throughout each day and through the seasons of the year [1]. Fernie and Holliday noted large reductions in residual-limb volume, particularly postoperatively, but also noted that the pattern of volume reduction is highly variable [2]. These variations within and across individuals necessitate a flexible approach to prosthetic prescription [3]. Because part of that approach involves measurement of the shape of the residual limb, an investigation into the accuracy and repeatability of amputee anthropometric devices is warranted.

Prosthetic practice faces a growing need for outcome measures and evidence of the benefits of service. The most direct outcome measures in prosthetics might be associated with movement, such as walking velocity or success

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Abbreviations: AP = anterior-posterior, ML = medial-lateral, MPT = mid-patellar tendon, SI = Système Internationale d' Unités (international system of units), TT-L = transtibial length, U-ML = universal AP-ML.

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in activities of daily living [4]. However, outcome measures can also provide a common language for the comparison of treatment protocols, and may include information about changing amputee anthropometrics and socket shape and fit [5]. One problem with the comparison of amputee anthropometrics is the wide range of available calipers, rulers, and tape measures [6]. In addition, a variety of tools for shape capture have been developed, including generally accepted computer-aided design/computer-aided manufacturing digitizers [7–9] along with custom-designed methods using X ray and cineradiography [10], finite element modeling [11], laser and optical capture methods [12–13], ultrasound [14], and spiral x-ray computed tomography [6,15–16]. Anecdotal observation suggests that even traditional hand-measurement devices vary in terms of precision, accuracy, and ease of use. Lunsford has urged the development of bias-free instruments to provide quantifiable measures of device benefits [17]. Outcome measures can only provide a common language for the comparison of socket shape and fit if the different tools used to measure anthropometrics have been independently determined.

This investigation assessed the performance of a number of common manual amputee anthropometric devices when prosthetic-orthotic practitioners and students recorded typical measurements on foam models of transtibial limbs. Instruments were assessed in terms of accuracy and reliability, and the two participant groups were compared for their ability to produce consistent and accurate measurements. Effective and ineffective instruments and measurement techniques were identified; these results have implications on both improving amputee locomotion through better socket fit and on anthropometry in general.

METHODS

The following common anthropometric measurements were assessed: residual-limb length (from mid-patellar tendon [MPT] to distal end), anterior-posterior (AP) distance at MPT, medial-lateral (ML) distance at mid-patella, and circumference at MPT and at 2 in. and 4 in. distal to the MPT. Each measurement was performed on three foam positive models of transtibial amputee residual limbs, labeled models "A," "B," and "C." Models A and C were identical models produced from the same computer-aided-design file at the Atlanta Department of Veterans Affairs Medical Center. Participants were not informed that models A and C were identical. Each model was mounted on a shaft and covered with two Cool Blue (lightweight 6 in. × 3 in. × 12 in.) prosthetic socks (SPS by Knit-Rite, Alpharetta, GA) and a 6 mm Alpha Uniform C-Liner (Ohio Willow Wood, Mt. Sterling, OH). The socks and liner were added for some compression to occur, mimicking soft tissue. Because this study assessed instrument accuracy and consistency and instrument use as opposed to anatomical knowledge and palpation technique, anatomical landmarks were marked on the Alpha liner covering each model. The following locations were identified: MPT for AP, length, and circumference measurements; medial and lateral marks at the mid-patella line for ML measurement; and both 2 and 4 in. distal to the MPT on the anterior aspect for additional circumferences. Each model was secured in a vise at a workstation in the fabrication laboratories of various prosthetics facilities in the Atlanta, Georgia, area and at the Center for Prosthetic and Orthotic Research and Education at Georgia Institute of Technology. The models were mounted such that participants would conduct measurements first on model A, then B, then C.

