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LIMB VOLUME MEASUREMENTS: A COMPARISON OF CIRCUMFERENTIAL TECHNIQUES AND OPTOELECTRONIC SYSTEMS AGAINST WATER DISPLACEMENT

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A chi c'è sempre stato,

A chi ha creduto in me sin dall'inizio,

A chi se n'è andato.

A te che più di chiunque altro avresti voluto esserci,

A mia mamma, Gabriella

ABSTRACT

Lymphoedema is a chronic, disabling, and worsening condition, that 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. 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 water displacement; however, this technique is not suitable for clinical routine, and therefore practitioners prefer to perform indirect measurements, using the fixed-heights technique or the segmental technique.

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. The main objective of this thesis work was therefore to acquire a complete set of data by means of various indirect measurement techniques, such as centimetric methods and optoelectronic systems, 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.

A summary of the main statistical indices obtained for the methods analysed is given in the table 0. All methods were compared with water volumetry, except the optoelectronic system, which was instead compared with the segmental technique.

		avg diff. [l]	avg error	25° perc.	50° perc.	75° perc.	std	m	q [l]	r^2	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 0 – Main statistical indices for the analysed methods.

ABSTRACT IN ITALIANO

Il linfedema è una condizione cronica, invalidante e degenerativa, che comporta una grave disabilità fisica e psicologica per il paziente, nonché una limitazione sociale ed un impegno economico. Tutti i principali autori internazionali concordano sul fatto che nel trattamento del linfedema sia necessaria una combinazione di diversi trattamenti, chiamata "Complex Physical Therapy" (C.P.T.), che consente di ottenere risultati clinici rapidi ed evidenti. Durante il primo giorno di trattamento, il fisioterapista inizia la fase intensiva eseguendo misurazioni volumetriche per stimare l'entità del linfedema. Per effettuare tali misurazioni si possono utilizzare tecniche dirette o indirette. Il gold standard è considerata la volumetria ad acqua; tuttavia, questa tecnica non è adatta alla pratica clinica di routine e quindi gli operatori preferiscono eseguire misurazioni indirette, come la tecnica delle altezze fisse o la tecnica segmentale.

In letteratura si riscontra un numero molto limitato di studi sulla validazione e il confronto dei diversi metodi di misurazione del volume di arti in pazienti affetti da linfedema. L'obiettivo principale di questo lavoro di tesi è pertanto quello di acquisire una serie completa di dati attraverso varie tecniche di misurazione indiretta, come i metodi centimetrici e i sistemi optoelettronici, e di confrontare criticamente i dati ottenuti con le varie tecniche tra essi e con quelli già presenti in letteratura. Un ulteriore obiettivo di questo lavoro di tesi è lo sviluppo di un'applicazione per tablet o smartphone che faciliti la raccolta dei dati ottenuti con la tecnica segmentale e che fornisca all'operatore indicazioni su come bendare l'arto edematoso.

Una sintesi dei principali indici statistici ottenuti per i metodi analizzati è riportata in tabella 0. Tutti i metodi sono stati confrontati con la volumetria ad acqua, tranne il sistema optoelettronico, che è stato invece confrontato con la tecnica segmentaria.

		avg diff. [l]	avg error	25° perc.	50° perc.	75° perc.	std	m	q [l]	r^2	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
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IGOODI SYSTEM	**ortho**	0,04	1,80 %	0,06%	0,71%	2,62%	3,04%	1,00	-0,05	0,998	0,824

Tabella 0 – Principali indici statistici per i metodi analizzati.

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1 – INTRODUCTION

1.1 – LYPMHATIC SYSTEM

The lymphatic system (figure 1) is a complex of capillaries, lymph vessels and organs within the body that guarantee the circulation of lymph, which is a fluid that fills the interstices between body cells, and it is composed by an aqueous part and a corpuscular part, mostly represented by lymphocytes [1].

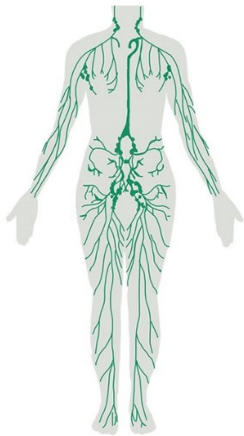


Figure 1 - Lymphatic system.

The main functions of the lymphatic system are:

- Draining: the lymphatic system drains all excess liquids and waste substances from the tissues.
- Metabolic: the lymph enables the absorption of triglycerides.
- Immunologic: the lymph nodes filter the lymph, blocking the transmission of pathogens and in many cases cancer cells.

In particular, the tissue drainage function prevents the dangerous stagnation of fluid. When this function fails, due to injury or dysfunction of the lymphatic system, lymph tends to stagnate and accumulate in the tissues. This condition is called lymphoedema, an oedema of lymphatic nature [2].

1.2 – LYMPHOEDEMA

According to the International Society of Lymphology (ISL), lymphoedema (figure 2 and 3) is an external and/or internal manifestation of lymphatic system insufficiency and deranged lymph transport, or, more simply, a symptom or sign resulting from underlying lymphatic disease [3].

Figure 2 - Lower limb lymphoedema.

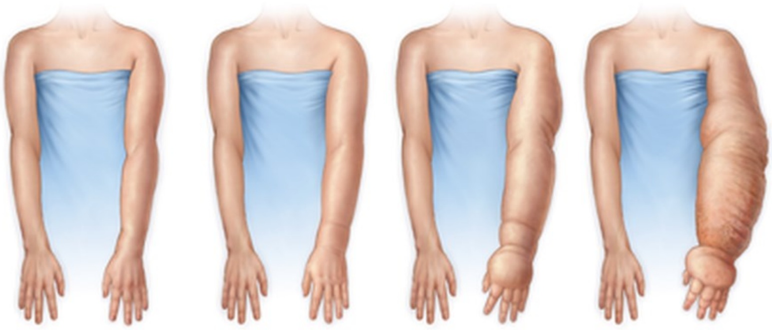


Figure 3 - Upper limb lymphoedema.

Epidemiological data from the World Health Organization (WHO) report that 300 million cases of lymphoedema are registered worldwide. In Italy, about 350.000 people suffer from this pathology and there are about 40.000 new cases every year, mainly women between the ages of 30 and 40. It is therefore a widespread pathology, with an evolving, disabling, and progressive character [4].

Lymphoedema is clearly manifested by chronic swelling of a limb, in 42% of cases involving the lower limb, involving the entire limb or only the proximal or distal portion. It also affects the upper limbs, face, genitals, and trunk. Generally, lymphoedema is asymmetrical, in which case one limb appears visibly more oedematous then the contralateral. Depending on the severity of the related pathological condition, this swelling may be more or less significant, ranging from mild to elephantiasis.

Lymphoedema can be primary or secondary [5, 6, 7]:

- Primary or congenital lymphoedema appears early in life and is a clinical manifestation of a defect in the lymphatic vessels or nodes. It is the least frequent cause of lymphoedema [8].
- Secondary lymphoedema is mainly due to damage to the lymphatic system caused by neoplasia, surgery, trauma, infection, or radiotherapy, leading to obstruction or disruption of the system. It is more often a consequence of malignancy or malignancy-associated treatments and a significant cancer survivorship problem. It is absolutely the most frequent cause of the disease and an analysis of the data in the literature shows that the incidence of secondary lymphoedema, despite improvements in surgical and radiotherapy techniques, remains high, about 20-30% of patients, either immediately or a few years after the surgery; this percentage can reach 60-80% when it is followed by radiation treatments [4, 6, 9, 10, 11].

Lymphoedema is thus manifested by an increase in the volume of the limb, which appears swollen. Other complications are associated with this pathology, such as the alteration of skin colour that tends to discolour and become hard if not adequately treated. Usually, the patient does not report pain, but difficulty in moving or flexing the affected limb and a constant perception of heaviness and constriction that may increase to the level of becoming disabling in daily actions, such as walking or driving [11, 12].

1.3 – TREATMENT

Lymphoedema therapy is divided into conservative and operative methods. Conservative therapy is considered the gold standard and studies on operative methods, which require surgery, have not shown better results than conservative therapy, and are only used if the latter has failed [13, 14].

Conservative therapy aims to reduce interstitial fluid, thereby improving lymphatic drainage and preventing progression to higher stages. For this purpose, Complex Physical Therapy (CPT) was developed. It provides a two-stage programme that can be applied to both adults and children for most areas of the body. The first phase, also called intensive phase, aims to reduce the volume and consistency of oedema through the compression bandage (figure 4), a technique which consists of overlapping layers of different material to deeply compress the treated tissues, while the second phase, also called maintenance phase aims to prevent the reappearance of oedema [15].

Figure 4 - Example of compression bandage for upper limbs for the intensive phase of lymphoedema therapy.

1.4 – VOLUMETRIC MEASUREMENTS

During the first day of treatment, the physiotherapist begins the intensive phase by performing a series of assessments such as volumetric measurement of the limbs, measurements of tissue consistency, weight measurement and photographic detection.

For the volumetric measurements, direct and indirect techniques can be used. The gold standard is a direct technique called water displacement, which directly measures the volume of the limb submerged in water. Indirect techniques calculate limb volumes from an accurate measurement of 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 [16, 17, 18].

Evaluation of the effectiveness of treatments for lymphoedema requires an accurate and easy-to-use method for the calculation of limb volumes. The most widely accepted measure of lymphoedema is the comparison between the volumes of the oedematous limb and the unaffected one, or between the oedematous limb before and after the intervention or the event that led to lymphoedema. Volumes are most accurately measured by water displacement, although this method is not convenient for routine clinical use, and most operators choose to perform indirect measurements [19].

1.4.1 - DIRECT MEASUREMENT TECHNIQUES

Water displacement (figure 5) is considered the gold standard. It is a direct technique based on Archimede's principle, according to which the volume of water displaced by an object is equal to the volume of the object itself. The limb is submerged up to a certain level inside a container filled with water and the volume 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 [16, 17, 20].

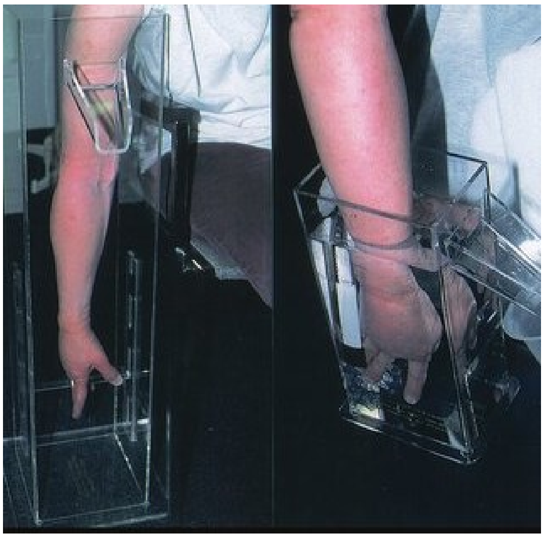


Figure 5 - Water displacement method

A review of the literature shows that this technique is simple, repeatable, non-invasive, very accurate and has good reproducibility, high accuracy, and high intra- and inter- operator reliability [16, 17, 20, 21, 22].

However, this method has some limitations: an accurate measurement requires a lot of time, adequate space, and a rather high cost, due to the hight water consumption, it requires considerable cooperation from the patient, especially in holding the limb still, cannot be used in case of major functional limitations, in which case the correct positioning of the limb in the container is too onerous, and requires careful hygiene of materials and disinfection of the container between patients. Moreover, it provides an estimate of the volume of the entire submerged limb segment but does not give an indication of the spatial distribution of oedema. These difficulties make water displacement unsuitable for routine use in clinical practice [23].

1.4.2 - INDIRECT MEASUREMENT TECHNIQUES

Indirect techniques calculate limb volumes from an accurate measurement of limb circumferences at various levels using a tape measure, but with a margin of error compared to direct volumetry; the more the shape of the various limb segments deviates from that of the geometric figure on which the formula is based, the grater the error will be [24];

The most used indirect measurement techniques at international level are:

- Fixed heights technique [23, 25]: limb circumferences are measured at fixed intervals of 5 cm for the upper limbs and 10 cm for the lower limbs. Although this method is very quick to perform, as it does not require the identification of anatomical landmarks, it does not allow easily comparable data to be obtained, as the measuring points are located differently in each patient, anatomically speaking. This does not fully satisfy practitioners of lymphoedema therapy, who require lymphoedema monitoring and assessment on constant measurement points in proportional terms, such as to facilitate the identification of recurring dysmorphic conditions on which a predefined compressive action can be developed.
- Segmental technique [23, 25]: this method identifies the points on which to take circumferential measurements, constant in proportion, using a procedure for fractions of the various heights/lengths. This procedure involves dividing the forearm and the leg into four equal parts, as well as the arm and the thigh, so that eight detection points are identified for both the lower and the upper limb. The segmental technique is therefore more time-consuming than the fixed height method, but it allows for more easily comparable data, and thus meets the needs of physiotherapists to a greater extent.

Among the various geometric approximations of the limb used by operators, the most accurate appears to be the succession of truncated cones (figure 6). The volume of a segment between two adjoining measured segments is computed by assuming a truncated cone; total limb volume is computed by summing the volumes of the single cones [24].

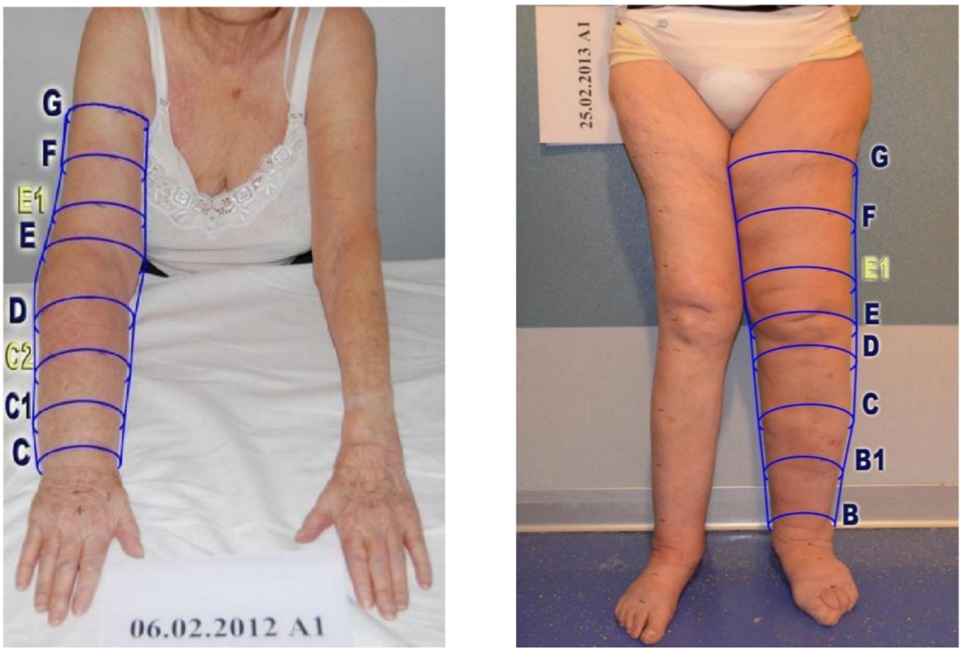


Figure 6 - Example of indirect measurement, in particular the segmental technique. In blue is shown the approximation of the upper and lower limb to a succession of truncated cones, the volumes of which will be obtained analytically.

The main reason why volumes calculated from anatomic landmarks are more accurate than volumes calculated from fixed heights is hypothesized to be that the latter method often involves a segment across the elbow or the knee joint, which are not conical in shape, and because the length of limbs are different in every patient [23].

These measurements have the advantage of being quick, cheap, and performed with readily available tools, and allow to highlight the distribution of oedema by comparing measurements of different limb segments.

1.5 – STATE OF THE ART

A very limited number of studies on the validation and comparison of various methods of measuring limb volumes in patients with lymphoedema are available in the literature to date; moreover, the data presented in the various studies are often incomplete and with conflicting results. This is attributable to the absence of a clear indirect measurement protocol shared by practitioners at international level.

A systematic literature review was conducted by Hidding et al. [26] on the basis of 50 studies comparing various methods of limb volume measurement in lymphoedema patients. Of these studies, 8 compare centimetric methods and water volumetry; in particular, all the studies deal with the fixed-height technique, but only one also deals with the segmental technique.

This review shows an average error of 6.6% when comparing data obtained from indirect measurements with those obtained from direct measurements; However, the data reported in the individual studies taken into consideration are very different from each other, since they were obtained following different measurement protocols in terms of distance between the various measuring points (5cm 8cm or 10cm), geometric approximation of the limb (single truncated cone, succession of truncated cones or succession of discs), experience of the operator (physiotherapist expert in the field, nurse or the patient himself) and positioning of the patient (sitting or lying down, although always with the limb in clinostatism).

Among the reviewed articles, the most comprehensive study with the most promising results appears to be the one conducted by Taylor R. et al. [23] on a heterogeneous group of 66 patients with or without upper extremity lymphoedema, comparing both the segmental technique and the 5cm height-fixed technique with water displacement. This study showed a higher accuracy of the segmental technique (average error of 1.7%) than the fixed-height technique (average error of 4.4%). However, no indications are given regarding the positioning of the patient and how the tape measure should be used (where it should be positioned in relation to the point at which the circumference is to be measured and how far it should be drawn by the operator when measuring).

A further study with satisfying results appears to be the one conducted by Deltombe T. et al. [24] on a group of 30 women with upper extremity lymphoedema. This study showed an average error of 3.1% when using the fixed-height technique compared to direct volumetry. Again, there are no indications on patient positioning and how to use the tape measure.

None of the studies analysed compares the data obtained on the upper and the lower limb, or examines the possibility of taking measurements in orthostatism, thus with the same positioning used for water displacement.

Furthermore, to date no validation studies of the use of optoelectronic systems - typically used to measure changes in volume (plethysmography) or movement (motion analysis and functional assessment) - for measuring static volumes such as limb volume in patients with lymphoedema are available.

1.6 – AIM OF THE THESIS

As introduced in the previous paragraphs, all major international authors agree in considering necessary in the treatment of lymphoedema a combination of different therapies called Complex Physical Therapy (CPT), through which it is possible to obtain rapid and evident clinical results. It should be noted, however, that the success of CPT is strictly dependent on the clinical experience of the operator, and that this wealth of knowledge has not yet been fully translated into clear and unambiguous indications that would favour their reproducibility and not mislead the operator, and at the same time favour the acquisition of predictable and reproducible results [22, 23, 24].

Studies prior to this thesis work, conducted by Dr. Farina G., a physiotherapist expert in lymphology and lymphoedema treatment, in collaboration with Politecnico di Milano, led to the development of a protocol for indirect measurement of both upper and lower limbs in patients with lymphoedema, based on the segmental technique with approximation of the limbs to a succession of truncated cones [25]. This protocol is innovative for two reasons: it presents detailed indications for taking measurements in both clinostatism and orthostatism, and involves the use of a flexible tape measure to the ends of which two dynamometers are connected, thus making the traction exerted on it controllable and reproducible in the various measurements.

The main objective of this thesis work is to validate this protocol by comparing the data obtained using the proposed segmental technique with water volumetry, considered the gold standard, with the fixed-height technique, the most widely used by practitioners, and with data found in the literature.

It was also deemed interesting to perform a validation of the use of two optoelectronic systems for measuring limb volumes. The first optoelectronic system is the one equipped in the TBM Lab of Politecnico di Milano, used for plethysmography and motion analysis, and the second is "the Gate" device, commercialized by IGOODI for the creation of avatars in virtual reality.

This study is intended to be more exhaustive than those found in literature, as it presents data obtained using highly reproducible protocols according to all previously reported methodologies, reporting a critical comparison between clinostatism and orthostatism, between upper and lower limb, and between centimetric methods, water volumetry and optoelectronic systems.

For those methods for which it is possible, it was decided to take the same measurements both in orthostatism, with the patient in bipodal support, and in clinostatism, with the patient lying on a couch. This choice is justified by the fact that both measurement methods are used in physiotherapy; in particular, taking measurement for the clinical evaluation of the limb volume, both before and during the treatment, is usually performed in clinostatism, while taking measurements for the realisation of compression braces, which the patient will have to wear during the treatment period, is usually performed in orthostatism.

