Relationship between interface pressures and pneumatic cuff inflation pressure at different assessment sites of the lower limb to aid soft exoskeleton design

Tjaša Kermavnar, Kevin J. O’Sullivan, Adam de Eyto and Leonard W. O’Sullivan, Design Factors, Health Research Institute & Bernal Institute, School of Design, University of Limerick, Limerick, Ireland

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Corresponding author:

Prof. Leonard W. O’Sullivan
School of Design and Health Research Institute
University of Limerick
Limerick V94 T9PX
Ireland
Tel: 00 353 61 234249
E-mail: leonard.osullivan@ul.ie
Abstract

Objective. To develop a means of predicting interface pressure from cuff inflation pressure during circumferential compression at the lower limb, in order to inform the design of soft exoskeletons.

Background. Excessive mechanical loading of tissues can cause discomfort and soft tissue injury. Most ergonomics studies on exoskeletons are of interface pressure, but soft exoskeletons apply circumferential pressures similar to tourniquet cuffs by way of cuff inflation pressure. This study details the relationship between interface and cuff inflation pressures for pneumatic tourniquet cuffs.

Method. Pneumatic cuffs of different widths were inflated to target pressures on (A) a rigid cylinder, (B) the dominant thigh and calf, and (C) knee of healthy participants standing still. Interface pressures were measured under the cuffs using a pressure-sensing mat. Average interface pressures were then compared to cuff inflation pressures. The influence of cuff width, cuff inflation pressure and participants’ anthropometric data on pressure transmission were assessed.

Results. A strong linear relationship between cuff inflation pressures and interface pressures was observed. Interface pressures were generally higher than cuff inflation pressures. The efficiency of pressure transmission to the lower limb depended on assessment site, adipose tissue thickness, cuff size, cuff inflation pressure and possibly limb circumference. Regression equations were developed to predict interface pressures at the thigh, calf and knee.

Conclusion. Interface pressures under pneumatic cuffs are influenced by the cuff size, cuff inflation pressure, and tissue compressibility. Predicted interface pressure from cuff inflation pressure and vice versa can be used to aid the design of soft exoskeletons.

Keywords: Soft exoskeleton-human contact, Interface pressure, Cuff inflation pressure, Pressure transmission efficiency.

Précis: Interface pressure measurements were performed during circumferential compression at the lower limb, in order to develop a means of predicting interface pressure from cuff inflation pressure to inform the design of soft exoskeletons.
1. Introduction

Lower limb soft exoskeletons are soft wearable robots mainly used for assistance with locomotion. They often apply tensile forces across joints to actuate movement, but may also help with joint stabilisation/stiffening in certain abnormal gait patterns (e.g., knee hyperextension, foot drop, ankle and knee instability and others). Soft exoskeletons typically apply forms of circumferential compression.

Several devices that apply circumferential compression to tissues are already in use for medical purposes, including compression bandages and garments (Becker et al., 2006; Liu et al., 2013; Macintyre, 2007), pneumatic cuffs (Doyle & Taillac, 2008; Khanna et al., 2008; Kumar & Alexander Walker, 2002), and vacuum and inflatable splints (Rose, 1973; Schetrumpf, 1973; Taly et al., 2002). The pressure exerted by such devices generates mechanical loading of soft tissues that are compressed against the underlying bone.

Excessive mechanical loading can cause local tissue injury, such as blisters, hematomas and necrosis of the skin (Olivecrona et al., 2006; Rudolph et al., 1990), nerve lesions (Horlocker et al., 2006) and muscular and vascular damage (Sinicina et al., 2007) due to excessive or prolonged compression that results in tissue deformation and locally disturbed perfusion (Nercessian et al., 2005; Olivecrona et al., 2006; Rudolph et al., 1990). Therefore, attempts have been made to establish safe pressure thresholds at the physical interfaces between the device and the user.

Interface pressure is defined as the average force per unit area acting normal to the body surface (Casey et al., 2010). For its assessment, different approaches have been undertaken thus far, including the use of computer models (Cristina Cristalli & Ursino, 1995; Deng & Liang, 2016; Lan et al., 2011), pressure measurements on rigid cylinder models (Macintyre, 2007; Segers et al., 2002), live
participants’ calves (Giele et al., 1997; John et al., 2007; Lurie et al., 2008), thighs (Crenshaw et al., 1988; Hughes et al., 2018; Macintyre, 2007; Roth et al., 2015), upper limbs (Casey et al., 2010; Macintyre, 2007), and on human cadavers (Crenshaw et al., 1988; Shaw & Murray, 1982). In the case of inflatable devices, such as pneumatic cuffs, the value of cuff inflation pressure (i.e. air pressure inside the pneumatic cuff) given by the manometer is considered to accurately reflect the actual mechanical pressure exerted at the skin surface (Roth et al., 2015). However, the proportion of pressure transmitted from the cuff to the surface of the limb and/or deeper tissues (i.e. the efficiency of pressure transmission) can vary, depending on the nature of mechanical loading (e.g. cuff inflation pressure and cuff design) and the nature of the intervening soft tissues (e.g. anatomical location and mechanical properties).

