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ORIGINAL RESEARCH

New Device to Measure Cross-Sectional Areas and Segmental Volumes of Objects and Limbs

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Purpose: High accuracy volume measurements have important implications in different medical and non-medical situations. All methods used to date have challenges to achieve a usable clinical accuracy. Moreover, current methods have limitations to measure segmental volumes. We developed a new device that is able to measure a continuous profile of the cross-sectional areas along an object. Herewith the total volume of an object or any part of it are correspondingly determined.

Methods: The Peracutus Aqua Meth (PAM) generates continuous profiles of cross-sectional areas. Water is pumped in or out of a measuring unit at a nearly fixed flow rate and the speed of the water level (dh/dt) is measured continuously using a pressure sensor at the bottom. The change of the water level is a measure for the cross-sectional area of an object at any height. Signal processing is required to obtain valuable measurements. Three static objects and an arm of a test object were measured to demonstrate the accuracy and repeatability of the new device.

Results: Cross-sectional areas of a PVC pipe obtained with the PAM and with a caliper were compared. The differences between the two methods were less than 1.3%. Volume measurements of two mannequin arms show standard deviations of 0.37% and 0.34%, respectively, whereas the standard deviation of the volume measurement of a genuine arm was only 1.07%. These figures surpass reported clinical accuracy.

Conclusion: The new device demonstrates that determining the cross-section and its volumes of objects is possible in an accurate, reliable, and objective way. The results show that segmental volume measurements of human limbs are possible. Application in clinical and non-clinical situations seems meaningful.

Keywords: volumetric, continuous profile, local volume, usable accuracy, objective

Introduction

High accuracy volume measurements have important implications in different situations. This holds for clinical environments, sport sciences, and technical/industrial environments. Observing changes in (local) limb volume is often difficult as increments and decrements are small and long treatment or exercising periods are needed for significant changes.

The measurement of limb volume with high precision is important for early detection of peripheral fluid build-up indicating, eg, starting edemas[1–3] or examination of increased or decreased muscle mass.[4–6] Further, during the treatment of edemic patients by manual massage or recovering from an operation, it is extremely important to measure changes in volumes in order to follow the impact of the treatment.[2,7,8] Because possible fluid accumulation may move from one part of the limb to another part, local changes in volume, ie, a precise segmental analysis, can help to monitor the treatment appropriately. The same applies to the evolution of muscle recovery after limb fracture, a period of injury of a top athlete or for the assessment of the effectivity and utility of the applied strength of a training program.[5,6,9–14] Also, accurate limb

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volume and cross-sectional area measurement is important when taking measures for, eg, compression garments and tools used in rehabilitation, and for the development of, eg, space suits.[15–17]

Although volumetric measurement is important, there are challenges related to the different techniques used.[12,18–21] A measuring method should be reliable, valid, convenient, non-invasive, quick, accurate, operator independent, easy to use, objective, and economically advantageous.[3,6,7,22–25]

In this paper we describe a measuring device, the Peracutus Aqua Meth (PAM, Peracutus B.V.), for measuring volumes of differently shaped objects. A detailed technical description of the PAM and of the measuring principle are presented for this new volumetric device. The PAM utilizes water for the measurement, but it does not make use of water displacement. Instead, a cross-sectional area is determined continuously along the length of a limb/object, resulting in a profile of cross-sectional areas. The profile enables the determination of the volume of any chosen segment of the limb/object.

The first prototype of the device was evaluated by measuring arms of healthy volunteers.[26]

Materials and Methods

Measurement Principle

An object is placed vertically in a cylinder and during filling or emptying of the cylinder, the height of the water column in the cylinder is measured continuously using a pressure sensor on the bottom. Water is pumped at a nearly fixed flow rate and therefore the change of the water level is a measure for the cross-sectional area of the object at a certain height. More specifically, the cross-sectional area of an object at any height is assessed by determining the speed of the water level (dh/dt) as function of the height (h). Thus, in the presence of an object, the following calculation for the cross-sectional area (A) for each height applies

$$\text{A\_Object} = \text{A\_Container} - \text{A\_Annular}$$

and, taking the calibration into account,

$$\text{A\_Annular} = \text{A\_Container}^{*}(\text{dh}/\text{dt\_reference})/(\text{dh}/\text{dt\_measurement})$$

which results into

$$\text{A\_Object} = \text{A\_Container}^{*}(1-(\text{dh}/\text{dt\_reference})/(\text{dh}/\text{dt\_measurement}))$$

