The Effect of Multi-Layer Bandage on the Interface Pressure Applied by Compression Bandages

Jawad Al Khaburi, Abbas A. Dehghani-Sanij, E. Andrea Nelson and Jerry Hutchinson

Abstract— Medical compression bandages are widely used in the treatment of chronic venous disorder. In order to design effective compression bandages, researchers have attempted to describe the interface pressure applied by multi-layer bandages using mathematical models. This paper reports on the work carried out to compare and validate the mathematical models used to describe the interface pressure applied by multi-layer bandages. Both analytical and experimental results showed that using simple multiplication of a number of bandage layers with the pressure applied by one layer of bandage or ignoring the increase in the limb radius due to former layers of bandage will result in overestimating the pressure. Experimental results showed that the mathematical models, which take into consideration the increase in the limb radius due to former bandage layers, are more accurate than the one which does not.

Index Terms—Compression bandages, FlexiForce, interface pressure, venous ulcer

I. INTRODUCTION

CHRONIC leg ulcers affect 1% of the adult population in developed countries, and the majority of leg ulcers are caused by venous disease [1], [2]. The impact of venous ulcers on quality of life is significant. It costs the NHS £300-600m annually [3]. Medical compression bandages (MCBs) are the cornerstone in the treatment of chronic venous ulcers [4]. MCBs should be applied with a pressure gradient reducing from the ankle to the knee [5], [6]. Insufficient or non-sustained compression therapy will be less effective than sufficient and sustained compression due to an impaired hemodynamic effect [5], [6]. Excessive bandage pressure can lead to tissue damage, pressure sores and necrosis [5], [6]. Reverse gradient compression is likely to worsen the condition as it increases the pressure in the veins [6]. Limb damage or treatment failure may result in limb amputation [5]. In order to design effective compression systems, improve practice and help nurses achieve the optimum pressure gradient, many researchers have attempted to describe or predict the interface pressure theoretically [7], [8]. Thomas [8] used the Law of Laplace, which is defined as the tension in the walls of a container being dependent on both the pressure of the container's content and its radius [9], to predict the interface pressure applied by single-layer MCB (see Equation 1).

J. Al Khaburi is a lecturer in Mechanical Engineering in the Engineering Department, the Higher College of Technology (HCT), Muscat, Sultanate of Oman. He was a PhD student in the School of Mechanical Engineering, University of Leeds, LS2 9JT, Leeds, UK (Corresponding author phone: 968 92154894, e-mail: j.alkhaburi@gmail.com)

A. A. Dehghani-Sanij is with School of Mechanical Engineering, University of Leeds, LS2 9JT, Leeds, UK (e-mail: A.Dehghani@leeds.ac.uk)

E. A. Nelson is with School of Healthcare, University of Leeds, LS2 9JT, Leeds, UK (e-mail: e.a.nelson@leeds.ac.uk)

J. Hutchinson is with ConvaTec Limited, CH5 2NU, Deeside, UK (email: jerry.hutchinson@convatec.com)

$$P = \frac{T}{R} \qquad (1)$$

Where, P is the interface pressure in Newton per metre square (N/m^2), T is the tension in bandage in (N) for $(1m)$ width of fabric and R is the curvature radius in (m).

In clinical practice, bandages are applied in the form of overlapping layers which results in multiple layers of fabric that overlay a particular point of the surface of the limb [5]. For example, MCBs applied with spiral 50 overlap technique will overlay the leg with two layers of bandage, MCBs applied with 33 overlap will result in three layers of bandage and MCBs applied with the figure-of-eight technique with 50 overlap will result in four layers of bandage [5]. In addition, many MCB systems involve the use of several layers of different MCB components. Therefore, in many situations researchers need to calculate the pressure applied by several layers of bandage. Thomas [8] extended his model to estimate the interface pressure induced by multi-layer bandage application (Equation 2).

$$P = \frac{nT}{Rw} \qquad (2)$$

Where, n is the number of bandage layers and w is the bandage width in (m).

