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# Comparing the Energy-Stretch Properties of Two Compression Bandage Systems in a Laboratory-Based Test under Controlled Conditions

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## ABSTRACT

**OBJECTIVE:** To compare the characteristics of two commercially available compression systems, a dual-compression bandage system (DCS) and a traditional two-layer bandage (TLB), using a laboratory bench test.

**METHODS:** The compression systems were evaluated in a computer-controlled tensile test to generate force-deflection curves for each sample. The compressive work and the theoretical pressure applied to the limb by the respective compression bandages were calculated at the maximum stretch and a stretch instructed by the manufacturers. The manufacturer of the DCS provides reference points on how much the bandage should be stretched to provide the desired pressure, and the TLB stretch was calculated from the product's datasheet.

**RESULTS:** The combined results of layers 1 and 2 for the DCS showed greater load and work than the TLB at both the maximum and recommended stretch. The recommended stretch for DCS and TLB was less than 50% of the deflection up to the breaking point.

**CONCLUSIONS:** The high work provided by the two layers of the DCS suggests a wider range of performance than the TLB when applied to the lower limb, especially after the limb volume is initially reduced by compression. Moreover, using the tensile test and the guide of the reference points on layers 1 and 2 from DCS, the calculated pressure achieved the expected values stated by the manufacturer. Human studies should be conducted to determine whether the reference points provided by DCS are beneficial for obtaining repeatable values.

**KEYWORDS:** bandage, compression, load, pressure, stretch, tensile test, work, wound healing

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## INTRODUCTION

Compression therapy is the standard of care for edema control and lower limb wound healing.[1,2] It also reduces the volume of the venous structure, enabling distorted venous valves to regain function and improving blood and lymph return to the heart and circulatory system.[1] The goal is to provide sustained therapeutic compression that effectively and comfortably reduces edema, accelerates healing, and prevents venous ulcers.[3–5] Studies have reported that pain and discomfort are primary contributing factors for patient nonadherence to or discontinuation of compression therapy.[6] Assessing the fit of compression therapy for the patient may improve treatment adherence, which then leads to better wound healing and may prevent recurrence.[7–9]

To accomplish therapeutic compression while optimizing comfort, the compressive energy applied to the limb should be determined. This energy is directly related to the properties of the bandage; however, the pressure applied to the surface of the limb also depends on other several factors. Researchers have investigated some mechanisms involved in applying pressure to the limb.[10] Chassagne et al[11] identified the bandage's mechanical properties, components, and stretch; the curvature of the limb; the application technique; and the interplay of friction with the mechanical properties of the bandage as critical elements that impact the level of the applied pressure. This list should also include time, because authors have reported that a dramatic change in limb circumference occurs early in the application cycle.[12]

The mechanical properties of the compression bandages can be measured through a tensile test, which involves the application of uniaxial force to measure the performance of a test wrap specimen, up to the point of it yielding or

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breaking, whether sharply or gradually. In this study, the researchers hypothesized that the shape of the force-deflection curve from extensometers determines how the bandage impacts pressure application over time.

### Estimated Sub-bandage Pressure and Applied Work

The Laplace sub-bandage pressure law is an equation that has been used to calculate sub-bandage theoretical pressure.[13] According to the Laplace law, pressure is directly proportional to the tension and inversely proportional to the circumference of the limb. Assuming that a bandage is applied at the same tension from ankle to knee, the pressure will be reduced, depending on the shape of the leg.[14] A lower circumference of the limb will result in a higher pressure (Supplemental Figure 1 [http://links.lww.com/NSW/A118] illustrates these pressure changes: the darker arrows represent higher pressure, and the clearer arrows represent lower pressure).

According to the Laplace law, when the limb is modeled as a cylinder, the internal pressure of the wall of the cylinder is the tension force over the radius (equation 1):

$$P = \frac{T(\text{tension})}{r\ (\text{radius})}$$

Thomas[13] modified the Laplace law to include bandage width and the number of layers applied so that the equation can be used to calculate the sub-bandage pressures of compression systems, as in clinical practice. The modified equation to calculate the pressure in a bandage is (equation 2):

$$P(\text{mm Hg}) = \frac{T(\text{tension in Newtons}) * n(\text{number of layers}) * k(\text{conversion unit factor})}{r(\text{radius in meters}) * w(\text{width of bandage in meters})}$$