Signal Processing and Outcome

Measurement signals are processed by a state-of-the-art Analog/Digital Converter (ADC type AD7730BRZ, Elco Jacobs B.V. Eindhoven, The Netherlands). The pressure is measured with a sample frequency of 200 Hz. Then, the signal is filtered against noise (Butterworth filter) resulting in a net sample frequency of 20 Hz. The digital resolution of the pressure signal is 7,064 points per mm water column. The filtered signal is sent to a Microsoft Excel file for additional data processing. Due to mechanical vibrations which are not intercepted by the ADC-filtering, resonance effects occur and a second filter, a moving average of 10 samples, is applied to render a smoother graph.

Each set of two subsequent results (measuring points) is processed and a profile of cross-sectional areas is derived. At each height the thickness of the cylinder slice depends on the local cross-sectional area of the object. Furthermore, the volume of a slice is approximated by the derivation A_Object * dh (slice). For A_Object, the averages of the slice start and slice end values are applied. The total volume of a selected segment is calculated very accurately by integration between any two chosen positions on the object, applying linear interpolation within the first and last slices.

Peracutus Aqua Meth

The Peracutus Aqua Meth consists of a storage tank and a cylindrical measuring unit (200 mm x 1,000 mm) (Figure 1). The storage tank is provided with two capacitive level switches and a temperature sensor, ensuring enough pre-warmed water for three measurements. Water is pumped using a flexible impeller pump (Combistar 2000 A, ZUWA-Zumpe GmbH, Laufen, Germany) from the pre-warmed (30°C ± 1°C) storage tank via silicon and hydraulic tubing and two

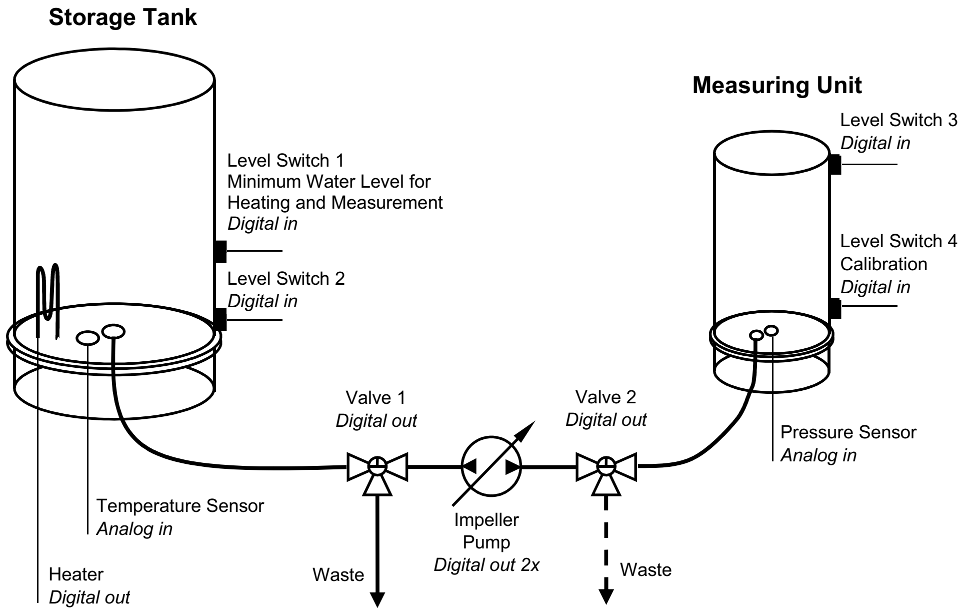

Figure 1 A schematic presentation of the Peracutus Aqua Meth.

three-way valves into the measuring unit. The pump is 3-phase alternating current fed and is regulated by frequency in terms of percentage of maximum turn frequency. The heater in the storage tank is a typical washing machine heater, 230 V and 1,950 W. All other components are electrically fed using weak current. The system is controlled by LabVIEW (National Instruments). A safety transformer (Weseman 1 phase medical transformer) is used in order to prevent electrical currents on the object.