However, the use of simple multiplication of the numbers of layers with the pressure induced by one layer to express the overall interface pressure was questioned by Wertheim et al. [10]. In addition, Melhuish et al. [11] have demonstrated in their work that as the tension in the applied bandage increases, the pressure increases too. They have also shown that the pressure decreases as the radius of the solid cylinder increases. Nevertheless, they reported that the amount of reduction in the applied pressure did not follow the predictions using Equation 1. In addition, they illustrated that the interface pressure would increase as the number of layers of bandage increases. However, they did not find a linear relationship between the applied pressure and the number of bandage layers as suggested by Thomas [8].

The problem with this derivation is that it does not consider the increase in the radius caused by additional layers of bandage i.e. the later bandage layers are applied to a larger radius medium with the overall radius equivalent to the sum of the limb radius and the bandage thickness. In previous works [12], [13], the authors derived two mathematical expressions to calculate the interface pressure applied by multi-layer bandage to a limb with known radii of curvature. The first expression is based on thin wall cylinder theory [14] (see Equation 3)

World Academy of Science, Engineering and Technology
International Journal of Mechanical and Mechatronics Engineering
Vol:5, No:6, 2011

and the second expression is based on thick wall cylinder theory [14] (see Equation 4). The difference between the thin and thick wall cylinder theories is that the radial stress in the direction of the wall thickness (bandage thickness) is assumed to be negligible [14].

$$P_n = \sum_{i=1}^{n} \frac{2T_i}{w_i D_i} \times 0.0075$$
$$\text{Where, } D_i = D + \sum_{i=1}^{n} 2t_{i-1} \tag{3}$$

Where, i is the bandage layer, t_{i-1} is the extended and compressed bandage layer thickness in (m), T_i is the tension in (N), w_i is the extended bandage width in (m), D is the limb diameter in (m), D_i is the combined limb diameter and previous bandage layers thickness in (m), and P_n is the pressure induced by n number of bandage layers in $(mmHg)$.

$$P_n = \sum_{i=1}^{n} \frac{T_i(D_i + t_i)}{\frac{1}{2}w_i D_i^2 + w_i t_i(D_i + t_i)} \times 0.0075$$
$$\text{Where, } D_i = D + \sum_{i=1}^{n} 2t_{i-1} \tag{4}$$

Where, i is the bandage layer, t_i is the extended and compressed bandage layer thickness in (m), T_i is the tension in (N), w_i is the extended bandage width in (m), D is the limb diameter in (m), D_i is the combined limb diameter and previous bandage layers thickness in (m), and P_n is the pressure induced by n number of bandage layers in $(mmHg)$.

This paper reports on the work carried out to compare Equations 2, 3 and 4 and simulate the pressures applied by an MCB to a real leg when the MCB is applied with a constant tension using the figure-of-eight technique. The paper also reports also on the experimental work carried out to find which of the three equations mentioned would estimate the pressures applied by a multi-layer MCB most accurately.

II. COMPUTATIONAL COMPARISON BETWEEN THE MULTI-LAYER MCB PRESSURE MODELS

A. Objective

To compare the pressure estimation models for multi-layer MCBs using the computational tools MATLAB R2009b (The MathWorks Inc, Massachusetts, USA) and LabView 2009 (NI, USA).

B. Methods and Materials

1) Comparing the Pressures Applied to Cylinders with Various Radii: In order to carry out the comparison, MATLAB R2009b was used to calculate the pressure, when a $100mm$ wide and $1mm$ thick MCB is applied with constant $4N$ tension using figure-of-eight application (4 layers of bandage) to cylinders with various radii between $10mm - 75mm$. The pressures were calculated using Equations 2, 3 and 4.

2) Comparing the Pressures Applied to a Real Leg: In order to illustrate the effect of bandage thickness on the interface pressure estimated over tendons and bony structures of the leg, an MCB with $1mm$ thick and $100mm$ wide is assumed to be applied with a constant $4N$ tension using figure-of-eight technique (4 layers of MCB) to a 3D model for a real human leg. The pressures applied by the MCB were estimated using Equations 2, 3 and 4 using a routine written in MATLAB R2009b. The leg local radii were measured from a 3D model for the left leg of a healthy participant at 103 different locations using SolidWorks 2009 (Dassault Systemes SolidWorks Corp, Massachusetts, USA). The 3D leg model was obtained by scanning the left leg of a healthy participant using NextEngine 3D scanner (model 2020i, NextEngine, California, USA) from ankle to knee. The pressure prediction was done using a program written in LabView2009.