Seven measurement tools were used in the study. Four tools assessed linear dimensions (AP diameter, ML diameter, and length), and three assessed circumference (**Figure 1**). Three devices were custom-designed for use in prosthetics and orthotics: the transtibial length (TT-L) caliper, the universal AP/ML (U-ML) caliper (Fillauer, Chattanooga, TN), and the VAPC caliper (T095000000, Seattle Systems, Poulsbo, WA). The VAPC caliper has an end designed for measuring AP distance and an end with more general arms suitable for ML measurement. The fourth linear measurement tool was a GPM anthropometer (SiberHegner, Zurich, Switzerland) often used for recording body segment parameters in a gait analysis laboratory.

In addition to a standard tape measure, two additional tapes were used (**Figure 1**). A spring tape incorporates a spring on the end. When circumference was recorded, each participant was instructed to pull the spring-loaded handle until a small mark on the shaft became visible. The goal of this device is to standardize the amount of tension each measurer applies to the tape and, therefore, the amount of soft tissue compression. A similar goal is designed in the circumferential tape. The end of the tape is inserted back into the tape measure body, forming a loop. Pressing the release button then tightens the tape measure around the measured object with a uniform tension. Participants were also instructed in the use of this device.

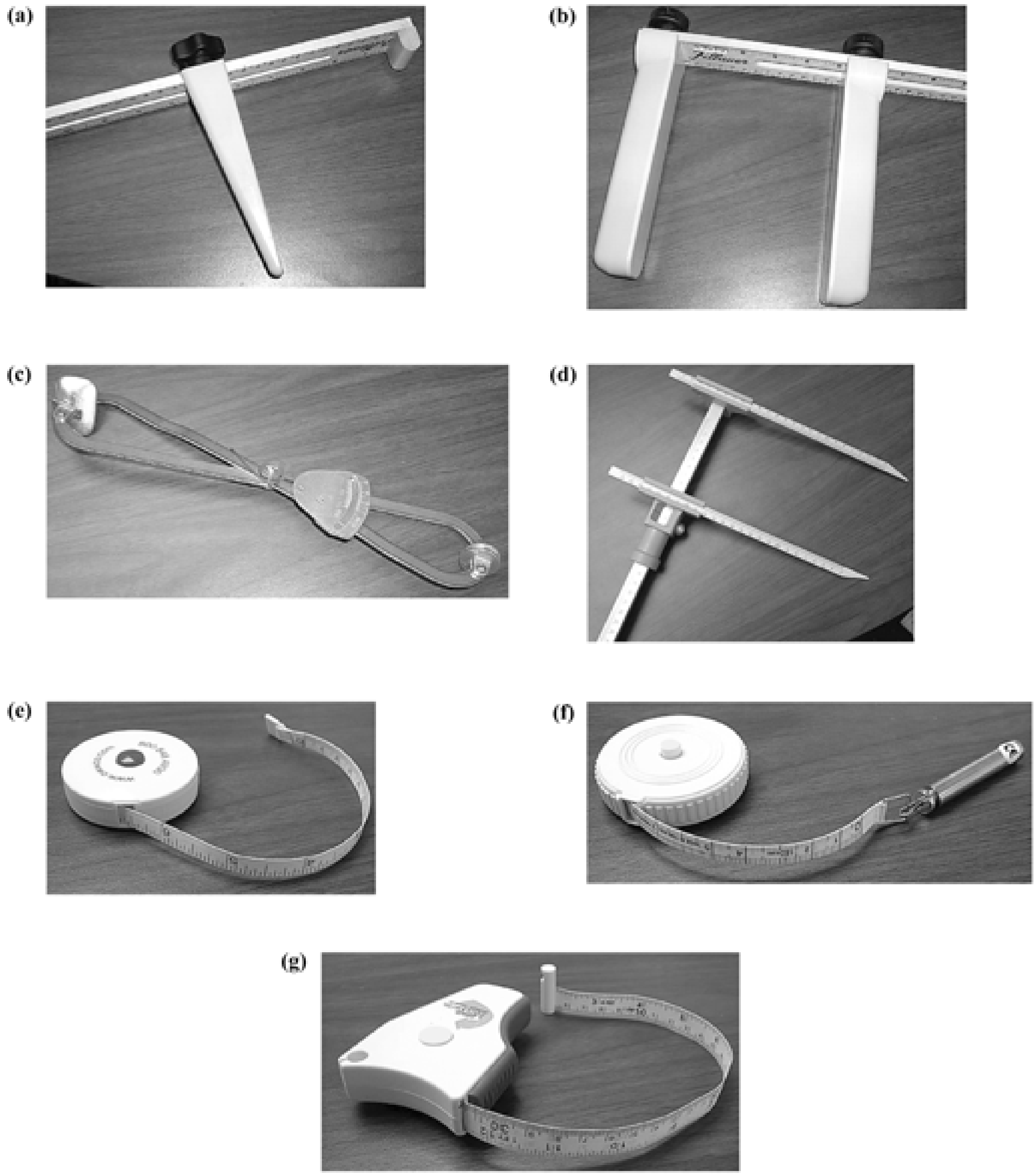

Figure 1.
Measurement devices: **(a)** transtibial length caliper, **(b)** GPM anthropometer, **(c)** universal anterior-posterior–medial-lateral caliper, **(d)** VAPC caliper, **(e)** standard tape, **(f)** spring tape, and **(g)** circumferential tape.

Two groups of participants conducted measurements: five students and eight practitioners. The student group comprised first-year graduate students in the Master of Science program in prosthetics and orthotics at Georgia Tech. These students were all currently enrolled in a transtibial prosthetics course at the time of the study and were aware of the anthropometric measurements involved, but they had received little practical training or experience in obtaining such measurements. The practitioner group was recruited from three local prosthetics/orthotics facilities at which the study was conducted. Practitioners ranged in experience from 2 years (postresidency) to 28 years. Each practitioner was familiar with all of the tools used, except for the anthropometer, although no consistent pattern existed regarding which tools were commonly used by each practitioner. None of the practitioners had ever used a similar anthropometer before. Each participant reviewed and signed an informed consent document prior to participation, and the study was conducted under the guidelines of the institutional review board for research involving human subjects.