In general, the pressure on the soft tissues under external compression was found to decrease with the anatomical depth of the tissue assessed (Hargens et al., 1987; Shaw & Murray, 1982). Using computer simulation, Deng and Liang (2016) found slightly more efficient pressure transmission from the cuff to the brachial artery at lower compared to higher cuff inflation pressures. Furthermore, interface pressure at given cuff inflation pressure has been shown to vary with variation in materials and geometric properties of pneumatic cuffs (Lurie et al., 2008; Naqvi et al., 2017). For example, significant differences in interface pressures and tissue deformation were found with different cuff bladder configurations, as the highest pressures occur directly beneath the air bladders (John et al., 2007). Moreover, interface pressures exceeded cuff inflation pressures when the air bladder of the pneumatic cuff reached around the entire circumference of the limb (John et al., 2007). On the other hand, Roth et al. (2015) reported significant loss in cuff inflation pressure transfer to the skin due to the use of a cushioning layer. Using an inflatable water-cuff, Manafi Khanian et al. (2016) found significantly lower interface pressures and a significantly more homogeneous interface pressure distribution compared to an air-cuff.
In this study, "wide" and "narrow" cuffs are defined relative to the "standard" pneumatic cuff for blood pressure measurement, that is at least 40% of the limb's circumference (ideally 46%); e.g. 12 cm for small adult arm circumferences, and 16 cm for large adult arm circumferences (Smith 2005). Wider cuffs transmit a greater percentage of their (i.e. cuff inflation) pressure to deeper tissues than narrower cuffs (Crenshaw et al., 1988). For narrower but not wider cuffs, the transmission of pressure to deeper tissues depends on limb circumference (Crenshaw et al., 1988).

Shaw and Murray (1982) found a significant inverse relationship between cadaveric thigh circumference and the percentage of cuff inflation pressure transmitted to superficial and deep soft tissues. A later study on participants refuted any influence of BMI and thigh circumference on pressure transmission to the limb surface, but did find significantly higher interface pressures at the area of the overlap of the cuff, which is strongly influenced by the limb’s circumference (Roth et al., 2015).

The magnitude of interface pressure and uniformity of its distribution under a pneumatic cuff is further influenced by the inhomogeneity and anisotropicity of human tissues (Daly & Odland, 1979; Fung, 1993), as well as the irregular geometry of the limbs (Manafi Khanian et al., 2016; Vannah & Childress, 1996). Different researchers reported an inhomogeneous transfer of pressure around the circumference of the limb (Lurie et al., 2008; Roth et al., 2015). Studies using pneumatic cuffs on model limbs, as well as compression sleeves on live participants’ thighs found higher interface pressures over smaller curvatures, which is in agreement with the Laplace Law (Macintyre, 2007; Segers et al., 2002). Laplace’s Law is widely used to calculate the pressure delivered by pressure garments (i.e. fabric under tension) to a cylinder (Macintyre 2007) in the following manner:

\[ P = \frac{T}{R} \]  
(Equation 1)
Where $P$ is cylindrical surface pressure, $T$ is fabric tension, and $R$ is the radius of curvature of the cylindrical surface (Zhao et al. 2017). Thus, the interface pressure increases when the radius of curvature under the fabric decreases and vice versa (Cheng et al. 1984; Macintyre 2007). However, the Laplace Law does not accurately predict interface pressures on limbs with circumferences under 25 cm (Macintyre, 2007).

