POLITECNICO MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

EXECUTIVE SUMMARY OF THE THESIS

Limb Volume Measurements: a comparison of Circumferential Techniques and Optoelectronic Systems against Water Displacement

MASTER THESIS IN BIOMEDICAL ENGINEERING – BBB

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1. Introduction

Lymphoedema is a chronic, disabling, and worsening condition if left untreated, characterised by increased limb volume and fibrosclerotic tissue involution. This condition represents a serious physical and psychological disability for the patient, as well as a major social, health and economic burden.

All major international authors agree that a combination of different treatments called 'Complex physical therapy' (C.P.T.) is necessary in the treatment of lymphoedema, which allows for rapid and clear clinical results. This therapy consists of two phases: the first, called the intensive phase, aims to reduce the volume of the lymphoedema through compression bandaging, while the second, called the maintenance phase, serves to prevent the reappearance of the lymphoedema.

During the first day of treatment, the physiotherapist begins the intensive phase by performing volumetric measurements to estimate the extent of lymphoedema. To perform this measurements, direct or indirect techniques can be used. The gold standard is considered to be the direct measurement method known as water displacement, which exploits Archimede's principle to determine the volume of the limb submerged in water; however, this technique is not suitable for clinical routine, and therefore practitioners prefer to perform indirect measurements. Indirect techniques calculate limb volume from measurements of limb circumferences at various levels using a tape and applying formulas for calculating the volumes of geometric solids, to which the various limb segments are assimilated.

The most used indirect measurement techniques at international level are the fixed-heights technique, according to which limb circumferences are measured at fixed intervals, and the segmental technique, according to which the points are identified on the basis of specific anatomical landmarks. Among the various geometric approximations of the limb used by operators, the most accurate appears to be the succession of truncated cones.

A very limited number of studies on the validation and comparison of different methods for measuring limb volumes in patients with lymphoedema are available in literature to date; moreover, the data presented disagree with each other. This is attributable to the absence of a clear measurement protocol shared by practitioners at international level. Among the reviewed articles, the most promising study appears to be the one conducted by Taylor et al., comparing both the segmental and the fixed heights technique with water displacement. This stud showed a higher accuracy of the segmental technique (average error of 1,7%) than the fixed-heights technique (average error of 4,4%).

To date, none of the studies present in literature compares the data obtained on the upper and the lower limb, examines the possibility of taking measurements in orthostatism, or validate the use of optoelectronic systems.

The main objective of this thesis work is to acquire a complete set of data by means of various indirect measurement techniques, such as centimetric methods (segmental technique and fixed-height technique) and optoelectronic systems (TBM Lab's optoelectronic system at the Politecnico di Milano and IGOODI's 'the Gate' technology), and to critically compare the data obtained with the various techniques with each other and with those already found in the literature. A further objective of this thesis work is the development of an application for tablets or smartphones that makes it easier to collect data obtained by using the segmental technique, and that provides the operator with indications on how to bandage the oedematous limb.

2. Material and Methods

In the study object of this thesis work, five methods were compared: water displacement, segmental technique, fixed-heights technique, optoelectronic system, and 'the Gate' system. To make the measurements reproducible and comparable, a detailed measurement protocol was followed for each of these techniques in terms of both instruments and procedure.

With regard to the segmental technique, it was decided to follow the same protocol used for elasto-compression bandages under the supervision of Dr. G. Farina, an expert physiotherapist in this field. This protocol foresees for both the upper and lower limbs the identification of eight anatomical landmarks (figure 1). Once these points have been identified, measurements on the contralateral limb and the oedematous limb are performed in both clinostatism and orthostatism.

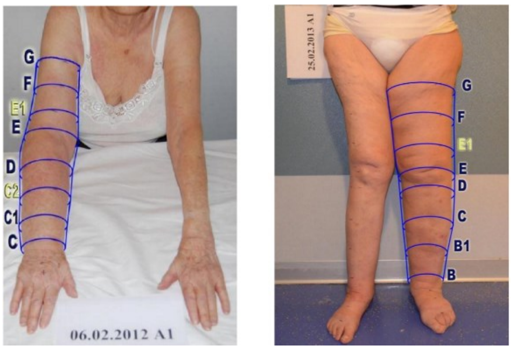

Figure 1 – Approximation of upper and lower limbs according to the segmental technique.