The conversion factor is needed to simplify the calculations and change pressure from Pascal to mm Hg. Using this equation to calculate or predict sub-bandage pressure remains controversial and has been challenging to demonstrate practically. There is still a discrepancy in the results when compared with clinical practice: Researchers have obtained different pressure measurements when using pressure sensors to determine the pressure of a bandage applied on human patients versus the results calculated by the modified Laplace law equation.[15–18] The tensile test has been broadly used to calculate the bandage's tension for use in the equation. Although an exact correlation is not always achieved, the Laplace law is still a reliable method to compare different bandages. A critical point to take into account when using this equation is to carefully select the tension force to use: The appropriate tension depends on the stretch, and the stretch is determined by the application technique.

Moreover, as the bandage is stretched, a certain work is deployed. By definition, work is the energy transferred to or from an object by the application of force along a displacement.[19] Therefore, work can be calculated as (equation 3):

$$W(F) = \int_A^B F(x)$$

where $W$ is calculated work, $F$ is applied load, and $A$ or $B$ is displacement or stretch.

Therefore, in compression bandages, work may be an important element to consider. It relates to both the applied load and the stretch, and it provides information on how the compressive work is sustained as the bandage is stretched. The compressive work involves all layers in a multiple-layer bandage system because it is assumed to be additive.

### Purpose

In this study, the researchers compared the characteristics of two commercially available compression systems, a novel dual-compression bandage system (DCS) and another traditional two-layer bandage compression system (TLB), using a laboratory bench test in a controlled environment. This nonclinical research aimed to determine the compressive work and the theoretical pressure applied to the limb by the respective compression bandages at a stretch instructed by the manufacturers. To find the manufacturers' recommended stretch, the authors used the reference guide points for DCS and calculated that of TLB from the product's datasheet. Moreover, the authors determined the properties of the compression systems at a full range up to the breaking point. Healthcare providers can benefit from an accurate understanding of the mechanisms of action of compression bandages because it can help them improve application techniques. For example, this knowledge might aid clinicians in applying optimized stretch, overlapping the bandages correctly, and properly securing the bandages, which could lead to better patient outcomes.

## METHODS

### Compression Bandage Systems

The DCS is composed of two active compression layers. Layer 1, a soft-padded short-stretch bandage, is intended to apply 80% of the compression. Layer 2, a long-stretch cohesive, is intended to apply 20% of the pressure and maintain the system in place. Both layers include reference points for how much the bandage should be stretched and overlapped to provide the desired pressure; the references points are located to achieve 50% overlap.

The conventional TLB consists of a comfort foam layer (layer 1) and a compression layer (layer 2). The comfort foam layer is a lamination of polyurethane foam and a cohesive bandage. It is intended to be used as the first inner layer of the two-layer system. The compression layer is a cohesive bandage that is designed to be used as the second, outer layer of the two-layer system. Layer 1 should be applied without stretch and with minimal overlap; layer 2 should be applied at the manufacturer's recommended maximum stretch with 50% overlap of the wrap.

## Procedure

The DCS and TLB were evaluated in a computer-controlled tensile test using the digital testing machine Chatillon LF Plus (AMETEK, Inc) and NEXYGEN FM software (AMETEK, Inc). Testing was performed in a controlled environment with an ambient temperature of 23 °C ± 2 °C and relative humidity of 50% ± 5%, which is specified in ISO 554-1976(E). Samples were removed from packaging materials and preconditioned by storing them in the test laboratory environment for a minimum of 12 hours before testing.

For each bandage system, three samples of each layer were cut into 70-mm lengths. Each sample was taken from different bandage rolls from different kits of the same bandage type. Samples were clamped (10 mm each side) in a full wrap width tensile fixture on the computer-controlled test machine to ensure that the force was distributed across the entire width (Figure 1). The effective gauge length was 50 mm for each sample.

Testing was performed in two experiments, using two replicates of the three samples of each bandage system by two different technicians to determine the tension applied at the instructed stretch.

(1) The first experiment tested the full range of elongation and load capacities of each compression bandage system; the systems were tested up to the breaking point. For this test, the software was set with the "Pull to Break" setting at a speed of 50 mm/min (following the prestandard ENV 12718 Medical compression hosiery; annex C method of determination of extensibility of hosiery),[20] and the break was set when the load dropped to 90% of the maximum. The deflection and the load were then recorded. Testing was performed one time per each sample (up to break).