The pressure transmitted to skin and deeper tissues (i.e. subcutaneous tissue, muscles, blood vessels, nerves) depends on the tissues’ mechanical properties (Cristina Cristalli & Ursino, 1995; Lurie et al., 2008), particularly compressibility (Lan et al., 2011), which is quantified by Poisson’s ratio. In incompressible tissues (Poisson’s ratio 0.5), the transmitted pressure correlates with the pneumatic pressure (Casey et al., 2010). However, real tissues (Poisson’s ratio 0.2-0.4) deform under compression due to migration of tissue fluids from the compressed region (Casey et al., 2010; Cristina Cristalli et al., 1993). Mechanically, deformation of tissues causes the non-uniform pressure distribution at the interface (Deng & Liang, 2016), with more effective pressure transmission over bony prominences than over soft anatomical sites (Giele et al., 1997). In fact, subcutaneous adipose tissue has been shown to significantly dampen pressure transmission to deeper tissues (Deng & Liang, 2016).

In previous study, we addressed the influence of circumferential compression at the thigh, calf and knee on discomfort and pain in the context of soft exoskeleton design (Kermavnar et al., 2019; Kermavnar, 2019). The discomfort and pain detection thresholds were reported in terms of pneumatic cuff inflation pressures. However, interface pressures can easily be measured by pressure mats and other types of interface pressure sensors, so this is most likely the method most developers of soft exoskeletons will use during the ergonomics assessment of their designs. Thus, the aim of this study was to develop a means of predicting interface pressure from cuff inflation pressure and vice versa at different sites of the lower limb, in order to inform soft exoskeleton design. For this purpose,
regression analysis was performed and prediction equations developed for interface pressures under pneumatic cuffs at the lower limb.

2. Method

2.1. Study overview

Interface and cuff inflation pressure measurements were performed in three separate sessions: on (1) a rigid cylinder, (2) human participants' thighs and calves, and (3) and human participants' knees. The latter two experiments were part of separate larger studies. In all three sessions, mean interface pressure (dependent variable) was measured by a pressure-sensing mat under the pneumatic cuffs at different cuff inflation pressures (independent variable).

2.2. Participants

Healthy volunteers were recruited from the University of Limerick. Volunteers were excluded from the study if any of the following criteria were present: (1) BMI $\geq 30$ kg/m$^2$; (2) current musculoskeletal, neurological, circulatory or endocrine condition or injury; (3) acute or chronic pain or muscle soreness resulting from vigorous exercise in the previous 48 hours; (4) current use of medication which interferes with sensory systems.

This research complied with the tenets of the Declaration of Helsinki and was approved by the Institutional Review Board at the University of Limerick (approval #2017_07_03_S&E). The study was approved by the University of Limerick Research Ethics Committee. Signed informed consent was obtained from all participants.

2.3. Equipment

2.3.1. Pressure-sensing mat
A flexible pressure-sensing mat (BodiTrak, Vista Medical Ltd.) was used for interface pressure measurements. Its area of 22.7 × 22.7 cm consists of 16 × 16 pressure sensors. In a preliminary experiment, the points of interest on the mat were established and marked with adhesive tape, as shown in Figure 1. The cross-section of the adhesive tapes (sensor H9) was positioned over the predefined measurement point for every assessment site on human participants to ensure repeatability of the experiments.

![Figure 1: Pressure-sensing mat; sensor array (left), positioning on the pneumatic cuff (right).](image)

The pressure-sensing mat was calibrated prior to testing to avoid potential inaccuracies due to long-term sensor drift. A pre-experimental study was performed with the pressure-sensing mat including visual examination of signals to assess the probability of short-term sensor drift, and no evidence of it was found.

2.3.2. **Pneumatic cuffs and cuff inflation rig**

A Hokanson SC5 tourniquet cuff (width 5 cm), Hokanson Rapid deflate SC12D cuff (width 12 cm), and Hokanson Contoured thigh cuff CC22 (width 22 cm) were used (Figure 2). The position of the pressure-sensing mat was permanently marked on each cuff to ensure repeatability of the experiments. The
mat was positioned under the centre of each cuff’s air bladder, so that none of the sensors were in contact with the inflation tube or the cuffs’ seams to avoid artefacts. The mat was adhered to each cuff separately for every measurement using double-sided adhesive film. The pneumatic cuffs were connected to a computer-controlled bespoke industrial pneumatic pressurized system (Design Pro, Rathkeale, Co. Limerick Ireland) which allowed for rapid inflation of the cuffs to target pressures, complete control of compression duration, and rapid cuff deflation (Kermavnar, 2019).

![Image of pneumatic cuffs](image)

**Figure 2:** Pneumatic cuffs used (left to right): Hokanson SCS tourniquet cuff, Hokanson Rapid deflate SC12D cuff, Hokanson Contoured thigh cuff CC22.

