Design of a Sensor-Enabled Testing Device for the TrueClot® Tourniquet Application Trainer

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Abstract

Tourniquets are devices that are used to stop traumatic bleeding and limit blood loss. Luna Labs USA, LLC developed a simulation bleeding control training product that teaches proper tourniquet application training: the TrueClot® Tourniquet Application Trainer (TAT). The TAT is a product that is worn over a mock patient's left shoulder and upper arm and is used to simulate a scenario in which an individual has sustained a traumatic injury to their arm. One of Luna's business partners, AeroHealthcare, expressed interest in the clinical relevance of the TAT, so Luna developed a project to address whether or not the tubing within the TAT requires the same amount of pressure to occlude as a typical brachial artery. This question was addressed through the design of a sensor-enabled testing device that evaluated the amount of pressure exerted on the TAT by a tourniquet. Key aspects of the project included research on typical limb occlusion pressures (LOPs), the selection and calibration of the force sensing resistor (FSR), and the testing of tourniquets with the FSR inserted within the TAT. The calibration of the FSR, determined through Instron testing, allowed for the voltage output of the FSR to be converted to force. The output force was then converted to pressure to be compared to the expected LOPs (2.5-5 psi). Testing different tourniquets over the TAT with the FSR inserted yielded results that stated (1) different tourniquets and different arm sizes impact the amount of pressure exerted on the tubing within the TAT and (2) the pressures exerted by the tourniquets on the TAT exceed the expected LOP range. This informs Luna that the TAT requires more pressure to stop blood flow than a typical arm.

Keywords: Tourniquet, Limb Occlusion Pressure, Force Sensing Resistor, Instron

Introduction

Tourniquets are devices that are used to stop blood flow through a vein or artery in the case of a traumatic injury, typically to a limb. They are applied very tightly around the circumference of the injured limb, thus compressing the tissues and vasculature surrounding the hemorrhaging blood vessels in order to stop blood flow and limit blood loss. Tourniquets made out of makeshift materials, such as belts and cloth, can be successful if they are applied correctly. However, they often fail, and it is much better to use an engineered tourniquet [1].

One of the most publicly known incidents of improper tourniquet application is the 2013 Boston Marathon bombing. During this event, 243 people were injured, and over 66 people received traumatic injuries to their extremities. Bystanders attempted to aid the victims by applying tourniquets to people who were experiencing traumatic bleeding. However, out of the 27 tourniquets that were applied to the victims, 26 were made out of makeshift materials, and the majority of them were applied improperly [2].

This event, along with other tragedies including the Sandy Hook Elementary School shooting in 2012, called attention to the public's lack of knowledge on bleeding control [3]. The Stop the Bleed program, a national public safety program designed to train laypeople and bystanders basic bleeding control skills, was inspired by these tragedies. Organizations, like Stop the Bleed, provide medical professionals with a platform to advocate for better bleeding control training for emergency medical services (EMS) and military personnel, as well as laypeople [4]. Luna Labs USA, LLC also became involved in this field and released a line of bleeding control simulation training products.

In an effort to ensure that their EMS providers receive realistic, high-quality tourniquet application training, Fairfax Fire and Rescue in Fairfax, VA specifically requested a wearable, bleeding simulation trainer from Luna Labs. Luna worked in conjunction with Fairfax to design such a product, ultimately creating the TrueClot® Tourniquet Application Trainer (TAT), which is the focus of this project [5].

Figure 1. Descriptive images of the TrueClot® Tourniquet Application Trainer (TAT). This figure labels and highlights the different components of the TAT: (A) labels all of the components of the TAT, (B) demonstrates how the TAT should be worn, (C) displays how a tourniquet should be applied over the TAT, and (D) is an up-close image of the form padding within the TAT.

The TAT (Figure 1) is a cuff that, when in use, is secured around the wearer's left shoulder and upper arm, and it consists of three main components: urethane and silicone padding, a tubing that ends at a synthetic wound to simulate an injury to the brachial artery, and a squeeze bottle that can be filled with either synthetic blood or water. The reason for the design of the TAT is two-fold. Firstly, tourniquet application training is more comprehensive when performed on individuals than when it is performed on mannequins because it allows the trainees to practice interacting with patients. However, correctly applying a tourniquet is extremely painful for the person to which it is being applied [6]. The design and use of the TAT reduces the amount of pain felt by the person to which the tourniquet is applied. Secondly, the TAT provides trainees with a visual feedback mechanism. Typical tourniquet application training on a mannequin or an uninjured simulated patient does not allow the trainee to witness the stoppage of blood flow out of a wound. The TAT, on the other hand, allows the trainee to visualize exactly when they have occluded the tubing within the TAT and, thus, correctly applied the tourniquet.

