Research Article

NEW APPROACH TO PREDICT PRESSURE PRODUCED BY ELASTIC TEXTILE IN THE THEREPEUTIC TREATMENT OF VENOUS LEG

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ABSTRACT

This paper presents the first theoretical and practical work on compression therapy using the Laplace law to estimate pressures under the bandages. Three woven articles are considered: the first uses a highly-twisted cotton warp yarn, the second a polyamide warp yarn and the third a spandex yarn warped with a cotton yarn. Starting from these woven fabrics, three models, E_5, E_6 and Ef have been developed with respective elongations of 108 %, 86 % and 92 % and specific mechanical behavior. The results show that than the single layer bandages develop much higher pressure than the multilayer bandages but the multilayer bandages exert much more uniform pressure than single layered bandages. Obtaining uniform pressure along the length of the leg is a positive result in this treatment. Average circumferences of the human body are used for the pressure calculations in four zones: C_1, C_2, C_3 and C_4.

Keywords: elastic textile; weaving technology; venous leg; pressure.

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1. INTRODUCTION

Due to the lower blood pressure in the venous system compared to the arterial system, the walls of the veins are thinner than the companion arteries and they have larger diameters. Thin walls enable veins to have a large capacity for expansion. This and the large diameter explain why veins store about 60% to 75% of the blood [1]. The valves are cusps and attached by their convex edges to the venous wall. Their concave margins are directed with the flow and lie against the wall as long as the flow is towards the heart. When blood flow reverses, the valves close [2]. The venous network in the lower limb is divided into three systems that work together to return blood to the heart. These systems are: the superficial veins, the deep veins and the perforator veins [3]. There are three major deep veins below the knee: the anterior tibia vein, posterior tibia vein and peroneal vein.

Above the knee, there are two major branches: the popliteal vein, which is formed by the tibia and peroneal veins, and the femoral vein which is the continuation of the popliteal vein [4]. Venous sinuses are closely related to deep veins as they are embedded in the belly of the calf muscles and are able to dilate and hold a large amount of blood. These veins play a significant role in the calf muscle pump function. Blood flow resistance is the opposition to flow and is a measure of the amount of friction blood encounters as it passes through the vessel. Blood viscosity, blood vessel length and diameter are factors influencing blood flow resistance. The primary function of the venous circulation is to return blood to the heart. There are four different mechanisms which work together and assisted by venous valves to help venous return [5].

As people inhale, abdominal pressure increases, squeezing the veins in the ventral body cavity and forcing blood towards the heart. At the same time, pressure in the chest decreases, allowing thoracic veins to expand and speeding blood entry into the right atrium.   As a result of arteries expansion due to heart contraction, veins that accompany deep arteries get stretched and attened, which aid in driving venous blood towards the heart. Weight bearing is thought to empty blood from the foot when the foot gets at during a gait cycle. During normal locomotion, the three venous pumps; the foot pump, the distal and proximal calf pumps work together to pump blood back to the heart.

Before weight bearing, the ankle is dorsiflexed, emptying the distal calf pump. Weight bearing empties the foot using foot pump. Immediately after the weight bearing, the ankle is plantarexed and the proximal calf pump empties blood into the popliteal vein and femoral vein [6]. A variety of bandages are used beneath compression bandages as padding layers in order to evenly distribute pressure and give protection [7]. These include polyurethane foam bandages and nonwoven orthopedic waddings but there is little published material which defines their use for this particular problem or whether they have the performance criteria necessary to provide adequate pressure distribution [8]. In order to distribute compression bandage pressure evenly around the limb it is essential that high pressures created at the tibia and fibula regions are absorbed by the padding bandage material. In bandages using single layer, the textile pressure is directly transmitted to the leg surface.

Compression therapy in the form of bandaging is an ancient treatment that has been used since to treat venous leg ulcers. The term compression could be defined as squeezing part of the body by mechanical influence. The logic behind using compression therapy in the treatment of venous leg is to provide an external pressure that works gainst the hydrostatic pressure and aids venous blood return.

In a recent systematic review of the literature about venous ulcers, compression increases the healing rates for venous leg compared with no compression and that high compression is more effective than moderate compression [9]. In another systematic review of the clinical evidence about the usage of compression to prevent the recurrence of venous ulcers, recurrence of ulcers may be less with the usage of high compression compared to low compression [10]. However, there is no evidence that high compression is more effective than moderate pressure for prevention (but there is limited research available) [11]. Therefore the aim of this study is to verify the pressure variation applied on the four leg zones.