### 2.4. Procedure

#### 2.4.1. Testing on a rigid cylinder

On the rigid cylinder (circumference 503 mm), the position of the pressure-sensing mat was permanently marked to ensure repeatability of the experiment. All three widths of pneumatic cuffs were tested. Each pneumatic cuff was mounted over the pressure-sensing mat and loosely wrapped with a non-elastic adhesive tape (Leukosilk, BSN medical GmbH, Hamburg, Germany) for even
distribution of pressure (Figure 3). The cuff was then inflated to target pressures of 10, 20, 30, 40, 50 and 60 kPa. The inflation lasted up to 5 seconds while the interface pressure was continuously recorded by the pressure-sensing mat.

![Image](image.png)

**Figure 3:** Positioning of the pressure-sensing mat and cuff on a rigid cylinder.

### 2.4.2. Testing on human participants

The participants attended a single testing session. Prior to beginning the experiment, written informed consent was obtained and participants were asked about their health status to ensure that they did not have any of the conditions that would preclude them from taking part in the study. Next, the following information were recorded: participants’ age and sex, Body Mass Index (BMI), Adipose Tissue Thickness (ATT) and limb circumference at the points of interest, over which the centre of the pressure-sensing mat was later positioned.

Adipose Tissue Thickness (ATT) and limb circumference were measured at 2/3 distance between greater trochanter and lateral epicondyle, over m. vastus lateralis at the thigh, and at the widest part of m. gastrocnemius (medial head) at the calf. The measuring points were selected due to subsequent monitoring of muscle oxygenation. At the knee, the circumference was measured at the centre of patella. The circumferences were measured using an anthropometric measuring tape, and the skinfold
thickness was measured using skinfold callipers. Similar to previous studies (Otte et al. 2002; Merrick et al. 2003), ATT was estimated by dividing the measured skinfold thickness in half.

All experiments were performed on the dominant limb with participants standing still. At the thigh and calf, all three widths of pneumatic cuffs were tested in a randomised order. The centre of the pressure-sensing mat (sensor H9) was positioned over the belly of m. vastus lateralis at \( \frac{2}{3} \) distance between greater trochanter and lateral epicondyle at the thigh, and over the medial head of m. gastrocnemius at the widest part of the calf. At the knee, testing was only performed using the 12-cm wide pneumatic cuff that extended over the entire joint but did not compress the adjacent softer parts of the limb. Sensor H9 of the pressure-sensing mat was positioned over the centre of patella. The pneumatic cuff was loosely wrapped with a non-elastic adhesive tape (Leukosilk, BSN medical GmbH, Hamburg, Germany) to ensure an even distribution of pressure, and secured in place with Velcro™ straps attached to a waist belt (Thermoskin Adjustable back stabiliser, United Pacific Industries Pty Ltd, Kilsyth, Australia) at the front and back to prevent it from slipping down the leg (Figure 4).

![Figure 4: Positioning of the pressure-sensing mat and cuff at the thigh (left), calf (middle) and knee (right).](image)

The cuff was then inflated to target pressures of 10, 20, 30 and 40 kPa at the thigh and calf, and additionally to 50 and 60 kPa at the knee. Cuff inflation to target pressure was as rapid as possible, in
the range of 0.3-0.7 s depending on cuff size and target pressure. The target pressure was then maintained for up to 5 seconds in order for the interface pressure readings by the pressure-sensing mat to stabilize.

2.5. Data analysis

The central sensors of the mat were aligned with the centre of the bladder of each cuff. To ensure that representative interface pressures were obtained, the results of an array of sensors were analysed, and the average, maximum and minimum interface pressures were recorded just before termination of cuff inflation (Figure 5).

![Figure 5: Sample output of interface pressure analysis using the pressure mat.](image)

The number of sensors included in the analysis depended on the cuff width, and was therefore smaller for the narrowest cuff (Figure 6): 8 × 3 for the smallest cuff and 8 × 6 for the two larger cuffs. The area analysed was presumed to include the muscles analysed in subsequent studies by near-infrared spectroscopy at the thigh and calf, and thus reflect the interface pressure causing the change in muscle oxygenation during circumferential compression. The mean, minimum and maximum pressures
recorded by the array of sensors were monitored in real time to detect and prevent possible artefacts due to cuff position, and the mean pressures were extracted and further analysed.

Figure 6: The array of pressure-sensing mat sensors, based on which the mean interface pressure was calculated for 5-cm cuff (dark grey), and 12-cm and 22-cm cuff (dark and light grey).