In the fixed-height technique, the upper limb is measured at regular intervals of 5cm, and the lower limb at regular intervals of 10cm; after the heights on the contralateral limb and the oedematous limb have been reported, measurements are again taken in both clinostatism and orthostatism.

Although optoelectronic systems are usually used to measure volume variations over time, such as in the case of plethysmography, it was considered interesting to evaluate in this thesis work whether these systems could also be accurate for obtaining static volumes, such as the volume of upper and lower limbs of patients with lymphoedema.

Since no optoelectronic system has ever been used for measuring limb volumes, it was first necessary to create new models for the application of markers. In particular, four new models were created: for the upper limb in clinostatism (41 markers), for the upper limb in orthostatism (49 markers), for the lower limb in clinostatism (46 markers), and for the lower limb in orthostatism (61 markers). It was considered to be the best choice to apply the markers at the same anatomical landmarks identified for the segmental technique.

Once the markers have been applied, their 3D coordinates are reconstructed by the Smart-DX optoelectronic system, consisting of eight infrared cameras. The volumes of the various body segments (forearm, arm, leg, thigh) are obtained automatically by Smart-Capture software following the tracking procedure (Figure 2), exploiting Gauss's theorem.

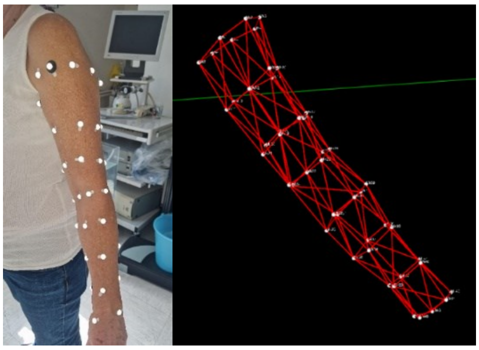

Figure 2 - Limb volume reconstruction using Smart-Capture software.

'The Gate' is a particular optoelectronic system developed by IGOODI that allows the creation of a 3D avatar through a total body scan lasting only a few seconds and performed by means of 128 cameras and height and weight sensors.

Once the avatar has been obtained, the patient's measurements will be taken directly via measurement software platform; some information, such as height and weight, will be obtained automatically, while the measurements of interest for the present study (the circumferences in accordance with the segmental technique and fixed-heights technique), can be acquired by means of a virtual tape, again via software (figure 3).

Figure 3 - Circumferential measurements taken with a virtual tape according to the segmental or the fixed-heights technique.

Measurements with direct volumetry are necessary to compare those obtained by the other techniques with the gold standard. The limb is immersed up to a certain level inside a container filled with water and the volume of water displaced by the limb is measured; the measurement is made by calculating the rise in the level of water inside the container or by collecting and measuring the water that has come out of the container after the limb has been immersed.

3. Data Analysis

A population of 22 volunteer subjects was selected for this study. 7 of them were not affected by lymphoedema, 8 were affected by unilateral upper limb lymphoedema, 6 were affected by unilateral lower limb lymphoedema and 1 was affected by both unilateral lower and upper limb lymphoedema. All the 22 subjects underwent direct volumetry and segmental technique. Due to cost, time, availability of the subject, operator, and instrumentation not all the subjects underwent the remaining measurement techniques. Specifically, 16 subjects underwent centimetric method according to the fixed heights technique, 16 subjects underwent optoelectronic system, 10 patients underwent IGOODI system.

The data were processed by using MATLAB software, through which the various measurement techniques were compared with each other and with the gold standard. Specifically, the main statistical indices (mean difference, mean percent error, 25th 50th and 75th percentile, standard deviation, linear correlation indices, p-value) were derived for each measurement method. Graphs were also constructed for a more immediate visualisation of the accuracy of the methods.