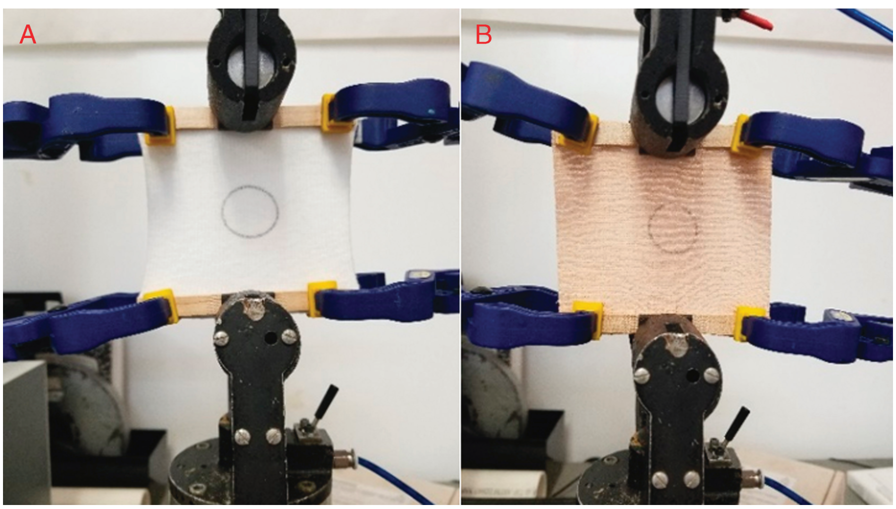
(2) The second experiment determined the amount of deflection recommended by the manufacturers. The DCS system was tested to determine the deflection or stretch needed for the reference points to form the circles specified by the manufacturer. The tensile test pulled up to the point where the dot reference from the compression system was a perfect circle. A template was used to guide the technician during the test to form the perfect circle in the reference points provided in the bandage. Testing was performed three times per each sample.

The TLB does not include reference guide points, so the recommended maximum deflection was determined by following the manufacturer's instructions in the product datasheet. According to the product's specifications, layer 1 should be applied with minimal tension just to conform to the shape of the leg, and layer 2 is intended to be applied at full stretch. The datasheet specifies that the length of layer 2 unstretched is 3.5 m, whereas the length at full stretch is 4.7 m. This indicates that the TLB needs to be stretched 34% to obtain the full stretch according to the manufacturer instructions. This corresponds to a deflection of 17 mm in the 50-mm sample.

## Data Analysis

From the first experiment, the researchers obtained the load-deflection curves and calculated the work, load, and deflection at the breaking point to observe the full capabilities of each bandage. An algorithm was developed in

**Figure 1. CIRCLE FORMED FOR THE DESIRED PRESSURE**
A, Layer 1; B, layer 2.



MATLAB 2017b (MathWorks) to calculate the work per equation 3; the algorithm also identified the load at the deflection/stretch points resulting from the second experiment. This load was used to calculate the theoretical pressure per equation 2. The number of layers was as recommended by the manufacturer. Both bandages were recommended to be at 50% overlap, which results in the number of layers (n = 2) in equation 2. For the DCS, the calculated pressure on layers 1 and 2 was summed. For the TLB, only the pressure on layer 2 was used because layer 1 is not designed to provide pressure, only comfort.

For the statistical analysis, NCSS statistical software (NCSS, LLC) was used. A one-way analysis of variance was performed to compare the deflection/elongation of the DCS in the repetitions of the three samples. Significance was considered at $P < .05$. In addition, a 95% CI was considered statistically significant for statistical analysis from each metric.

## RESULTS

### Full Capabilities of Each Compression Bandage System

The first experiment gave the tensile test results up to the breaking point (yield), showing the full capabilities of elongation and load characteristics of each compression bandage layer.[21] The full range in load deflection for each material is shown in Figure 2, and the full range in work deflection is shown in Figure 3 (see also Supplemental Figure 2 [http://links.lww.com/NSW/A119] and Supplemental Figure 3 [http://links.lww.com/NSW/A120]). The DCS showed a greater load in both layers compared with the TLB. Layer 1 from the TLB showed greater elongation and work than did layer 1 from DCS. It is worth mentioning that layer 1 of the TLB is not intended to provide compression; however, the results show that if layer 1 of the TLB is applied with stretch, it would also apply additional compression to the leg. On the contrary, both layers of the DCS are intended to apply compression. Results are shown in Table 1.