Each participant was given a form with a picture of each device and blanks for the appropriate measurement for models A, B, and C. Following explanation of the use of each instrument, the marks on each model were identified and a general description of the measurements was provided. For example, for the limb length measurement, participants were told, “This dot is the mid-patellar tendon. Measure length from this dot to the distal end using the anthropometer and the TT-L gauge.” Participants were permitted to record values in either English or Système Internationale d’Unités (international system of units [SI]) for any measurement. The TT-L and the anthropometer were used to measure length from the MPT mark to the distal end. The U-ML, anthropometer, and VAPC were used to measure ML diameter at the marks provided. Participants used the VAPC and anthropometer to measure AP diameter at the MPT mark. They used all three tape measures to measure circumference at the MPT mark and at marks 2 and 4 in. distal to the MPT. The sizes of models A and C were beyond the 5 in. scale of the VAPC so that device was only used for AP and ML measurements on model B. Consequently, each participant recorded a total of 44 measurements. On average, the measurements took approximately 15 min to 20 min to complete.

A thorough investigation of the accuracy of each measurement device would require comparison of multiple samples of each device to a broad series of known linear dimensions determined to a very high degree of accuracy. While this type of investigation was not the focus of this work, determining which instruments used were more or less accurate versus a single known dimension was nonetheless useful. Each linear measurement device was tested against a known length of 4.9991 in. with the use of a Starrett No. 755 (L. S. Starrett Co., Athol, Massachusetts) digital caliper standard on a Starrett surface plate and a Mitutoyo No. 167 length standard set (Tokyo, Japan). These systems verified the known length to the nearest 0.0001 in. This length was similar to most measurements recorded for the models but small enough to allow measurement by the VAPC. Tape measures were compared to a known length of 14.9949 in., a value similar to the circumferences of the models.