Both the segmental technique (figure 4) and the fixed-heights technique (figure 5) proved to be very accurate, slightly overestimating the volume obtained by volumetry.

With regard to the optoelectronic system, the data obtained are not satisfactory (figure 6), because of the systematic underestimation of limb volume in both clinostatism and orthostatism.

'The Gate' system is very competitive with the centimetric techniques in terms of accuracy when compared with water displacement. For all the measurements carried out using this system, the comparison with the corresponding centimetric technique showed an almost perfect match of the data (figure 7).

A summary of the main statistical indices obtained for the methods analysed is given in the table 1. All methods were compared with water volumetry, except the optoelectronic system, which was instead compared with the segmental technique.

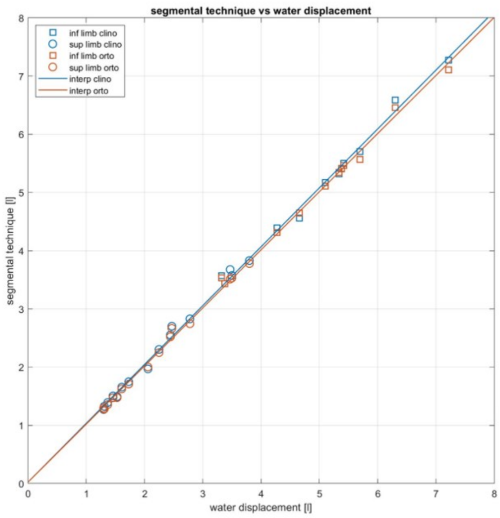

Figure 4 - Segmental technique comparison with water displacement in clinostatism (blue) and orthostatism (red).

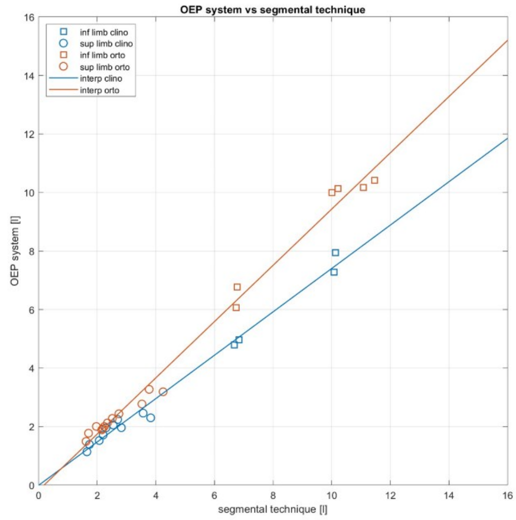

Figure 6 – OEP system comparison with segmental technique in clinostatism (blue) and orthostatism (red).

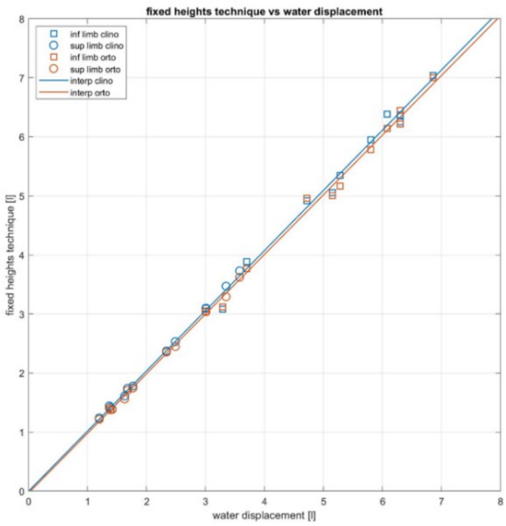

Figure 5 - Segmental technique comparison with water displacement in clinostatism (blue) and orthostatism (red).