### Stretch (Deflection) Recommended by the Manufacturer

The second experiment determined the deflection/stretch as recommended by the manufacturer. For the DCS, the authors tested the recommended reference points; deflection was obtained with the tensile test stretching the bandage until a perfect circle was formed (Supplemental Figure 4 [http://links.lww.com/NSW/A121]). There was no significant difference in the deflection for the three samples to reach the reference points recommended by the manufacturer ($P > .05$; Figure 4). For the TLB, the authors calculated the deflection/stretch of 50 to be 17 mm at full range.

### Compressive Work and Theoretical Pressure at a Stretch Recommended by the Manufacturer

The authors used deflection at a stretch recommended by the manufacturers to identify the load required to calculate the theoretical pressure. For the DCS, they used the load at the deflection determined from the tensile test in the second experiment, and for the TLB, they used the load at 34% of the sample size (50 mm).

Results showed that the recommended stretch for both DCS and TLB is less than 50% of the deflection up to the breaking point and fall before the exponential phase from the load-deflection curve (Table 2 and Figures 2 and 3). At the recommended deflection point, the DCS obtained more load and more work than did the TLB. The recommended load resulted in theoretical pressure values from 70 mm Hg to 39 mm Hg for the DCS, and from 52 mm Hg to 29 mm Hg for the TLB, for leg circumferences from

**Figure 2.** LOAD-DEFLECTION CURVES

A, Layer 1; B, layer 2.

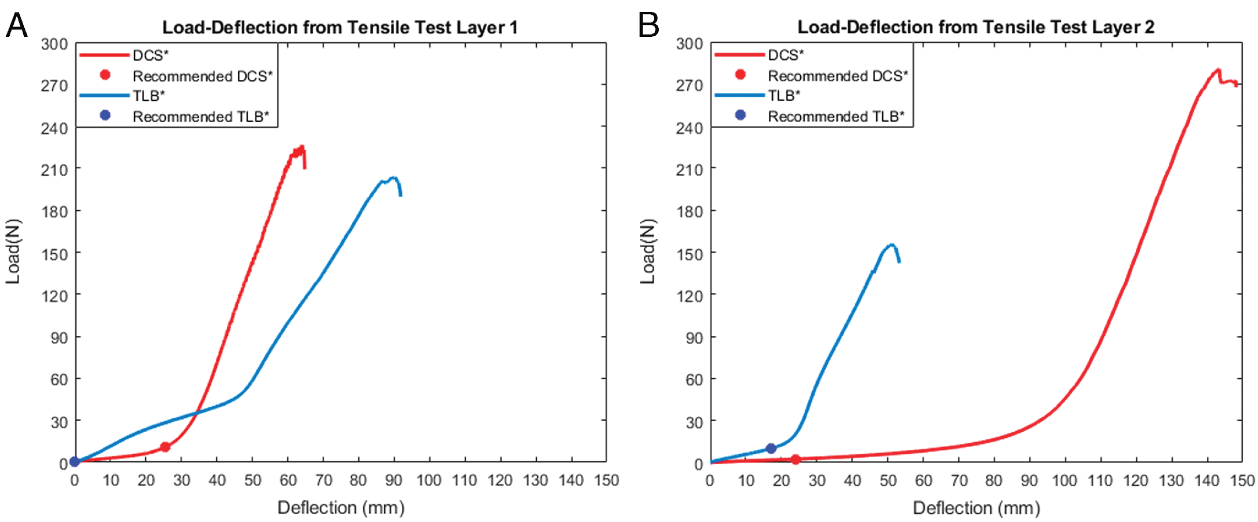
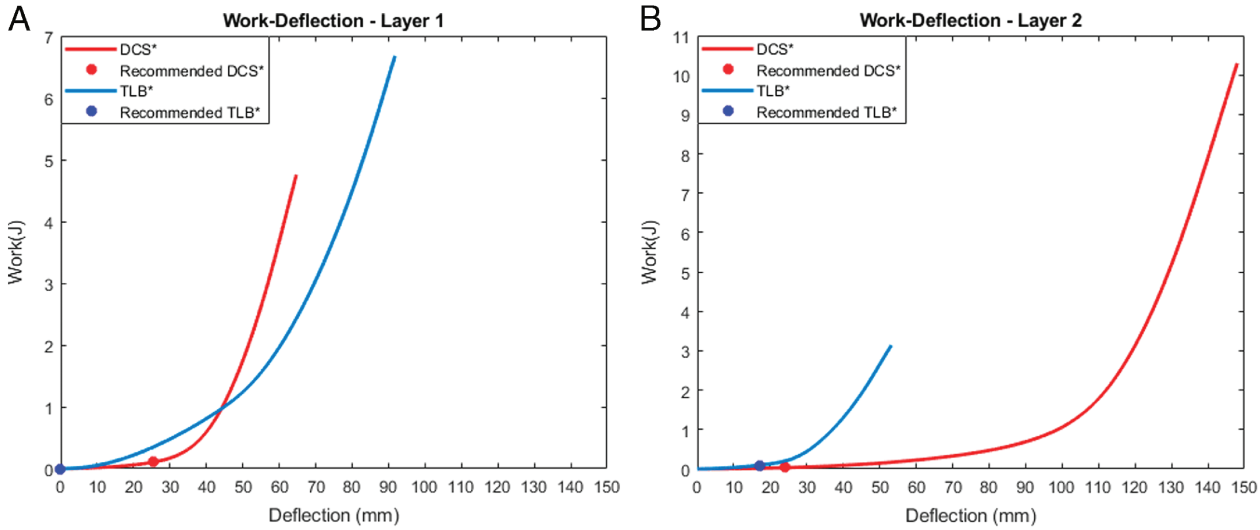