Project Description and Goals

One of Luna Labs USA's partners, AeroHealthcare, expressed interest in the clinical relevance of the TAT, especially when paired with their new tourniquet design: the RapidStop tourniquet. Therefore, Luna formulated the question of whether or not the tubing within the TAT occludes within the same pressure range as a real brachial artery upon tourniquet application. The goal of the project was to address this question through the design of a sensor-enabled testing device for the TrueClot® Tourniquet Application Trainer (TAT).

The outline of the project was established to be a three-step process. For the first aim, a literature review would be conducted to determine the minimum pressure at which a typical brachial artery occludes (i.e., the limb occlusion pressure). The determined limb occlusion pressure (LOP) range would be used as a design constraint to determine what sensor to select for use with the device. In the second aim, once the sensor was selected, testing would be done to determine a calibration curve that would allow the data from the sensor to be converted to pressure values. For the third aim, the calibrated sensor would sit beneath the tubing in the TAT in order to test the pressure exerted on the tubing by both windlass and ratcheting tourniquets. The tourniquets that would be used for testing would all require manual pretensioning: the process of tightening a tourniquet very tightly around the injured limb before using the specific tightening mechanism of the tourniquet. However, the windlass tourniquets would be tightened further by the winding of a rod (i.e., the windlass), while the ratcheting tourniquets would be tightened by a ratcheting mechanism. The data from the testing conducted in this aim would be used to inform Luna of the clinical relevance of their TAT, and depending on the results, Luna would decide whether changes need to be made to the TAT design.

Materials and Methods

Design Constraints, Specifications, and Assumptions

Before designing the sensor-enabled testing device, it was necessary to understand the design constraints of the project. Literature reviews of limb occlusion pressures (LOPs) were performed to find an ideal pressure range [7-8]. The literature reviews provided insight as to how LOPs are measured and information on a range of pressures that would be important for the sensor to be capable of recognizing. The minimal pressure range determined to be critical for the sensor-enabled testing device to be able to detect was 2.5-5.0 psi. The word minimal is used because while it is necessary for the sensor to read values in the literature-reported range, it is acceptable for tourniquets to exert pressure values greater than what the literature describes. For example, additional pressure may be required for larger patients with excess adipose or muscle tissue.

Other design constraints included the length, thickness, sensitivity, and durability of the sensor. They were determined by the generally small space available for the sensor to occupy between the foam and outer nylon layer of the TAT. Specifically, the length constraint was derived from the length of the padded cuff on the TAT, and it accounted for various placements of the tourniquet along the upper arm as well as different tourniquet widths, which typically range from one to three inches. As a result, the range of acceptable lengths was 1.5-6.0 inches. This was an important constraint because if the selected sensor is not long enough, the sensor would only read the pressure being applied by the tourniquet within a limited region of the upper arm, thus resulting in an inaccurate measurement. The thickness constraint range stemmed from the volume of space available within the pocket of the TAT, ranging from 0.1-2.0 mm. The constraint of the sensor sensitivity was guided by the variability in range of the LOPs from the literature, so it was determined that the sensor did not require a particularly high sensitivity. Therefore, our acceptable range was 0.01-0.5 psi. The durability of the sensor was described as the number of uses, a frequently used quantification of device or product life span, and it was determined based on anticipation of how much testing would be done using the device. Therefore, the acceptable durability range was 1,000-1,000,000 uses.

Based on the design constraints, the sensor that was selected for use in this device was a force sensing resistor (FSR). These sensors, at their most basic level, consist of two thin membranes separated by a small pocket of air. This gap is caused by a spacer in between the two membranes. One of the membranes has a printed, interdigitated circuit pattern, while the other is coated with a carbon-based FSR ink. When a reasonable amount of force is applied to the top membrane, bringing it into contact with the bottom membrane, the FSR ink creates a short circuit across the printed circuit pattern, thus creating an inversely proportional relationship between the applied force and the resistance between the interdigitated circuit fingers. The interdigitated circuit fingers are also otherwise known as the active area, which is the region of the FSR containing the elements that actually read input. The rest of the FSR, a thin black border running around its perimeter, is essentially a dead zone that cannot read input

During use, the FSR would be inserted beneath the outer nylon layer of the TAT, and resting directly on this nylon layer is the simulated artery, so a few assumptions were made at the beginning of the project. The first assumption was that, during tourniquet application, the pressure exerted on the sensor underneath all these layers is the same as the pressure exerted on the tubing. Essentially, there would be no loss of force or dissipation of force as it traveled through the tubing and the outer nylon layer of the TAT before it reached the sensor. Additionally, it was known that the volume of space available for the sensor to rest inside the TAT was very small. As a result, during testing scenarios involving the sensor being inserted into the TAT, there would exist some resting, initial force experienced by the sensor before any external force was applied. However, the second assumption was that the initial force on the sensor (due to the fabric of the TAT) would become negligible as more external force is applied by an Instron or a tourniquet.