A further objective of this thesis work is the development of an app for tablets and 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, based on algorithms once again proposed by Dr. Farina.

2 – MATERIAL AND METHODS

The following chapter will present in detail all the tools that were used for the thesis work. The chapter is divided into four main sections:

- Centimetric methods: segmental and fixed-heights techniques.
- Direct volumetry: water displacement technique.
- Optoelectronic system: Smart-DX motion capture system.
- IGOODI: "The Gate" technology.

2.1 – CENTIMETRIC METHODS

As mentioned in the introductory chapter, centimetric methods involve measuring limb volumes by approximating them to a succession of solid geometric elements, in particular truncated cones, of each of which the lower circumference, the upper circumference and the distance between the two (the height of the limb) are known. The total volume of the limb will be approximated by the sum of the volumes of the solids that model it. The volume of a truncated cone can be analytically derived using the following formula:

$$V = \frac{\left(C_s^2 + C_i^2 + C_s \cdot C_i\right) \cdot h}{12\pi}$$

Where V is the volume of the truncated cone, C_s is the upper circumference, C_i is the lower circumference and h is the height of the solid.

Traditionally, only a tape measure is used for taking measurements with centimetric methods, and the points of interest are highlighted using a simple pen or marker. However, for the present study, it was decided to take measurements with different instruments, according to the protocol proposed by dr. Farina, which would reduce intra- and inter-operator variability.

The instrumentation (figure 7) is as follows:

- Rigid folding plastic tape measure for measuring the lengths of various body segments and distances between consecutive measuring points. Choosing to use a rigid tape measure instead of a pliable tape measure avoids limb surface irregularities influencing length and distance measurements.
- Tape measure equipped with a sliding dynamometer, to detect circumferences at the target points. The presence of the dynamometer allows a controlled traction to be applied to the tape measure in terms of force, which must be sufficient to keep the tape in traction, but not excessive enough to compress the patient's limb.
- Thin pen, to highlight points of interest where circumferences have to be measured. The use of a fine pen allows greater precision in drawing marks on the patient's limb.

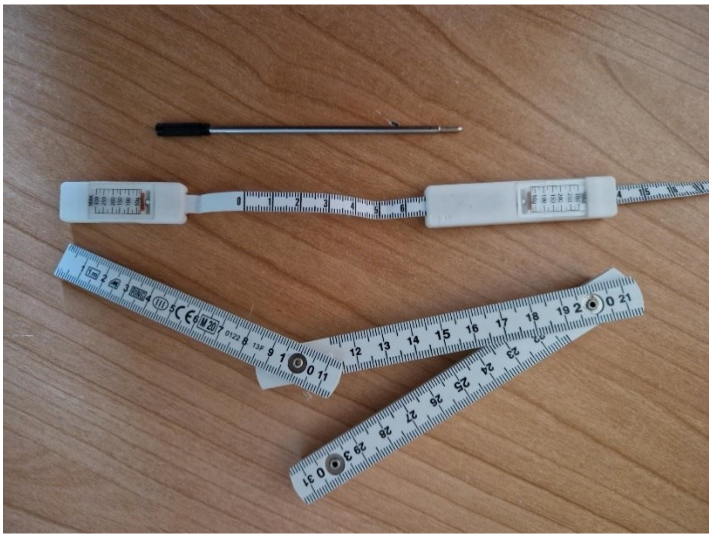


Figure 7 - Instruments for centimetric measurements: thin pen (top), tape measure with sliding dynamometer (middle), rigid folding plastic tape (bottom)

Both the fixed heights method and the segmental technique will be analysed in detail below, as both are used in physiotherapy today.

2.1.1 – SEGMENTAL TECHNIQUE

Lower limbs [25]

The patient is laid on a couch in a supine position and, starting from the eumorphic limb, point measurements are taken using a tape measure.

The first point measured is **point B** (figure 8), or the narrowest point at supramalleolar level. A mark is drawn over the tape measure on the side of the leg.

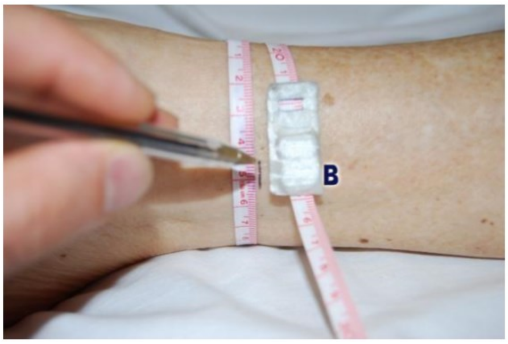


Figure 8 - point B detection using the tape measure.

Point D (figure 9), or the point below the styloid apophysis, is measured by bending the limb at 90° and by placing the tape measure transverse to the longitudinal axis of the segment at the level of the superior-posterior III of the leg at the medial popliteal fossa. A mark is drawn below the tape measure on the side of the leg.

Figure 9 - Point D detection using the tape measure.

Point E (figure 10), or knee is measured by bending the limb to approximately 30° and by placing the tape measure at the level of the inferior-posterior III of the leg at the lateral popliteal fossa. Then, extending the limb, a mark is made under the tape measure on the side of the leg.

Figure 10 - Point E detection using tape measure.

For the measurement of **point C** (figure 11), or the bulkiest point of the calf muscle, the patient is placed in an orthostatic position with the limbs extended ad spaced at pelvic height. The folding ruler is then placed parallel to the longitudinal axis of the leg with the initial part placed on the ground and the upper part placed along the boundary of the medial gastrocnemius from the lateral gastrocnemius. The distance between the lower support point at the gastrocnemius and the upper point at which the tape measure was separated from it is measured. Finally, the mean value of this distance is calculated, and a mark is drawn directly on the lateral part of the leg in correspondence to this measurement.

Figure 11 - Point C detection.

Given the impossibility if objectively identifying the insertion of the gastrocnemius, unless assessed by ultrasound, **point B1** (figure 12), or insertion point of the lower calf muscle, is identified as an intermediate point between point B and point C.

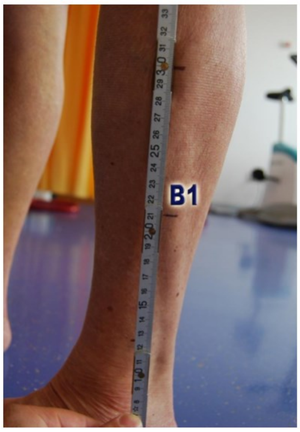


Figure 12 - Point B1 detection.

Leg length can be calculated as the difference between the height of point E (the knee), and the height of point B (the ankle).

Once the leg measurement has been completed, the thigh height is measured, starting with the detection of **point G** (figure 13), or gluteal fold. To determinate the latter, the tape measure is placed transverse to the axis of the segment at the gluteal fold. A mark is made under the tape measure in the lateral thigh area.

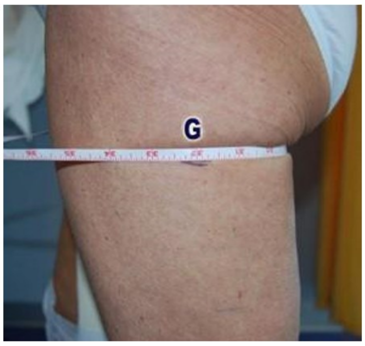


Figure 13 - Point C detection using tape measure.

The height of the thigh is measured by placing the folding rule parallel to the axis of the segment, measuring the distance between point E and G. Dividing this height into three equal parts, the intermediate **points E1 and F** (figure 14) are identified and traced: E1 is located at 1/3 of the thigh height and F is located at 2/3 of the thigh height.

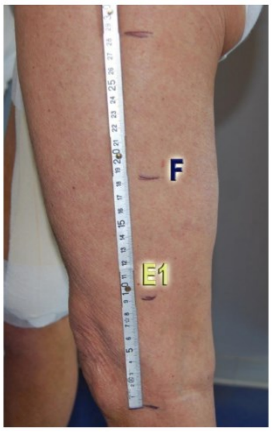


Figure 14 - Points E1 and F detection

Once the operation on the pathological limb is completed, the heights are replicated on the healthy contralateral limb.

Once all the anatomical landmarks have been identified, circumference measurements are taken either in clinostatism and in orthostatism. In both cases, it is important that the lower limbs are perfectly extended, but not in hyper-extension at the knee level, and that they are distanced pelvis height.

Upper limbs [25]

Measurements of the upper limb are performed by first placing the patient in an orthostatic position with the eumorphic limb lying along the hip. The limb is then slightly abducted so that the tape measure could be placed inside the axillary cavity. By drawing a mark under the tape measure, **point G** (figure 15) is identified.

Figure 15 - Point G detection using tape measure.

Next, the patient is placed lying on a couch with the eumorphic upper limb abducted 45° fully extended and resting. Assuming this position, **point C** (figure 16), or wrist, is identified on the flexor surface of the forearm, between the hypothenar and thenar folds and a mark is traced.

Figure 16 - Point C detection.

Once point C has been identified, **point E** (figure 17), or elbow, is located by flexing the forearm on the arm by approximately 90° and drawing a mark on the flexural surface at the cubital fold.

Figure 17 - Point E detection.

The length of the forearm is measured from point C to point E by extending the limb again with the hand in line with the axis of the forearm and this length is divided into four equal parts to identify the following points: **point C1** (figure 18) placed at 1/4 of the height of the forearm from point C; **point D** (figure 18), or bulkiest point of the forearm, placed at 3/4 of the height of the forearm from point C; **point C2** (figure 18), or intermediate point between points C1 and D, placed at 1/2 the height of the forearm.

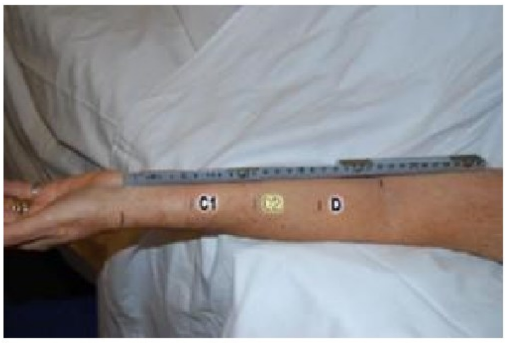


Figure 18 - Points C1, C2 and D detection.

Finally, the length of the arm is measured from point E to the previously measured point G and divided into three equal parts on which the points to identify the following points: **point F** (figure 19), or intermediate point of the arm, placed at

2/3 of the height of the arm from point E; **point E1** (figure 19) or intermediate point between E and F placed at 1/3 of the height of the arm from point E.

Figure 19 - Points E1 and F detection.

Once the operation on the pathological limb is completed, the heights are replicated on the healthy contralateral limb.

Once all the anatomical landmarks have been identified, circumference measurements are taken either in clinostatism and in orthostatism. In both cases, it is important that the arm is abducted 45° and fully extended, but not in hyper-extension at the elbow level.

2.1.2 – FIXED HEIGHTS TECHNIQUE

The fixed heights technique requires a much simpler procedure than the segmental technique. For both the lower limb and the upper limb, the points where the circumferences are to be measured are identified in clinostatism, with the patient positioned as described in the previous section about the segmental technique. For the **upper limbs**, a mark is drawn every **5 cm**, starting from the hypothenar fold and ending as close as possible to the axillary cavity; for the **lower limbs**, marks are drawn every **10 cm** starting from the floor and ending as close as possible to the gluteal fold.

Once the points of interest have been identified, the circumferences are measured in both clinostatism and orthostatism, again in the same manner as for the segmental technique.

For both the lower limb and the upper limb, either if using the fixed heights technique or the segmental technique, it is essential that when taking measurements, the operator is positioned in front of the point whose circumference is to be measured. The tape measure must be positioned perpendicular to the axis of the segment of interest, so that the two ends are one above and one below the previously traced mark. For the tape to be correctly stretched, the operator must exert a force of 25g on both ends (figure 19).

Figure 20 – Operator using tape measure.

2.2 – DIRECT VOLUMETRY

As mentioned in the introduction, water displacement is considered the gold standard for measuring volumes of body segments. The technique is based on Archimedes' principle, according to which the volume of water displaced by a body immersed in it is equal to the volume of the body itself.

During the studies object of this thesis, the following instrumentation was used to perform direct volumetric measurements:

- Container of size 60 cm x 25 cm x 35 cm (figure 20), thus containing a volume of 57 L of water, filled up to the spout from which the water flows out when the limb of interest is immersed.
- Bucket for collecting water (figure 20), positioned below the spout.
- Graduated container (figure 20), with a maximum capacity of 1L, used for measuring the volume of water flowing out from the container following the immersion of the body segment of interest.

Figure 21 - Strumentary for water displacement measurements.

The container is filled with water at room temperature; this is essential so that the patient does not undergo vasoconstriction or vasodilation, phenomena that could lead to changes in the volume of the limb, in particular reducing its volume in the first case and increasing it in the second one [16].

For a correct measurement of the volume of the segment of interest, it is necessary for the limb to be immersed very slowly in water, to avoid creating fluid displacements that would invalidate the measurement. It is also essential that the segment of interest is immersed perpendicularly to the ground and kept stable once it has reached the predetermined level [16]. To do this, whenever possible measurements were always taken by two operators, one holding the patient in position and the other verifying that the limb was immersed to the desired height (figure 22).

Figure 22 - Operator holding patient's limb still.

Lower limbs

Volumetric measurements by water displacement can be particularly onerous in the lower limbs, especially in elderly, overweight or physically debilitated patients.

First, the patient is asked to sit on the couch, which is raised as high as possible, and the foot is submerged in water up to the 10 cm mark, if the volume is for comparison with the fixed-height technique, or up to point B, if the comparison is with the segmental technique. The limb is held in position until the water stops flowing out of the container (figure 23). The volume of water flowing out can be measured to obtain the volume of the foot; however, as this is not the subject of the present study, this volume is simply removed.

Figure 23 - Foot volume removal with water displacement technique.

Afterwards, the patient is asked to stand up. The patient should only stand on one limb, the one contralateral to the limb to be immersed in water. Since it is impossible to fully immerse the lower limb due to the size of the container, in the current study we have always tried to immerse the limb at least up to the first available point above the knee (the E1 point in the case of comparison with the segmental technique, or the 50 cm point in most cases for comparison with the fixed height technique). The choice of never stopping before the knee is dictated by the fact that the latter is the portion with the most irregular shape, and therefore the one on which the other measurement techniques could deviate the most from the volumetry.

To make the measurement as easy as possible, the patient is placed on a height-adjustable platform positioned next to the container so that he does not have to balance on a bending limb. Again, the patient is held as still as possible with the limb submerged up to the level of interest until the water stops leaking out of the container (figure 24). When the liquid stops flowing out, the volume is measured using the graduated container.

Figure 24 - Patient standing on the adjustable platform with the oedematous limb submerged in water up to the point E1.

Upper limbs

Volumetric measurements for the upper limbs are easier than for the lower limbs, because the patient is not required to balance in a monopodalic stance, but can position himself either standing or sitting, as it is most comfortable for him, with the trunk in flexion so as to allow the immersion of the limb whose volume is to be measured.

The measurement procedure is similar to that described for the lower limb: first, the hand is immersed up to the wrist, identified by the C1 point for the segmental technique or by the 0 cm height for the fixed height technique, which is held in position until the water stops flowing from the container; this amount of water, representative of the volume of the wrist, is removed. Then, the limb is immersed in the container, entirely if possible, or if this is not possible up to the highest available point above the elbow; the fluid that is expelled from the container during the immersion is measured and is representative of the volume of the upper limb up to the height of interest (figure 25).

Figure 25 - Procedure for measuring upper limb volumes with water displacement technique.

Either for the lower limb or the upper limb, if on the same patient the volumetry is to be compared with both the segmental technique and the fixed-height method, the procedure is carried out in a larger number of steps, measuring the volumes of individual segments, and then adding them up. For example, if, on the same patient we wanted to measure the volume of the lower limb between point B and point E1, and between 10 cm and 50 cm, and assuming that point B is below 10 cm and point E1 is above 50 cm, first the ankle will be immersed up to point B, and the volume coming out of the container will be discarded, then the limb will be inserted first up to height 10 cm, then up to 50 cm, and finally up to point E1. The volume of the limb between 10 cm and 50 cm is then measured in a single measurement, while the volume of the limb between point B and point E1 will be obtained as the sum of the 3 measured volumes.

2.3 – OPTOELECTRONIC SYSTEM

3D stereophotogrammetric systems, or optoelectronic systems, are devices that use stereo imaging technology to detect three-dimensional positions of objects or surfaces. In the clinical field, these devices are used for a variety of applications, including plethysmography and motion analysis. Specifically, these systems utilise cameras that project an infrared beam into their field of view and acquire data from reflective landmarks attached to the subject, which refract the beam projected by the cameras. Once the infrared beam is refracted by the markers, the cameras are able to follow their movements by describing through special analysis software all the kinematic characteristics of the motion [27].

The positioning of the cameras describes a volume within which movement can be analysed, and the analysis volume is the "lowest common denominator space" of each camera's field of view. The markers applied on the subject are said to be "passive" when they do not have their own light and reflect the infrared light from the cameras, while they are said to be "active" when they illuminate themselves; the placement of the markers on the subject's landmarks is done manually. The way in which the markers are applied is called a "model"; there are many of them in the literature, but some analysis require protocols that have not yet been studied, so the placement of markers is customised [27].

In order to calibrate the acquisition zone that the cameras can capture, specific methods are used; most systems require two types of calibration, one static and one dynamic. Static calibration is performed through the acquisition by the cameras of a calibration tern, representing the three axes of motion and positioned in the acquisition area, while dynamic calibration is performed through a wand of known dimensions that is moved within the acquisition volume of the cameras. Both the triad and the calibration wand are composed of passive reflective markers, whose relative distance is known by the acquisition system. The more precise and accurate the calibration process, the better the analysis will be in terms of accuracy and error reduction [27, 28].

For the position of a marker, whether on the subject or in the reference system for calibration, to be reconstructed with 3D co-ordinates, it is essential that it is "seen" by at least two cameras. When a single marker is seen by two or more cameras, its position, defined by the three-dimensional coordinates in the reference system of the laboratory, can be calculated by stereophotogrammetry, being known the position, orientation, and the internal parameters of each camera [28].

Once the 3D coordinates (X, Y, Z) of the different markers are acquired with reference to an arbitrary coordinate system, a closed surface is defined by connecting the points to form triangles (each marker is one point of the mesh of triangles). For each triangle, the area (A_i) and the direction of the normal of the plane defined by that triangle are determined [28].

Successively, the internal volume of the shape is computed using the Gauss' theorem. Let S be a closed surface enclosing the volume V, and let F be a vector field defined at every point of V. Then:

$$\int_S \vec{F} \cdot \vec{n}\, dS = \int_V \nabla \vec{F}\, dV$$

where S is the surface, V the volume enclosed by S, F is an arbitrary vector, n is the outward-pointing unit normal vector at different points of S.

If we choose an arbitrary vector with a unit divergence, the previous equation becomes:

$$\int_S \vec{F} \cdot \vec{n}\, dS = \int_V dV = V$$

and the integral is computed by means of an easier surface integral. Passing from continuous to discrete form, the equation becomes:

$$\sum_{i=1}^{K} \vec{F} \cdot \vec{n}_i A_i = V$$

Where K is the total number of triangles, A_i is the area of the ith triangle, n is the normal unit vector of the ith triangle.

This procedure allows the direct computation of the volume of a body segment approximated by a closed mesh of triangles [28].

In summary, stereophotogrammetric systems are advanced tools mainly used in plethysmography and motion analysis to accurately measure volumes or three-dimensional movements of the human body.

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. The study was conducted using the optoelectronic system of the TBML laboratory of the Politecnico di Milano (figure 26), which is normally used in the field of plethysmography. The optoelectronic system, marketed by BTS bioengineering, consists of 8 smart-dx infrared cameras, and uses smart-capture software for image acquisition, marker tracking and data processing.

Figure 26 - Smart dx optoelectronic system in use at TBML laboratory (Politecnico di Milano).