**Figure 3.** **WORK-DEFLECTION CURVES**

A, Layer 1; B, layer 2.




18 cm to 32 cm. As anticipated, a lower circumference led to higher pressures (Figure 5).

## DISCUSSION

The tensile test and calculations of load, work, and deflection are useful for comparing the full capabilities of compression systems. Figures 2 and 3 show the ranges of load and deflection (elongation) from the bandages when they are about to break. The maximum values up to the breaking point are not intended to be used in clinical practice. However, they show the full capacity of the systems. The greater the gap between the breaking point and the typical application elongation, the less likely the bandage is to yield and permanently deform, which means the bandage may be used successfully in multiple applications.

The calculation of work depends on both the load and the deflection. It has been hypothesized that higher work is better for maintaining sustained compression, especially after the bandage application when the limb volume changed.[22,23] In addition, a lower work in the compressive force might lead to a drop in the therapeutic pressure.[24] From the work-deflection curves showed in Figure 3, both layers of the DCS provided high work at a maximum stretch as opposed to only layer 2 of the TLB. Also, the work given by layers 1 and 2 was higher for the DCS than for the TLB at a stretch recommended by the manufacturer. This indicates the potential ability of the DCS to offer a wider range of performance, adjusting to the curvature of the leg when it is applied. This becomes important with changing limb volume, particularly in the early stages of compression bandage application where the change in the limb volume is dramatic.[25,26]

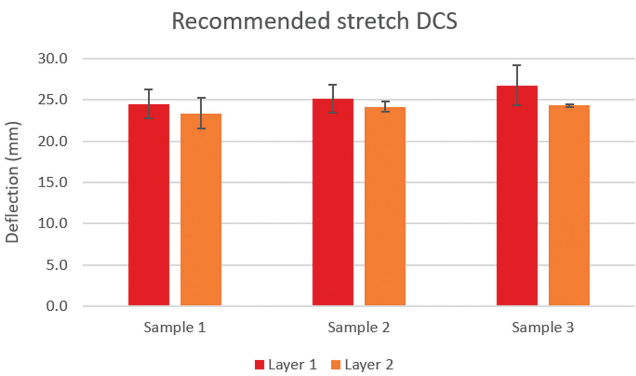
As seen in the curves in Figures 2 and 3, the load increased as the bandage was stretched. This load is translated into pressure when applied to the limb. Results showed that the elongation recommended by the manufacturer in the DCS layer 1 is near the beginning of the exponential phase of the load, whereas layer 2 was not in the exponential phase; this provides a greater range before starting to add more tension. The linear range of change is hypothetically more predictable to the end user than the changes in the exponential range, because small changes in stretch (deflection) after the exponential phase will lead to higher force, which is translated into higher pressure and potentially could lead to unsafe pressure values. It was also observed that even though layer 1 from the TLB is not designed to apply pressure, it has the capability to add tension force that can be translated