All data were analysed using IBM® SPSS Statistics software Version 25, with significance set at p < 0.05. One-way repeated measure ANOVAs were performed for each assessment site, with cuff inflation pressure as the within-subjects factor and interface pressure as the dependent variable. Regression analysis was performed using interface pressure as the dependent variable, and cuff inflation pressure, BMI, ATT and limb circumference as the independent variables to identify the possible contribution of each variable to interface pressure, and to develop prediction equations for interface pressures under pneumatic cuffs at the lower limb. Numerical data are presented as mean and standard deviation (SD), unless specified otherwise.
3. Results

3.1. Participants

Participants for both sessions of this study were recruited from the University of Limerick. Testing was performed at the thighs and calves of 12 participants (6 male, 6 female), aged 22-57 years (35.5 ± 9.8 years), and at the knees of 23 participants (13 male, 10 female), aged 19-57 years (25.6 ± 10.4 years). Anthropometric data are summarised in Table 1 for each assessment site respectively.

Table 1: Participants’ anthropometric data for each assessment site.

<table>
<thead>
<tr>
<th></th>
<th>MALE</th>
<th>FEMALE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BMI (kg/m²)</td>
<td>Circumference (mm)</td>
</tr>
<tr>
<td>THIGH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>25.9</td>
<td>501.7</td>
</tr>
<tr>
<td>SD</td>
<td>2.7</td>
<td>18.6</td>
</tr>
<tr>
<td>Median</td>
<td>26.4</td>
<td>502.5</td>
</tr>
<tr>
<td>CALF</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>25.9</td>
<td>394.2</td>
</tr>
<tr>
<td>SD</td>
<td>2.7</td>
<td>17.7</td>
</tr>
<tr>
<td>Median</td>
<td>26.4</td>
<td>400.0</td>
</tr>
<tr>
<td>KNEE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>24.5</td>
<td>384.7</td>
</tr>
<tr>
<td>SD</td>
<td>2.1</td>
<td>25.9</td>
</tr>
<tr>
<td>Median</td>
<td>24.2</td>
<td>380.0</td>
</tr>
</tbody>
</table>

BMI – Body mass index, ATT – Adipose tissue thickness.
3.2. **Mean interface pressures**

The mean interface pressures recorded at each assessment site and cuff inflation pressure are presented in Table 2. For acuity, the actual cuff inflation pressures as measured by the rig sensing system are reported, as they differed slightly from the target cuff inflation pressures.

The mean interface pressures at the target cuff inflation pressures were generally lower on the rigid cylinder than on human participants, and the pressures at the knee were lower than those at the thigh and calf. At the thigh, mean interface pressures under the 5-cm and 22-cm cuff were lower than at the calf; however, the opposite was recorded using the 12-cm cuff.

**Table 2:** Mean interface pressures at predefined pneumatic cuff inflation pressures for a rigid cylinder and human participants’ thigh, calf and knee.

<table>
<thead>
<tr>
<th>Cuff width (cm)</th>
<th>Cuff inflation pressure (kPa)</th>
<th>Interface pressure (kPa)</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Rigid cylinder</td>
<td>Thigh</td>
<td>Calf</td>
<td>Knee</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>13.1</td>
<td>9.3 (2.3)</td>
<td>9.8 (1.2)</td>
<td>12.0 (1.2)</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>22.7</td>
<td>19.9 (4.8)</td>
<td>21.2 (2.8)</td>
<td>26.8 (2.7)</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>32.1</td>
<td>31.2 (6.4)</td>
<td>32.0 (3.5)</td>
<td>39.7 (3.4)</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>42.1</td>
<td>41.3 (6.8)</td>
<td>40.6 (4.5)</td>
<td>51.2 (4.3)</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>51.6</td>
<td>50.5 (8.0)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>61.4</td>
<td>59.6 (9.9)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>13.1</td>
<td>9.2 (1.3)</td>
<td>14.1 (2.9)</td>
<td>14.4 (1.3)</td>
<td>9.8 (2.8)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>22.7</td>
<td>21.8 (2.3)</td>
<td>32.5 (2.2)</td>
<td>32.0 (2.2)</td>
<td>27.0 (3.4)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>32.1</td>
<td>35.5 (2.0)</td>
<td>47.8 (0.8)</td>
<td>46.0 (3.5)</td>
<td>42.4 (3.2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>42.1</td>
<td>45.7 (2.3)</td>
<td>61.2 (1.4)</td>
<td>60.3 (2.4)</td>
<td>54.6 (3.3)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>51.6</td>
<td>56.3 (3.1)</td>
<td>-</td>
<td>-</td>
<td>65.5 (4.3)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>61.4</td>
<td>67.6 (4.0)</td>
<td>-</td>
<td>-</td>
<td>74.5 (7.0)</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>13.1</td>
<td>10.8 (2.3)</td>
<td>13.8 (0.8)</td>
<td>15.4 (0.9)</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>22.7</td>
<td>25.3 (3.6)</td>
<td>29.5 (1.9)</td>
<td>32.4 (2.3)</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>32.1</td>
<td>34.6 (7.4)</td>
<td>44.3 (2.3)</td>
<td>47.8 (1.6)</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>42.1</td>
<td>-</td>
<td>55.4 (5.9)</td>
<td>60.6 (2.3)</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>
The differences between interface pressures under pneumatic cuffs of different widths are presented in Figures 7-9; the interface pressures under the 12-cm cuff at the knee are presented in Figure 10. On the rigid cylinder, cuff inflation pressures above 40 kPa could not be tested with the largest cuff due to its tapered shape, therefore the results were excluded from the repeated measures ANOVA. Comparing the remaining results, interface pressures were significantly lower (p = 0.018) under the 5-cm cuff than the 12-cm cuff. At the thigh, cuff width significantly influenced the interface pressure (p < 0.001) with the highest pressures recorded using the 12-cm cuff and the lowest using the 5-cm cuff. At the calf, interface pressures under the smallest cuff were significantly lower than under each of the larger cuffs (p < 0.001). Interface pressures under the 12-cm cuff were lower than under the 22-cm cuff, however the difference between them was not significant (p = 0.061).