First, the measuring unit is filled upwards till a capacitive level switch at the bottom of the measuring unit (switch 4), and the pressure (height) is set to zero (calibration level). Then, data acquisition starts while pumping water in the measuring unit with a nearly fixed flow rate of 0.35 dm^3 per second till a predetermined height regulated by the upper capacitive level switch (switch 3). The water is then almost immediately pumped out and the second data acquisition starts. Both measurements take about 1 minute. The water leaves the system via three-way valve 1 to the drain. Emptying the storage tank occurs via valve 2. Water is not reused.

During filling and emptying of the measuring unit, the height of the water column is measured using a pressure sensor (Sendosensor SS115, Elco Jacobs B.V. Eindhoven, The Netherlands) at the bottom of the cylinder.

Detrimental influence on the pressure signal is minimized by applying flow diffusing geometry: outgoing water is conducted to the perimeter of the measuring unit, declining the flow velocity and leading the water away from the sensor.

In order to validate the measuring system, profiles of cross-sectional areas of a piece of PVC pipe, the arms of two mannequins, and the arm of a voluntary test object were determined. Data acquisition for the current study was only done while emptying the cylinder.

System Characteristic

The speed of the water level (dh/dt) corresponds to the number of resolution points per measurement sample. The relation between dh/dt and h, ie, the system characteristic, in the measuring unit without an object is not constant nor linear and is depending on the outlet height of the water, container and piping geometry, temperature of the water, and pump characteristics. Therefore, a calibration is needed to determine the characteristic curve for the measuring system.

Statistics

Descriptive statistics were applied to determine means and standard deviations of the measurements.

Availability of Data

The data that support the findings of this study are available from the corresponding author, FH, upon reasonable request.

Results

Before measuring an object, the system curve (system characteristic) is determined without an object present, while pumping water out of the measuring unit in about 1 minute. The system curve is not completely equal over the full range of water levels. The system curve depends amongst others on the counter pressure in the pump, caused by the discharge height of the water column and the resistance of the water in the tubing. The ratio between highest and lowest values was less than 5% over the full range of water levels. Increased counter pressure results in a downward shift of an object profile. Further, a downward shift of 0.5 cm^2 was measured per °C increase in temperature (not shown).

The system curve is appropriately described by a second degree polynomial dh = $ah^2 + bh + c$ (dh: resolution points; h: cm). For the measurement of the piece of PVC pipe the system curve was determined from a series of five measurements. At 30°C the curve was described by dh = 0.0045 h^2 – 2.975 h – 4,828.4. Converted to cross-sectional area the signal carries a noise level of only approximately 0.5 cm^2. This curve was also used to evaluate the measurements on the arm of a voluntary test subject. As a result of adjustments in the measurement unit the system curve was repeated before measurements of the mannequin arms. It was described by dh = 0.0176 h^2 – 4.6343 h – 4,961.2, based on a series of six measurements. During the measurements the system characteristics are regarded as invariable.

A static PVC pipe with a cross-sectional area (diameter) of approximately 75 mm upon which a PVC socket and a cap were present was measured both with the PAM and with a caliper. Figure 2 shows the profile of cross-sectional areas of the pipe. Although the measurement is based on vertical movement of the water the position on the cylinder is presented on the horizontal axis; the corresponding cross-sectional areas are presented on the vertical axis. As the measurement, ie, data acquisition, was carried out by pumping water out of the measuring unit (cylinder), the time lapse is from right to left in the Figure. From the top of the pipe (right) to position 32 cm (A) cross-sectional areas of 44.2 cm^2 were measured, with a noise level of approximately 0.5 cm^2 as was seen with the system curve.