**Table 1.** **COMPARISON OF LOAD, WORK, AND DEFLECTION IN TENSILE TEST UP TO BREAKING POINT**

| | Layer 1 (n = 3), Mean ± 95% CI | | | Layer 2 (n = 3), Mean ± 95% CI | | |
|---|---|---|---|---|---|---|
| **Compression System** | **Load (N)** | **Work (J)** | **Deflection (mm)** | **Load (N)** | **Work (J)** | **Deflection (mm)** |
| DCS | 230.4 ± 7.8 | 4.2 ± 0.1 | 63.4 ± 1.2 | 282.7 ± 26.5 | 8.4 ± 2 | 144.5 ± 6.1 |
| TLB | 205.6 ± 20.1 | 6.7 ± 0.6 | 89.5 ± 7 | 157.8 ± 19.2 | 2.6 ± 0.53 | 50.4 ± 3.1 |

Abbreviations: DCS, dual-compression bandage system; TLB, two-layer bandage.

**Figure 4. DEFLECTION FOR THE DCS WITH A FORMED CIRCLE FOLLOWING THE REFERENCE POINT FOR LAYER 1 AND LAYER 2**




Abbreviation: DCS, dual-compression bandage system.

into pressure if it is stretched more than the manufacturer recommends. Moreover, the load applied by the bandage is related to the level of the stretch of the bandage. According to the load-deflection curve from the tensile test (Figures 2 and 3), small changes in elongation (deflection) could lead to a higher value on load, which translates into higher pressure values, especially when the deflection of the bandage is near the exponential phase of the load curve. This highlights the importance of clinicians applying the compression bandage following the manufacturer's instructions.[22]

The deflection recommended by the manufacturer was also evaluated in this bench test. From the second experiment, good repeatability was obtained using the pressure guide provided by the DCS and a template as a guide to form a circle. Because the TLB does not have reference points or a guide to measure how much the bandage should be stretched, the repeatability of obtaining the recommended stretch could not be evaluated. Repeatability may be subject to the human visual error when deciding which is the correct position when the circle is achieved. This determination could be impacted by a clinician's training, experience, and parallax error.

The DCS manufacturer's literature indicates that layer 1 is intended to apply 80% of the compression and layer 2 is intended to apply only 20% of the compression. These expected values were consistent with the results from the load and the work at the deflection recommended by the manufacturer obtained by the tensile test. Thus, the pressure values can be achieved when the manufacturer's instructions are followed (Table 1). Results highlight the value of the reference points provided by the DCS in applying the bandage correctly. This is especially important to a person new to the application of compression bandages and to experienced individuals who are changing from one compression system to another.[27]

The Laplace law equation has been compared with model and human studies, but most of the results have not been consistent with the expected values.[17] A critical point to consider when using this equation is what load to use in the calculation. This challenge was acknowledged in a study that demonstrated the effectiveness of the modified Laplace law equation.[16] Thomas[16] reported on a method to apply a uniform load by applying known weights to the bandage, achieving a good correlation between the results and the expected values of the equation. The present study demonstrates the importance of the stretch/elongation of each layer of the compression systems in determining the force applied, as shown in Figures 2 and 3. The deflection obtained following the reference points DCS in the tensile test was useful for calculating the theoretical pressure using the Laplace law.

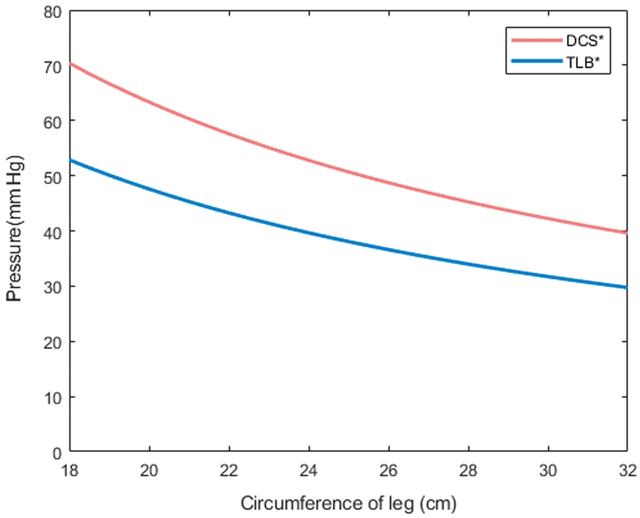
Pressure is directly proportional to the force applied and indirectly proportional to the surface area to which it is applied. The authors observed that the same bandage tension could lead to different pressure values, depending on the circumference of the limb (Figure 5). The DCS obtained higher theoretical values than the TLB; the values obtained from both the DCS and the TLB were within the ranges from other previous studies.[28] The present research demonstrated that repeatable results could be obtained following the reference guide points provided by the DCS. The pressure guide included in the DCS offers the advantage of indicating the amount of pressure and overlap needed to obtain therapeutic pressure. In addition, clinicians can be confident in applying the target pressure to the lower limb according to the safe ranges established in clinical practice.[28]