Circuit Design and Development

Once the design constraints for the device were fully determined, the circuit was ready to be developed. The materials used for the circuit were an Arduino Uno kit, a soldering station, the FSR, and the Arduino code **(**Figure 2). The components of the Arduino Uno kit used for this project were six wires, a 10k**Ω** resistor, a breadboard, the Arduino Uno, and a USB power cable, which is connected to a laptop for power. The soldering station was used to solder two wires to the FSR to ensure a very stable connection. The last material used in the development of the sensor-enabled testing device was Arduino code. At first, an open-source Arduino code for measuring the approximate Newton force detected by the FSR was found online and modified to fit our project design. This initial code was important as it

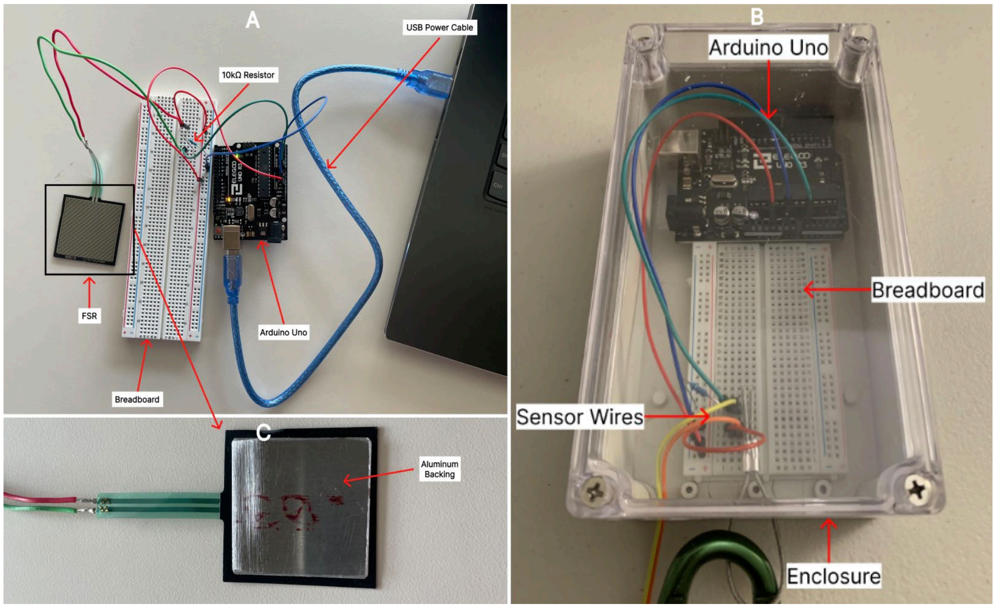

Figure 2. Descriptive images of the sensor-enabled testing device. This figure shows the components and final iteration of the device: (A) labels all of the different components of the electronics, (B) shows the electronics enclosed within a case for a more compact version of the device, and (C) labels the aluminum backing that is adhered to the back of the force sensing resistor.

aided in the interpretation of how the FSR interacts with the Arduino Uno: it provided an understanding of how the analog sensor readings worked in addition to the sensor itself. However, new code was eventually developed that involved converting the voltage to force and pressure values based on the active area of the specific FSR used in this project.

As for the construction of the circuit itself, it involved connecting one end of the FSR to power and connecting the other end to a 10kΩ resistor that was connected to ground. Then, the point between the fixed 10kΩ resistor and the variable FSR resistor was connected to the analog input of the Arduino Uno. This analog input is what enabled the reading of voltage and force values from the sensor using the code. Applying force to the FSR causes a change in the overall total resistance of the circuit, and this change in resistance causes a change in voltage across the fixed 10kΩ resistor. The subsequent change in voltage is what is measured and reported by the Arduino Uno once the code is run and a force is exerted on the FSR.