For both upper and lower limbs, the acquisition protocol is the same. The markers, which are passive, after being sterilised are applied to the patient lying on the couch according to the clinostatism model. After the clinostatism acquisition is performed, the patient is asked to stand up, and the markers necessary for the orthostatism model are added. The acquisition in orthostatism is then performed and then the markers are removed.

Using Smart Capture software (figure 27), the markers are numbered as described by the models, and automatically the volumes of the forearm, arm and whole limb (for the upper limb), and of the thigh, leg and whole limb (for the lower limb), are then derived by triangulation using the Gauss theorem described above.

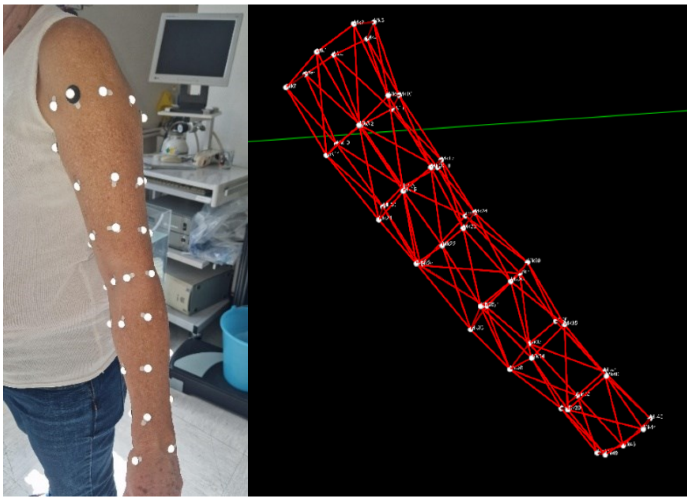


Figure 27 - The positions of the markers placed on the patient's limb (left) are reported by the Smart Capture software (right), through which the tracking procedure is performed.

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, which will be described in detail later.

2.3.1 – MODELS

The following models were developed in such a way as to use a sufficient number of markers to model the limb surface of interest even in patients with larger limbs, but not too many, to avoid the possibility that, especially in patients with smaller limbs, several markers might not be recognised as distinct by the cameras.

It was decided to place the markers in correspondence with the anatomical landmarks, according to the previously described segmental technique. This choice is dictated by two aspects: the first is the possibility of comparing in this way the accuracy of the optoelectronic system with that of the segmental technique; the second is for the convenience of the operator and of the patient, as both types of measurement are carried out on the same patient, so it is not necessary to re-identify the points at which the markers need to be positioned.

As the upper and lower limbs are different in terms of both morphology and size, it was decided to develop different models for the two. In particular, a model for clinostatism and a model for orthostatism were developed for both.

Lower limbs, Clinostatism

For the application of the 46 markers required for the clinostatism acquisition of the lower limb, the patient is asked to lie supine on the couch, with legs apart and feet upwards, taking particular care that the limb whose volume is to be measured is fully supported on the couch.

At **points B, B1, C, D and E**, the model provides the application of 5 markers: one in the anterior position, one in the lateral position, one in the medial position, two as close as possible to the point of contact with the couch, two in the postero-lateral and postero-medial positions (Figure 28).

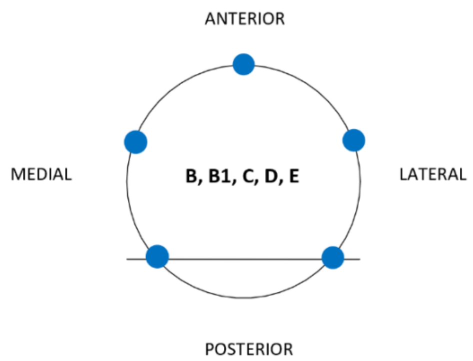


Figure 28 - Model for points B, B1, C, D, E in clinostatism

At **points E1, F and G**, 7 markers must be applied: one in an anterior position, one in an antero-lateral position, one in an antero-medial position, one in a lateral position, one in a medial position, two as close as possible to the point of contact with the couch, in a postero-lateral and postero-medial position (Figure 29).

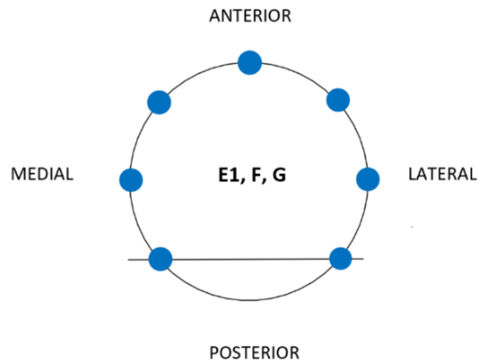


Figure 29 - Model for points E1, F, G in clinostatism.

Lower limbs, Orthostatism

After the acquisition in clinostatism, the patient is asked to stand up, taking care that markers are not dropped or removed, as the previously positioned markers will have to be kept in the same positions for the acquisition in orthostatism, for which it will only be necessary to add 15 more, making a total of 61 markers.

At **point B**, 1 marker must be added at the rear (in red, figure 30) to the 5 markers already present.

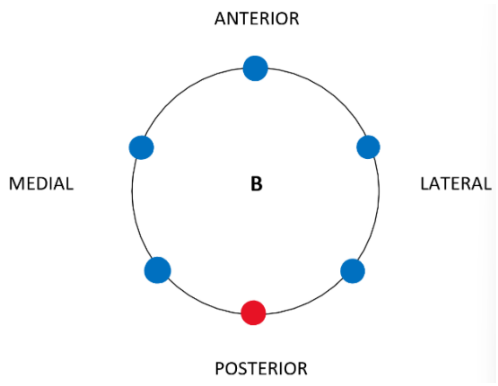


Figure 30 - Model for point B in orthostatism.

At **points B1, C, D, and E**, 2 markers must be added to the 5 markers already present, one more lateral and one more medial (in red, figure 31).

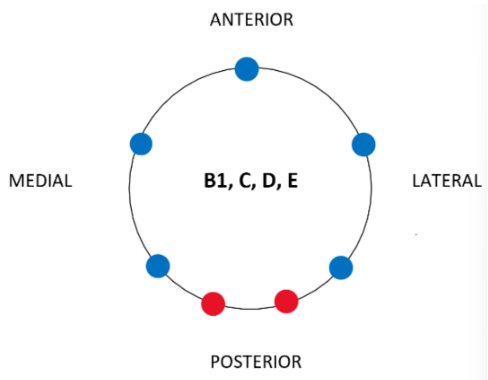


Figure 31 - Model for points B1, C, D, E in orthostatism.

As in the previous case, 2 markers should be added at **points E1, F and G**, to the 7 already present, one more lateral and one more medial (in red, figure 32).

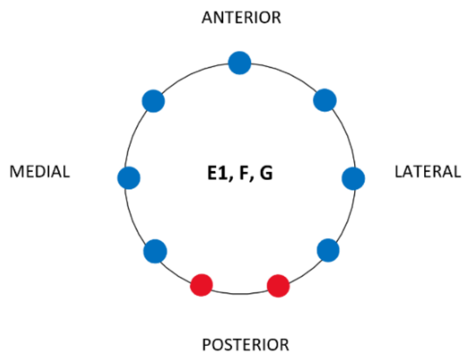


Figure 32 - Model for points E1, F, G in orthostatism.

Upper limbs, Clinostatism

For the application of the 41 markers required for the clinostatism acquisition of the upper limb, the patient is asked to lie supine on the couch, with the limb abducted by 45°, supported on the couch up to the elbow, and with the palm facing upwards.

5 markers must be applied at **points C, C1 and C2**, one in a posterior position, one in a postero-lateral position, one in a postero-medial position, one in an antero-lateral position and one in an antero-medial position (Figure 33).

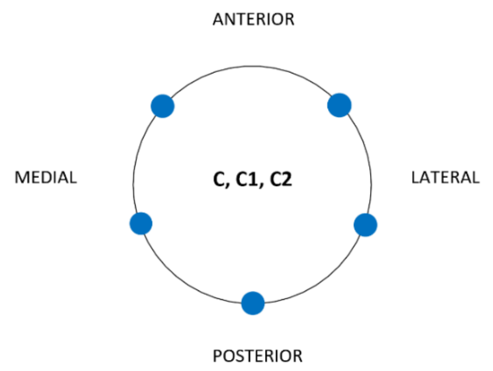


Figure 33 - Model for points C, C1, C2 in clinostatism.

6 markers are to be applied in correspondence with **point D**, one in anterior position, one in posterior position, one in antero-lateral position, one in antero-medial position, one in postero-lateral position and one in postero-medial position (Figure 34).

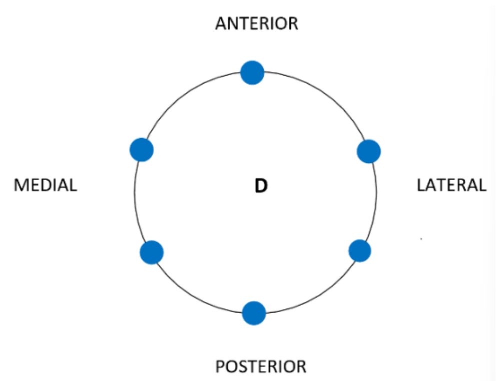


Figure 34 - Model for point D in clinostatism.

5 markers should be applied at **points E, E1, F and G**, one in the anterior position, one in the antero-lateral position, one in the antero-medial position and two as close as possible to the point of contact with the couch, one postero-lateral and one antero-lateral (Figure 35).

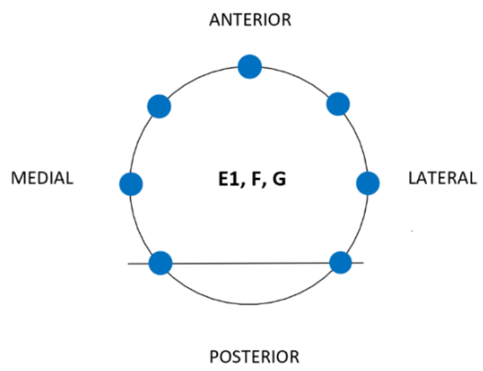


Figure 35 - Model for points E1, F, G in clinostatism.

Upper limbs, Orthostatism

After the acquisition in clinostatism, the patient is asked to stand up with the limb abducted by 30° with the hand open, supported and the palm placed anteriorly, again taking care that the markers do not fall or are removed, as the markers previously positioned must be maintained in the same positions for the acquisition in orthostatism, for which it will only be necessary to add a further 7 markers, making a total of 49 markers.

Points C, C1, C2 and D remain unchanged in terms of the number and positioning of markers in relation to clinostatism (Figure 36).

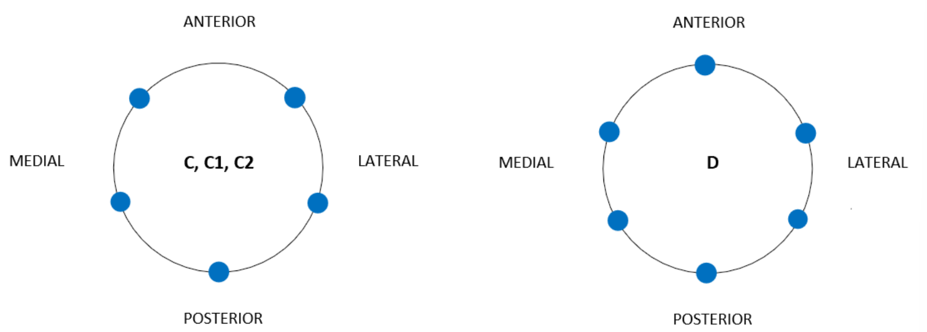


Figure 36 - Model for points C, C1, C2, D in orthostatism.

At **point E**, one marker must be added to the 5 previously positioned markers at the rear (in red, figure 37).

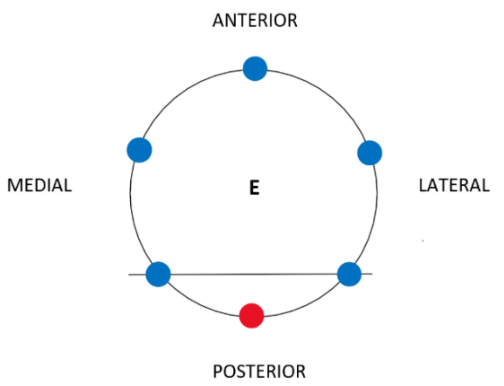


Figure 37 - Model for point E in orthostatism.

Instead, at **points E1, F and G**, two markers must be added to those previously applied, in a posterior position, one more lateral and one more medial (in red, figure 38).

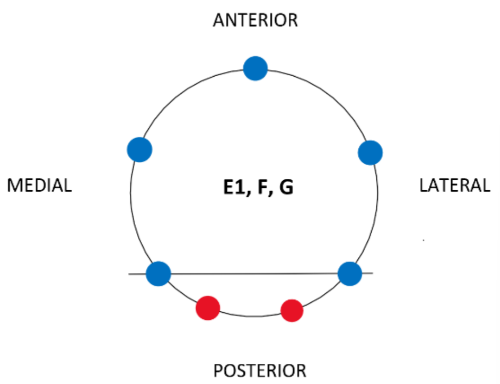


Figure 38 - Model for points E1, F, G in orthostatism.

2.4 – IGOODI – THE GATE TECHNOLOGY

The innovative proprietary scanning cabin described in this section, commercialized as "the Gate" (figure 39) by IGOODI, is a photogrammetry-based 3D reconstruction studio that offers an autonomous scanning experience guided by a virtual avatar assistant to help through the process and without the need of a supervisor, designed to create a 3D avatar which is a virtual twin of the subject.

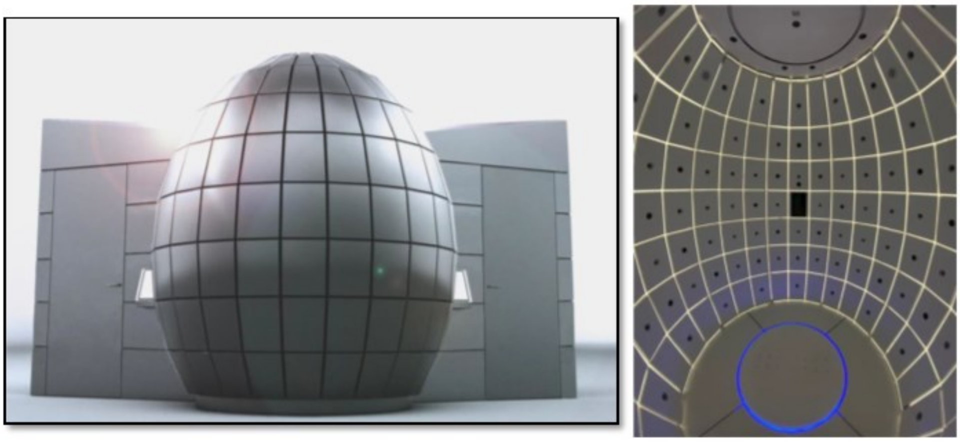


Figure 39 - The Gate, as seen externally and internally.

The process entails a concurrent capture of 128 industrial cameras and sensors that capture height and weight. The height is captured via ultrasonic sensors connected to an Arduino that then send the data to the controlling software for calculating the height. The weight is captured by 2x2 load sensors that also send data via ethernet measurements to the Gate software.

The procedure takes place within the body scanner cabin, which is completely enclosed for privacy purposes since the scanning is performed in underwear.

The production process of the avatar is composed of various steps: the first step is the photogrammetry reconstruction of the 3D model based on the photos; the next steps are retopology, texturing and rigging, and finally transforming the 3D model into a unity-compatible asset. The following diagram (figure 40) depicts the steps of the pipeline.

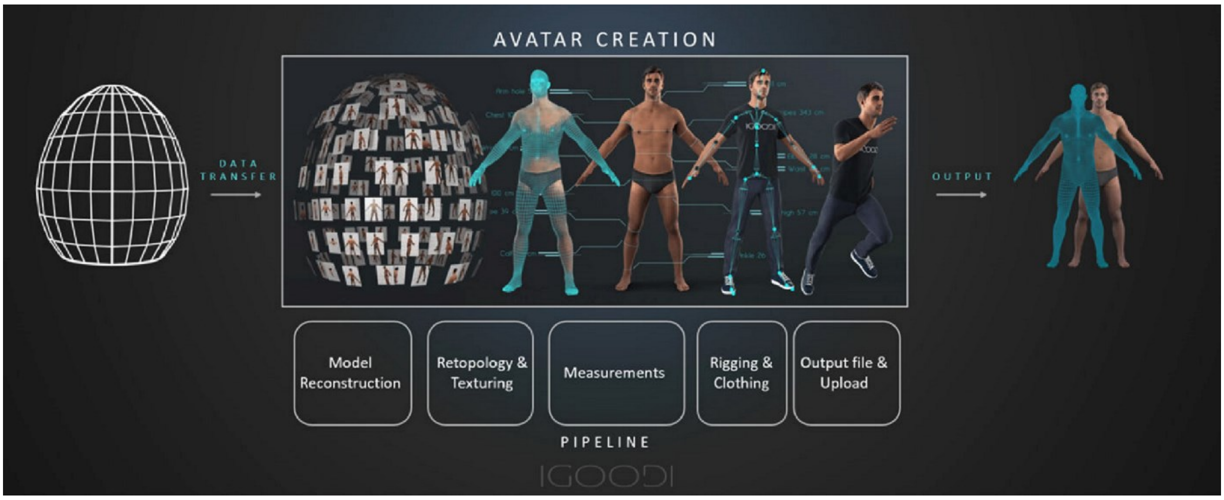


Figure 40 – End-to-end process, from scanning to the final outcome.

During the acquisition, the patient follows the process presented by the avatar assistant inside the Gate and, during the various steps, is guided to assume a specific pose that ensures the best positioning for the 3D reconstruction. The pose is called the "A-pose" (figure 41), that is with legs slightly apart and arms extended in parallel from the body and in a 45° angle.

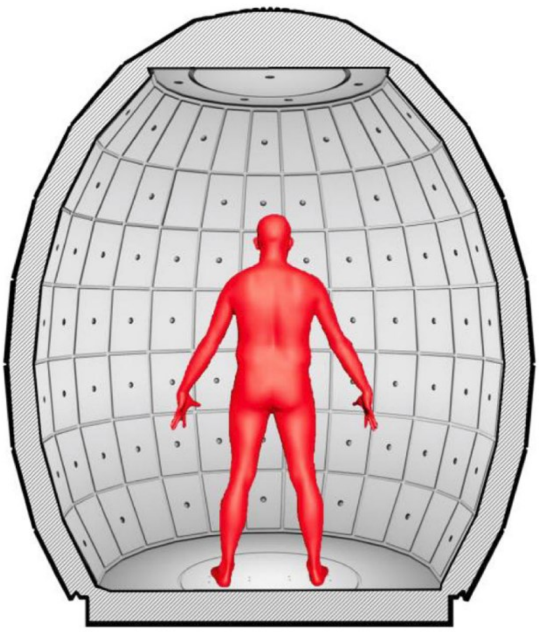


Figure 41 - The scanning position and the A-Pose inside the Gate.

Once the avatar has been obtained, the patient's measurements will be taken directly via software; some information, such as height and weight, will be obtained automatically (figure 42), while the measurements of interest for the present study (the circumferences in accordance with the segmental technique and the fixed-heights technique), can be acquired by means of a virtual tape, again using software (figure 43).

Figure 42 – Anthropometric measurements.

Figure 43 - Circumferential measurements taken with a virtual tape, in this case according to the fixed-heights technique.

For the study conducted in this thesis work, it is essential that the avatar of the subject is taken on the same day as the measurement taken using centimetric methods and direct volumetry for two reasons: the volume of the limbs, especially if affected by lymphoedema, could vary considerably even within a few days, and the comparison between the various methods would then be compromised; furthermore, by scanning immediately after taking measurements, the same marks traced on the patient's limbs during the centimetric technique, whether at fixed heights or segmental, can be used for virtual measurement using the IGOODI software.

Since the software does not have a function for the direct calculation of volumes of body segments, it was decided in the present study to use the same approximation as for the centimetric methods, the approximation of the limb to a succession of truncated cones. This choice also allows for more comparable data with these methods.