C. Results, Analysis and Discussion

1) Comparing the Pressures Applied to Cylinders with Various Radii: Results are reported in Fig. 1, which illustrates that using simple multiplication will result in overestimating the pressure. The difference between the pressures calculated using thin and thick wall cylinder models is small with the differences between the pressures calculated using Equations 3 and 4 being significant (pressure difference is > 5) at small radii of curvature.
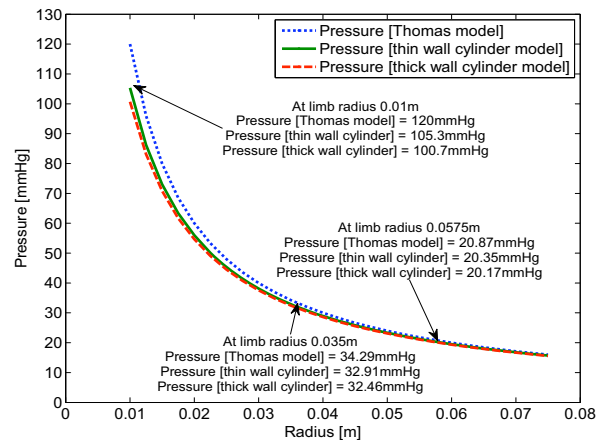

Fig. 1. Pressure calculated using three models; [8] model, thin wall cylinder model and thick wall cylinder model vs. radius

2) Comparing the Pressures Applied to a Real Leg: Simulation results are illustrated in Fig. 2. The white areas on the three plots demonstrate that Thomas's model [8] will overestimate the pressure over the bony prominence. In addition, the three plots indicate that despite the low tension levels, which the bandage is assumed to be applied with, dangerous levels of pressure (more than $60mmHg$) will be applied to the leg areas with sharp curvatures [15]. However, the model based on thick cylinder (Equation 4 reports smaller areas of dangerous peak pressure than the ones reported by Thomas's model Equation 2.

The clinical importance of the new models reported in this section lies in their ability to explain some of the experimental

World Academy of Science, Engineering and Technology
International Journal of Mechanical and Mechatronics Engineering
Vol:5, No:6, 2011

results reported by other researchers. For example Dale et al. [16] have reported that when they applied a cohesive bandage as the fourth part of four-component system, the bandage produced only 73.2 of the pressure produced when it was applied directly to the limb at the same extension and overlap. This has led some researchers to think that when stockings are superimposed, the overall pressure is given by simple addition of pressure that these stockings provide when they are applied individually to the leg, whereas applying MCBs on top of each other will result in minor increase in the interface pressure [17]. The above models explain the reason behind the apparent differences in the behavior of bandages and stockings. Superimposing stockings involves the use of two to three stockings i.e. two to three layers of thin pressure garment. This means that when the sum of the interface pressure applied by individual stockings is compared to the interface pressure when they are superimposed, there will be very small differences in the pressure. However, when bandages are superimposed, they involve a higher number of bandage layers. This will have an impact on the interface pressure due to the larger increase in limb diameter. This means that superimposing bandages will result in a noticeable reduction in the interface pressure as compared to the sum of their individual pressures when they are applied directly to the limb.

III. EXPERIMENTAL VALIDATION FOR THE MULTI-LAYER MCB PRESSURE MODELS

A. Objective:

To compare the estimated pressure applied by multi-layer MCBs using theoretical models with those measured experimentally.

B. Materials and Method

1) The test rig: A simple test rig was designed (Fig. 3). The rig is composed of a cylinder of $0.114m$ diameter and $0.55m$ length, a wooden base with a clamp with rubber padding to hold the bandage tightly from one of its two ends, a load carrier to fasten the other side of the bandage, and a $1.6kg$ load which is hung from the load carrier and used to apply constant known tension to the bandage ($15.97N$). The width and thickness of the bandage used in the experiment when stretched were $105mm$ and $1.1mm$ respectively.