Figure 7: Interface pressure on the rigid cylinder for different cuff inflation pressures applied by different widths of pneumatic cuffs.
Figure 8: Interface pressure at the thigh for different cuff inflation pressures applied by different widths of pneumatic cuffs. Error bars: ± 1 SE

Figure 9: Interface pressure at the calf for different cuff inflation pressures applied by different widths of pneumatic cuffs. Error bars: ± 1 SE

Figure 10: Interface pressure at the knee for different cuff inflation pressures, using a 12-cm cuff. Error bars: ± 1 SE
3.3. Regression analysis

The results of regression analysis (Table 3) show high correlation between interface pressure, cuff inflation pressure and cuff width (where used) at all assessment sites. At the calf, ATT was also found to significantly influence interface pressure \( (p = 0.011) \). On the other hand, limb circumference at the point of measurement did not show significant influence on interface pressure \( (p = 0.138, 0.243 \text{ and } 0.672 \text{ for thigh, calf and knee respectively}) \), neither did BMI \( (p = 0.255, 0.184 \text{ and } 0.928 \text{ for thigh, calf and knee respectively}) \).

Table 3: Regression equations for prediction of interface pressure at different assessment sites.

<table>
<thead>
<tr>
<th>Interface pressure</th>
<th>( R^2 )</th>
<th>( p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>RIGID CYLINDER</td>
<td>0.989</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>(Constant) - 7.923</td>
<td></td>
<td>0.001</td>
</tr>
<tr>
<td>+ 1.142 \times Cuff inflation pressure</td>
<td>&lt; 0.001</td>
<td></td>
</tr>
<tr>
<td>+ 0.303 \times Cuff width</td>
<td>0.006</td>
<td></td>
</tr>
<tr>
<td>THIGH</td>
<td>0.876</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>(Constant) - 11.128</td>
<td></td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>+ 1.379 \times Cuff inflation pressure</td>
<td>&lt; 0.001</td>
<td></td>
</tr>
<tr>
<td>+ 0.518 \times Cuff width</td>
<td>&lt; 0.001</td>
<td></td>
</tr>
<tr>
<td>CALF</td>
<td>0.965</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>(Constant) - 8.090</td>
<td></td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>+ 1.497 \times Cuff inflation pressure</td>
<td>&lt; 0.001</td>
<td></td>
</tr>
<tr>
<td>+ 0.367 \times Cuff width</td>
<td>&lt; 0.001</td>
<td></td>
</tr>
<tr>
<td>- 0.182 \times ATT</td>
<td>0.011</td>
<td></td>
</tr>
<tr>
<td>KNEE</td>
<td>0.914</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>(Constant) - 2.912</td>
<td></td>
<td>0.042</td>
</tr>
<tr>
<td>+ 1.320 \times Cuff inflation pressure</td>
<td>&lt; 0.001</td>
<td></td>
</tr>
</tbody>
</table>

The interface pressures as predicted by the regression equations versus the measured interface pressures are plotted in Figure 11.
4. **Discussion**

4.1. **Overall relationship between the inflation and interface pressure**

Our findings detail that there is a strong linear relationship between cuff inflation pressures and interface pressures when tested on a rigid cylinder, as well as the thigh, calf and knee. This is largely as expected. However, there are a number of important insights in the context of soft exoskeleton interface effects.