2. MATERIAL AND METHODS

Using the Laplace law to estimate the pressure under bandage, it's necessary to take into account two factors: the bandage width B and the number of applied layers N. The calculated value of sub-bandage pressure is the average pressure to be exerted by bandage on leg whose

circumference is known. To reduce the pressure variations in a given area under the bandage, padding can be used under compression materials [12]. Many types of textiles are composed of woven yarn, each thread composed of a plurality of fibers or yarns twisted together. Other, more advanced, the yarn cross sections may be elliptical, lenticular or racetrack. The factor that changes the most is the vessel diameter. The relation between the flow (Q), the difference in blood pressure (Δ_{PB}) and the peripheral resistance (Δ_{RP}) is summarized in Equation 1.

$$Q = \frac{\Delta_{PB}}{\Delta_{RP}} \tag{1}$$

The equation illustrates the importance of the difference in the blood pressure to the flow. However, in order to maintain a reasonable degree of simplicity, the banding pressure can be formulated by mathematical expression:

$$P_i - P_e = \frac{T_1}{r} + \frac{T_2}{r} \tag{2}$$

$$P = P_i - P_e = \frac{2T}{r} \tag{3}$$

(P_i - The internal pressure, P_e -The external pressure, T_1 - The positive tension of textile, T_2 - The negative tension of textile, R - The curvature radius, T- Tension of bandage).

Equation (3) shows that pressure inside of a spherical surface is always greater than external pressure, but the difference tends to zero when the radius tends to infinity (when the surface becomes flat). However, pressure difference increases if the radius becomes smaller and tends to infinity as r tends to zero. When the wall is perfectly cylindrical, simply use the following (4).

$$P = \frac{T}{r} \tag{4}$$

This law is applied in many sectors of science, including medicine, to calculate the forces exerted on blood vessels and alveoli filled with fluid. It is necessary to use the measuring unit's conversion of measurement, that is to say, using units pertaining to each other. The most common unit used is Pascal for measuring the pressure and Newton unit as measure of force,

but in medical field, other units are often used. To reduce errors due to measurement units, it is important to consider a constant coefficient of conversion of measurement units K and equation (4) takes the following form:

$$P = \frac{T}{r} \cdot K \tag{5}$$

$$P = \frac{F}{2 \cdot \pi \cdot r \cdot B} \tag{6}$$

F- the resultant force of the applied tension.

In case of a single bandage layer applied, the pressure is exerted on surface covered by the textile. This pressure will be determined by total force applied on fabric and width of the bandage in relation to the definition of pressure. Pressure applied is proportional to the force on the textile and inversely proportional to the application surface. The original formula for calculating pressure is expressed as:

$$P = \frac{T \cdot N}{L \cdot B} \tag{7}$$

To move from one measurement unit to another and to avoid significant errors due to conversion of measurement units, it is useful to consider a constant K in final equation.

Consider the following case with: N = 1 layer ; B = 0,10 m ; r = 0,04 m ; T =15 N = 1.53 kgf ; L = 0.25 m, the pressure (P) under the bandage can be calculated as follows:

$$P = \frac{15}{0.04 \cdot 0.1} = 3750 \quad Pa \tag{8}$$

$$P = 3750 \cdot 0{,}0075 = 28.125 \quad mm\,Hg \tag{9}$$

P' (mm Hg); T' (Kgf); L' (m); B' (m), then:

$$P' = \frac{T' \cdot N \cdot K}{L' \cdot B'} \tag{10}$$

After substitution numerical values given above:

$$28.125 = \frac{1.53 \cdot N \cdot K}{(2 \cdot 3{,}1416 \cdot 0.04 \cdot 100) \cdot 10} = \frac{1.53 \cdot K}{251{,}328} : \qquad then: K = 4620 \tag{11}$$

P - Pressure (mmHg), T - Tension (Kgf), L – The circumference (cm), B - Width (cm),

N - Number of layers applied.

When applying of a bandage, several forces arise may be mentioned: the longitudinal tension, the transverse tension, the pressure applied by the textile, the reaction force of the leg surface, the friction between textiles and leg area, shear forces, longitudinal and transverse textile flexion forces. When it comes to more layers, the upper layers still exert pressure on the lower layers. The total tension developed by an elastic band is equal to the sum of warp tensions yarns. The result is that the number of layers (N), applied with a constant tension is proportional to the number of warp yarns in a point of application on the leg surface. Therefore it is essential to consider the number of layers in the calculations.