**Table 2. COMPARISON OF LOAD, WORK AT DEFLECTION RECOMMENDED BY THE MANUFACTURER**

| | Layer 1 (n = 3), Mean ± 95% CI | | | Layer 2 (n = 3), Mean ± 95% CI | | |
|---|---|---|---|---|---|---|
| Compression System | Load (N) | Work (J) | Deflection (mm) | Load (N) | Work (J) | Deflection (mm) |
| DCS | 11 ± 0.9 | 0.1 ± 0 | 25.5 ± 1.2 | 2.5 ± 0.1 | 0.03 ± 0 | 24 ± 0.6 |
| TLB | 0[a] | 0[a] | 0[a] | 10.1 ± 1.4 | 0.09 ± 0.02 | 17[b] |

Abbreviations: DSC, dual-compression bandage system; TLB, two-layer bandage.
[a]Layer not intended to provide pressure
[b]Calculated from datasheet (n = 1).

**Figure 5.** THEORETICAL CALCULATED PRESSURE AT 18- TO 32-CM CIRCUMFERENCE




Abbreviations: DCS, dual-compression bandage system; TLB, two-layer bandage.

### Implications for Clinical Practice

The majority of limb reduction occurs immediately following bandage application, which causes pressure to drop very shortly thereafter. For example, within 2 hours after bandage application, the pressure will drop by 25% to 50%, even without movement.[29] Because the first layer of the TLB is a padding layer not intended to apply compression, and the second layer is intended to apply 100% of the compression, a portion of the pressure exerted during bandage application will be absorbed by the padding layer.[30] In addition, because layer 2 is intended to be used at 100% stretch, the TLB might be prone to yielding or breaking, decreasing the elastic properties and reducing compression over time.[31,32] In contrast, the DCS layer 1 reshapes the limb and applies 80% of the intended pressure; the remaining 20% is applied by layer 2, which also maintains the system in place. This helps in maintaining a sustained therapeutic compression for a longer time, especially after limb reduction.

The correct application of the compression systems is subject to the individual operator's technique. Understanding the properties of the compression system and acknowledging the influence of the stretch in the pressure applied to the limb would help healthcare providers obtain better outcomes. Moreover, this study demonstrated that if the manufacturer's instructions are followed, the theoretical pressure in the expected ranges can be obtained. These authors hypothesize that this study could be translated to clinical practice by applying the compression bandages following the manufacturers' instructions. Human studies are needed to demonstrate whether the equivalent repeatability of this study is achieved.

### Limitations

This study was performed in a bench test with the bandage stretched at a 0° angle and only considered the tension when pulled in the vertical axis across the full bandage width. More forces are involved when the bandage is applied to a limb. Moreover, the authors acknowledge that other mechanical properties of the compression bandages not included in this study, such as stiffness (elastic modulus), may influence performance. Bandages with greater stiffness provide higher pressure under minimum stretch.[33] Additional studies should be conducted with human participants to determine whether the reference guide provided by the DCS is beneficial for obtaining repeatable values. Future research should also evaluate whether the bandages provide the therapeutic level of compression that results in compressive grip or friction even as the leg volume reduces.

## CONCLUSIONS

The force/deflection curve helps explain why the DCS provides better performance throughout its elastic deflection during limb size reduction, which could lead to better wound-healing outcomes. Results from the curve used for the calculated pressure demonstrate that the DCS can provide effective compression consistently over a greater range of limb volume, which is an important characteristic for providing therapeutic pressure even after limb reduction has occurred.

Using the tensile test and the guide of the reference points on layers 1 and 2 of the DCS, the calculated pressure achieved the expected values by the manufacturer. This study provided controlled testing results that further explain why some human studies have shown the ability of the visual guide of the reference points on layers 1 and 2 from DCS to provide consistent and continuous compression.[34] ●

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