2) Sensors: Four FlexiForce sensors (Tekscan, Boston, USA) from the lowest force range ($0-4.4N$) ($0-464mmHg$) were used in this experiment. They were connected to a conditioning circuit providing 5V. The conditioning circuit amplified and filtered the signal using a low-pass filter with cut-off frequency set to $10Hz$, which was found experimentally to remove most of the noise in the signal. The circuit output was connected to a screw terminal board (LPR-68, NI, USA), which, in turn, was connected to a Mass Term 6225 USB DAQ card (NI, USA).

The sensors were calibrated using an aneroid sphygmomanometer for the pressure range $0 - 80mmHg$ ($0 - 10.7kN/m^2$) to reduce the errors introduced by the curved nature of the cylinders used in this experiment and the reported
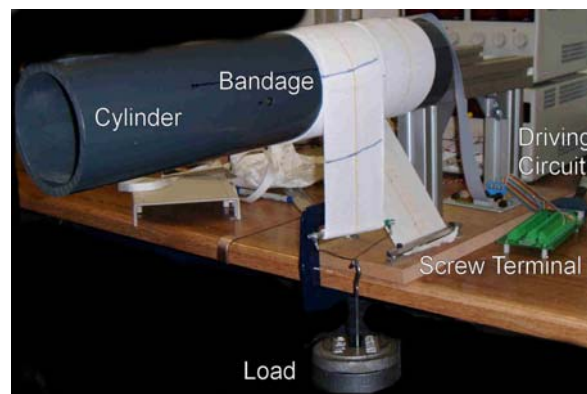

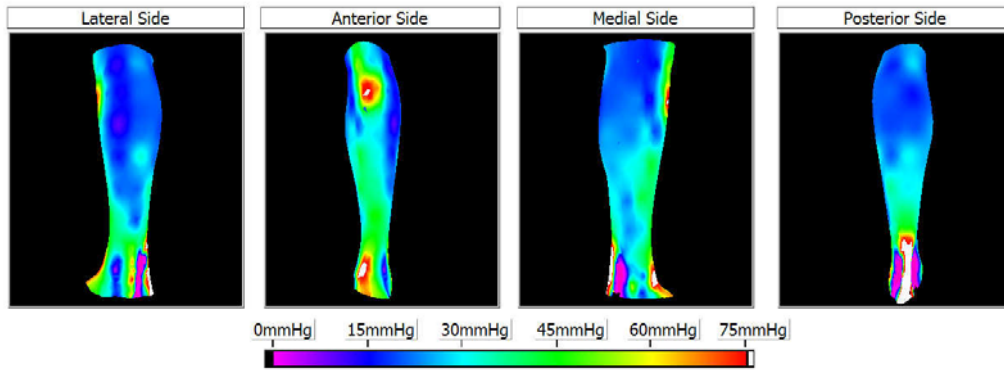Fig. 3.   Rig used in the experiment

errors linked to bending flexible sensors over curved surfaces [18]. The calibration was carried out on the same cylinder used in the experiment. The aneroid sphygmomanometer cuff was inflated by $10mmHg$ ($1.3kN/m^2$) increments from $0mmHg$ to $80mmHg$ ($10.7kN/m^2$) and then deflated by $10mmHg$ decrements to $0mmHg$. The inflating and deflating processes were used to address the hysteresis problem associated with these sensors and it followed other researchers' recommendations [19]. The process was repeated 15 times to overcome the repeatability error associated with both the sensor and the aneroid sphygmomanometer. A linear fitting line was used to describe the pressure ($mmHg$) relative of the measured voltage. The data obtained through the calibration process were used to evaluate the sensors' nonlinearity, repeatability hysteresis and accuracy, where accuracy here is defined as the summation of the nonlinearity, repeatability and hysteresis errors for the sensor.