The level of compression generated by a bandage system is determined by complex interactions between the following main factors: the physical structure of the textile, the elastic properties, the size and form of the member, the qualification of nurses. In the model above, the pressure created by a bandage after installation depends on: the tension in the fabric, the number of layers applied, the radius of the member,

2. MODELISATION

2.1. Model applied for one layer

The pressure generated by a rigid or elastic material is inversely proportional to the circumference in the point of application; in this case it seems significant to consider the thickness of the fabric on the value of the applied pressure.
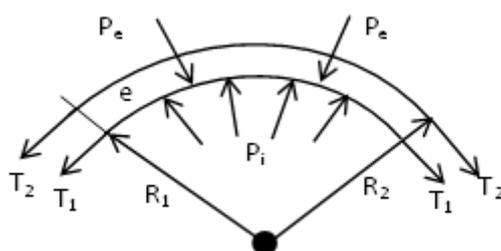
Fig.1. Model taking into account the thickness of the bandage

In this approach, the bandage is assumed cylindrical shape with a thickness (e) as shown in

Figure 1. It is useful to introduce the following data to conclude on the influence of the thickness of the material.

$$T_M = \frac{T_1 + T_2}{2} \tag{13}$$

$$D_1 = 2R_1 \tag{14}$$

$$D_2 = 2R_2 \tag{15}$$

T_M : Medium tension applied (N), D_1 : Inside application diameter (m), D_2: Outside application diameter (m).

The wall of the cylinder is subject to three types of stresses, circumferential, longitudinal and transverse. If the ratio between the fabric thickness and the radius at the point of application is less than 0.1, then the longitudinal stresses are negligible. In this case, thickness of the elastic band is not considered. In the opposite case it is necessary to take into account the thickness as in the case of multilayer bandages. Usually the number of layers cannot exceed 4. The hoop stress (tangential) may be described as a function of the applied tension (T), the length (L) of an element and the thickness (e). Based on the above assumptions, the hoop stress can be presented by the following equation:

$$\sigma_H = \frac{P \cdot D}{2e} \tag{16}$$

σ_H : Tangentiel stress (N/m^2), P : Internal pressure (N/m^2), D : Application diameter (m)
e : Material thickness (m), B : Bandage Width (m)

$$\sigma_H = \frac{F}{S} = \frac{T}{e \cdot B} \tag{17}$$

S: The application surface

And:

$$P = C \cdot \frac{2T}{D \cdot B} \quad , \quad C = 0.0075 \tag{18}$$

This equation does not take into account the thickness of the fabric, thus the thickness of the bandage does not influence the pressure interface produced by the applied textile. This model is used to calculate the pressure in the case of use of layer.

2.2. Model applied for multiple layers

Considering two elastic textiles made from textile materials with elastic moduli E_1 and E_2 (N /m$_2$), the radius applied in centers of the two materials are respectively R_1 and R_2 and

having thicknesses e_1 and e_2, as illustrated in Figure 2.
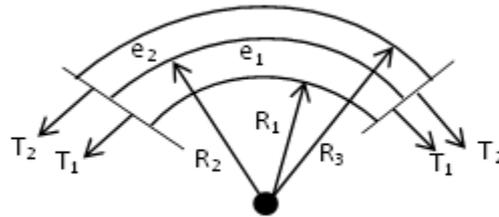
Fig.2. Model taking into account the thickness and number of layers

The total tension (T) applied distributed between the two fabrics is presented by the equation (19).

$$T = \sigma_1 \cdot 2\pi \cdot R_1' \cdot e_1 + \sigma_2 \cdot 2\pi \cdot R_2' \cdot e_2 \tag{19}$$

$R_1' = R_2 - R_1$

$R_2' = R_3 - R_2$

σ_1 maximum stress of textiles 1

σ_2 maximum stresse of textile 2

By compatibility, the two textiles develop the same axial stress(ε):

$$\varepsilon = \frac{\sigma_1}{E_1} = \frac{\sigma_2}{E_2} \tag{20}$$

Combining expressions (19) and (20), the following equation defines the total tension applied by the two textiles:

$$T = \frac{(\varepsilon E_1 \cdot 2\pi \cdot R_1 \cdot e_1 + \varepsilon \cdot E_2 \cdot 2\pi \cdot R_2 \cdot e_2)}{C} = \frac{\varepsilon 2\pi (E_1 R_1 e_1 + E_2 R_2 e_2)}{C} \tag{21}$$