All results were converted to centimeters for analysis. The goal of data analysis was to address four major questions: which instrument was most accurate, which group was more consistent, which instruments produced inconsistent measurements, and which measurements and measurement sites produced the most inconsistent measurements. Each question required a slightly different analysis.

Instrument accuracy was a straightforward comparison of each instrument to a known value. Division of measurement results by subject group was performed in a comparison of means and an exploratory statistics module (SPSS 11.0.1, Chicago, IL), with results used as dependent variables and participant group (students versus practitioners) as a factor. In addition, each measurer’s error in the repeated measurements of identical models A and C was calculated as the absolute value of the result for model A minus the result for model C. The mean error and maximum error were determined for each practitioner. For analysis of instruments and measurement sites, the mean, standard deviation, and range (overall maximum minus minimum) were calculated for each measurement across all subjects. Comparisons of standard deviation (σ) and range were more meaningful than direct comparison of means because of the variability in physical dimension being measured at various sites.

RESULTS

Data were analyzed to address several questions:

- Which group was more consistent?
- Which instrument was most accurate?

- Which instruments produced the most inconsistent measurements?
- Which measurements and measurement sites produced the most inconsistent measurements?

Which Group (Students vs. Practitioners) Was More Consistent?

This question was addressed in two ways. First, the standard deviation and range of each measurement for each group was compared. Next, the ability of each group to make consistent measurements on identical models A and C was assessed.

The practitioners produced larger standard deviations and ranges than the students in a slight majority of measurements (standard deviation comparison: 53% of measurements, range comparison: 64% of measurements). The sum of average student ranges across all measurements was 22.9 cm versus 43.4 cm for experienced practitioners. Students were generally more consistent with linear measurements (length, AP, ML) while experienced practitioners were more consistent with measures of circumference. Students produced larger standard deviations than experienced practitioners in only 26 percent of linear measurements as opposed to 70 percent of circumference measurements.

Students and practitioners showed similarly small error values when repeating measurements of models A and C. The single largest difference in a measurement of model A versus C was 2 cm, when an experienced practitioner measured the ML distance with an anthropometer as 15 cm for model A and 13 cm for model C. While the largest error was 2 cm, the average error for all measurements across all subjects was only 2 mm (**Figure 2**).