3 – DATA ANALYSIS AND DISCUSSION

In this chapter, data obtained from the comparison of the various measurement methods will be presented. The results will be analysed critically, comparing them with those already found in the literature. In particular, the chapter is divided into three sections:

- Statistical sample: population that participated in the study, inclusion, and exclusion criteria.
- Data analysis: graphs and statistical indices.
- Discussion: critical considerations on the analysed methods.

3.1 – STATISTICAL SAMPLE

A population of 22 volunteer subjects was selected for this study. 7 subjects 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. The study subjects have been chosen so as to have a heterogeneous population in terms of gender, age, weight, and severity of the pathological condition. All subjects were adults and have been informed of the procedures they would undergo and of any complications associated with them by an informed consent form which they carefully examined and signed.

All the 22 subjects underwent direct volumetry and centimetric method according to the segmental technique. Not all of them underwent the remaining measurement techniques due time, costs, availability of subject, operator, instrumentation. Specifically, 16 subjects underwent centimetric method according to the fixed heights technique, 16 subjects underwent optoelectronic system, 10 subjects underwent IGOODI system.

patient	age	gender	height and weight	condition	limb	technique
1	24	M	183 cm 80 kg	healthy	upper lower	segmental fixed heights OEP IGOODI
2	23	M	195 cm 102 kg	healthy	upper	segmental OEP
3	24	F	167 cm 55 kg	healthy	lower	segmental OEP
4	24	M	180 cm 75 kg	healthy	upper	segmental OEP
5	23	F	182 cm 70 kg	healthy	upper	segmental OEP
6	76	F	165 cm 92 kg	pathological	lower	segmental fixed heights OEP
7	77	F	173 cm 75 kg	pathological	upper	segmental fixed heights OEP
8	24	F	155 cm 46 kg	healthy	upper lower	segmental fixed heights OEP
9	57	F	160 cm 61 kg	pathological	upper	segmental fixed heights OEP
10	89	F	153 cm 55 kg	pathological	upper	segmental fixed heights OEP
11	65	F	170 cm 62 kg	pathological	upper	segmental fixed heights OEP IGOODI
12	59	F	165 cm 87 kg	pathological	upper	segmental fixed heights OEP
13	19	F	165 cm 55 kg	healthy	upper lower	segmental fixed heights OEP IGOODI
14	62	F	158 cm 56 kg	pathological	lower	segmental fixed heights OEP
15	87	M	180 cm 95 kg	pathological	upper lower	segmental fixed heights OEP IGOODI
16	33	M	178 cm 76 kg	pathological	lower	segmental fixed heights OEP IGOODI
17	66	F	165 cm 67 kg	pathological	upper	segmental fixed heights OEP
18	60	F	155 cm 70 kg	pathological	lower	segmental fixed heights
19	74	F	158 cm 78 kg	pathological	upper	segmental fixed heights IGOODI
20	70	M	170 cm 81 kg	pathological	lower	segmental fixed heights IGOODI
21	56	F	165 cm 77 kg	pathological	upper	segmental fixed heights IGOODI
22	33	M	170 cm 86 kg	pathological	lower	segmental fixed heights IGOODI

Table 1 – Characteristics of the population.

3.2 – DATA ANALYSIS

Data obtained from the measurements were processed using MATLAB software, by means of which the various measurement techniques were compared with the gold standard and with each other. The following statistical indices were derived for each measurement method:

- Mean difference and mean percent error: indices of accuracy of the methods, in particular of the deviation between the measurements obtained with the analysed method and the comparison method.
- 25th percentile, 50th percentile (median) and 75th percentile: indices of the error distribution between the analysed method and the comparison method.
- Standard deviation (std): index of reproducibility of the measurements, in particular the data dispersion of the analysed method compared to the comparison method, in relation to the mean error.
- Linear correlation indices: slope (m) and intersection (q) of the interpolation line between the measurement with the analysed method and the comparison method, and coefficient of determination (r2) between the two methods, indices of method accuracy and reproducibility.
- p-value: index of statistical significance.

For a more immediate visualisation of the comparison between the methods, it was decided to represent the data by means of two types of graphs:

- Linear correlation graph: on the y-axis we find the measurements obtained with the technique under analysis, while on the x-axis we find the measurements obtained with the comparison technique. The graph also shows the interpolating line of the data sample.
- Bland-Altman graph: On the y-axis we find the difference between the measurements obtained with the technique under analysis and the comparison technique, while on the x-axis we find the average between the two measurements.

3.2.1 – SEGMENTAL TECHNIQUE

The segmental technique has been compared with water displacement, which is considered the gold standard. Not allowing direct volumetry to measure the limb in its entirety, it was decided to compare the two methods by the volume obtained up to the highest point measurable by volumetry, which is point E1 in most cases.

Although water volumetry only allows measurements to be taken in orthostatism, it was decided to take both orthostatism and clinostatism measurements using the segmental technique.

The data obtained showed:

- Excellent accuracy in both clinostatism (mean error = 1.78 %, m = 1,01) and orthostatism (mean error = 0.39 %, m = 1,00);
- Excellent reproducibility in both clinostatism (r2 = 0.997, std = 3,00 %) and orthostatism (r2 = 0.998, std = 2,52 %);
- Slight systematic overestimation of volume compared to that obtained with direct volumetry greater in clinostatism (mean difference = 0.06 l) than in orthostatism (mean difference = 0.02 l).

No significant differences were found comparing data obtained on subjects without lymphoedema and on subjects with lymphoedema (figure 47).

Statistical indices

	avg diff.	avg error	25° perc.	50° perc.	75° perc.	Std	m	q	r^2	p
clino	0,06 l	1,78%	0,65%	1,49%	2,80%	3,00%	1,01	0,02 l	0,997	0,819
ortho	0,02 l	0,39%	-1,20%	0,05%	0,96%	2,52%	1,00	0,02 l	0,998	0,934

Table 2 – Statistical indices of the comparison between segmental technique and water displacement.

Linear correlation graphs

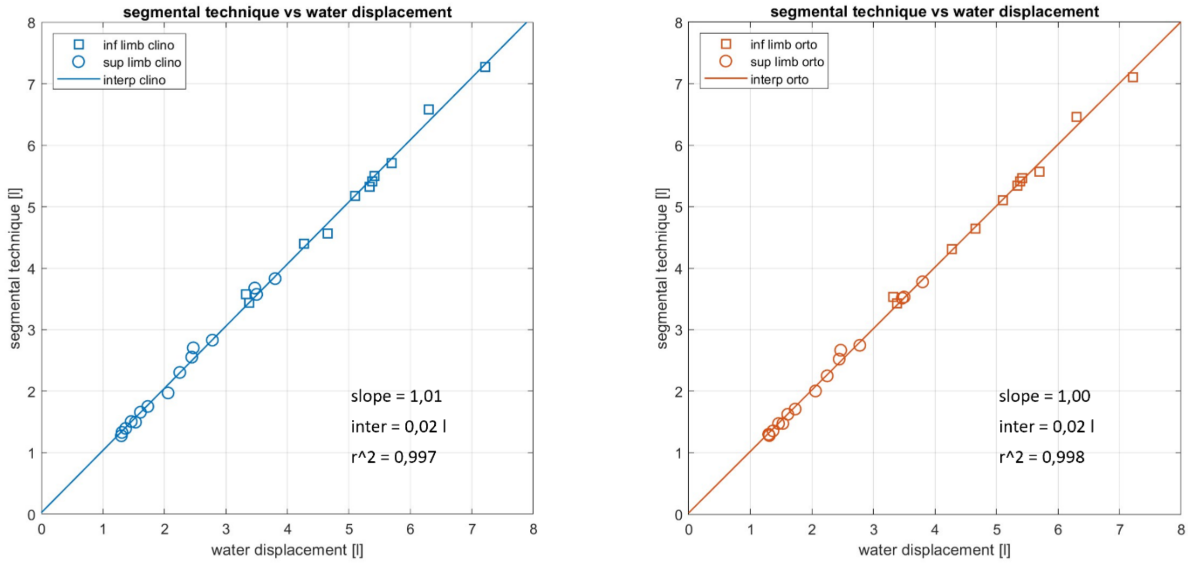


Figure 44 - Linear correlation graphs between segmental technique and water displacement.

Bland-Altman graphs

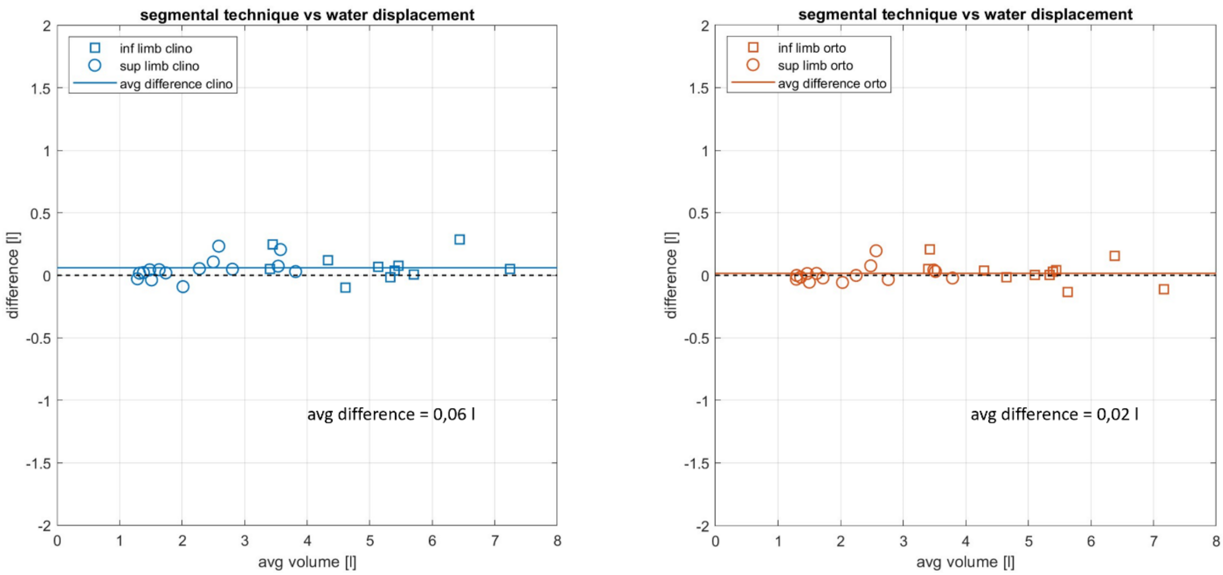


Figure 45 – Bland-Altman graphs between segmental technique and water displacement.

Clinostatism and Orthostatism comparison graphs

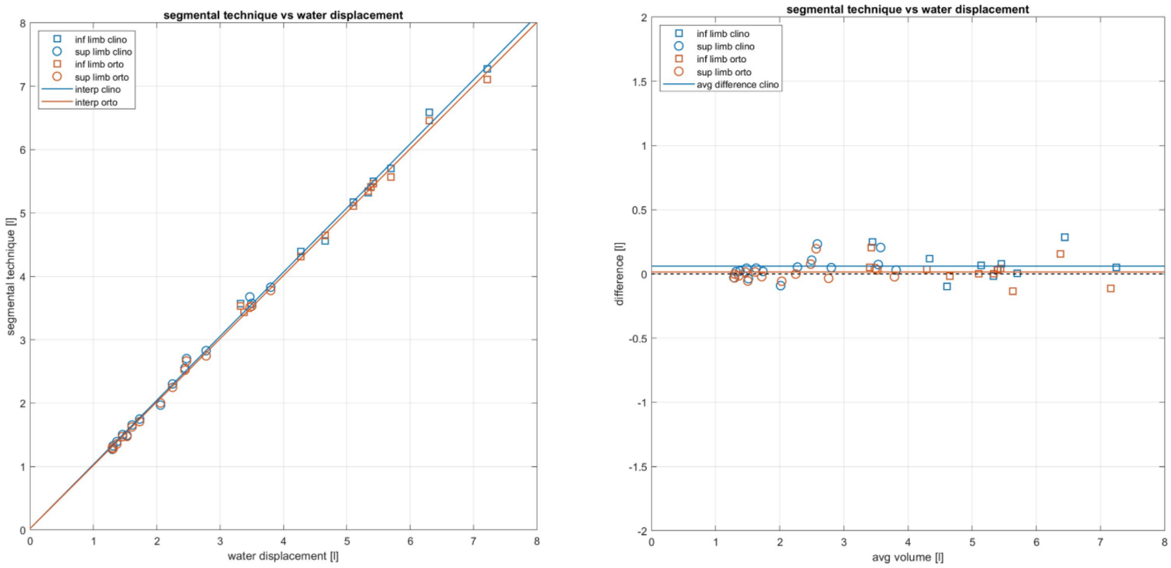


Figure 46 - Comparison graphs between clinostatism and orthostatism for the segmental technique.

Healthy and Oedemaous limb comparison graph

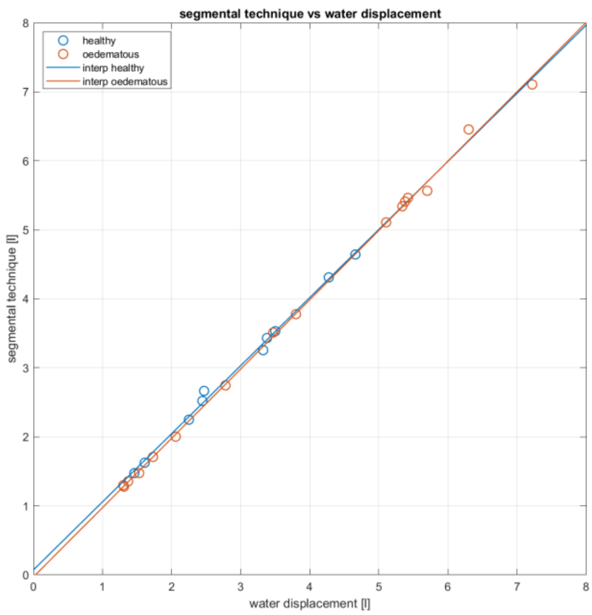


Figure 47 - Comparison graph between healthy limbs and oedematous limbs in orthostatism for the segmental technique vs water displacement.

3.2.2 – FIXED-HEIGHTS TECHNIQUE

The fixed heights technique has been compared with water displacement, which is considered the gold standard. Not allowing direct volumetry to measure the limb in its entirety, it was decided to compare the two methods by the volume obtained up to the highest point measurable by volumetry, in most cases the point immediately above the elbow or knee.

Although water volumetry only allows measurements to be taken in orthostatism, it was decided to take both orthostatism and clinostatism measurements using the fixed-heights technique.

The data obtained showed:

- Excellent accuracy in both clinostatism (mean error = 1.79 %, m = 1,01) and orthostatism (mean error = -0.13 %, m = 1,01);
- Excellent reproducibility in both clinostatism (r2 = 0.997, std = 2,81 %) and orthostatism (r2 = 0.998, std = 2,42 %);
- Slight systematic evrestimation of volume in clinostatism (mean difference = 0.06 l) and no difference in orthostatism (mean difference = 0.00 l). Contrary to the hypothesis, the average difference found in the case where there was an elbow or knee correspondence was not significantly lower than in the case where there was no correspondence (Figure 51).

Statistical indices

	avg diff.	avg error	25° perc.	50° perc.	75° perc.	std	m	q	r^2	p
clino	0,06 l	1,79%	0,61%	2,62%	3,62%	2,81%	1,01	0,00 l	0,997	0,983
ortho	0,00 l	-0,13%	-1,74%	0,59 %	1,58%	2,42%	1,01	-0,03 l	0,998	0,983

Table 3 – Statistical indices of the comparison between fixed-heights technique and water displacement.

Linear correlation graphs

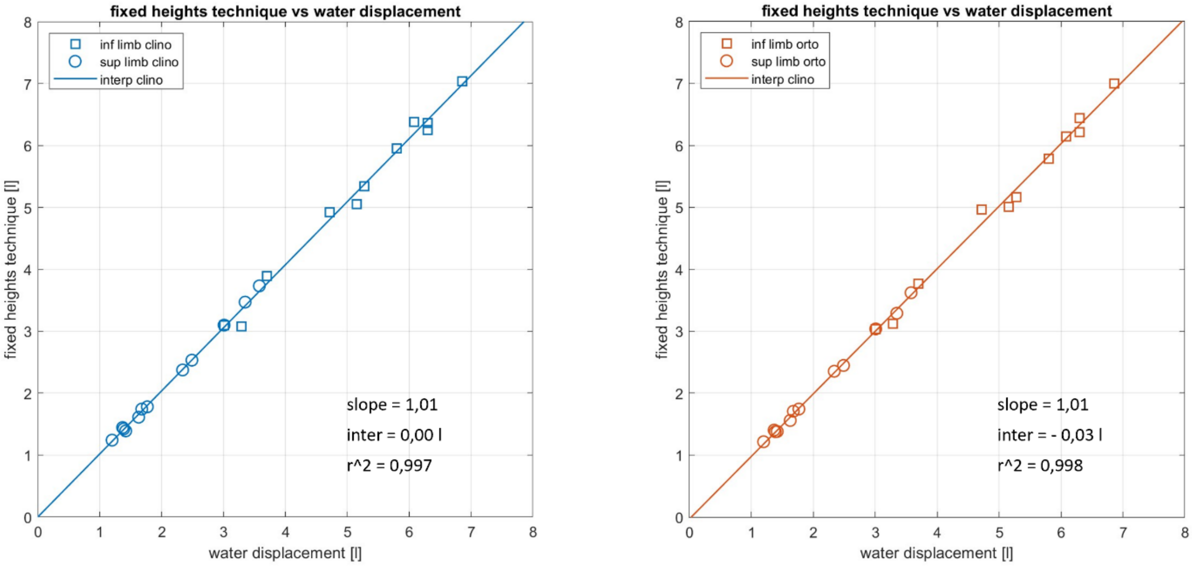


Figure 48 - Linear correlation graphs between fixed-heights technique and water displacement.

Bland-Altman graphs

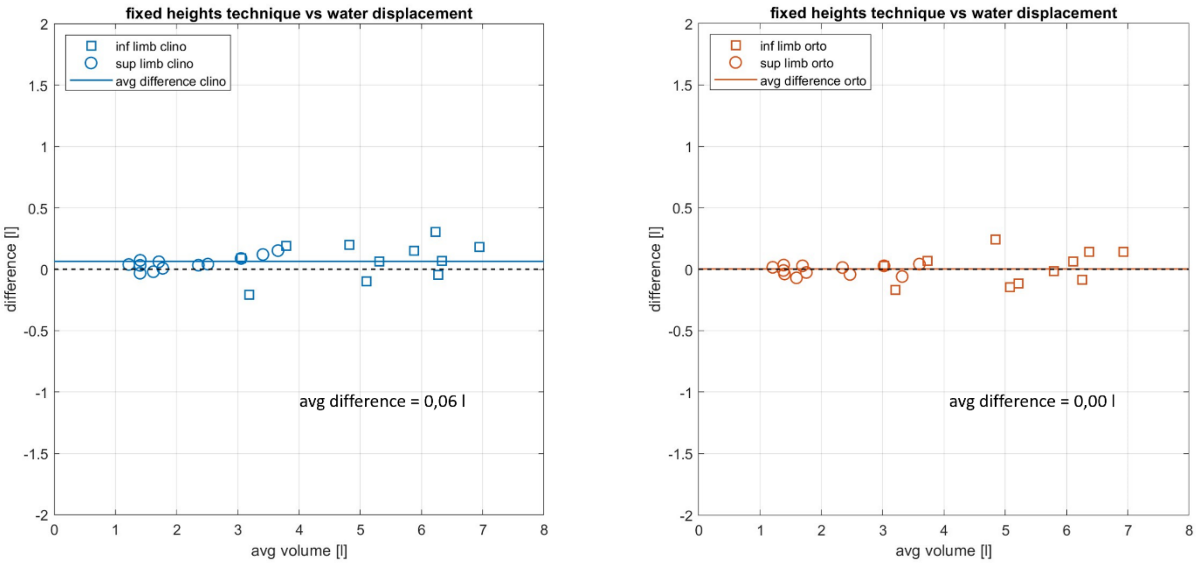
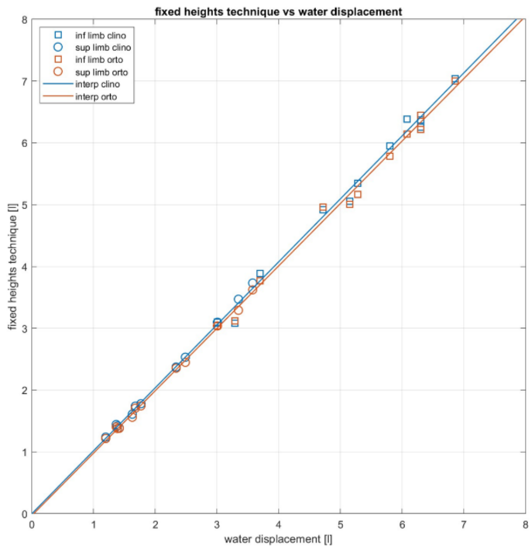


Figure 49 – Bland-Altman graphs between fixed-heights technique and water displacement.