Because of the thicknesses e_1 et e_2 are very small ($\frac{e_1}{R_1} < \frac{1}{10}$, et $\frac{e_2}{R_2} < \frac{1}{10}$), the radius R_1 et R_2 are the same then: ($R = R_1 = R_2$), and using the Laplace low:

$$P = \frac{T}{R} = \left(\frac{1}{R}\right)\frac{\varepsilon \cdot 2\pi \cdot R(E_1 \cdot e_1 + E_2 \cdot e_2)}{C} \frac{\varepsilon \cdot 2\pi(E_1 \cdot e_1 + E_2 \cdot e_2)}{C} \tag{22}$$

If three layers are used with the same or different bandages, and applying with the same principle of very small thickness, the three layers will have a total pressure on the leg of:

$$P = \frac{\varepsilon \cdot 2\pi(E_1 \cdot e_1 + E_2 \cdot e_2 + E_3 \cdot e_3)}{C} \tag{23}$$

E_3, e_3 are respectively the elastic modulus and the thickness of the third band. If this hypothesis is always true for the case where one uses several materials with different elastic modulus, then

the pressure exerted by (n) layers is presented by the following expression:

$$P = \frac{\varepsilon 2\pi \sum_{i=1}^{n}(E_i \cdot e_i)}{C}$$

(24)

3. RESULTS AND DISCUSSION

The calculations are done for each section with three turns on the prototype in the four zones as shown in figure 3:
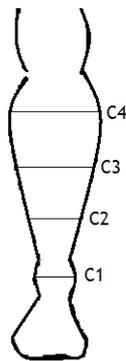
Fig.3. Shape of leg with the considered zones

$C_1 = 260$ mm - Section of the ankle
$C_2 = 280$ mm - section above the ankle
$C_3 = 330$ mm - Section below the calf
$C_4 = 390$ mm - calf section

The final properties of textiles depend more or less on many different technical and technological parameters, which should already be adjusted during the design phase of a textile. To predict interfacial pressure induced by different textile structure on a curved surface of the human body, the relationship between the tensile properties of an elastic fabric, the curvature of the shaped surface, and the pressure of the skin and textile interfacial may be formulated into a mathematical expression.

The different degrees of elasticity and materials strength with different degrees of weave tension can induce different degrees of pressure on patients. A lot of elastic textile fabrics are produced using weaving needle looms techniques.

Therefore, a variety of samples were adopted until an optimum bandage will produce. For all calculations and practical experiences we used the three samples taken during work earlier as shown in Table 1.

Table 1. Characteristics of the study samples

Characteristics	Designations	Units	Samples		
			E_6	E_5	E_f
Twist rate of warp yarns direction	k	Tr/m	900	900	900
Weft density	P_{tr}	Yarns/10 cm	180	90	126
Weft average diameter	d_{tr}	mm	0.20	0.20	0.20
Elongation under fixed load (800	Al	%	108	86	92
Widh	B	mm	100	100	100
Structure	-	-	Plain weave	Plain weave	Plain weave

This includes the tension applied on to textiles and corresponding elongations during each phase in the ascending or descending direction. It should be noted that the elongations and the tensions applied onto the textile are important parameters for the calculation of the pressure in use. They also help to make conclusions in the practical application of bandages. In Table 2, 3, 4 and 5 are presented the tensions (T) values specific to each sample (E) and the corresponding elongations (A_l) and the tensions are calculated experimentally.

Table 2. Pressures calculated on samples E_5, E_6 and Ef in the C_1 zone

E_5 :TensionT_5 (cN)x10	E_5C_1 : Pressure P_5	E_6 : Tension T6 (cN)x10	E_6C_1 : Pressure	E_f : Tension T_f (cN)x10	E_fC_1 : Pressure P_f
14	7,46	28	14,93	21	11,19
20	10,66	39	20,79	30	15,99
28	14,93	54	28,79	41	21,86
36	19,19	67	35,72	50	26,65
45	23,99	79	42,11	58	30,92
52	27,72	87	46,38	65	34,65
61	32,52	96	51,18	71	37,85
68	36,25	101	53,84	78	41,58
74	39,45	104	55,44	82	43,71
80	42,65	107	57,04	88	46,91
86	45,84	108	57,57	92	49,04