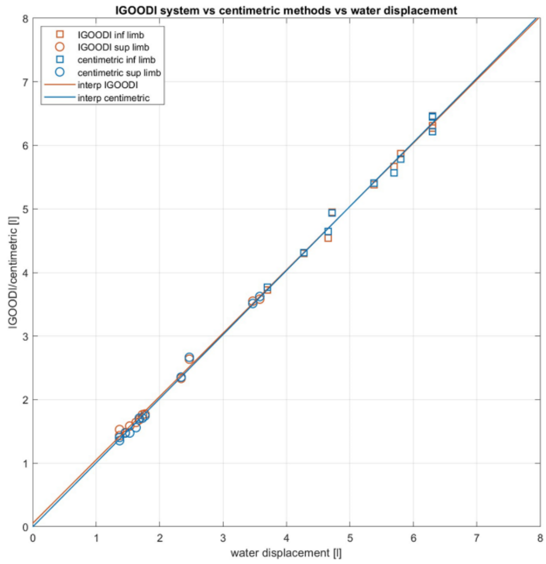

Figure 7 – IGOODI system (red) and centimetric methods (blue) comparison with water displacement.

		avg diff. [l]	avg error	25° perc.	50° perc.	75° perc.	std	m	q [l]	r²	p
SEGMENTAL TECHNIQUE	**clino**	0,06	1,78%	0,65%	1,49%	2,80%	3,00%	1,01	0,02	0,997	0,819
	ortho	0,02	0,39%	-1,20%	0,05%	0,96%	2,52%	1,00	0,02	0,998	0,934
FIXED-HEIGHTS TECHNIQUE	**clino**	0,06	1,79%	0,61%	2,62%	3,62%	2,81%	1,01	0,00	0,997	0,983
	ortho	0,00	-0,13%	-1,74%	0,59%	1,58%	2,42%	1,01	-0,03	0,998	0,983
OPTOELECTRONIC SYSTEM	**clino**	-1,11	-25,6%	-30,6%	-26,9%	-20,2%	6,72%	0,74	-0,01	0,987	0,124
	ortho	-0,37	-8,75%	-12,2%	-9,64%	-0,81%	7,52%	0,96	-0,18	0,998	0,132
IGOODI SYSTEM	**ortho**	0,04	1,80 %	0,06%	0,71%	2,62%	3,04%	1,00	-0,05	0,998	0,824

Table 1 – Main statistical indices for the analysed methods.

4. Results Discussion

Water displacement, considered the gold standard and therefore used as a method of comparison with the various methods analysed in this thesis work, proved to be difficult to use and not without possible sources of error. The main limitations identified for this measurement technique are the need for cooperation of the patient with at least two operators to hold the limb still in the correct position, the impossibility of getting an overview of the distribution of oedema in the various sections of the limb, and in most cases the impossibility of measuring the limb in its entirety, having to the stop at the nearest point immediately above the elbow or knee.

For the segmental and fixed-heights techniques, the volume measured in clinostatism is greater than the one measured in orthostatism, presumably due to tissue relaxation. The error introduced for the upper limb is slightly greater than that introduced for the lower limb, presumably due to the greater irregularity of the limb. It was hypothesised that the segmental technique would be more accurate than the fixed-height technique in cases where the fixed-height technique does not match the elbow or knee; however, data obtained are not sufficient to confirm this hypothesis.

As well as being very accurate, both methods are quick, economical, and practicable almost anywhere, require no effort by patient, allow the volume of the limb to be estimated in its entirety and give an idea of the distribution of oedema in the various sections.

For these reasons, both the segmental technique and the fixed-height technique, if performed with the appropriate measuring instruments and following a detailed protocol, can be used for routine clinical practice. The segmental technique can be considered superior to the fixed-height technique, because although the identification of the anatomical landmarks requires a longer time and more experience on the part of the operator, the data obtained with it are more comparable, allowing an algorithmic step-by-step procedure to be followed for the subsequent treatment phases.

Regarding the optoelectronic system, the systematic underestimation of limb volume in both clinostatism and orthostatism is presumably related to the approximation of the limb (the markers are connected by straight lines, thus approximating the various circumferences to polygonal and the various segments to polyhedral). In addition to not being sufficiently accurate, the measurement procedure is time-consuming, both due to the application of the markers and the tracking procedure of the acquired data, and requires a laboratory equipped with an optoelectronic system, which is very expensive.