Once the circuit was created and the code was modified, the initial sensor-enabled testing device was established. However, the design was iterated upon one more time. It was realized that a more compact and portable design would be favorable when conducting testing with the tourniquets in the future. As a result, an enclosure and a smaller breadboard were acquired in addition to obtaining two new wires that extended the length of the connection between the sensor and the breadboard. The new breadboard and Arduino Uno were both able to fit into the enclosure together but a few modifications needed to be made to ensure that (1) the Arduino Uno could still be powered by the USB cable, (2) the entire enclosure could be secured to the TAT, and (3) the FSR could still plug into the breadboard from outside the enclosure. First, a Dremel was used to create an opening for the USB power cable in order to be able to plug it into the Arduino Uno while the lid of the enclosure was secured. Next, a drill was used to create holes through which a cable could be looped and allow for a carabiner to be clipped. This way, the carabiner could be used to attach the electronics to the TAT later during tourniquet testing. Last, the drill was again used to create an additional hole to enable the wires of the FSR to connect to the breadboard while the lid of the enclosure was secured. The end product was a compact and portable container that protected the circuit and allowed for it to be secured to the TAT.

Instron Testing: FSR on Flat Setup

The next step of the process was to begin compressive Instron testing. The purpose of conducting Instron tests was to develop a calibration curve for the FSR. The benefit of using an Instron for this process was that it allowed for the control and knowledge of the force applied to the FSR. From this, a relationship, or calibration curve, could be discovered between applied force and voltage. The materials needed for this round of Instron testing included the Instron itself, an actuator, the sensor-enabled testing device, and a thin piece of square-shaped aluminum (Figure 3).

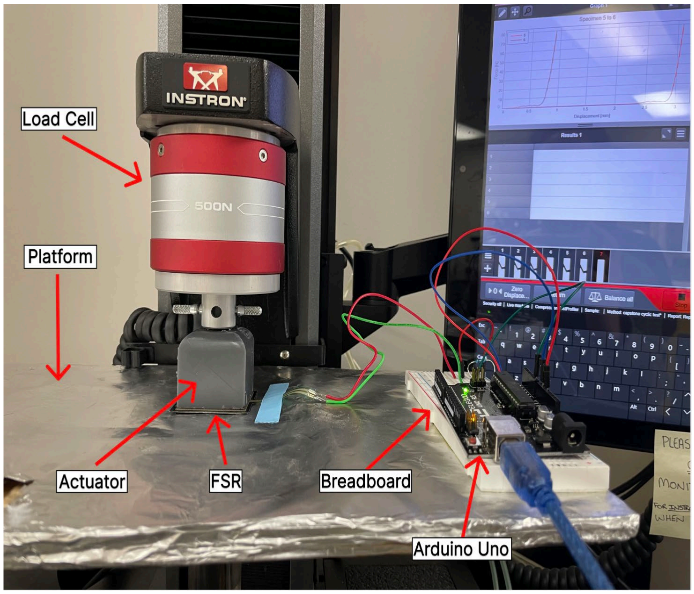

Figure 3. Instron machine testing setup with the force sensing resistor (FSR) on a flat surface. This testing setup was used in order to inform the shape of the calibration curve expected from the testing setup with the FSR within the TAT.

An actuator, which is connected to the load cell of the Instron, is essentially a tool used by the Instron to apply pressure to a precise area. The actuator, in this case, was composed of 3D-printed resin and had the same dimensions as the active area of the sensor (1.5in x 1.5in). The thin piece of aluminum was adhered to the back of the sensor and also had the same dimensions as the active area of the FSR. The inclusion of this backing was necessary because the sensor was slightly flexible, and flexing of the sensor during testing would induce a small voltage change and cause inaccurate readings. Therefore, a rigid, yet thin and lightweight backing was added to mitigate this flexing. The test was performed by first securing the FSR to the Instron platform and lining it up directly with the actuator. Next, the Intron was programmed to perform a compressive test at a certain force, for example 10N. Then, the sensor-enabled testing device was powered on in order to start obtaining readings from the FSR. Finally, the Instron test was initiated, and once it completed, the corresponding force and voltage values were recorded. For example, a voltage of 4.63V was observed when the applied force by the Instron reached 10N. As a result, a data pair was obtained (e.g., a 10N force corresponded with a 4.63V output). Three trials were performed: three sets of voltage and force pairs for each increment of 5N between 10N and 60N.

Instron Testing: FSR Inserted Within Tourniquet Application Trainer

The final step of the Instron testing process was essentially the same process as above but applied with a different setup. This time, the FSR was inserted into the TAT, the TAT was placed over a mannequin arm. The whole mannequin-TAT unit was then placed inside the Instron **(**Figure 4**)**.