Table 3. Pressures calculated on samples E_5, E_6 and Ef in the C_2 zone

E_5 : Tension cNx10	E_5C_2 : Pressure	E_6 : Tension cNx10	E_6C_1 : Pressure	E_f : Tension cNx10	E_fC_2 : Pressure
14	6,93	28	13,86	21	10,4
20	9,9	39	19,31	30	14,85
28	13,86	54	26,73	41	20,3
36	17,82	67	33,17	50	24,75
45	22,26	79	39,11	58	28,71
52	25,74	87	43,07	65	32,18
61	30,2	96	47,52	71	35,15
68	33,66	101	49,99	78	38,61
74	36,63	104	51,48	82	40,59
80	39,6	107	52,97	88	43,56
86	42,57	108	53,46	92	45,54

Table 4. Pressures calculated on samples E_5, E_6 and Ef in the C_3 zone

E_5 : Tension cNx10	E_5C_3 : Pressure	E_6 : Tension cNx10	E_6C_3 : Pressure	E_f : Tension cNx10	E_fC_3 : Pressure
14	5,88	28	11,76	21	8,82
20	8,4	39	16,38	30	12,6
28	11,76	54	22,68	41	17,22
36	15,12	67	28,14	50	21
45	18,9	79	33,18	58	24,36
52	21,84	87	36,54	65	27,3
61	25,62	96	40,32	71	29,82
68	28,56	101	42,42	78	32,76
74	31,08	104	43,68	82	34,44
80	33,6	107	44,94	88	36,96
86	36,12	108	45,36	92	38,64

Table 5. Pressures calculated on samples E_5, E_6 and Ef in the C_1 zone

E_5 : Tension cNx10	E_5C_4 : Pressure	E_6 : Tension cNx10	E_6C_4 : Pressure mm	E_f : Tension cNx10	E_fC_4 : Pressure mm
14	4,98	28	9,95	21	7,46
20	7,11	39	13,56	30	10,66
28	9,95	54	19,19	41	14,57
36	12,79	67	23,81	50	17,77
45	15,99	79	28,08	58	20,61
52	18,48	87	30,91	65	23,1
61	21,68	96	34,12	71	25,23
68	24,17	101	35,89	78	27,72
74	26,3	104	36,96	82	29,14
80	28,43	107	38,03	88	31,27
86	30,56	108	38,38	92	32,7

From graphs in figures 3, 4, 5, 6, 7 and 8, it is clear that the tension is the first factor that directly influences with a large percentage on the pressure of the textile surface. These graphic data are very important because they can clearly see the applied tensions and choose them for a good practical application of hospital bandages. In the graphs which follow, C is the circumference in (mm) and P is the pressure in (mm Hg).
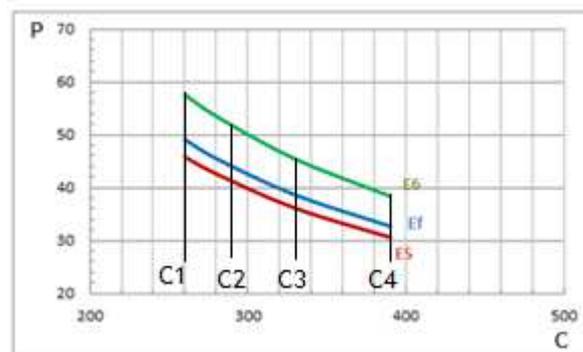
3.1. Textile single layer
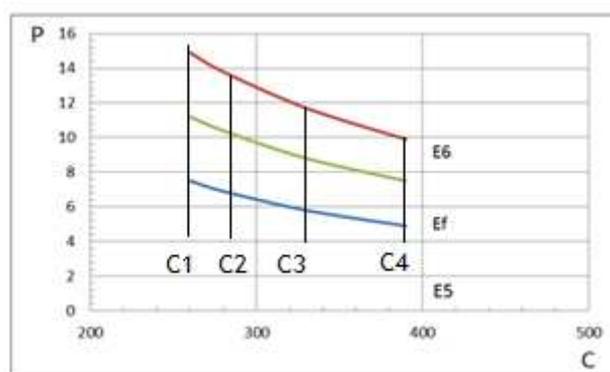
Fig.4. Relation between the pressure and the circumference of the leg (minimum pressure)
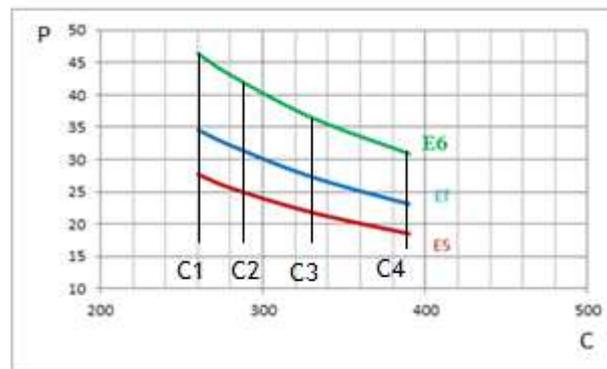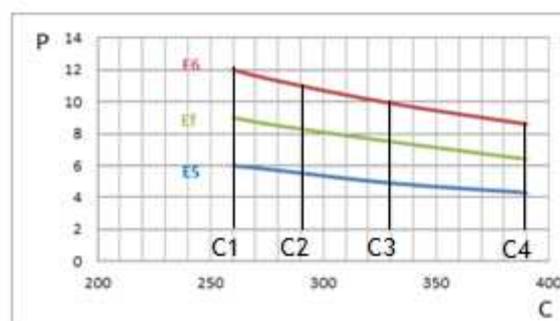
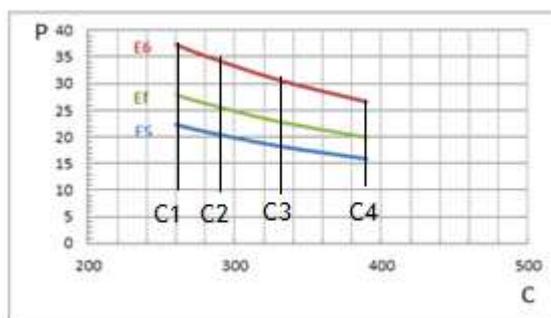**Fig.5.** Relation between the pressure and the circumference of the leg (medium pressure)