The signals for calibration were acquired using a program written in LabView 8.6 (NI, USA) and the fitting lines were obtained using PASW 17 (SPSS Inc., Chicago, USA).
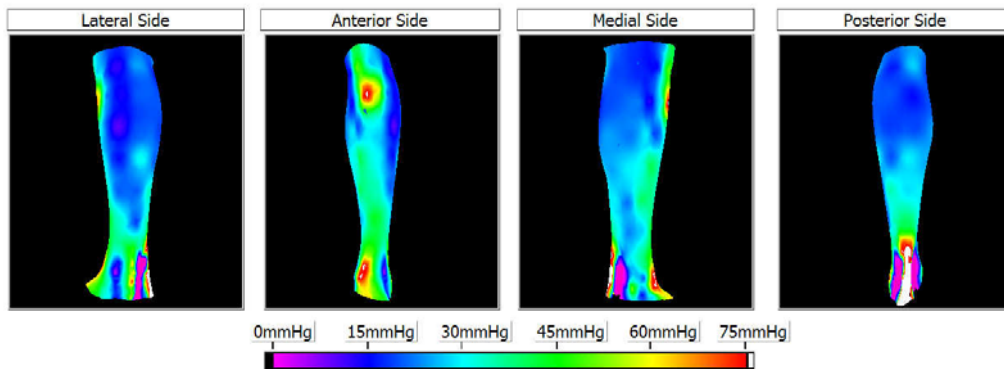
The four sensors were mounted on top of the cylinder next to one other. The average of the sensor pressure outputs was used in reporting the measured pressure instead of values reported by the individual sensors in order to account for known deficiencies with Flexiforce sensors. This, in theory, should reduce the uncertainty of the measurement.

3) Pressure measurement display program: A program was written in LabView 8.6 to acquire the signals, convert them into the equivalent pressure values, display them using numerical values and store the voltage and pressure values in separate files for further processing. The signals were sampled at $1kHz$ and a software-based 2nd order low pass filter with $10Hz$ cut-off frequency was used to filter out the signals.

4) Tension-elongation interconnection for the bandage used in the experiment: Instron 4301 (Instron, High Wycombe, UK) was used to measure the tension developed in the bandage while it was extended at a constant speed of 100mm/min. A 100N load cell was used to measure the tension in the bandage (SurePress®, ConvaTec Limited, Deeside, UK). The device gauge length was set to 100mm. Custom-made jaws with 100mm width were used to clamp the bandage. The device was

World Academy of Science, Engineering and Technology
International Journal of Mechanical and Mechatronics Engineering
Vol:5, No:6, 2011

(a) The pressure calculated using the pressure model reported by [8] (Equation 2

(b) The pressure calculated using the pressure model based on thin cylinder wall theory (Equation 3
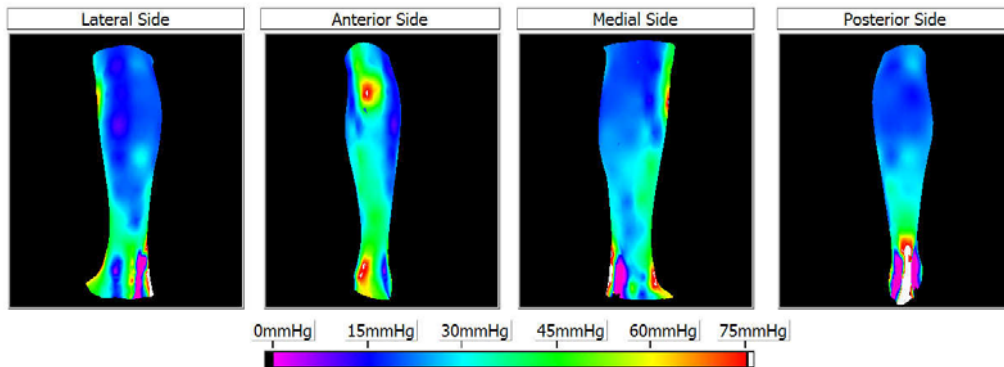
(c) The pressure calculated using the pressure model based on thick cylinder wall theory (Equation 4

Fig. 2. The simulated pressure map over a real leg when a bandage is applied to the leg with figure-of-eight technique (four layers) with a constant tension of $4N$

set to conduct a cyclic test for the $0-100$ extension range for 4 cycles. The load cell output was sampled at $5Hz$. MATLAB R2009b (The MathWorks Inc, Massachusetts, USA) was used to fit a 4th order polynomial fitting-line for the loading side of the fourth cycle of the tension-elongation curves.