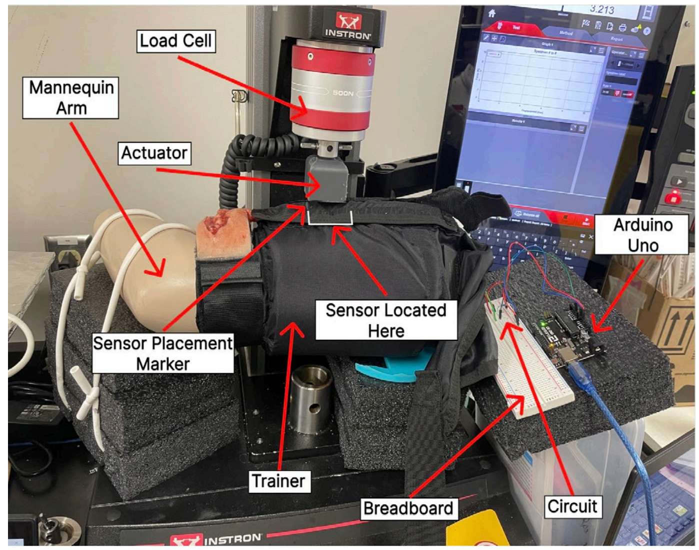

Figure 4. Instron machine testing setup with the force sensing resistor (FSR) inside the TAT. The TAT was placed on a mannequin arm in order to simulate a training scenario within the Instron. The data from this setup resulted in the formulation of a calibration curve that allowed the voltage output from the FSR to be converted to force and, subsequently, to pressure.

The reason for performing this second round of testing was because it provided information about how the FSR would perform within the TAT as well as how it would function in conjunction with a geometry similar to that of a real human arm. The mannequin-TAT unit had to be angled within the Instron in such a manner that it could allow for the load cell and actuator to line up with the sensor, and it also needed to be secured to prevent it from shifting during testing. These two goals were achieved by first placing the mannequin-TAT unit on stacked blocks of polyethylene foam. Then, silicone tubing was stretched around the polyethylene foam and the mannequin arm until it was tight enough to prevent the mannequin-TAT unit from shifting around on top of the polyethylene foam stacks (Figure 4). The way this test was run was by first inserting the FSR into the TAT and lining up the actuator with the region of the TAT where the FSR was located. To ensure that the sensor was inserted into the same location every time testing was performed, markings were made on the outside of the TAT in silver permanent marker. Finally, the Instron test was initiated in the same manner as the previous tests, and once it was completed, the corresponding force and voltage values were recorded. Six trials were performed using this setup: six sets of voltage and force values were recorded for each increment of 5N between 10N and 60N.

Results

In order to determine a mathematical relationship between the voltage output and the applied force, the results from the Instron tests were plotted using force versus voltage graphs, where force is F (in Newtons) and voltage is V (in Volts). The data from the tests performed while the FSR was secured to a flat surface within the Instron was used to inform the expected trend of the force versus voltage data (Figure 5a). The data from the second set of testing with the FSR inserted within the TAT experienced a similar trend compared to the first set of data (Figure 5b). An asymptote is seen as both of the fitted curves approach 5V, which is what was expected based on the voltage limitations of the Arduino Uno. Both of the curves of best fit were determined by rearranging logarithmic equations into exponential equations. This step was crucial because the original data was organized in sets of voltage versus force, with force as the independent variable and voltage output as the dependent variable, which exhibited logarithmic trends. The logarithmic equations were then rearranged to their exponential forms in order to create equations that outputted a force value as a pressure applied to the FSR changed the overall voltage of the circuit.

The baseline curve from Figure 5a (Equation 1) was created to examine the baseline performance of the FSR. Figure 5b illustrates a trend with similar behavior to the baseline equation, where there is a positive correlation between the voltage and force when the FSR is inserted within the TAT. This data also shows that there was an initial measured force of less than 10N on the FSR before initiation of the Instron testing with the TAT. It can be assumed that initial reading was due to the force exerted by the fabric and foam of the TAT resting on the FSR. However, an initial assumption was made that this force would be negligible due to the fact that the FSR required an activation force, and the measured force was less than that of the activation force. The curve of best fit for the second set of data was used as the final calibration curve for the FSR because it most accurately represented how the voltage output would change while the FSR was inserted within the TAT (Equation 2).