Fig.6. Relationship between the pressure and leg circumference (maximum pressures)

For the applied minimum pressures, the pressure difference at the ankle bandage between the E_5 and E_6 is 7.4 mm Hg. The same pressure difference at the calf level is 5 mmHg. For the applied maximum pressures, the pressure difference at the ankle between E_5 and E_6 is 11.8 mm Hg. The same pressure difference at calf level is 7.8 mm Hg.
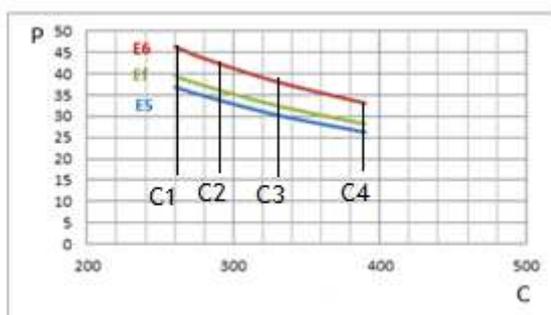
3.2. Multiple layer textile

Fig.7. Relation between the pressure and the circumference of the leg (minimum pressure)

Fig.8. Relation between the pressure and the circumference of the leg (medium pressure)

Fig.9. Relationship between the pressure and leg circumference (maximum pressures)

We note that the pressure difference at the ankle is much greater than the pressure difference at the calf, this also confirms when employing low pressure and high pressure. If we consider the final sample E_f, and the same assumptions, the pressure difference is 3.7 mm Hg compared with E_5 bandage at the ankle in the case of minimum pressure values while the pressure difference at the calf with the value of the sample E_5, is 2.6 mm Hg. In the case of the maximum values of applied pressure, at the ankle, the pressure difference between E_f and E_5 bandage is 3.3 mm Hg, and 2.1 mm Hg at the calf for the same bandage.

4. CONCLUSION

The E_f bandage exerts moderate pressures compared to other models because the pressure difference with the other tires is low; the difference between the ankle and calf in the case of Ef bandage for minimum values is 1.1 mm Hg while the same difference for the E_6 band is 2.4 mm Hg. The difference in pressure between the ankle and calf in the case of pressure to the Ef bandage is 1.2 mm Hg while the same difference for the E_5 sample is 4 mm Hg.

The results show that simple bandages multilayer develop much higher pressure than those said multilayer, the multilayer bandages exert much more uniform pressure than single layered bandages. Considering the same bandage with an application of multiple layers, we can say that the bandage E_f presents the optimal characteristics and has moderate pressures compared to other models because the pressure difference with the other bandage is low. The pressures are more uniform and the results are satisfactory as they are within the limits of the standards indicated previously.

5. ACKNOWLEDGEMENTS

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