5) Computing pressures from the levels of extension: The bandage used in the experiment was marked every $50mm$. These marks were used to measure the extension in the bandage material using a measuring tape when it was applied to the cylinder. The extension readings were then used to estimate the tension forces in the bandage, which were used to compute the interface pressures using Equations 23 and 4. The estimation of tension from extension was found using

the fourth loading cycle of the tension extension curves of the bandage, which was obtained using Instron 4031. Pressure calculation was done through a routine written in MATLAB R2009b.

6) Experiment protocol: Three layers of bandage were applied to the cylinder on the same area where the force sensors were mounted. The last layer of the bandage was attached to the $1.6kg$ load. The three layers bandage was applied 10 times to reduce the uncertainty in the pressure measurements due to the systematic errors associated with the sensors used in the experiment. In each of these iterations, the extension in the three layers was measured and used to estimate the tension and subsequently calculate the pressure using Thomas', thin

World Academy of Science, Engineering and Technology
International Journal of Mechanical and Mechatronics Engineering
Vol:5, No:6, 2011

wall cylinder and thick wall cylinder models for multi-layer bandages (Equations 2, 3 and 4). The pressure calculated was then compared to the measured pressure.

C. Results, Analysis and Discussion

1) Sensors: The average accuracy of the sensors used in the experiment was found to be $\pm 20.86 mmHg$ ($\pm 2.78 kN/m^2$), where accuracy is defined as the combined nonlinearity, repeatability and hysteresis errors for each sensor. However, some of the repeatability errors might have been caused by the calibration method. In theory, taking the average of the four sensors output to report the pressures will reduce the accuracy error to $\pm 11 mmHg$ ($\pm 1.47 kN/m^2$).

2) Tension-Elongation interconnection for the MCB used in the experiment: Fig. 4 shows the 4th order polynomial fitting line used to fit the loading side of the tension elongation curve obtained for the bandage used for the extension range $0 - 100$.
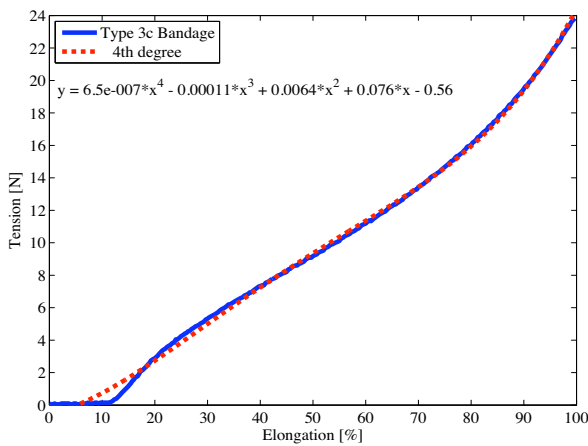

Fig. 4. 4th order polynomial fitting-lines for the 4th loading cycle of the tension-elongation curves for the range $0 - 100\%$ elongation the bandage used in the experiment

3) Models validation: The summary of the results and the statistical analysis are provided in Table I and Fig. 5. The mean of the pressures calculated using Equations 2, 3 and 4 from the levels of extensions in the bandage were found to be $44.36 mmHg$ ($5.91 kN/m^2$), $43.44 mmHg$ ($5.79 kN/m^2$) and $43.08 mmHg$ ($5.74 kN/m^2$) respectively. The mean of the averaged measured pressures was $34.70 mmHg$ ($4.63 kN/m^2$).

Considering the transducer error after using the averaging as $\pm 11 mmHg$ ($\pm 1.47 kN/m^2$), which is reported earlier, and the variation in the averaged measured pressures as $1.47 mmHg$ ($196 N/m^2$), which is reported in Table I, then the error of the mean of the averaged measured pressure has been calculated and found to be $\pm 4.81 mmHg$ ($\pm 641 N/m^2$). This means that the 95 CI of the mean of the averaged measured pressures ($29.89 - 39.51 mmHg$) overlaps the 95 CI of the mean of the computed pressures using thin wall cylinder theory model (Equation 3) ($39.34 - 47.54 mmHg$) and thick wall cylinder theory model (Equation 4) ($39.01 - 27.14 mmHg$). This indicates that multiplying the pressures applied by one layer of bandage with the number of bandage layers or