$$F = e^{\frac{V-4.43}{0.0911}} \qquad [1]$$

$$F = \frac{10^{\frac{V-4.62}{0.198}} + 5}{0.6116} \qquad [2]$$

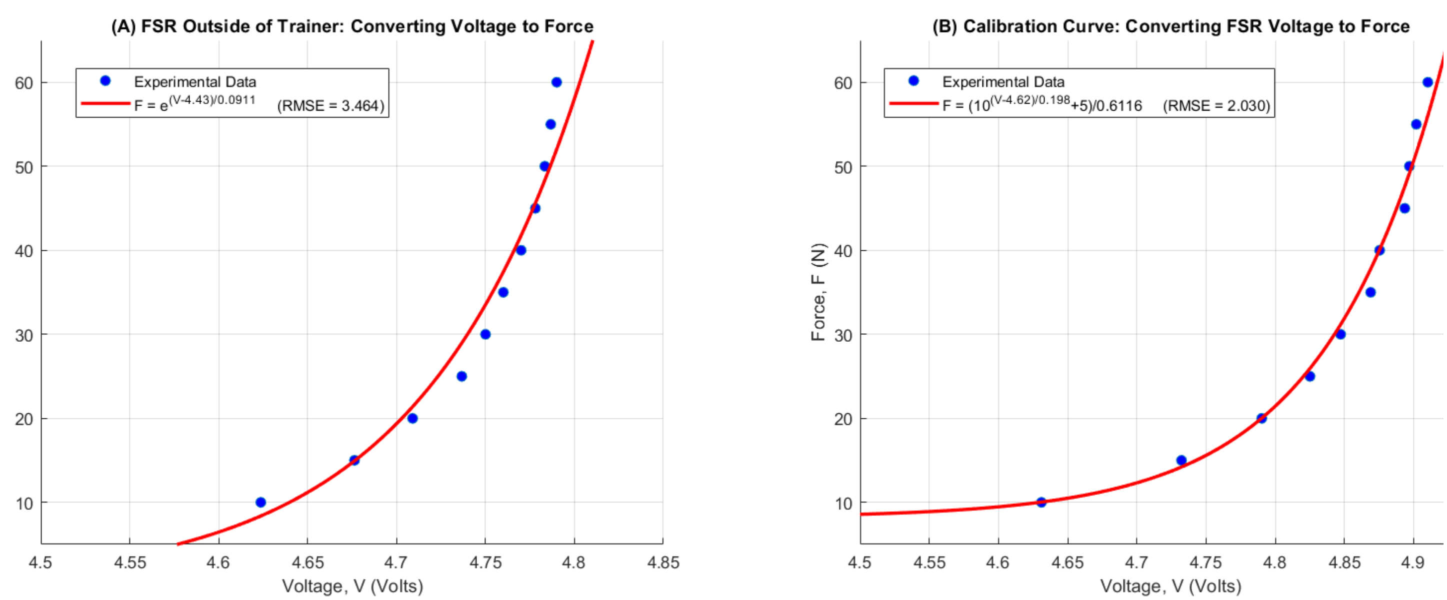

Figure 5. Curves of best fit from Instron testing. The plots show force versus voltage data, where voltage, V is measured in Volts and force, F is measured in Newtons. (A) Curve of best fit resulting from Instron tests with the force sensing resistor (FSR) on a flat surface. This curve fits the data with a root mean square error value of 3.464. The shape of the curve informed the expectations for the shape of the calibration curve. (B) Curve of best fit resulting from Instron tests with the force sensing resistor placed within the TAT. The calibration curve fits the data with a root mean square error value of 2.030. This curve allows the voltage output from the FSR to be converted to force while the FSR is inside the TAT.

The root mean square error (RMSE) was calculated to quantify the fit of the curves. When taken into context with the forces, the baseline curve had an RMSE of 3.464N. The RMSE value was low considering the range of forces that was tested: 10N to 60N. The RMSE for the final calibration curve was lower, at a value of 2.030N [9]. Comparatively between the two equations, the calibration curve had a better fit to its respective dataset as its RMSE value was lower than that of the baseline curve.

After the relationship between voltage and force was determined with the calibration curve (Equation II), the equation was added to the Arduino code. Equation II outputs force in Newtons, so this output was converted to pounds per square inch (psi) within the Arduino code by first dividing the force by a conversion factor of 4.448. This conversion changed the units of force from Newtons to pound-force (lbf). This new unit of force was divided by the active area of the FSR, $2.25in^2$, in order to achieve a final output of pressure in psi. Converting the output of the calibration curve to psi within the Arduino code allowed for real-time testing to be performed on the TAT.