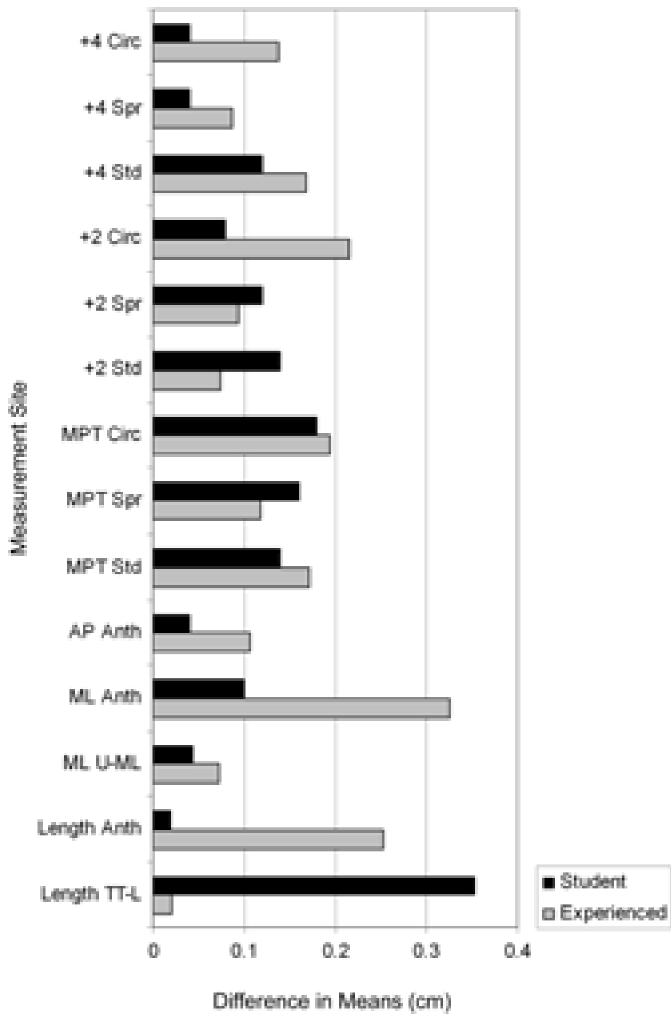

Figure 2.
Model A vs. model C error by measurement site. Absolute value of mean value for all students and all practitioners at each measurement site on model A minus mean value for measurements of identical model C. Circ = circumferential tape measure, Spr = spring tape measure, Std = standard tape measure, MPT = mid-patellar tendon, AP = anterior-posterior, Anth = anthropometer, ML = medial-lateral, U-ML = universal AP-ML caliper, TT-L = transtibial length caliper.

Which Instrument Was Most Accurate?

The anthropometer, the U-ML caliper, and the standard tape measure were all tested to be accurate within 0.01 mm when compared against a single known length comparable to those measured in this study (**Table**). The circumferential tape measure was similarly accurate, but it should be noted that this instrument is difficult to compare to a known linear dimension because of its built-in curvature. We started tests for this tape measure at approximately 10 cm from zero to enable linear measures. The curvature of the circumferential tape measure contributed to some error in the study when the instrument's fixed radius of curvature did not match with the radius of curvature of the model being measured.

The TT-L caliper was also very accurate, but does lend itself to error in an accuracy test because the end of the device meant to be placed on the patellar tendon is a curved surface and is difficult to compare to a discrete mark.

The only device in the study with substantial inaccuracies was the VAPC. Although the scale of the tested VAPC extends from 0 in. to 5 in., measurements of a known standard of 5 in. were off the scale. Consequently, the VAPC was compared to a known standard of approximately 4 in. (3.9975 in.). Errors on the ML end exceeded

Table.
Accuracy of measurement devices compared to known standard linear dimension, in order from least to greatest absolute error. VAPC was compared to shorter standard length because measurement of 4.9991 in. standard exceeded 5 in. scale on VAPC by approximately 0.25 in. For devices with scales in centimeters and inches, both errors are provided, along with conversion of error on Système Internationale d'Unités (international system of units) scale to inches for comparison.

Measurement Device	Standard Length (in.)	Measured Length (in.)	Error (in.)	Measured Length (cm)	Error (cm)	Centimeter Error Expressed (in.)
U-ML Caliper	4.9991	5.0000	–0.0009	12.7000	–0.0023	–0.0009
Anthropometer	4.9991	N/A	N/A	12.6900	0.0077	0.0030
Standard Tape	14.9949	15.0000	–0.0051	38.1000	–0.0130	–0.0051
Circumferential Tape	14.9949	15.0000	–0.0051	38.1000	–0.0130	–0.0051
Spring Tape	14.9949	15.0625	–0.0676	38.2000	–0.1130	–0.0445
TT-L Caliper	4.9991	4.9375	0.0616	12.5000	0.1977	0.0778
VAPC AP End	3.9975	4.1875	–0.1900	10.5000	–0.3463	–0.1364
VAPC ML End	3.9975	4.2500	–0.2525	10.7500	–0.5963	–0.2348

U-ML = universal anterior-posterior–medial-lateral
ML = medial-lateral
TT-L = transtibial length
AP = anterior-posterior
N/A = not applicable

0.25 in. Compounding practical error is that the scale on the VAPC is very difficult to use and read, with poorly contrasting tick marks and numbers and unusual divisions.

All instruments except for the anthropometer had scales in inches and centimeters. In general, each scale produced similar error (**Table**); however, each scale varied in terms of precision. The most precise SI scales were on the tape measures and the anthropometer and were marked to the nearest millimeter. The TT-L and U-ML calipers were only marked to the nearest 0.5 cm. All English unit scales (except for the VAPC) were marked to the nearest sixteenth of an inch.