The socket on the pipe with a ring at both edges is observed between positions 32 and 23 cm. Then, between position 23 and 5 cm again cross-sectional areas of 44.2 cm^2 were observed, interrupted by some dips and peaks (H) which were caused by moving the pipe three times downwards and upwards. The response of the system was fast. As expected, the

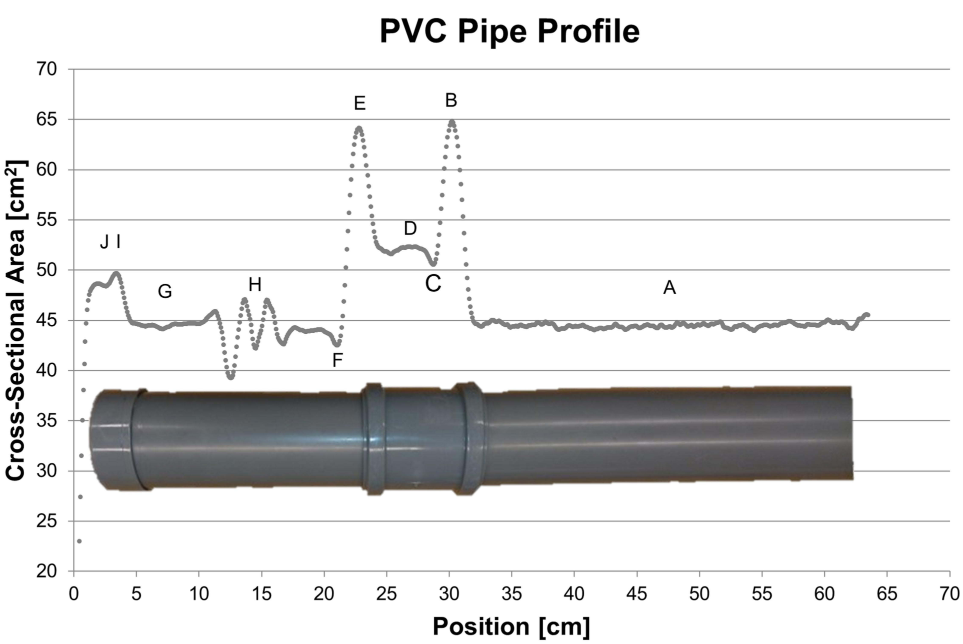

Figure 2 Profile of cross-sectional areas of a PVC pipe with socket and cap. Remarkable features in the graph are indicated (see text and Table 1 and Table 2).

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dynamic intervention resulted in fluctuations in the graph, though the integral over the specific length of the tube (profile) did not change. Finally, the tube cover is seen in the graph between positions 5 and 1 cm.

Cross-sectional areas obtained with the PAM and calculated areas from diameter measurements with a caliper were nearly equal (Table 1). As abrupt discontinuities were present on the object possible overshoot of signals, ie, the minimum/maximum peak value of the signal, was assessed. At three out of five positions the signal overshoot could be calculated (Table 2). However, the additional cross-sectional areas of about 20 cm^2 (B) and 12 cm^2 (E), respectively, of both small rings on the socket, were not wide enough to let the signal settle to its stable level and overshoot could not be quantified.

The overall filter settings as applied enables an absolute measurement of cross-sectional areas with an accuracy of less than 1 cm^2.

The same filter settings were then applied to measure arms of two mannequins, 10 times each, statically fixed in the measuring unit. The profiles of cross-sectional areas as a function of the height, ie, the position in the cylinder and thus on the fixed arm, are shown in Figure 3. The measurements were carried out by pumping water out of the measuring unit (cylinder), and therefore the time lapse in fact is from right to left in the figure. However, the graphs are described starting at the bottom of the cylinder (left), showing first the finger, hand, and the rest of the arm.