Three different tourniquets and two mannequin arms were used to test the occlusion pressure of the TAT against a range of variables. The first tourniquet, the Combat Application Tourniquet (CAT), is one of the most widely used tourniquets, and it utilizes a windlass rod to tighten the tourniquet after pretensioning by pulling on the tourniquet straps. The second tourniquet, the SAM XT extremity tourniquet (SAM), has the same windlass tightening mechanism as the CAT, but has a different pretensioning mechanism. The pretensioning mechanism used for the SAM tourniquet improves upon the design of the CAT by using a buckle technology which auto-locks at a predetermined amount of circumferential force [10]. The last tourniquet is the RapidStop® tourniquet (RAPID) by AeroHealthcare. The RAPID uses the same pretensioning mechanism as the CAT; however, it uses a ratchet mechanism, similar to that of a ski boot, rather than a windlass rod. Additionally, the two mannequin arms were different sizes: Arm 1 had a circumference of 21.99 inches, and Arm 2 had a circumference of 18.85 inches. It was hypothesized that the different tourniquet types and arm sizes would have an effect on the occlusion pressure of the TAT.

The process for testing the different tourniquets and arm sizes began with inserting the FSR into the TAT at a position two inches above the synthetic wound. The TAT was then placed on one of the mannequin arms, and the squeeze bottle was filled with water. The test was initiated when the bottle was elevated slightly above the TAT and squeezed rhythmically in order to mimic the heart pumping blood through the brachial artery. The water flowed through the tubing and out of the synthetic wound at the base of the TAT. As the tourniquet was applied to occlude the tubing, it was positioned so that the band of the tourniquet completely covered the active area of the FSR. During application, each tourniquet was first pretensioned to a constant pressure of 10 psi before they were tightened further through the use of either the windlass or the ratcheting mechanism. Data was gathered for each tourniquet on both of the mannequin arms through a series of 10 trials.

After testing each of the tourniquet and mannequin arm combinations, it was observed that there were differences in the occlusion pressure of the TAT depending on the type of tourniquet and the size of the arm (Figure 6). The SAM tourniquet was the only tourniquet that resulted in similar occlusion pressures across the two mannequin arms: it was observed that the overall recorded occlusion pressures from the CAT and RAPID tourniquets decreased from Arm 1 to Arm 2. Figure 6 demonstrates that when the tourniquets were tested on Arm 2, the occlusion pressures fell closer within the LOP range from the design constraints than when the tourniquets were tested on Arm 1.

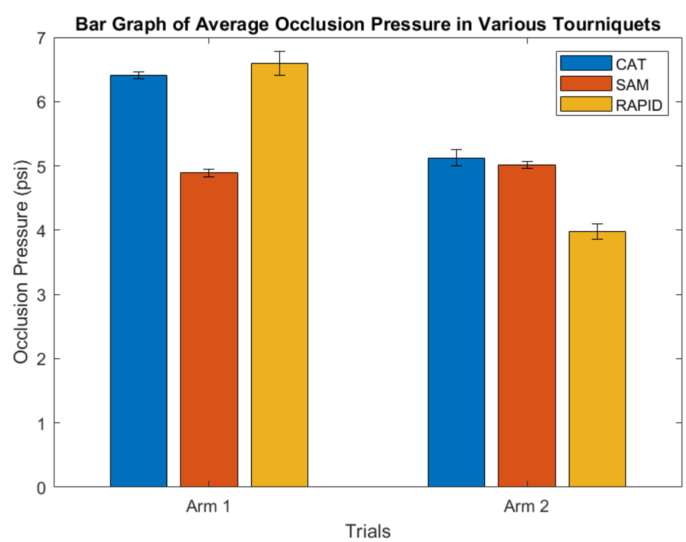

Figure 6. Bar graph of average occlusion pressures from the CAT, SAM, and RAPID tourniquets. The error bars were calculated using the standard error formula and the low standard error shows that there was a limited amount of spread between the data points

An ANOVA test was performed on the average occlusion pressures to determine if there were significant differences between the trials in Figure 6. The ANOVA test had three null hypotheses: (1) the type of tourniquet has no effect on the pressure at which the TAT occludes, (2) the size of the mannequin arm has no effect on the pressure at which the TAT occludes, and (3) the effect of arm size on occlusion pressure does not depend on the effect of the tourniquet type and vice versa, meaning that there is no interaction between the variables. Through the ANOVA test, there was determined to be a statistically significant difference in average TAT occlusion pressures both by tourniquet type ($F = 27.87$ and $p < 0.0001$) and by arm size ($F = 196.38$ and $p < 0.0001$). A significant interaction effect between the tourniquets and the mannequin arm size was also observed ($F = 77.37$ and $p < 0.0001$).