Which Instruments Produced the Most Inconsistent Measurements?

All the measurements for each instrument were averaged across all subjects. An initial investigation determined that the anthropometer produced the largest standard deviation (0.615 cm) and the largest range (2.41 cm). Additional investigation determined that the majority of this variability could be attributed to a single subject, one of the practitioners (the same subject who produced the maximum "A vs. C error" reported previously). A box-and-whisker analysis determined outliers for each measurement [18]. The single subject in question had 11 measurements identified as outliers. The remaining subjects averaged 3.4 outliers each. Because the largest of these outliers were for measurements with the anthropometer (**Figure 3**), exclusion of this subject from the instrument analysis produced markedly different results for instrument consistency. The standard deviation for the anthropometer was reduced to 0.236 cm, and the range was reduced to 0.833 cm (**Figure 4**). In the analysis excluding the outlying subject, the instrument producing the least consistent results was the VAPC, followed closely by the TT-L caliper (**Figure 4**). The most consistent instruments in each analysis were the tape measures. The

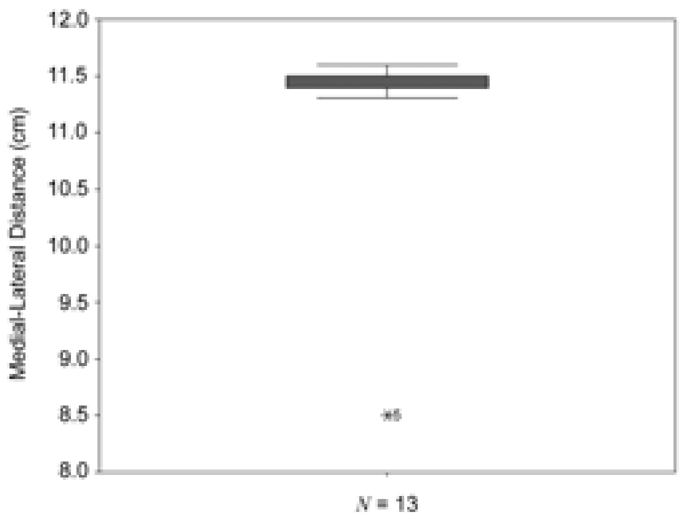

Figure 3.
Box-and-whiskers plot of anthropometer measurement (cm) of medial-lateral distance on model B. Outlier measurement, indicated with asterisk, was 5 cm. Excluding outlier, bold horizontal line is median of remaining data along with box and whiskers.

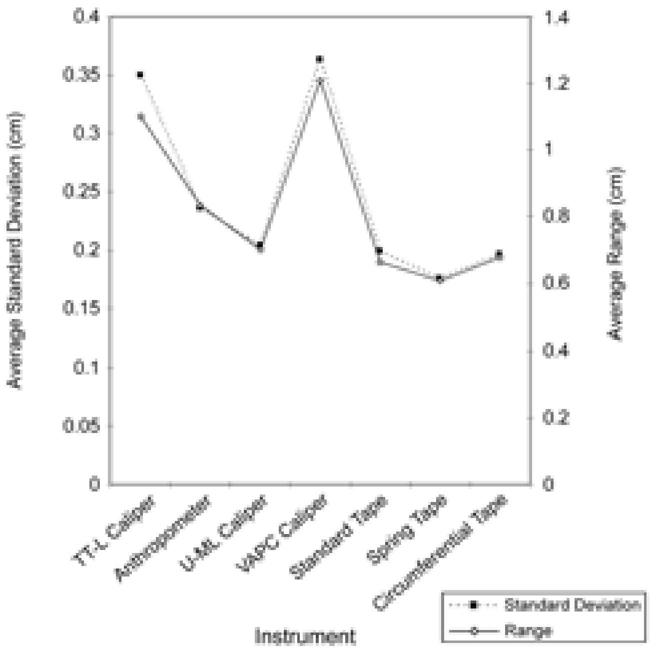

Figure 4.
Average standard deviation (left axis scale) and range (right axis scale) in centimeters across all subjects, excluding outlier subject, for each measurement device. TT-L = transtibial length, U-ML = universal anterior-posterior–medial-lateral.

spring tape measure did produce very slightly more consistent measurements, but the differences versus the two other tape measures were not clinically significant.