Clinostatism and Orthostatism comparison graphs



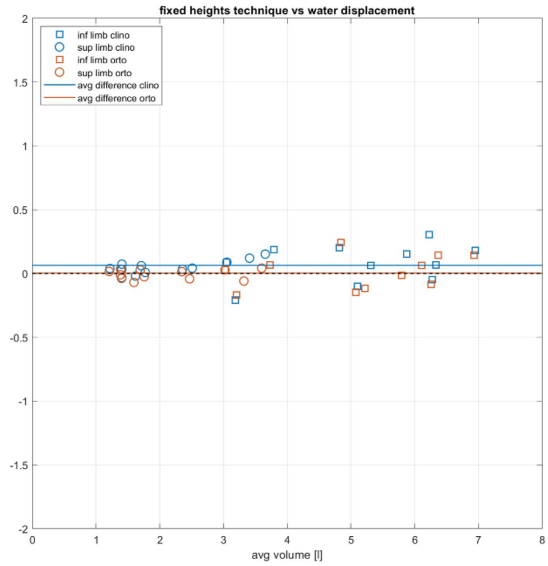


Figure 50 - Comparison graphs between clinostatism and orthostatism for the fixed-heights technique.

Elbow or Knee Correspondance comparison graphs

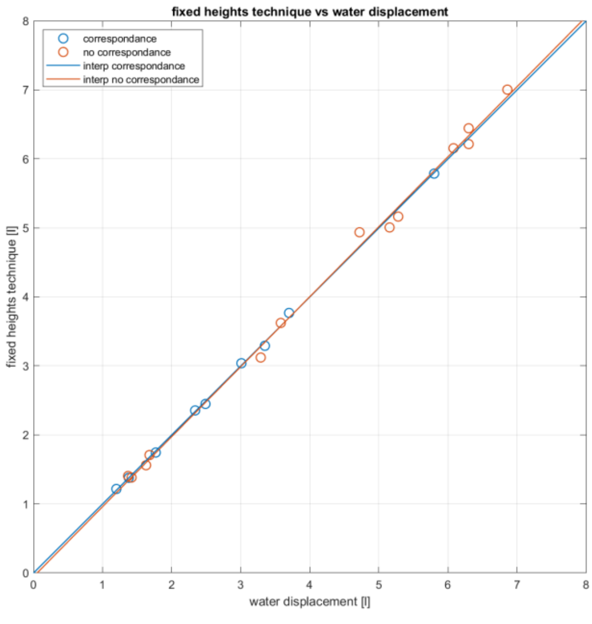


Figure 51 – Comparison graph between correspondence and no correspondence case at knee or elbow joints in orthostatism for the fixed-heights technique vs water displacement.

3.2.3 – OPTOELECTRONIC SYSTEM

Measurements obtained with the optoelectronic system were compared with the segmental technique instead of water volumetry. This choice was dictated by the absence of models that would allow a comparison between the two techniques in cases where there is no volumetric measurement of the limb in its entirety (models, to date, only allow measurement of the volume of the forearm, arm, leg, thigh or whole limb). A comparison with the segmental technique can still be considered valid, as the latter has proved to be extremely accurate.

Again, the comparison is made in both clinostatism and orthostatism.

The data obtained showed:

- Bad accuracy in both clinostatism (mean error = -25,6 % %, m = 0,74) and orthostatism (mean error = -8,75 %, m = 0,96);
- Good reproducibility in both clinostatism (r2 = 0.987, std = 6,72 %) and orthostatism (r2 = 0.998, std = 7,52 %);
- Systematic underestimation of volume compared to that obtained with direct volumetry greater in clinostatism (mean difference = -1,11 l) than in orthostatism (mean difference = -0,37 l).

Statistical indices

	avg diff.	avg error	25° perc.	50° perc.	75° perc.	std	m	q	r^2	p
clino	-1,11 l	-25,6%	-30,6%	-26,9%	-20,2%	6,72%	0,74	-0,01 l	0,987	0,124
ortho	-0,37 l	-8,75%	-12,2%	-9,64%	-0,81%	7,52%	0,96	-0,18 l	0,998	0,132

Table 4 – Statistical indices of the comparison between OEP system and segmental technique.

Linear correlation graphs

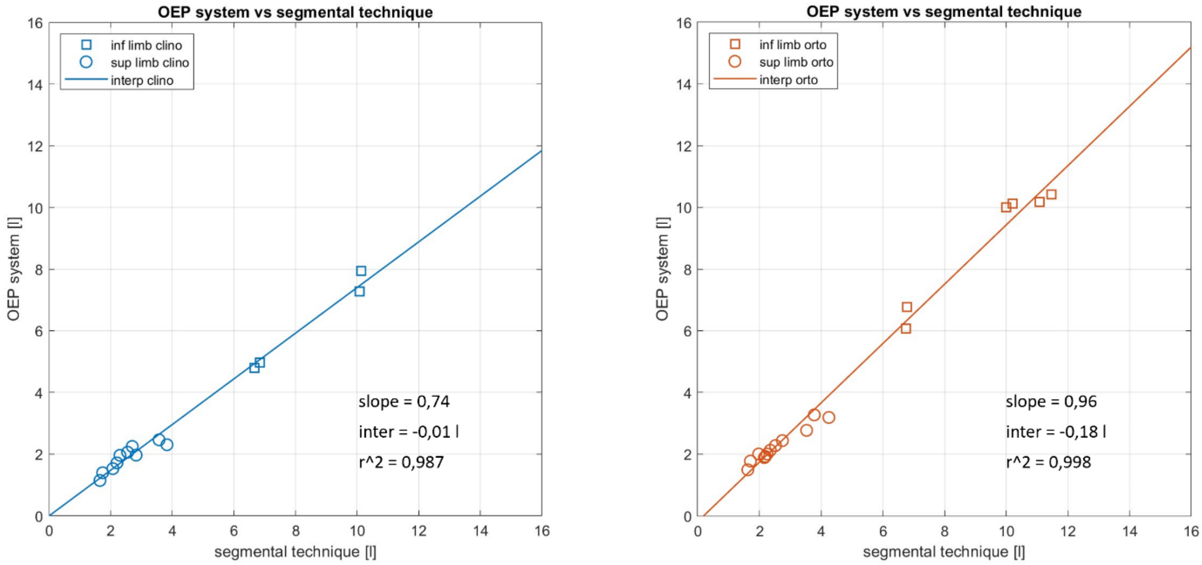


Figure 52 - Linear correlation graphs between OEP system technique and segmental technique.

Bland-Altman graphs

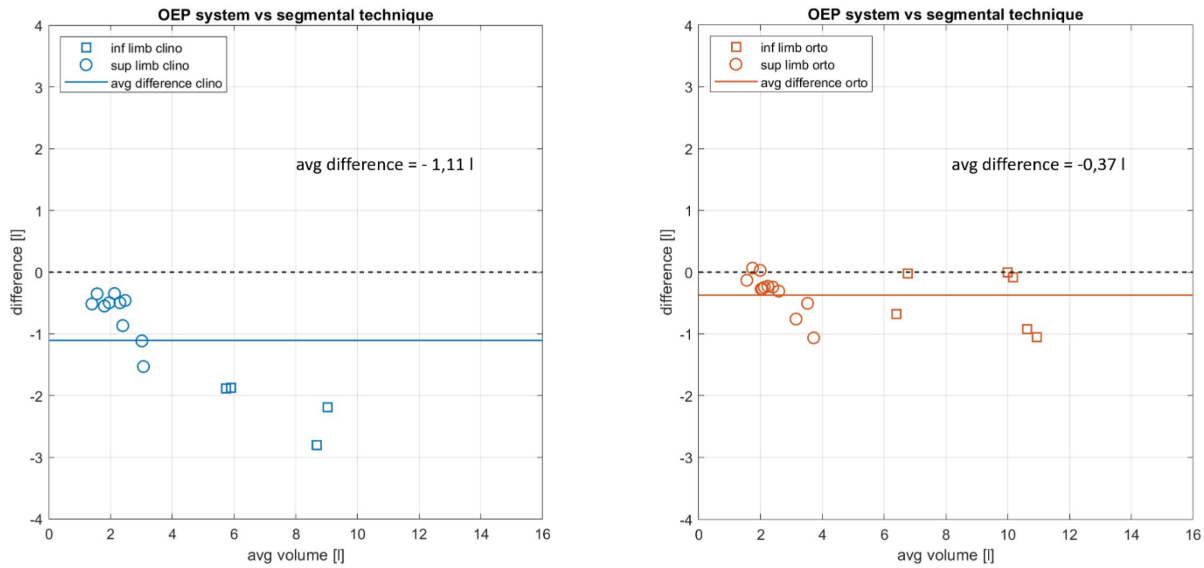


Figure 53 – Bland-Altman graphs between OEP system and segmental technique.

Clinostatism and Orthostatism comparison graphs

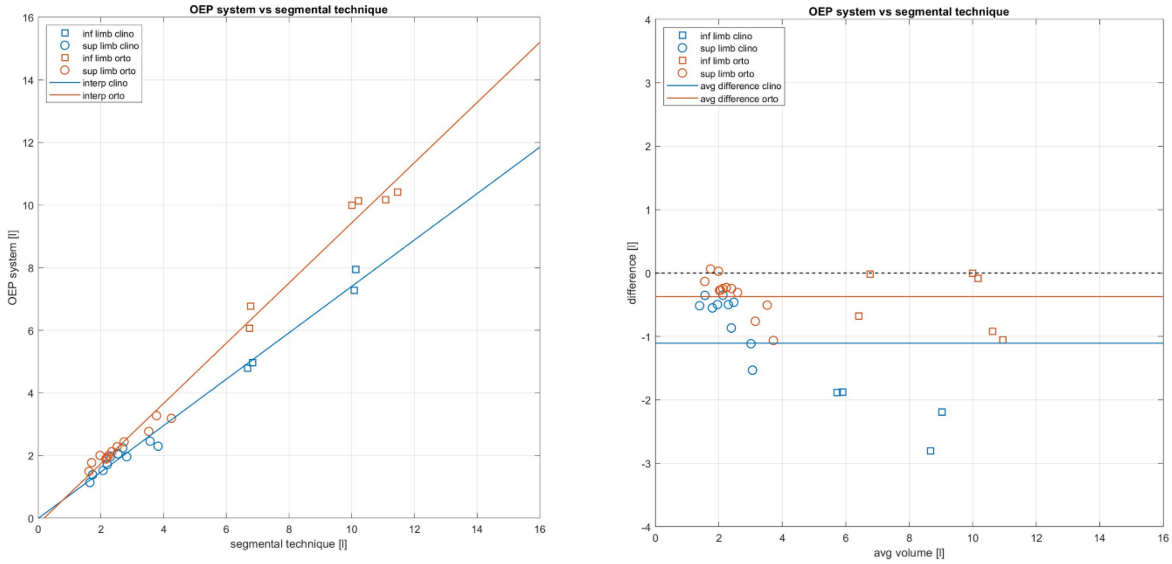


Figure 54 - Comparison graphs between clinostatism and orthostatism for the OEP system.

3.2.4 – IGOODI SYSTEM

The IGOODI optoelectronic system has been compared with water displacement, which is considered the gold standard. Not allowing direct volumetry to measure the limb in its entirety, it was decided to compare the two methods by the volume obtained up to the highest point measurable by volumetry, in most cases the point immediately above the elbow or knee.

The IGOODI system only provides for positioning in orthostatism; therefore, the comparison was made with volumetry and, for each measurement, with the corresponding centimetric technique (segmental or fixed heights).

The data obtained showed:

– Excellent accuracy (mean error = 1.8 %, m = 1,00);
– Excellent reproducibility (r2 = 0.998, std = 3,04 %);
– Slight systematic overestimation of volume compared to that obtained with direct volumetry (mean difference = 0.04 l).

'The Gate' exploits the same points used for the segmental technique or the fixed height technique and approximates the limb in the same way. Therefore, a comparison between the two techniques was deemed appropriate. This comparison showed an almost perfect overlapping of the volumes obtained using IGOODI's optoelectronic system and the corresponding centimetric technique (figure 57).

Statistical indices

	avg diff.	avg error	25° perc.	50° perc.	75° perc.	std	m	q	r^2	p
ortho	0,04 l	1,80 %	0,06%	0,71%	2,62%	3,04%	1,00	-0,05 l	0,998	0,824

Table 5 – Statistical indices of the comparison between IGOODI system and water displacement.

Linear correlation graph

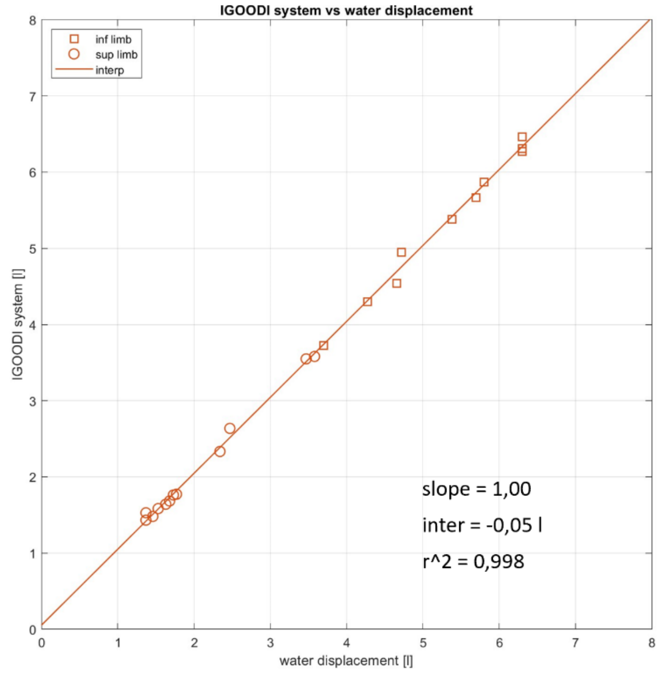


Figure 55 - Linear correlation graphs between IGOODI system and water displacement.

Bland-Altman graph

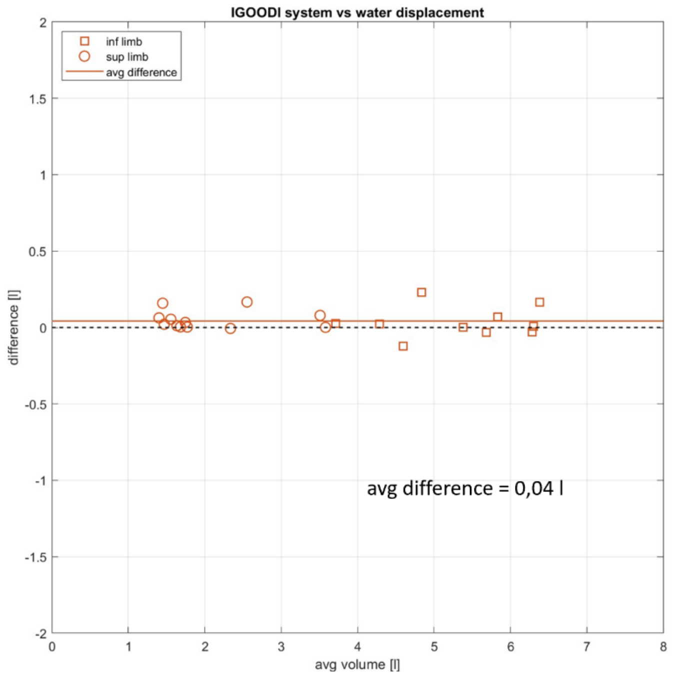


Figure 56 – Bland-Altman graphs between IGOODI system and water displacement.

IGOODI and centimetric methods comparison graphs

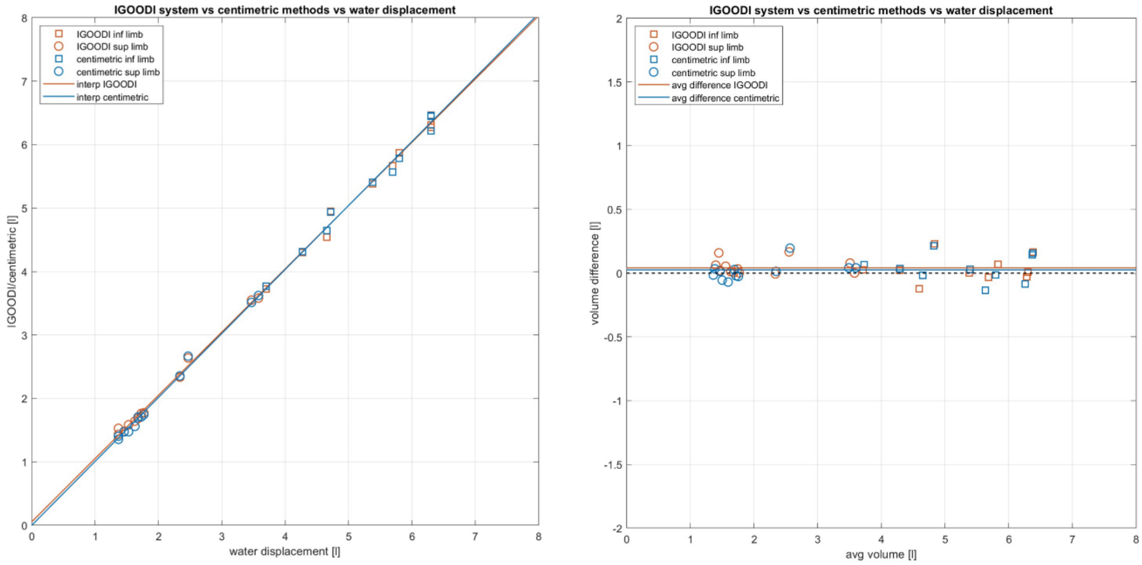


Figure 57 - Comparison graphs between IGOODI system and centimetric methods.

3.3 – DISCUSSION

3.3.1 – WATER DISPLACEMENT

Water displacement, considered the gold standard, proved to be inconvenient to use and not without possible sources of error.

First of all, in order to be able to carry out the measurements correctly, it is necessary for the patient to cooperate in remaining as still as possible with the limb positioned as indicated throughout the measurement procedure; furthermore, the correct positioning of the patient requires the collaboration of two operators, the first to keep the limb in the correct position, and the second to check that it is submerged up to the correct level and perfectly perpendicular to the surface of the water. Moreover, if the patient were to move, the water would start to oscillate in the container and the measurement would be affected.

In addition, it is difficult to keep water at a temperature that does not cause vasoconstriction or vasodilation of the submerged limb.

Furthermore, these complications are compounded by the fact that the measurement times are rather long, and in any case do not give an idea of the distribution of the lymphoedema and its extent in relation to the contralateral limb, unless further measurements are taken.

For this series of reasons, it is evident that it is not suitable to apply water displacement for routine clinical practice. It is convenient to use instead a more ecological method, comfortable for the patient, easily performed by a single operator, economical and that allows to have an idea of the distribution of the lymphoedema in the various sections of the limb.

3.3.2 – CENTIMETRIC METHODS

In agreement with data obtained in the literature, centimetric methods tend to overestimate the measurement obtained with water volumetry. This deviation can presumably be attributed to the geometric approximation of the limb to a succession of truncated cones, or to the fact that volumetric measurements are performed in water, which could lead to vasoconstriction of the limb.