The first part of the graphs represent the no-object-zones, which in these examples are approximately between 0 (calibration level) and 8 cm and 0 and 13 cm in the cylinder, respectively. Between these positions, the noise was again

Table 1 Comparison of Cross-Sectional Areas Measured with the PAM and with a Caliper

Range (cm)		Cross-Sectional Area (cm^2)		Delta	
		PAM	Caliper[a]	(cm^2)	%
A	63–32	44.46	44.10 (0.17)	0.36	0.8
D	28–25	52.05	52.27 (0.11)	−0.22	−0.4
G	10–5	44.48	44.22 (0.24)	0.26	0.6
H	[b]	[b]	[b]	[b]	[b]
J	2.8–1.6	48.51	49.14 (0.20)	−0.63	−1.3

Notes: [a]Calculated from mean of three diameter measurements; segment A was measured at three positions (a total of nine measurements). The corresponding standard deviations are shown in parentheses. [b]Not applicable.

Table 2 Overshoot of Signals Due to Abrupt Discontinuities on the Object

Position (cm)		Cross-Sectional Area (cm^2)		Signal Overshoot	
		PAM	Caliper[a]	(cm^2)[c]	%[d]
B	30.2	64.78	64.40	[b]	[b]
C	28.7	50.53	52.27	−1.74	−14.3
E	22.8	64.13	64.28	[b]	[b]
F	21.1	42.50	44.20	−1.70	−8.5
I	3.4	49.65	49.14	0.51	10.4

Notes: [a]Calculated from mean of three diameter measurements. [b]Not applicable. [c]Delta between the peak value minus the actual value. [d]Delta between the peak value minus the actual value, relative to the step value.

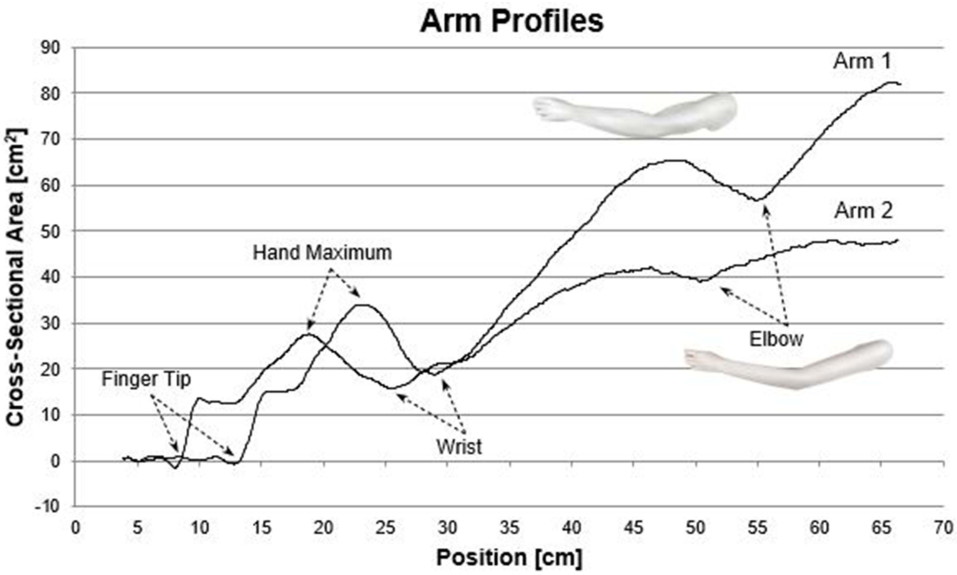

Figure 3 Profiles of cross-sectional areas of arms of two mannequins. Only the first of 10 measured profiles are presented.

approximately 0.5 cm^2. The arms were about 53 and 58 cm in the water column, and the maximum cross-sectional areas of the upper arms were around 83 and 48 cm^2, respectively.

The values in the no-object zones were slightly above the x-axis during the measurements; this must have derived from differences in system characteristics between the measurements and determining the system curve.

Mannequin arm volumes were then calculated by integration between two chosen positions on the measuring unit (Table 3). Percentage standard deviations for volume determinations were around only 0.35%.

Both mannequin arms measured do not have any abrupt discontinuities and the impact of signal overshoot is considered negligable.