In general, interface pressures tended to be higher than cuff inflation pressures, which is contrary to the findings of Roth *et al.* (Roth et al., 2015), who reported significantly lower interface than cuff
inflation pressures under a thigh tourniquet. One of the reasons for diminished pressure transmission was the use of cotton padding to cushion the tourniquet; however, measurement was also performed on patients lying supine during surgery, meaning that their limbs were relaxed. During standing, as in our experiments, muscles are naturally active in order to maintain balance, therefore their stiffness is increased and compressibility decreases, which might explain the obtained results. In fact, Hughes et al. found interface pressure to be lower than cuff inflation pressure at rest, and higher during exercise (Hughes et al., 2018). Casey et al. also found the interface pressures to be higher than cuff inflation pressures at the upper limb and pressures over 100 mmHg (13.3 kPa) despite the use of cotton wool (Casey et al., 2010).

4.2. The influence of assessment site on pressure transmission

Important differences in pressure transmission were observed with regards to assessment site. Mean interface pressures resembled the cuff inflation pressures most closely on the rigid cylinder (mean absolute difference 2.8 kPa) and least at the knee (mean absolute difference 9.6 kPa), followed closely by the calf (mean absolute difference 9.2 kPa). The absolute differences were also most consistent on the cylinder (SD = 1.6 kPa), but least at the thigh (SD = 6.7 kPa). The raw differences between the two pressures were consistently larger at higher cuff inflation pressures, ranging from -3.9 to 6.2 kPa on the cylinder, -3.3 to 19.1 kPa at the thigh, -1.1 to 18.5 kPa at the calf, and -3.3 to 13.9 kPa at the knee.

Comparison of the results obtained at the thigh and calf could to a certain extent confirm the abovementioned influence of Poisson’s ratio on pressure transmission (Casey et al., 2010). Namely, an overall larger volume of soft tissue and larger adipose tissue thickness at the thigh could have accounted for larger compressibility of the thigh and thus less efficient pressure transmission from the pneumatic cuff to the limb. However, higher interface pressures at the calf than at the thigh when using the 12-cm cuff suggest the possibility of additional factors influencing pressure transmission, as described below. The results also suggest that compressibility of the soft tissues decreases with
compression, and its effect is most prominent at the thigh, possibly due to relatively larger volumes of muscle tissue compared to other assessment sites.

4.3. The influence of cuff width on pressure transmission

On the rigid cylinder, interface pressures were consistently lower than cuff inflation pressures under the smallest cuff, but tended to be higher under wider cuffs. A similar pattern was observed at the thigh but not the calf, where pressure transmission was more effective and the interface pressures exceeded cuff inflation pressures with only one exception (i.e. the combination of the smallest cuff and lowest cuff inflation pressure). As the length of the cuff’s air bladder increases with the width, we postulate that the smallest bladder might not have reached around the complete circumference of the thigh and cylinder, thus decreasing pressure transmission as mentioned above (John et al., 2007).

In agreement with previous findings (Crenshaw et al., 1988), wider cuffs were more efficient at transmitting pressure to the tissues. It is not clear, however, why the interface pressures at the thigh were higher under the 12-cm cuff than under the 22-cm cuff.

4.4. The influence of other factors on pressure transmission

Mean interface pressures were generally higher at the lower limb than on the rigid cylinder. A reason for that could be the more pronounced curvature of the limb at the assessment site compared to the cylinder. The comparison of the cylinder cross section and the high and calf, obtained by anthropometric measurements (i.e. the antero-posterior and medio-lateral width) is presented in Figure 12.
In agreement with previous findings (Roth et al., 2015), BMI and limb circumference did not significantly influence interface pressures. On the other hand, significant reduction of interface pressure at the calf occurred with increasing adipose tissue thickness, presumably due to its dampening effect on pressure transmission. Interestingly, the effect of ATT was not significant at the thigh. Also surprisingly, interface pressures at the knee were lower than at the thigh and calf despite the scarceness of soft tissue.