The higher error committed in clinostatism measurements is not due to a lower accuracy of the method when performed in clinostatism, but presumably to the tissue relaxation that occurs when the patient is lying on the couch. It is therefore insufficient data to determine if measurements taken in one mode or the other are more accurate.

The error introduced by upper limb measurements is slightly greater than that introduced by lower limb measurements. This may be attributed to the greater irregularity of the upper limb.

It was assumed 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 conclusion.

Although the two techniques are competitive in terms of accuracy, the segmental technique, being based on the identification of anatomical landmarks, is more reproducible, making the data obtained through it more comparable. In addition, by exploiting the same anatomical landmarks used in the context of elasto-compression, it allows the regulation of compression therapy through the use of algorithms.

Thus, as can be seen from the statistical indices and graphs in the previous section, both centimetric techniques, when performed by experienced operators, with the appropriate measuring instruments and following a clear and detailed measurement protocol, are accurate and suitable for routine clinical practice.

Moreover, both techniques are very economical, as they only require readily available instruments, they are quick to perform, especially the fixed height technique, they give an idea of the distribution of lymphoedema, and the measurements can be conveniently taken anywhere, whether in a clinic or at the patient's home.

In conclusion, centimetric methods are very accurate, quick and economical, provide complete information on the entity and the distribution of lymphoedema, and can be performed everywhere. These factors make the segmental technique and the fixed-height technique successful compared to the other measurement methods analysed.

The segmental technique is superior to the fixed-height technique due to its greater comparability and reproducibility.

3.3.3 – OPTOELECTRONIC SYSTEM

With regard to the optoelectronic system, the data obtained are not as satisfactory as those concerning the other methods. In particular, the systematic underestimation of limb volume in both clinostatism and orthostatism shows that these methods cannot be used in routine clinical practice.

This underestimation is presumably due to the greater approximation of the limb with respect to that used for centimetric methods (the markers are connected by straight lines, thus approximating the various circumferences to polygonal and the various segments to polyhedral). In particular, measurements in clinostatism differ greatly from those taken in orthostatism due to the use of a smaller number of markers, given the impossibility of applying them in the areas of contact with the bed.

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 also very expensive.

In conclusion, the optoelectronic system is not a valid alternative to volumetry and centimetric methods for the acquisition of static volumes, although it is a successful tool in other areas such as plethysmography or motion analysis.

3.3.4 – “THE GATE” IGOODI SYSTEM

The IGOODI optoelectronic system proved to be competitive with the centimetric techniques in terms of accuracy (average error of 1.8%). In particular, as can be deduced from the statistical indices and graphs shown in the previous section, for all the measurements carried out using this system, the comparison with the corresponding centimetric technique showed an almost perfect match of the data obtained. 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 cannot be used in 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.

3.3.4 – PROS AND CONS TABLE

To give a more immediate idea of the advantages and disadvantages of the various methods analysed in this thesis study, a summary table is given below.

METHOD	PROS	CONS
Water displacement	- Gold standard - Economical - Can be performed anywhere	- Time consuming - Uncomfortable for the patient and the operator - Not free from sources of error - Not ecological - Does not highlight the oedema distribution - Cannot measure the limb in its entirety
Segmental technique	- High accuracy - High reproducibility - Comparable data - Economical - Ecological - Can be performed anywhere - Highlights the oedema distribution	- Requires operator experience in identifying anatomical landmarks - Identification of anatomical landmarks lengthens the procedure
Fixed-heights technique	- High accuracy - High reproducibility - Economical - Ecological - Can be performed anywhere - Highlights the oedema distribution - Quick as it does not require identification of anatomical landmarks	- Poorly comparable data
OEP system	- Reproducible - Comparable data - Highlights the oedema distribution	- Inaccurate - Expensive - Needs a laboratory equipped with an OEP system - Time consuming - Requires operator experience
IGOODI system	- High accuracy - High reproducibility - Easily comparable data - Highlights the oedema distribution - Quick acquisition time	- Expensive - Executable only where 'the Gate' is present at IGOODI - Time consuming for the operator

4 – CONCLUSIONS

The results obtained confirmed that the use of centimetric methods for routine clinical practice is not only reasonable, but also advantageous compared to direct volumetry.

Water volumetry was confirmed to be a theoretical gold standard, which leads to a series of issues that make it unusable in routine clinical practice.

Both centimetric methods (segmental technique and fixed-height technique), as well as IGOODI's optoelectronic system 'the Gate', were confirmed to be very accurate, and therefore utilized in the clinical practice.

Data obtained for the optoelectronic system employed at the Politecnico di Milano were not satisfying in terms of accuracy.

The segmental technique was considered to be the best of the techniques analysed; in addition to being competitive with the fixed-height technique and the IGOODI system in terms of accuracy, it allows a greater inter-patient comparability of the results obtained, and for an algorithmic and standardised elasto-compressive bandaging procedure to be followed.

Possible interesting future developments to this thesis work are an analysis of the inter-operator variability of the centimetric methods performed by means of the described protocols, and an implementation of the measurement protocols on the virtual measurement platform of IGOODI, so as to automate the taking of measurements on avatars.

5 – “LIMB VOLUMES” ANDROID APPLICATION

This chapter will present the "Limb Volumes" application (figure 58), developed to facilitate the acquisition of measurements according to the segmental technique, which is considered to be the best method among those proposed in this thesis work.

Figure 58 - Limb Volumes Application Logo.

5.1 – THE PROJECT

As mentioned in the introduction, during the first day of treatment, the physiotherapist begins the intensive phase of CPT by taking volumetric measurements of the limbs and tissue consistency, to proceed with compression bandaging on the basis of the data obtained. To date, there is no shared protocol on how to bandage, so it was decided to follow in this project the one proposed by Dr. Farina, which provides a series of algorithms, which indicate, on the basis of the measurements taken, the number of overlaps to be made with the elastic bandage at each identified anatomical landmark. As these algorithms are detailed and complex, following them is an onerous process that can easily mislead the operator, as well as being time-consuming.

The above-mentioned algorithms were developed by Dr. Farina for use following measurements performed according to the segmental technique, again as described in the protocol by him developed, and are available in the appendix.

This project was initiated with the aim of developing an application that would support the practitioners in their clinical practice. The aim of the application is to make it easier for the operator to take measurements and to provide guidance on how to bandage, without the user having to follow the previously introduced algorithms himself.

More specifically, the application 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 above-mentioned bandaging algorithms.

Since the thesis student had no experience in application development, it was decided to develop 'Limb Volumes' with the 'App Inventor' software, created in 2010 by Google and owned by the Massachusetts Institute of Technology (MIT), which enables the development of simple applications via a pre-compiled working environment based on Scheme and Java computer languages.

5.2 – APPLICATION INTERFACE AND FUNCTIONS

The application to date consists of 3 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 3 sections will be described in detail in this chapter. In particular, the functions that allow the operator to interface with the application will be explained, so that these can be understood by the practitioner and replicated or implemented in any future developments of the application.

5.2.1 – SCREEN 1 – DATI PAZIENTE

When opening the application, the 'Patient Data' screen will appear, requiring the following fields to be filled in (figure 59):

- Personal data (name, surname, sex, date of birth, tax code);
- Anthropometric data (height, weight);
- Anamnestic data (oedematous limb, oedema diagnosis, surgery, post-surgery therapy).

The only field on this screen that does not have to be filled in manually is the body mass index (BMI), which is obtained by means of the "Ricava BMI" function (figure 60). This function obtains the BMI according to the following formula:

$$BMI = \frac{weight}{height^2}$$

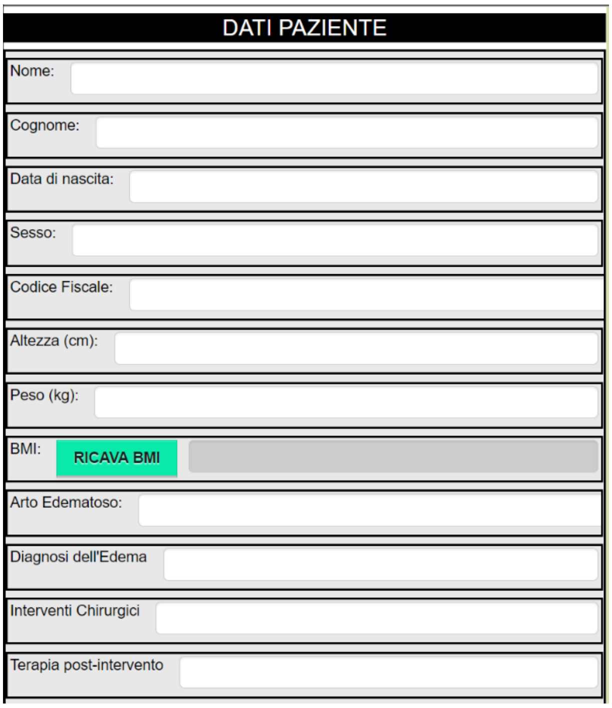


Figure 59 - Screen 1 "DATI PAZIENTE"; fields to be filled in with patient data.

Figure 60 - Block diagram of the "Ricava BMI" function.

The screen also features the "Salva dati" button, which allows the data entered on the screen to be kept in memory, and "Carica dati" button, which allows the screen to be automatically filled with the last data kept in memory (Figure 61). Using the "Misure arto superiore" and "Misure arto inferiore" buttons, it is possible to switch from screen 1 to screens 2 and 3 respectively (Fig. 61).

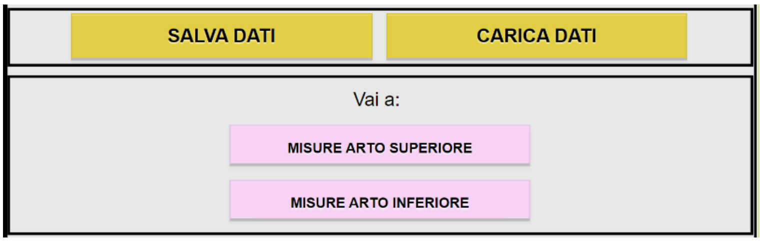


Figure 61 - screen 1 "DATI PAZIENTE"; buttons to save in memory and load the entered patient data, and to proceed to the next screens.

5.2.2 – SCREEN 2 – MISURE ARTO SUPERIORE

Screen 2, designed to facilitate the assessment and treatment of upper limb lymphoedema, can be divided into 4 sections:

- Measurement of lengths, heights and circumferences;
- Calculation of volumes;
- Calculation of percentage deviations;
- Tissue consistency index (TCI) and overlap calculation.

In each of the sections, the blank fields must be filled in by the operator, while the grey fields are automatically obtained by the application when requested using the buttons on the screen.

Lengths, Heights, and Circumferences

First of all, after having identified on the patient the points C, E, G of the arm, in the modalities described in the section "Segmental Technique" of the chapter "Materials and Methods", the operator is asked to enter in the proper fields (figure 62) the data concerning:

- Forearm length C-E;
- Arm length E-G.

Then, by pressing on the "Ricava misure mancanti" button (figure 63), the homonymous function (figure 64) allows the following measurements to be obtained (figure 65, left):

- Total length C-G: sum of forearm and arm lengths;
- Height C, C1 and C2: 1/4, 1/4 and 3/4 of the forearm length respectively;
- Height E1, F: 1/3 and 2/3 of the arm length respectively;
- Height G: corresponding to the length of the arm.

Once the heights of the various reference points are known, the operator must enter the circumferences of the reference points into the appropriate fields (figure 65, right), which are again obtained in the manner described in the "Segmentary Technique" section of the "Materials and Methods" chapter.

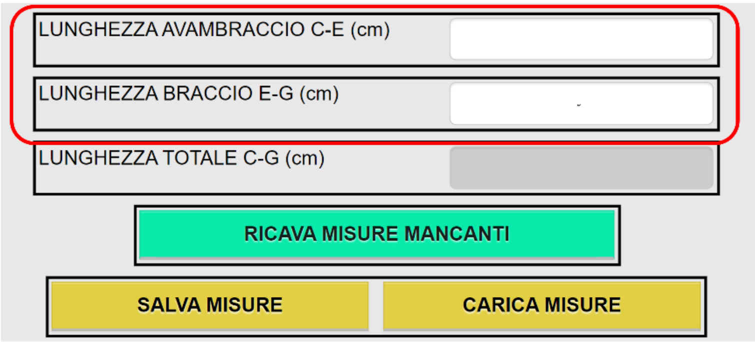


Figure 62 - Screen 2 “MISURE ARTO SUPERIORE”; fields to be filled in with forearm and arm lengths of the patient's limbs.

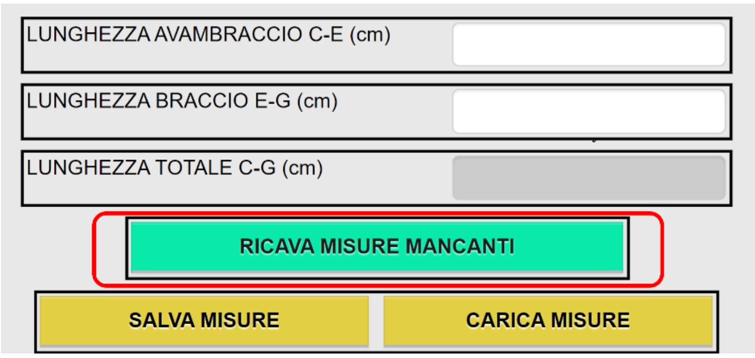


Figure 6344 - Screen 2 “MISURE ARTO SUPERIORE”; button to obtain the missing measurements via the "Ricava misure mancanti" function.

Figure 64 - Block diagram of the "Ricava misure mancanti" function.

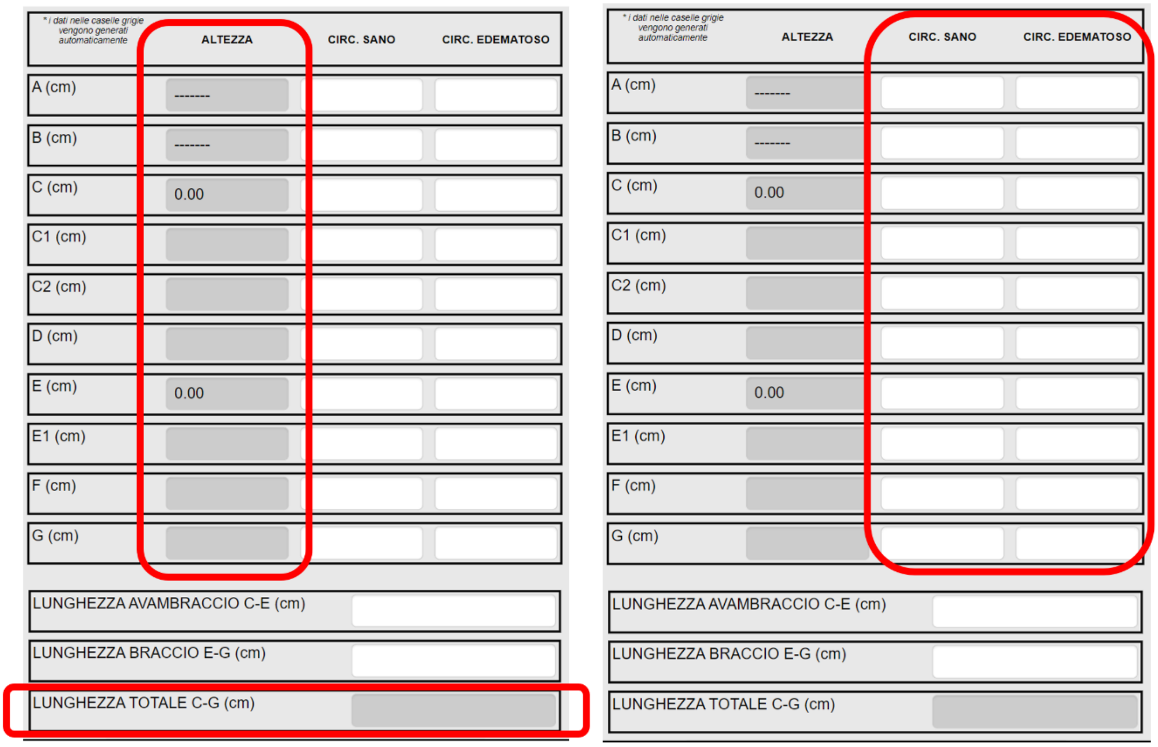


Figure 6545 - Screen 2 "MISURE ARTO SUPERIORE"; on the left, the fields filled in via the "Ricava misure mancanti" function; on the right, fields to be filled in with upper limb circumferences.

The measurements reported can be saved in the memory by means of the "Salva misure" button and can also be automatically reinserted by means of the "Carica misure" button (figure 66). It is important to remember that measurements are kept in memory even after closing the application, until they are overwritten.

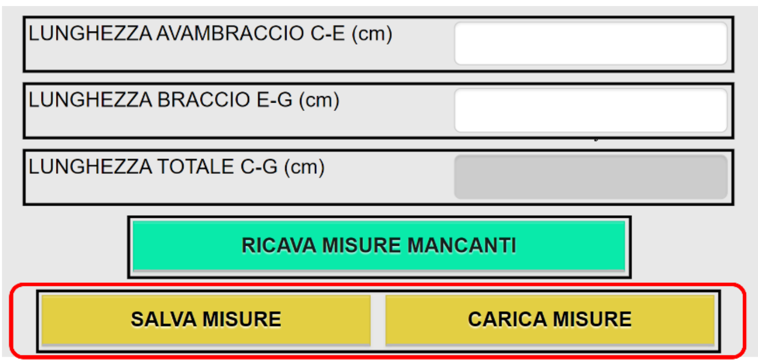


Figure 6646 - screen 2 "MISURE ARTO SUPERIORE"; buttons to save in memory and load the entered patient measurements.

Volumes

By pressing the "Ricava volumi" button, the application provides the volumes of the forearm, arm and upper limb of both the healthy limb and the oedematous limb (Figure 67), obtained by approximating the limb to a succession of truncated cones, according to the formula introduced in the "Centimetric methods" section of the "Materials and methods" chapter, implemented in the function of the homonymous button (Figure 68).

More specifically, the volume of the forearm will be obtained as the sum of the volumes of 4 truncated cones (those between C and C1, C1 and C2, C2 and D, D and E), the volume of the arm will be obtained as the sum of 3 truncated cones (those between E and E1, E1 and F, F and G), while the total volume of the upper limb will be obtained simply as the sum of the volumes of the forearm and arm.

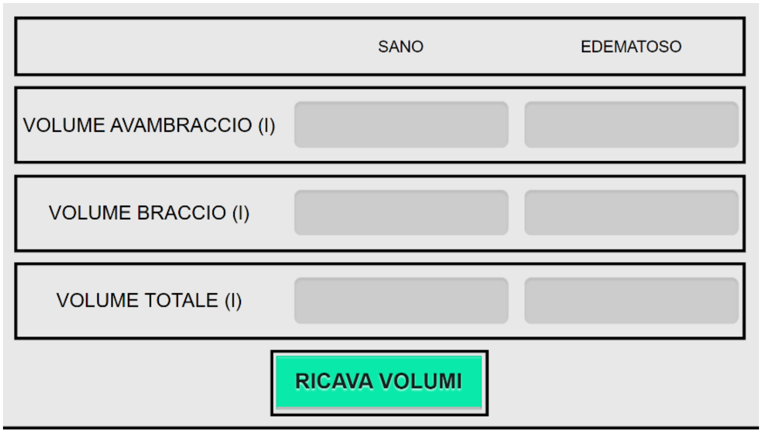


Figure 67 - screen 2 "MISURE ARTO SUPERIORE"; button to obtain patient's upper limbs volumes.

Figure 6847 - Block diagram of the "Ricava volumi" function.

Percentage deviations

By pressing the "Ricava discostamenti %" button (Figure 69), the application provides:

- Percentage deviations between circumference of contralateral limb and oedematous limb at all anatomical landmarks.
- Percentage deviations between forearm, arm and upper limb volume of contralateral limb and oedematous limb.

The "Ricava discostamenti" function (Figure 70) operates using the following formulas:

$$dC\ (\%) = \frac{C_o - C_c}{C_c} \cdot 100 \qquad\qquad dV(\%) = \frac{V_o - V_c}{V_c} \cdot 100$$

where dC(%) and dV(%) are the percentage deviations of circumference and volume, C_o and V_o are circumferences and volumes of the oedematous limb, and C_c and V_c are circumferences and volumes of the contralateral limb.