A final set of measurements was performed on the left arm of a voluntary test subject. The profiles of ten consecutive measurements are presented in Figure 4. After each measurement the volunteer got up and put her arm back in the measuring unit. The ten measurements took a total of about 40 minutes. Obviously, the arm was not every time at exactly the same position (depth) in the measuring unit. All profiles were therefore aligned by setting the finger tips of all profiles at 0. The arm volume was then calculated between positions 0 and 55 cm. The mean arm volume based on the ten measurements was 2,319 cm^3 with a standard deviation of 24.90 cm^3 (1.07%).

Under the conditions used the method results in a nearly continuous measurement. The thickness of each measured slice depends on the local cross-sectional area of the arm (see Materials and Method section). During the measurements, the nearly constant flow of the descending water was 0.35 dm^3/s. Having a tube internal diameter of 189.4 mm

Table 3 Calculated Mean Volumes Between Two Chosen Positions of Arms 1 and 2

	Part of the Arm (Position in cm)	Mean Volume (mL)	Range (mL)*	Standard Deviation	
				(mL)	%
Arm 1	12.6–66.0	2393.1	32.09	8.90	0.37
Arm 2	8.0–66.0	1621.4	17.11	5.47	0.34

Note: *Difference between the largest and smallest values.

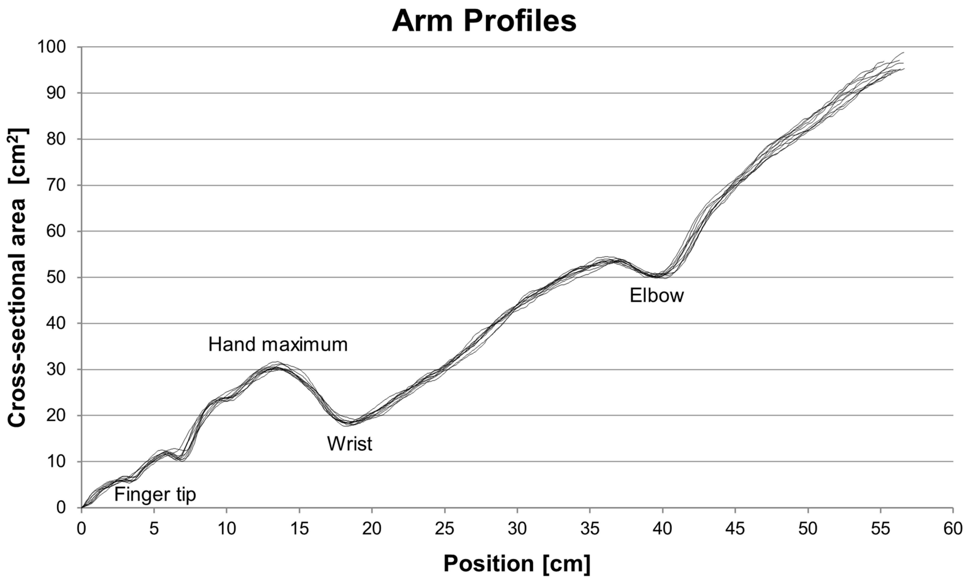

Figure 4 Ten profiles of cross-sectional areas of the left arm of a voluntary test subject. The profiles have been aligned by setting the finger tips of all profiles at 0.

(measuring unit) and a sample frequency of 20 Hz, slice thicknesses were between 0.7 mm at the fingertip to 1.1 mm at a cross-sectional area of 83 cm^2.

Discussion

Several different measuring principles are used to determine the volume of a limb or an object.[6] Water displacement with overflow is often regarded as the gold standard, mostly based on its repeatability.[1,27] With the PAM we introduce a new volumetric method using water without displacement and overflow, in which water movement determined with a pressure sensor poses as a core element. The measuring principle is based on the local cross-sectional area in a container with an object and the corresponding change in water surface level.

The system curve, which is measured in the absence of an object, is not linear nor constant. Different system curves are obtained mainly due to moving and setting up the device, whereby the outlet height of the water is especially important as it influences the counter pressure in the pump. Further, the temperature of the water may be a changing variable. The frequency needed for determining the system characteristic will in the end be depending on the robustness of the measuring system (contamination, wear of components, etc.).