Statistical Analysis	Computed Pressures (Thomas) [mmHg]	Computed Pressures (Thin Wall Cylinder) [mmHg]	Computed Pressures (Thick Wall Cylinder) [mmHg]	Averaged Measured Pressures [mmHg]
Mean	44.36	43.44	43.08	34.70
SD	8.30	8.11	8.04	6.58
SE	1.86	1.81	1.80	1.47
Upper 95% spread	60.36	59.34	58.84	47.60
Lower 95% spread	28.10	27.55	27.32	21.80
Upper 95% CI	48.56	47.54	47.14	38.02
Lower 95% CI	40.17	39.34	39.01	31.37

ignoring the increase radius of the limb due to former applied bandage layers might result in reporting pressures which are higher than the actual pressures applied to the leg. It is worth mentioning that the 95 confidence intervals of the mean of the averaged measured pressure ($29.89 - 39.51 mmHg$) is higher than those reported in Table I ($31.37 - 38.02 mmHg$) as the former has been calculated by considering both the variation in the measurement and the transducer error, while the latter has been calculated by considering the 95% CI of the mean from the SE of the mean.

Fig. 5 shows that the pressures measured were significantly different from the computed pressures using Equations 2, 3 and 4. Nevertheless, for the first two iterations, the calculated and measured values were much closer to each other than the other eight iterations, which might be explained by the fact that the tension was calculated from the fitting loading line for the fourth cycle tension-elongation curve for the bandage; thus, the fourth cycle might not present a good approximation for the tension elongation relationship, knowing that the bandage performance degrades with usage. In addition, due to the nature of bandage application, the tension applied in the first and second layers might be affected heavily by the large hysteresis in the tension elongation curves. Other factors like friction might have also contributed to the difference between the measured and calculated pressures.

Despite the fact that 95% CI of the mean measured pressures overlaps the 95% CI of the mean of the computed pressures using Equations 3 and 4, the results illustrated in Fig. 5 raise doubts about the validity of the models. Therefore, another set of experiments is recommended where every single MCB layer is connected to a hung load. Bandages also need to be changed through the experiment to avoid potential problems of material degradation.

IV. CONCLUSION

In summary, the paper has described the work carried out to compare the mathematical models used to describe the interface pressure applied by multi-layer bandage and validate them experimentally. Ignoring the increase in the limb size

World Academy of Science, Engineering and Technology
International Journal of Mechanical and Mechatronics Engineering
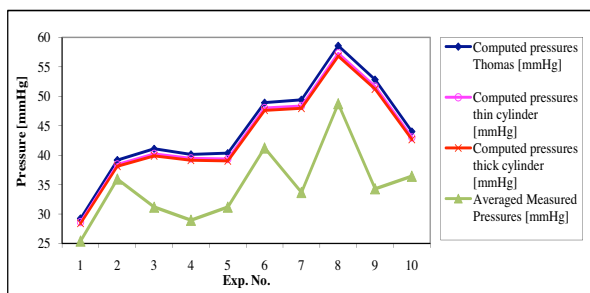Vol:5, No:6, 2011

Fig. 5. The experimental results in validating the models developed to calculate the pressure applied by multi-layer MCBs. Lines connecting the pressure values are for illustrative purposes

(radius) caused by former layers of bandage, when the bandage is applied with several layers to the limb, was found both analytically and experimentally to result in overestimating the amount of pressure applied by the bandage to the limb. The two formulae, which take into consideration the increase in limb radius in estimating the applied pressure were found experimentally to report pressure (95% CI of the mean) which overlaps the pressures measured using FlexiForce sensors. This indicates that the models might be able to explain the interface pressures applied by multi-layer MCB. This was not the case for the mathematical model proposed by Thomas (Equation 2).