For these reasons, the optoelectronic system cannot be used for routine clinical practice.

Being 'The Gate' IGOODI system competitive with the centimetric techniques in terms of accuracy there is therefore insufficient evidence to demonstrate whether from a purely accuracy point of view this system is better or worse than the centimetric methods. Taking measurements on an avatar instead of directly on the patient is advantageous in terms of discomfort and time required at the patient. However, taking measurements via software takes the operator a longer time. Furthermore, although the acquisition itself is very fast, the patient is still required to travel to IGOODI, where "the Gate" system is located, and the points at which measurements are to be taken following the acquisition must still be identified.

In conclusion, "The Gate" IGOODI system is competitive respect to the other procedures under investigation in this study, but it is not suitable for routine clinical practice to date, and cannot be considered superior to them, as it has no advantages that justify its use as an alternative to centimetric methods.

5. Conclusions

Among the methods analysed, only the optoelectronic system is considered unsuitable for measuring static volumes. The other methods are accurate and have a series of advantages over water volumetry that justify their use in clinical practice. However, the segmental technique is considered to be better than the fixed height technique and the IGOODI 'the gate' system, because it is comparable to the latter in terms of accuracy, but better in terms of inter-patient comparability of results.

6. 'Limb Volumes' app

Having the segmental technique proved to be the best method among the ones analysed, it was deemed interesting to start the development of a smartphone app that would support the practitioners in the acquisition of measurements according to this technique.

The aim of the app is to make it easier for the operator to take measurements and to provide guidance on how to bandage. More specifically, 'Limb Volumes' intends to meet the following requirements:

- Accelerate the data entry process, minimising possible errors in data entry through a simple and intuitive interface.
- Reduce the time needed to assess the pathology, by automatically performing a series of mathematical calculations necessary to assess the deformity of the oedematous limb with respect to the healthy contralateral one.
- Standardise intensive treatment by providing indications derived from the bandaging algorithms proposed by dr. Farina.

It was decided to develop 'Limb Volumes' with the 'App Inventor' software, which enables the development of simple applications via a pre-compiled working environment based on Scheme and Java computer languages.

To date, the application consists of three sections:

- 'Dati paziente', which allows the entry of the patient's personal, anthropometric, and anamnestic data.
- 'Misure arto superiore', which guides the operator in taking measurements and treating the upper limbs.
- 'Misure arto inferiore', which guides the operator in taking measurements and treating the lower limbs.

The application project cannot be considered finished at this stage, as it only assists the operator during the first day of treatment. In order for 'Limb Volumes' to be considered a complete application, the following specifications will have to be implemented:

- Add additional screens that allow entering the measurements taken day by day, comparing them with those obtained during the first day of treatment.
- Allow data from several patients to be stored in memory, and possibly automatically converted into documents that can be downloaded and shared directly with the patient.
- Implement graphs that provide an immediate representation of the distribution of oedema on the pathological limb and its relief during treatment.

Although these specifications have not yet been met, the application is nonetheless a useful tool to support practitioners in their clinical practice, thanks to its simple and intuitive interface, and its use allows treatment times to be reduced, while at the same time minimising errors related to measuring and bandaging procedures.

7. Bibliography

[1] Baldone C.G., Brizzi E., Castorina S., Camparini L. Anatomia umana, vol.1. Edizione Ermes 2019.

[2] Michelini S. et al., Linee Guida Italiane sul Linfedema. European Journal of Physical and Rehabilitation Medicine. 2007.

[3] Taylor R. et al. Reliability and Validity of Arm Volume Measurements for Assessment of Lymphoedema. Physical Therapy. 2006

[4] Farina G., Zappa G., Porcella E., Tacchetti G., Bartoletti R., Stasi E., Riboli A., Cappello S., Campo G. Misurazione volumetrica indiretta degli arti linfedematosi secondo la tecnica segmentaria. Giornale Italiano di Linfologia.

[5] Latchford, J.R. Casley-Smith. Estimating Limb Volumes and Alterations in Peripheral Oedema from Circumferences Measured at Different Intervals. Lymphology. 1997.