Measurements with the PAM appear to be very accurate and repeatable. Cross-sectional area profiles are obtained and volumes calculated. Three static objects, a PVC pipe, and two mannequin arms were measured as examples; percentage standard deviations being around 0.35% for the arms. This is in accordance with or better than values found by others using static objects for volume measurements.[6,25,28–30] Measuring the arm of a test person resulted in a standard deviation of only 1.07% (Figure 4). This shows that also measuring limbs with the PAM can be done very accurately.

Current techniques to determine volumes locally are water displacement, girth, and caliper measurements, MRI imaging, X-ray tomography, ultrasound, and three dimensional imaging.[21,31–34] The distance between girth measurements on a limb determines the length of the segment that is used in the calculation of geometric volume. This segment length has not been standardized,[18] and varies from 1 cm,[6] 3 cm,[27,35–37] 4 cm,[6,20,25,28,38–43] 5 cm[44] to 10 cm and more and in between.[14,18,44–49] The Perometer measures a change in volume every 2.54–4.7 mm.[8,21,28,42,50,51] In contrast, the slice thickness using the PAM is 1.1 mm or less measuring an arm. This enables extreme local volume determination.

Standard methods, as well as techniques in development like three dimensional imaging, are becoming more and more suitable for clinical applications. Results obtained with the PAM are currently equal or more accurate, though compared to the different shape-capture methods. Moreover, there is no clinical learning curve involved for using the PAM and costs are very low.[23,24,32–34]

Determining (local) volumes with the girth, caliper, the Perometer, and three dimensional imaging require geometric formulas to evaluate raw data.[12,20,37,52–54] In contrast, no geometric volume formulas are used to process the data obtained with the PAM; the measurement is shape-independent.

Abrupt discontinuities on an object cause small overshoots of the signal (Figure 2 and Table 2). These dips and peaks in a profile can be completely prevented by reducing the flow rate. No or hardly any overshoot was observed while measuring the mannequin arms and the arm of a test person (Figures 3 and 4), showing that the PAM is suitable for accurate measurements of human limbs.

Results obtained with the PAM are digitally available, enabling an easy comparison with measurements done at different times. Moreover, important anatomical positions like finger tips, wrist, elbow, and upper arm can be marked. In current practice this is usually problematic and results obtained with different measuring methods, eg, girth, Bravometer, and 3D-imaging, are not interchangeable and the absolute values remain unknown. The anatomic markers present in the PAM profiles can be used to align the profiles of different measurements and to compare specific segments (intervals in the profiles) of the limb.[20]

Obtaining exact profiles with the PAM is sensitive to the extent to which the fingers are stretched during the measurement, which may lead to wrong conclusions. This can largely be overcome by the introduction of a newly-defined anatomic parameter (Houwen et al, Segmental limb profiles of cross-sectional area determination of test subjects. In preparation).

Evidence obtained so far shows the possibility of using the PAM in different applications like health care, sport sciences and technical/industrial environments to measure local volumes.

Conclusion

The PAM measures the speed of the water level (dh/dt) at any height using a pressure sensor. The data are converted to continuous profiles of cross-sectional areas with a high accuracy and repeatability. No geometric formulas are needed to process data and therefore accurate volumes are obtained of an object or any segment thereof.

Slices with a height of 1.1 mm or less are easily achieved, enabling a high resolution with respect to differences in cross-sectional area. As no abrupt discontinuities are present on a human limb the PAM is suited to determine segmental as well as total volumes of limbs.

The PAM achieves usable accuracy in clinical and non-clinical environments.

Acknowledgments

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Disclosure

FH is owner of Peracutus B.V. This company is developing a medical device to assess (local) volume changes in limbs and other objects. DvS is closely related to Peracutus B.V whereas J.S. was co-owner of Peracutus B.V. This research received no specific grant from any funding agency in the public, commercial or not-for-profit sectors. Dr Frans Houwen has a patent EP3128910B1 issued to Peracutus Holding B.V., and a patent US10895453B2 issued to Peracutus Holding B.V. The authors report no other conflicts of interest in this work.

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