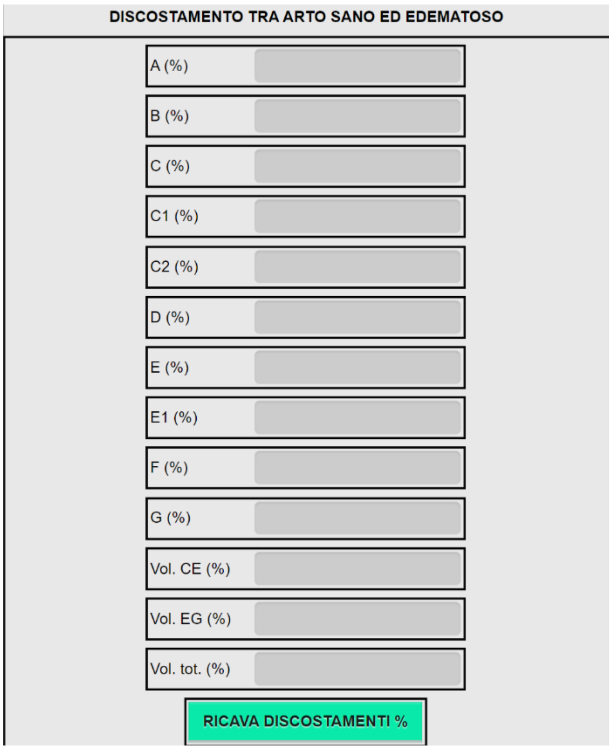


Figure 69 - screen 2 "MISURE ARTO SUPERIORE"; button to obtain patient's upper limb circumferential and volumetric deviations.

Figure 70 - Block diagram of the "Ricava discostamenti" function.

Overlap calculation

Finally, after entering the tissue consistency index, it is possible to obtain the number of overlaps in accordance with the bandage algorithms for the upper limb (given in the appendix) by pressing the "Calcola sovrapposizioni" button (figure 71).

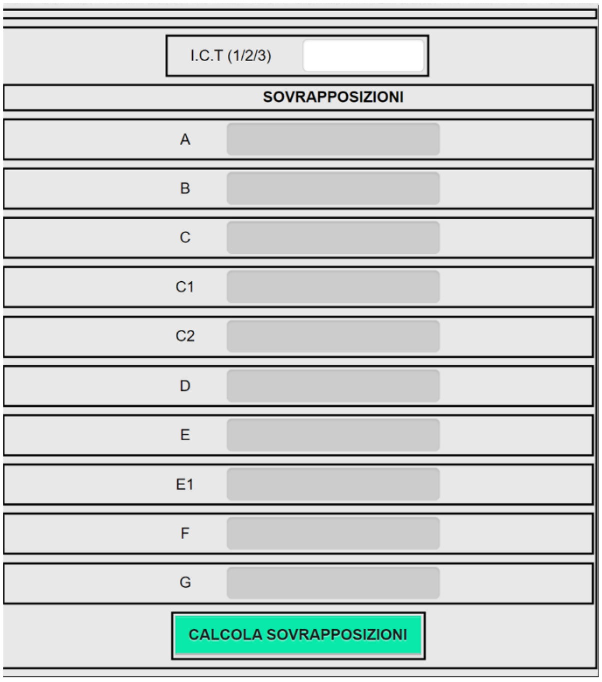


Figure 481 - screen 2 "MISURE ARTO SUPERIORE"; on the top, the field to be filled in with the ICT of the patient; on the bottom, the button to get the bandage overlaps to apply at each anathomic landmark, according to the proposed algorythm.

5.2.3 – SCREEN 3 – MISURE ARTO INFERIORE

Screen 3, designed to facilitate the assessment and treatment of upper lower lymphoedema, can be divided into 4 sections:

- Measurement of lengths, heights and circumferences;
- Calculation of volumes;
- Calculation of percentage deviations;
- Tissue consistency index (TCI) and overlap calculation.

In each of the sections, the blank fields must be filled in by the operator, while the grey fields are automatically obtained by the application when requested using the buttons on the screen.

Lengths, Heights, and Circumferences

First of all, after having identified on the patient the points C, E, G of the arm, in the modalities described in the section "Segmental Technique" of the chapter "Materials and Methods", the operator is asked to enter in the proper fields (figure 72) the data concerning:

- Leg lenght A-E;
- thigh lenght E-G;
- Heights of points B, C and D;

Then, by pressing on the "Ricava misure mancanti" button (figure 73), the homonymous function (figure 74) allows the following measurements to be obtained (figure 75, left):

- Total length C-G: sum of leg and thigh lengths;
- Height B1: intermediate point between B and C;
- Height E1, F: 1/3 and 2/3 of the thigh length respectively;
- Height G: corresponding to the length of the thigh.

Once the heights of the various reference points are known, the operator must enter the circumferences of the reference points into the appropriate fields (figure 75, right), which are again obtained in the manner described in the "Segmentary Technique" section of the "Materials and Methods" chapter.

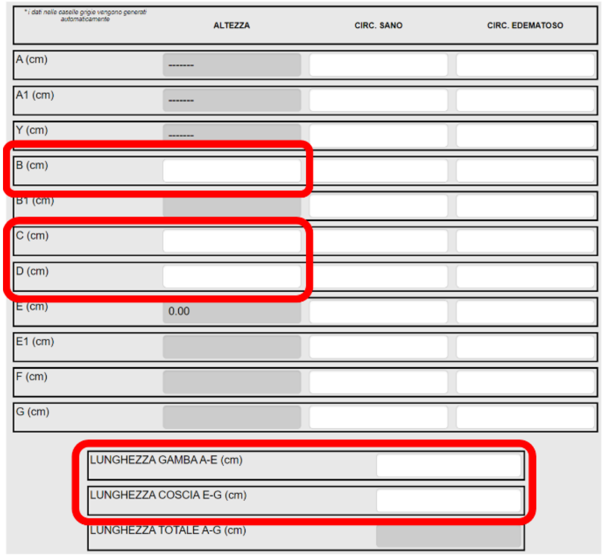


Figure 7249 - Screen 3 “MISURE ARTO INFERIORE8IE”; fields to be filled in with thigh and leg lengths of the patient's limbs, and with heights B ,C, D.

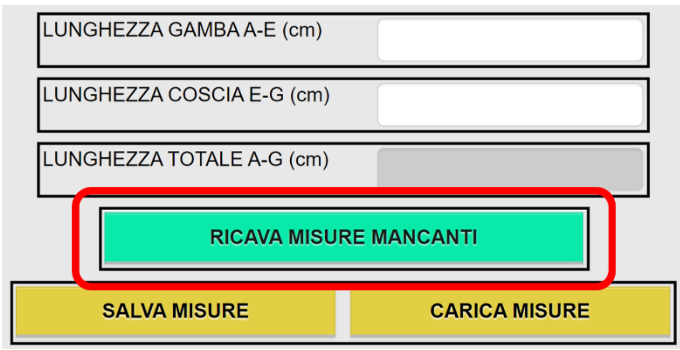


Figure 73 - Screen 3 “MISURE ARTO INFERIORE”; button to obtain the missing measurements via the "Ricava misure mancanti" function.

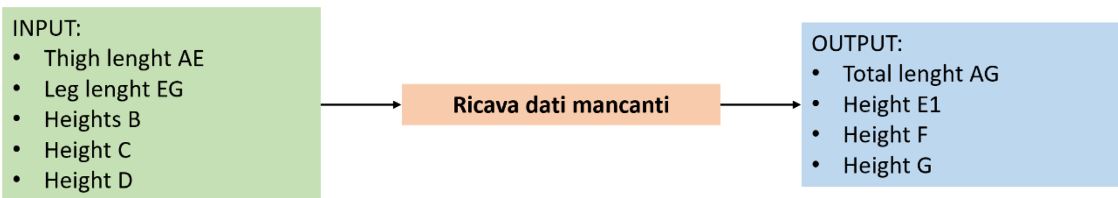


Figure 7450 - Block diagram of the "Ricava misure mancanti" function.

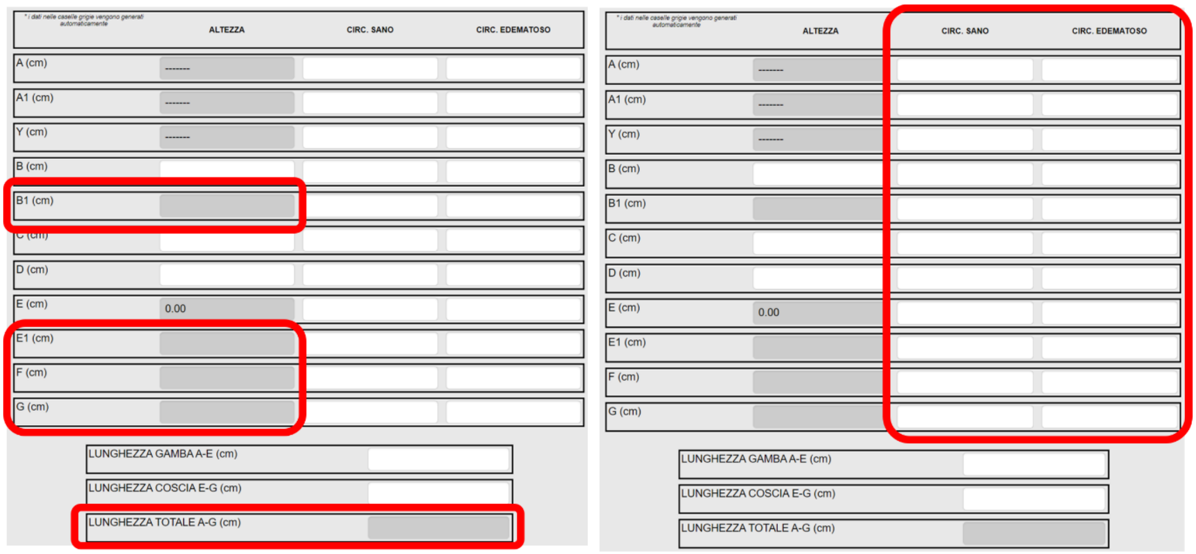


Figure 75 - Screen 3 "MISURE ARTO INFERIORE"; on the left, the fields filled in via the "Ricava misure mancanti" function; on the right, fields to be filled in with lower limb circumferences.

The measurements reported can be saved in the memory by means of the "Salva misure" button and can also be automatically reinserted by means of the "Carica misure" button (figure 76). It is important to remember that measurements are kept in memory even after closing the application, until they are overwritten.

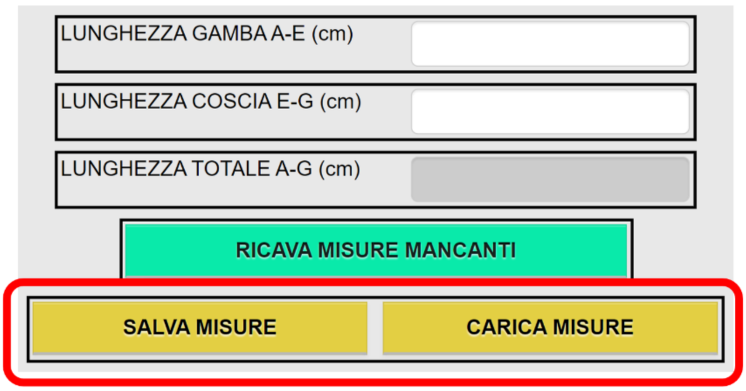


Figure 76 - Screen 3 "MISURE ARTO INFERIORE"; buttons to save in memory and load the entered patient measurements.

Volumes

By pressing the "Ricava volumi" button, the application provides the volumes of the thigh, leg and lower limb of both the healthy and the oedematous limbs (Figure 77), obtained by approximating the limb to a succession of truncated cones, according to the formula introduced in the "Centimetric methods" section of the "Materials and methods" chapter, implemented in the function of the homonymous button (Figure 78).

More specifically, the volume of the leg will be obtained as the sum of the volumes of 4 truncated cones (those between B and B1, B1 and C, C and D, D and E), the volume of the thigh will be obtained as the sum of 3 truncated cones (those between E and E1, E1 and F, F and G), while the total volume of the upper limb will be obtained simply as the sum of the volumes of the thigh and leg.

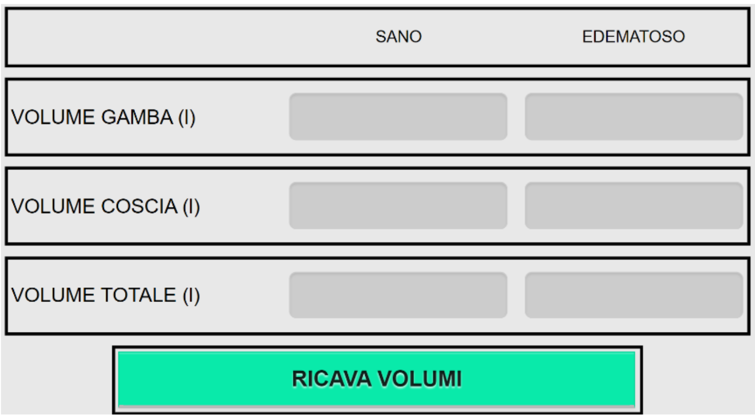


Figure 77 - screen 3 "MISURE ARTO INFERIORE"; button to obtain patient's lower limbs volumes.

Figure 7851 - Block diagram of the "Ricava volumi" function.

Percentage deviations

By pressing the "Ricava discostamenti %" button (Figure 79), the application provides:

– Percentage deviations between circumference of contralateral limb and oedematous limb at all anatomical landmarks.
– Percentage deviations between forearm, arm and upper limb volume of contralateral limb and oedematous limb.

The "Ricava discostamenti" function (Figure 80) operates using the following formulas:

$$dC\ (\%) = \frac{C_o - C_c}{C_c} \cdot 100 \qquad dV(\%) = \frac{V_o - V_c}{V_c} \cdot 100$$

where dC(%) and dV(%) are the percentage deviations of circumference and volume, C_o and V_o are circumferences and volumes of the oedematous limb, and C_c and V_c are circumferences and volumes of the contralateral limb.

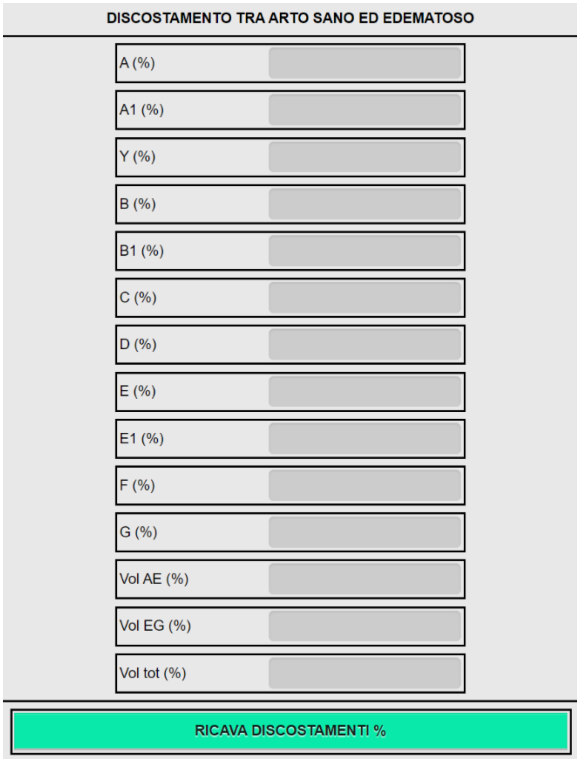


Figure 5279 -screen 3 "MISURE ARTO INFERIORE"; button to obtain patient's lower limb circumferential and volumetric deviations.

Figure 80 -Block diagram of the "Ricava discostamenti" function.

Overlap calculation

Finally, after entering the tissue consistency index, it is possible to obtain the number of overlaps in accordance with the bandage algorithms for the upper limb (given in the appendix) by pressing the "Calcola sovrapposizioni" button (figure 81).

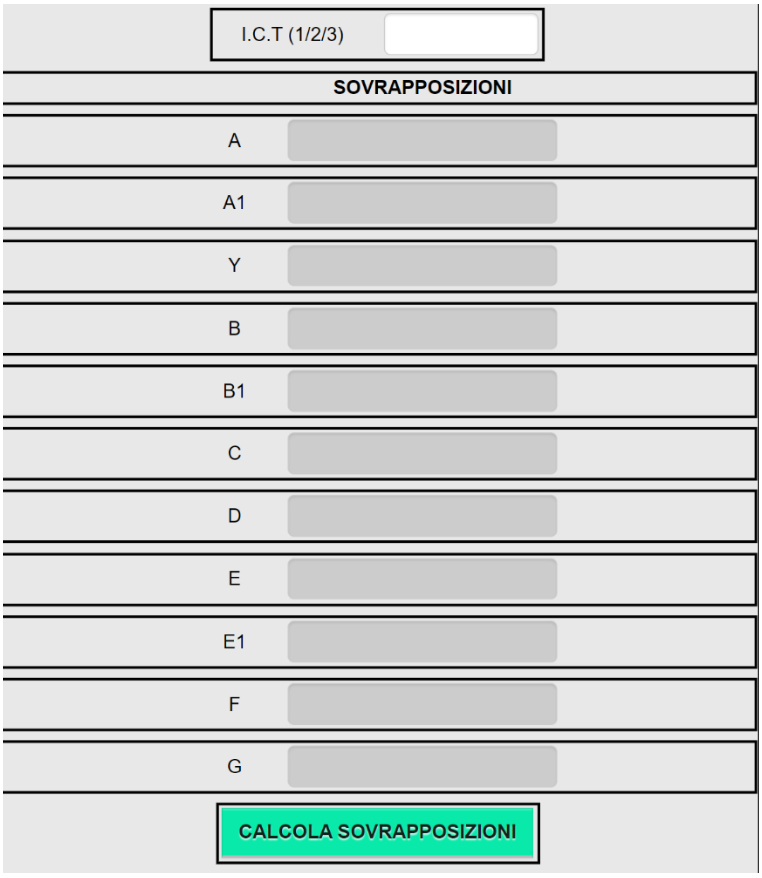


Figure 81 - Screen 2 "MISURE ARTO INFERIORE"; on the top, the field to be filled in with the ICT of the patient; on the bottom, the button to get the bandage overlaps to apply at each anathomic landmark, according to the proposed algorythm.