Which Measurements and Measurement Sites Produced the Most Inconsistent Measurements?

Analysis of problematic measurements again showed data skewed by the subject who produced errors when using the anthropometer. These outliers caused all measurement sites that included the anthropometer to be abnormally variable. With the outlier subject excluded, the most problematic measurement was length, which produced an average range of 1.42 cm. Measurers were most consistent when measuring the AP distance. Within the circumference category (and including data from all subjects), measurers were most consistent at the site 2 in. distal to the MPT (σ = 0.15 cm). Measurers were more variable at the MPT (σ = 0.20 cm), and most variable at 4 in. distal to the MPT (σ = 0.23 cm).

In the comparison of measurements for A versus C error, no measurement produced more than 1.5 mm mean error.

DISCUSSION

Anthropometric measurement is an important part of clinical practice in prosthetics and orthotics, and the accuracy and consistency of such measurement may become more important as the need for outcomes and evidence-based practice grows. This study assessed the accuracy and reliability of a number of common anthropometric measurement tools using foam models of transtibial amputee limbs.

The results should be understood within the intended scope of the study. The experimental method was limited in a number of ways. Measurement of accuracy was confined to the devices used in the study and therefore included only one sample of each device. Therefore, no generalizations should be made about the general accuracy of the devices mentioned. Nonetheless, understanding the accuracy of each device helps in interpretation of reliability results. The pool of subjects introduces natural variability in the data. Different subjects had experience with different instruments, and many expressed a strong preference for a certain instrument. One would expect that if a given practitioner has substantial experience with a given device and uses it in practice daily, that subject's variability for that device would be reduced. However, it is difficult to control for "preferred device" in an experimental design such as this one, and because subject preferences were widespread, the data likely do not reflect a general bias. Finally, the study is limited in its ability to reflect the actual variability that might be encountered in practice because the models were covered by material less flexible than human soft tissue, and the aspect of anatomical palpation was removed. Nonetheless, Commean et al. found no significant differences in measurements of a plaster positive vs. measurements made directly on the residual limb [16].

The consistency data recorded here are similar to the limited data that exist in the literature. Commean et al. recorded approximately 1 mm variation in repeated caliper measurements in a single session [16]. Differences exist in standards sought for accuracy and in thresholds for clinical significance. Krouskrop et al. designed a shape sensor and specified a minimum accuracy of 0.25 cm [11]. When determining the minimum sample size for adequate statistical power, Convery et al. used 1.0 mm as a threshold for clinical significance in cast rectification [5], which might be considered somewhat low. The same study measured models with an accuracy of 0.05 mm. None of these studies used the more common AP and ML gauges tested here, but interestingly all used some sort of caliper (similar to the GPM anthropometer) as the "gold standard" for their tests.

From observation during this study and from general anecdotal evidence, practitioners clearly vary in their measurement technique. Some are meticulous to the point of inefficiency, while others are rapid and casual to the point of inaccuracy. Without quantification of the general variability in measurement, the impact of these variable techniques cannot be understood. One lesson learned is that clinically significant errors can occur when technique is poor or when the measurement device is used improperly. The need to exclude the entire data set of one practitioner in parts of this analysis (**Figure 3**) underscores the need for a basic understanding of measurement technique and instrument use. Observation of subjects revealed what may be several common sources of inconsistency. Measurement of length is greatly affected by how level the caliper is held, likely contributing to the inconsistency of use of the TT-L caliper (**Figure 4**). Likewise, measurement of circumference is affected by how vertical the tape is wrapped around the limb. In particular, a circumferential tape measure should be released and reinserted for every measure. Sliding the tape down the limb and pressing the release button produced overestimations of circumference. (However, the results show that these errors were typically not clinically significant.) The reading on the wooden U-ML and TT-L calipers changes when the sliding caliper is tightened, adding some complexity to the measurement, whereas there is no "play" in the caliper arms of the anthropometer, reducing the potential for error.