4.5. Application to soft exoskeleton design

Due to their design and function, soft exoskeletons are more likely to exert circumferential compression than point pressure on the body. The findings of this study and our previous studies on discomfort (Kermavnar et al., 2019; Kermavnar, 2019) show that pressures applied to the limbs differ from the pressures transmitted and thus experienced (i.e. interface pressures), depending on the compressed tissue characteristics and the equipment used. The pressures experienced by the wearer determine whether they will perceive discomfort and whether the loading could cause injury to the tissues. Moreover, interface pressures are typically used in safety guidelines for wearable devices, as their monitoring is rather uncomplicated.

The regression equations reported here can be used to predict interface pressures at the typical sites of human-soft exoskeleton contact during circumferential compression. In combination with the data
on discomfort and pain reported in our previous studies (Kermavnar et al., 2019; Kermavnar, 2019), we can conclude the following: (1) interface pressures that are likely to cause discomfort are 16.8-37.5 kPa at the thigh, 21.4-90.3 kPa at the calf, and 15.2-37.2 kPa at the knee; and (2) interface pressures that are likely to cause pain are 49.6-75.9 kPa at the thigh, 78.8-90.3 kPa at the calf, and 66.9-77.1 kPa at the knee. The lower limits apply to continuous compression and the higher to intermittent compression.

4.6. Limitations

A larger group of participants was tested at the knee than at the thigh and calf, which might influence the comparability of results. Moreover, only one cuff size was appropriate for testing at the knee, and the largest cuff might not have made complete contact with the rigid cylinder due to its tapered design for use on limbs. Finally, pressures above 42.1 kPa were not tested on participants’ thighs and calves in order to avoid causing pain based on the pain detection thresholds obtained in previous studies.

5. Conclusions

In this study we aimed to develop a means of predicting interface pressure from cuff inflation pressure, in order to inform the design of soft exoskeletons that apply circumferential compression at the lower limb. The results show a strong linear relationship between cuff inflation pressures and interface pressures, with the latter generally exceeding the former. Mean interface pressures were also generally higher at the lower limb than on a rigid cylinder. The efficiency of pressure transmission to the lower limb depended on assessment site, adipose tissue thickness, cuff size, cuff inflation pressure and possibly limb circumference. Interface pressures at the knee were lowest for all comparable cuff inflation pressures. Pressure transmission increased with compression, more prominently at sites with larger volumes of compressible (soft) tissue. Wider cuffs transmitted pressure more efficiently than narrower at the thigh, but not the calf. At the calf, mean interface
pressures under the narrowest and widest cuff, but not the 12-cm cuff were higher than at the thigh. BMI and limb circumference did not significantly influence interface pressures, although the results using the smallest cuff might have been influenced by the circumference of the assessment site due to air bladder size. Finally, regression equations were developed to predict interface pressures at the typical sites of human-soft exoskeleton contact during circumferential compression, which can in combination with data on discomfort and pain aid the design of soft exoskeletons.

Key points:

- There is a strong linear relationship between cuff inflation pressures and interface pressures.
- Interface pressures during circumferential compression generally exceed interface pressures.
- The efficiency of pressure transmission to the lower limb depends on assessment site, adipose tissue thickness, cuff size, and cuff inflation pressure.
- Regression equations can be used to predict interface pressures at the typical sites of human-soft exoskeleton contact during circumferential compression.

6. References


Kermavnar, T., O'Sullivan, K., de Eyto, A. and O'Sullivan, L. (2019). Discomfort/pain and tissue oxygenation at the lower limb during circumferential compression: application to soft exoskeleton design. *Human Factors, Accepted for publication.*


Biographies:

**Tjaša Kermavnar**, MD, BDes, graduated in 2012 from Medical Faculty in Ljubljana, Slovenia; and in 2013 from the Academy of Fine Arts and Design in Ljubljana, Slovenia. In 2016, she started her PhD research study in ergonomics aspects of human-exosuit interaction at the School of Design, University of Limerick, Ireland.

**Kevin J. O’Sullivan**, BSc, MSc. In 2010, he graduated with a BSc in Product Design, and in 2016 with a master’s degree in medical device design. He is currently a Senior Research Fellow in the School of Design.

**Adam de Eyto**, BDes, Ph.D., Head of School of Design, University of Limerick, Ireland. Graduated from The National College of Art & Design, Dublin, Ireland, with a BDes (Industrial Design) in 1995, and with a PhD from Bournemouth University UK in 2009.

**Leonard W. O’Sullivan** is an Associate Professor in the School of Design. His research interests are in human factors of human robot interaction, to include exoskeleton interaction (hard and soft) and technology adoption aspects affecting users’ experience of robotics.