REFERENCES

[1] J. L.Beebe-Dimmer, J. R. Pfeifer, J. S. Engle and D.Schottenfeld, "The epidemiology of chronic venous insufficiency and varicose veins," *Annals of Epidemiology*, vol. 15, no. 3, pp. 175-184, Mar. 2005.
[2] C. V. Ruckley, C. J. Evans, P. L. Allan, A. J. Lee and F. G. Fowkes, "Chronic venous insufficiency: Clinical and duplex correlations. The Edinburgh Vein Study of venous disorders in the general population," *Journal of Vascular Surgery*, vol. 36, no. 3, pp. 520-525, 2002.
[3] S. O'Meara, J. Tierney, N. Cullum, M. J. Bland, P. J. Franks, T. Mole and M. Scriven, "Four layer bandage compared with short stretch bandage for venous leg ulcers: systematic review and meta-analysis of randomised controlled trials with data from individual patients," *BMJ*, vol. 338, pp. b1344, Apr. 2009.
[4] S. O'Meara, N. A. Cullum and E. A. Nelson, "Compression for venous leg ulcers," *Cochrane Database of Systematic Reviews*, (1), 2009.
[5] C. Moffatt, *Compression Therapy in Practice*, Aberdeen: Wound UK Publishing, 2007, 228pp.
[6] E. A. Nelson, *A Study of Patient and Nurse Factors Influencing Sub-Bandage Pressure*, Strathclyde: Stracthclyde University, 2001, 215 pp.
[7] P. De Bruyne and T. Dvorak, "The pressure exerted by an elastic stocking and its measurement," *Medical and Biological Engineering and Computing*, vol. 14, no. 1, pp. 94-96,1976.
[8] S. Thomas, "The use of the Laplace equation in the calculation of sub-bandage pressure," *EWMA journal*, vol. 3, no. 1, pp. 21-23, 2003.
[9] J. R. Basford, "The law of Laplace and its relevance to contemporary medicine and rehabilitation," *Archives of Physical Medicine and Rehabilitation*, vol. 83, no. 8, pp. 11651170, 2002.
[10] D. Wertheim, J. Melhuish, R. Williams and K. Harding, "Measurement of forces associated with compression therapy," *Medical and Biological Engineering and Computing*, vol. 37, no. 1, pp. 31-34, Jan. 1999.
[11] J. M. Melhuish, M. Clark, R. Williams and K. G. Harding, "The physics of sub-bandage pressure measurement," *Journal of Wound Care*, vol. 9, no. 7, pp. 308-310, Jul. 2000.
[12] J. A. J. Al Khaburi, *Pressure mapping of medical compression bandages used for venous leg ulcer treatment*, Leeds: University of Leeds, 2010, 300 pp.
[13] J. Al Khaburi, E. A. Nelson, J. Hutchinson and A. A. Dehghani-Sanij, "Impact of multi-layered compression bandages on sub-bandage interface pressure: a model," *Phlebology*, vol. 26, no.2, pp. 75-83, Mar 2011.
[14] E. J. Hearn, *Mechanics of Materials Volume 1: An Introduction to the Mechanics of Elastic and Plastic Deformation of Solids and Structural Materials*, Oxford: Butterworth-Heinemann, 1997, 450 pp.
[15] S. Thomas and P. Fram, "Laboratory-based evaluation of a compression-bandaging system," *Nursing Times*, vol. 99, no. 40, pp. 24-28, 2003.
[16] J. J. Dale, C.V. Ruckley, B. Gibson, D. Brown, A. J. Lee and R. J. Prescott, "Multi-layer compression: comparison of four Different four-layer bandage systems applied to the leg," *European Journal of Vascular and Endovascular Surgery*, vol. 27, no. 1, pp. 94-99, Jan. 2004.
[17] A. Cornu-Thenard, P. Boivin, P. H. Carpentier, F. Courtet and P. Ngo, "Superimposed Elastic Stockings: Pressure Measurements," *Dermatologic Surgery*, vol. 33, no. 3, pp. 269-275, Mar. 2007.
[18] M. Ferguson-Pell, S. Hagisawa and D. Bain, "Evaluation of a sensor for low interface pressure applications," *Medical Engineering & Physics*, vol. 22, no. 9, pp. 657-663, Nov. 2000.
[19] E. R. Komi, J. R. Roberts and S. J. Rothberg, "Evaluation of thin, flexible sensors for time-resolved grip force measurement." *Journal of Mechanical Engineering Science*, vol. 221, pp. 1687-1699, Nov. 2007.
[20] W. Bolton, *Measurement and instrumentation systems*, Oxford: Newnes, 1996, 412 pp.