While most would expect that grossly improper technique produces clinically significant errors, an unknown addressed by the study is the alternative question: when technique is proper and devices are used correctly, is there substantial variability in measurements among the general population? Fortunately, the general population of prosthetists and orthotists appears to be quite consistent. Natural variability was noted, and appeared to be normally distributed, but was rarely clinically significant. The general results for model A versus model C are an example in which the mean error for any one measurement did not exceed 1.5 mm. This is a particularly small value when other inaccuracies associated with fabricating a prosthesis are considered, but is possibly important when monitoring volume change in a residual limb.

Results from two devices were particularly interesting. While the anthropometer was among the most accurate devices studied, it represented a disparity among the subject groups. The students in the study all had experience with the GPM anthropometer through a clinical gait analysis laboratory series. None of the practitioners had experience with an anthropometer of this sort. While several practitioners expressed a preference for the device, this disparity in experience contributed to two major results. The students were generally slightly more consistent than the practitioners, particularly in the linear measurements. Also, the outlier subject had the most problems with the instrument, suggesting improper use or reading of measurements. The second interesting device is the VAPC. This was by far the least accurate device (**Table**), and when the outlier subject was removed it was also the device that produced the least consistent measurements (**Figure 4**). No physical reason exists why these two results should be correlated. One can measure quite consistently with an inaccurate ruler. Because the VAPC failed in both accuracy and reliability, it is not recommended for documentation of anthropometrics unless users can independently verify both.

Because computer-aided design and manufacturing techniques might provide a more objective and readily available tool for the assessment of amputee anthropometrics, future research should compare the accuracy and reliability of conventional measurement techniques to digital and automated measurement techniques. In addition, the current study was not designed to provide a controlled analysis of measurement technique and the implications of different techniques, which might also be a topic for future investigation.

CONCLUSION

This study provides evidence that improper measurement technique or poor understanding of a measurement device can lead to clinically significant errors. However, when technique is proper and devices are used correctly, the general variability in measurements is not clinically significant. In the study, students were slightly more consistent than experienced practitioners; students were more consistent with linear measurements, while experienced practitioners were more consistent with circumferential measures. The following summarizes the study's observations concerning measurement techniques and measurement devices:

- Techniques:
  - For length measurements, calipers must be held parallel to the long axis of the residual limb. Small deviations produce large errors.
  - For circumference measurements, the tape measure should be wrapped around the limb in a plane perpendicular to the long axis of the residual limb. In this study, tape tension was not a significant factor in measurement error; however, more fleshy residual limbs would likely increase the importance of consistent wrapping tension.
  - For circumference measurements of a region at which the limb tapers substantially, the proximal edge of the tape, which maintains closer contact to the limb, should be used for the measurement.
- Instruments:
  - The precision of the instrument is important. If multiple scales are available on the same instrument (for example, inches and centimeters), use the scale that provides greater precision.
  - The type of tape measure used did not affect the results of this study, suggesting that tension is less important than anticipated; however, as mentioned, more fleshy residual limbs might produce a different result.
  - The VAPC used in this study was both inaccurate and unreliable.

Improvement of measurement devices and techniques has impact beyond the direct possibility of improving amputee locomotion. Anthropometry has applications in ergonomics, design of assistive devices, assessment of the impact of disease on the growth and development of children, and understanding of specific anatomical pathologies, such as musculoskeletal foot deformities, to name just a few. Improvement of measurement devices and techniques might not only improve prosthetic service but also allow the profession of prosthetics to contribute to a number of rehabilitative disciplines.

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