The p-values from the ANOVA tests were less than 0.0001 for all three cases, so they were subsequently less than the predetermined significance value of 0.05. Additionally, each of the F values were much greater than their respective critical F values (3.183, 4.034, and 3.183). This signified that there were significant differences in the TAT occlusion pressures resulting from the different tourniquets and mannequin arms, and the three null hypotheses were rejected.

Discussion

The purpose of this project was to create a sensor-enabled testing device that could assess whether or not the occlusion pressure required to stop simulated blood flow in the TAT was clinically relevant to the LOPs seen in the literature. Previously, there had been no known information about how the TAT occlusion pressure is affected by tourniquet type or by the size of the arm over which the TAT is worn. After the design and calibration of the sensor-enabled testing device, which was successful in producing consistent readings, it became possible to test the occlusion pressure of the TAT. The initial hypothesis was that different-sized arms as well as different tourniquet types would affect the pressure necessary to fully occlude the simulated artery within the TAT. Through testing, it was proven that the hypothesis was correct: different-sized arms and different tourniquets do have a significant effect on the occlusion pressure of the synthetic artery.

There were a few factors that could have contributed to error in the experimental occlusion pressures. One factor is the rate and force at which the squeeze bottle was compressed. In order to minimize variability in the flow rate of the fluid, the same team member was tasked with squeezing the bottle across each of the trials. Another potential error factor was the fit of the TAT on the mannequin arms. Although the TAT was created to be a “one size fits all” training device, it does not sit as flush against the shoulder and upper arm of a smaller user as it does on larger users. This means that the use of the smaller mannequin arm may have introduced a gap between the TAT and the arm, altering the pressure required for full occlusion of the tubing. In addition to the squeezing of the bottle and the arm sizes, likely one of the largest sources of error for the project was the inability to perform Instron testing with water flowing through the tubing of the TAT. Luna’s Instron machine is expensive, and pumping water through the TAT while it was in the Instron could have damaged the equipment. Therefore, compressive testing had to be performed and the resulting voltage values had to be recorded without the added pressure of fluid in the tubing, which may have led to an inaccurate calibration curve.

A few additional limitations that were outside the scope of the experimental testing may have also affected the results of this project. One of the biggest challenges was finding a sensor that best fit the design constraints with only a limited supply of suitable options. There were various FSRs which fit within the space between the foam and the nylon TAT fabric; however, the options were limited both by the cost of the sensors and their shipment windows. Another significant limitation was the amount of research available on LOPs as they relate to traumatic injuries. The LOP range determined within the design constraints was derived from literature that was focused solely in surgical settings because there is no current research on the amount of pressure needed to occlude a limb that has sustained a traumatic injury. The amount of pressure needed to occlude a limb with a traumatic, open wound is likely different from a limb without a wound, so this may have caused the predetermined LOP range to be imprecise. Additionally, due to the fact that the LOP range was derived from clinical studies, which were drastically different from the experimental setup of this project, it was not possible to perform direct statistical analysis on how the measured TAT occlusion pressures related to the LOP range.

In order to improve upon the errors and limitations for future research, it would be useful to expand the sample size of arms on which the occlusion pressure of the TAT is tested: the same experiment should be conducted with arms of more than two different sizes. It would also be useful to determine a method of ensuring that the fluid is pumped through the tubing at a constant flow rate as well as finding a way to perform compressive testing without the risk of damaging costly equipment.

A facet of the sensor-enabled testing device, specifically, that could be improved would be to add a portable 5V power source to the circuit (i.e., a battery) rather than limiting the use of the device to the vicinity of a laptop. A subsequent improvement to the design would be adding a liquid crystal display (LCD) to the circuit board to display the pressures detected by the FSR directly on the device. After the power supply and the LCD are fully integrated into the system, then the device would have the potential to be incorporated within the Luna Labs USA TrueClot® Tourniquet Application Trainer training kit. This would allow it to be marketed as a product that gave instant, quantitative feedback on occlusion pressure in addition to its pre-existing qualitative feedback.

The main takeaway from this project is that the tubing within the TrueClot® Tourniquet Application Trainer requires more pressure to occlude than a typical brachial artery, as most of the experimental pressures exceeded the typical LOP range of 2.5-5 psi. Therefore quantitatively, the TAT does not provide clinically relevant training. However qualitatively, the TAT is still an effective tourniquet application training product. It is better to teach trainees to apply more pressure than necessary than to teach them to not to apply enough pressure. Situations where tourniquets are necessary are often the difference between life and death, and it is extremely important for the individual applying the tourniquet to know how to apply one properly. An injured limb will occlude at exceedingly high pressures, but it will not occlude at pressures that are too low.

End Matter

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