FUTURE DEVELOPMENTS OF THE PROJECT

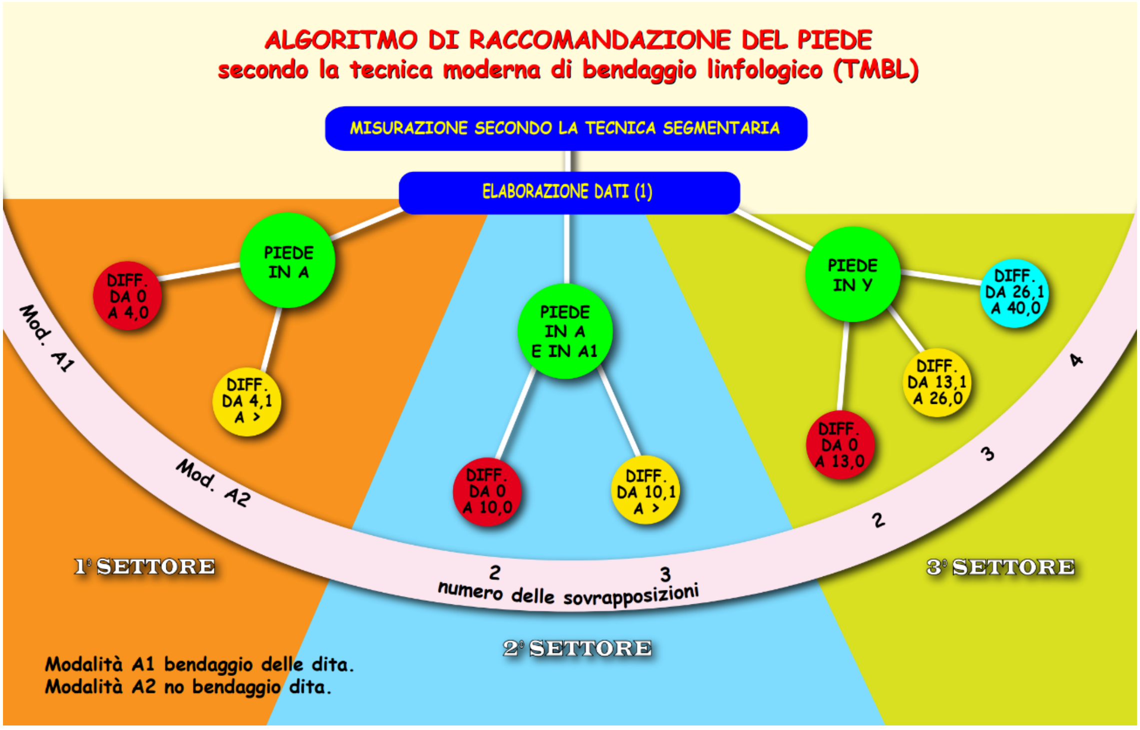
The application project cannot be considered finished at this stage, as it only assists the operator during the first day of treatment. In order for 'Limb Volumes' to be considered a complete application, the following specifications will have to be implemented:

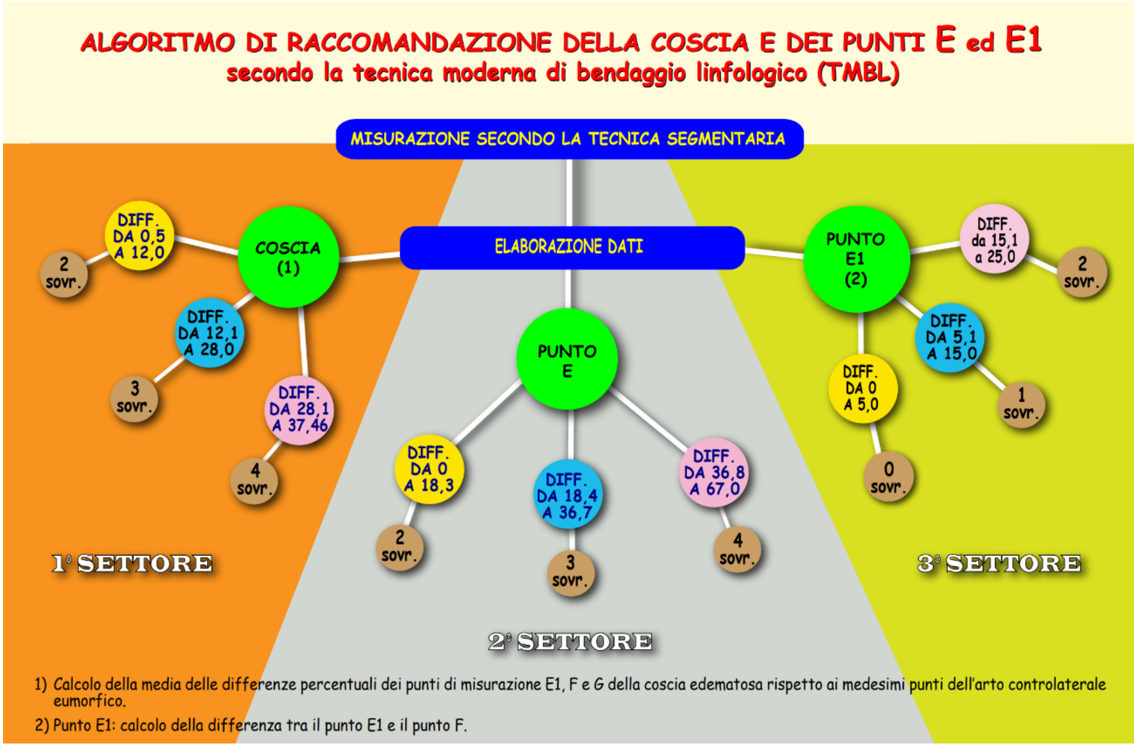
- Add additional screens that allow entering the measurements taken day by day, comparing them with those obtained during the first day of treatment.
- Allow data from several patients to be stored in memory, and possibly automatically converted into documents that can be downloaded and shared directly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

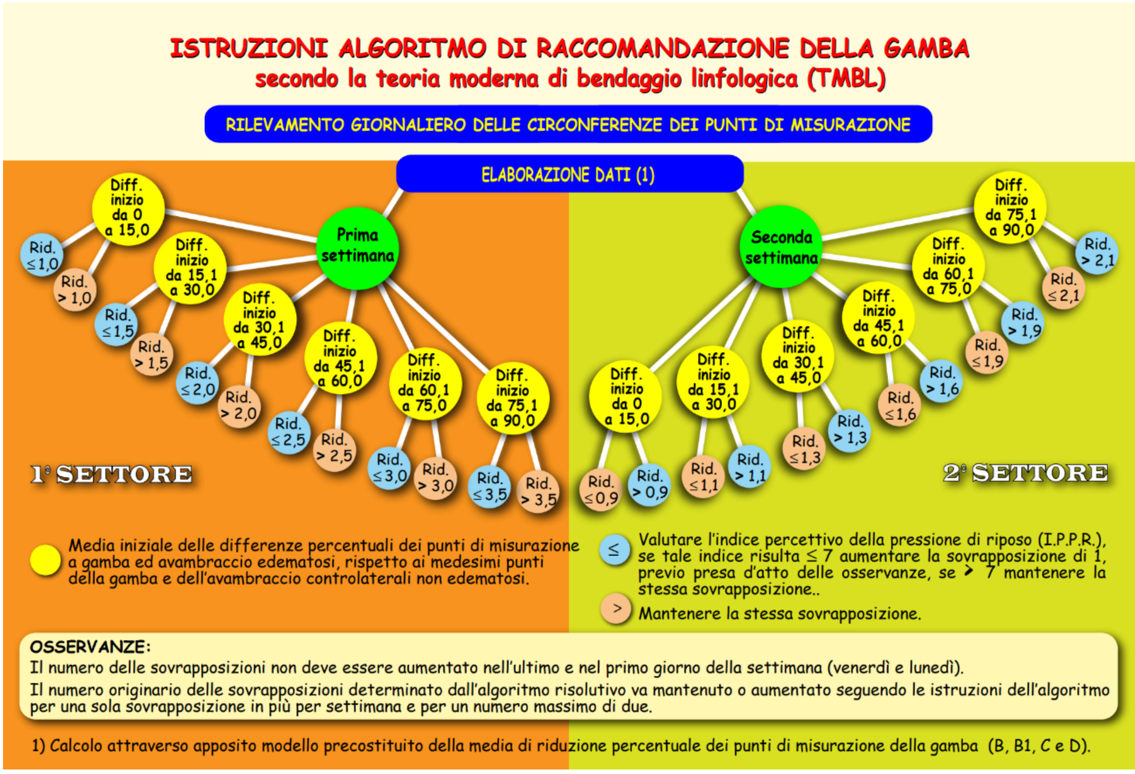
Although these specifications have not yet been met, the application is nonetheless a useful tool to support practitioners in their clinical practice, thanks to its simple and intuitive interface, and its use allows treatment times to be reduced, while at the same time minimising errors related to measuring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

ATTACHMENTS

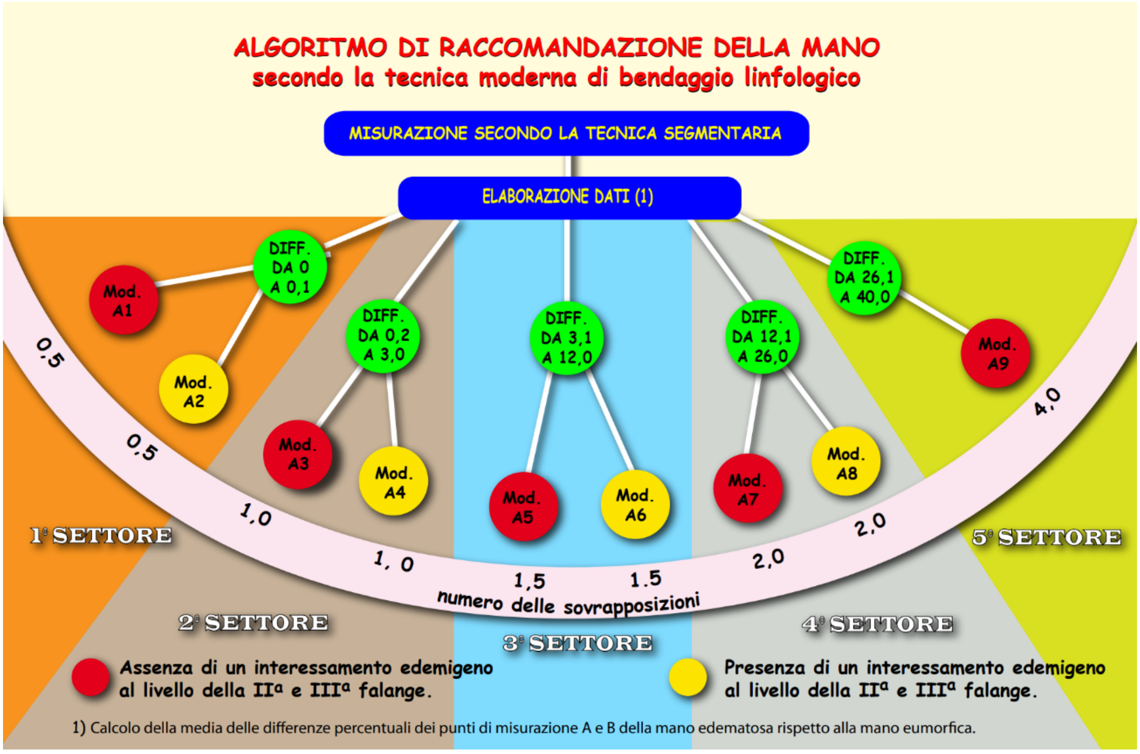
LOWER LIMBS BANDAGE ALGORITHMS

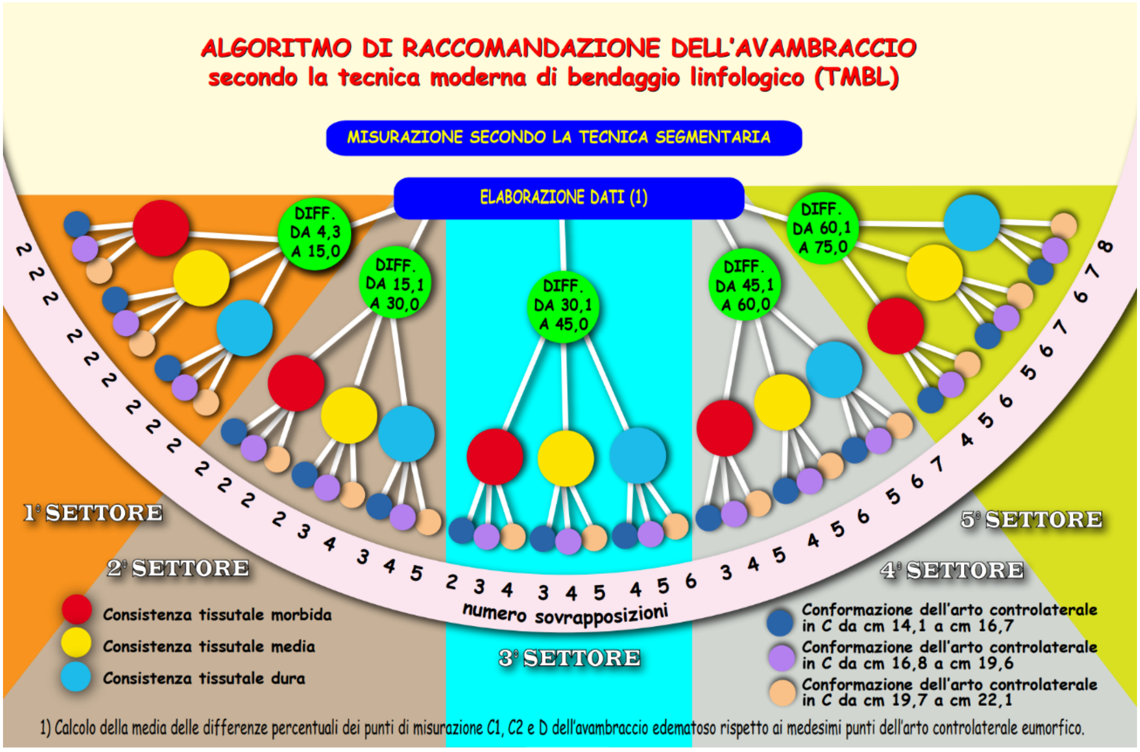



ALGORITMO DI RACCOMANDAZIONE DELLA COSCIA E DEI PUNTI E ed E1
secondo la tecnica moderna di bendaggio linfologico (TMBL)
MISURAZIONE SECONDO LA TECNICA SEGMENTARIA
ELABORAZIONE DATI
COSCIA (1)
DIFF. DA 0,5 A 12,0
2 sovr.
DIFF. DA 12,1 A 28,0
3 sovr.
DIFF. DA 28,1 A 37,46
4 sovr.
PUNTO E
DIFF. DA 0 A 18,3
2 sovr.
DIFF. DA 18,4 A 36,7
3 sovr.
DIFF. DA 36,8 A 67,0
4 sovr.
PUNTO E1 (2)
DIFF. da 15,1 a 25,0
2 sovr.
DIFF. DA 5,1 A 15,0
1 sovr.
DIFF. DA 0 A 5,0
0 sovr.
1° SETTORE
2° SETTORE
3° SETTORE
1) Calcolo della media delle differenze percentuali dei punti di misurazione E1, F e G della coscia edematosa rispetto ai medesimi punti dell'arto controlaterale eumorfico.
2) Punto E1: calcolo della differenza tra il punto E1 e il punto F.


ISTRUZIONI ALGORITMO DI RACCOMANDAZIONE DELLA GAMBA
secondo la teoria moderna di bendaggio linfologica (TMBL)
RILEVAMENTO GIORNALIERO DELLE CIRCONFERENZE DEI PUNTI DI MISURAZIONE
ELABORAZIONE DATI (1)
Prima settimana
Diff. inizio da 0 a 15,0
Rid. ≤1,0
Rid. > 1,0
Diff. inizio da 15,1 a 30,0
Rid. ≤1,5
Rid. > 1,5
Diff. inizio da 30,1 a 45,0
Rid. ≤2,0
Rid. > 2,0
Diff. inizio da 45,1 a 60,0
Rid. ≤2,5
Rid. > 2,5
Diff. inizio da 60,1 a 75,0
Rid. ≤3,0
Rid. > 3,0
Diff. inizio da 75,1 a 90,0
Rid. ≤3,5
Rid. > 3,5
Seconda settimana
Diff. inizio da 0 a 15,0
Rid. ≤0,9
Rid. > 0,9
Diff. inizio da 15,1 a 30,0
Rid. ≤1,1
Rid. > 1,1
Diff. inizio da 30,1 a 45,0
Rid. ≤1,3
Rid. > 1,3
Diff. inizio da 45,1 a 60,0
Rid. ≤1,6
Rid. > 1,6
Diff. inizio da 60,1 a 75,0
Rid. ≤1,9
Rid. > 1,9
Diff. inizio da 75,1 a 90,0
Rid. ≤2,1
Rid. > 2,1
1° SETTORE
2° SETTORE
Media iniziale delle differenze percentuali dei punti di misurazione a gamba ed avambraccio edematosi, rispetto ai medesimi punti della gamba e dell'avambraccio controlaterali non edematosi.
≤ Valutare l'indice percettivo della pressione di riposo (I.P.P.R.), se tale indice risulta ≤ 7 aumentare la sovrapposizione di 1, previo presa d'atto delle osservanze, se > 7 mantenere la stessa sovrapposizione..
> Mantenere la stessa sovrapposizione.
OSSERVANZE:
Il numero delle sovrapposizioni non deve essere aumentato nell'ultimo e nel primo giorno della settimana (venerdì e lunedì).
Il numero originario delle sovrapposizioni determinato dall'algoritmo risolutivo va mantenuto o aumentato seguendo le istruzioni dell'algoritmo per una sola sovrapposizione in più per settimana e per un numero massimo di due.
1) Calcolo attraverso apposito modello precostituito della media di riduzione percentuale dei punti di misurazione della gamba (B, B1, C e D).

UPPER LIMB BANDAGE ALGORITHMS





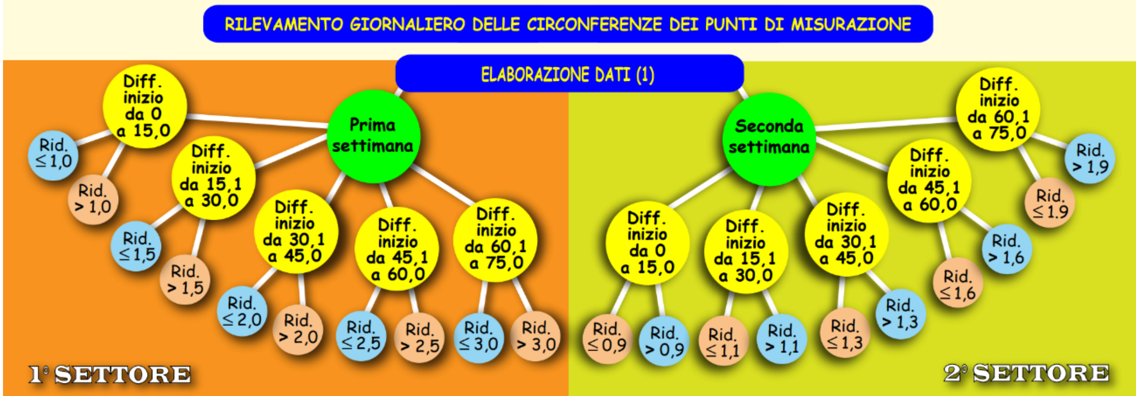
ALGORITMO DI RACCOMANDAZIONE DEL BRACCIO E DEI PUNTI C, E ed E1
secondo la tecnica moderna di bendaggio linfologico (TMBL)

1) Braccio: calcolo della media delle differenze percentuali dei punti di misurazione E1, F e G del braccio edematoso rispetto ai medesimi punti dell'arto controlaterale eumorfico.

2) Punto E1: calcolo della differenza tra il punto E1 e il punto F.

- (bianco) Differenza tra il punto di misurazione E1 rispetto al punto F da 0,0 a 5,0 nessuna sovrapposizione in più rispetto a quella contravvenuta a braccio.
- (magenta) Differenza tra il punto di misurazione E1 rispetto al punto F da 5,1 a 15,0 una sovrapposizione in più sul punto E1 rispetto a quella contravvenuta a braccio.
- (verde) Differenza tra il punto di misurazione E1 rispetto al punto F da 15,1 a 25,0 due sovrapposizioni in più sul punto E1 rispetto a quella contravvenuta a braccio.

ISTRUZIONI ALGORITMO DI RACCOMANDAZIONE DELL'AVAMBRACCIO
secondo la teoria moderna di bendaggio linfologica (TMBL)



- (giallo) Media iniziale delle differenze percentuali dei punti di misurazione a gamba ed avambraccio edematosi, rispetto ai medesimi punti della gamba e dell'avambraccio controlaterali non edematosi.
- ≤ Valutare l'indice percettivo della pressione di riposo (I.P.P.R.), se tale indice risulta ≤ 7 aumentare la sovrapposizione di 1, previo presa d'atto delle osservanze, se > 7 mantenere la stessa sovrapposizione..
- > Mantenere la stessa sovrapposizione.

OSSERVANZE:
Il numero delle sovrapposizioni non deve essere aumentato nell'ultimo e nel primo giorno della settimana (venerdì e lunedì).
Il numero originario delle sovrapposizioni determinato dall'algoritmo risolutivo va mantenuto o aumentato seguendo le istruzioni dell'algoritmo per una sola sovrapposizione in più per settimana e per un numero massimo di due.

1) Calcolo attraverso apposito modello precostituito della media di riduzione percentuale dei punti di misurazione dell'avambraccio (C1, C2 e D).

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