Smart Tourniquet System

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***Abstract*—Tourniquet-related nerve injury (TRNI) can be a significant risk in medical settings where tourniquets are applied for extended periods or under high pressure [1]. The compression of the underlying nerve by the tourniquet cuff can lead to neuropraxia and other long-term peripheral nerve complications. Tourniquets are important for controlling hemorrhage in emergency situations; however, incorrect application can cause long-term damage [2]. To address this challenge, our objective is to develop a cost-effective pressure control system that utilizes advanced filtering and peak detection algorithms to automatically adjust tourniquet pressure. The system dynamically responds to user heart rate and pressure fluctuations along the tourniquet membrane, significantly reducing the risk of TRNI. The device integrates a microcontroller, pulse oximeter, accelerometers, pressure transducer, pneumatic pump, and solenoid valves to ensure precise and efficient pressure regulation.**

***Index Terms*—Control System, Pulse Oximeter, Microcontroller, Pressure Transducer, Limb Occlusion Pressure, Accelerometer, Pneumatic, Tourniquet**

I. Introduction

Tourniquets are devices that cut off blood flow to extremities of the body by applying external pressure. Tourniquets may be used to stop rapid blood loss or allow doctors to more easily perform operations on patients with a minimized blood field. Although tourniquets are shown to be useful in surgical and emergency situations, complications occur frequently with their use [3]. Studies have reported that pneumatic tourniquet systems are used in more than 1,000,000 surgical procedures annually in North America [2]. In addition to this, non-pneumatic tourniquets are widely used in emergency, military, and prehospital settings [4]. A study found that 5.5% of 110 tourniquet applications in pre-hospital settings resulted in neurological complications [5]. These non-pneumatic devices create a significant potential for injury, which can result from an excessively high tourniquet pressure level and lead to long-term injuries. A survey of 151 orthopedic surgeons estimated the rate of tourniquet-related nerve injury to be around 1 in 8,000 in surgical situations [1]. However, this rate of injury is likely much higher in emergency situations with non-trained medical professionals. Factors affecting the rates of complication include stress from the situation, lack of control feedback of the tourniquet pressure, and the lack of patient vital signs information for informed tourniquet application personalization.

Applying high pressure to the extremities can lead to muscle ischemia, a condition characterized by the complete blockage of blood flow to the muscles. Prolonged ischemia can cause hypoxia, paralysis, and nerve death in extreme cases. This disruption can impair nerve function, resulting in symptoms such as numbness, tingling, and weakness in the affected area [6]. Muscle tissue begins to suffer irreversible damage due to ischemia after just 2 hours of continuous tourniquet application [6]. A simple description of the progression of tourniquet-use related injuries that occur over time can be seen in Figure 1. Ultimately, current tourniquet guidelines remain inadequately informed. While it is recommended that a tourniquet device be used between 1-3 hours with some rest in between [7], there is no definitive guidance for tourniquet application time. To ensure safe tourniquet application, specific guidelines should be personalized for application time in conjunction with minimum limb occlusion pressure (LOP). The minimum LOP is defined as the lowest pressure that is needed to stop blood flow to a limb.

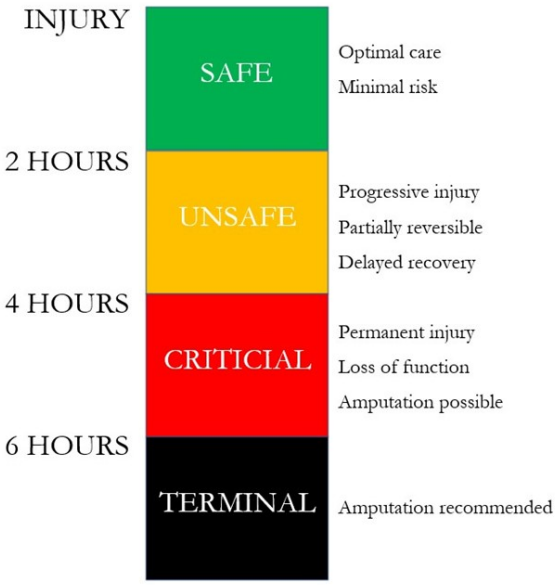

Fig. 1: Chart illustrating the progression of injury risk over time with tourniquet use. Safe use is limited to 2 hours in controlled cases, after which injuries become progressively worse. After 6 hours, terminal damage is likely, with amputation often recommended [8].

Pressures exceeding the minimum LOP by more than 100 mmHg for extended durations have been strongly associated with an increased risk of nerve and tissue damage [6]. This risk is particularly pronounced with non-pneumatic tourniquets, which lack precise feedback mechanisms to indicate the ap-

plied pressure on the patient's limb. Ideally, tourniquets should be tightened until the LOP is achieved; however, determining this exact occlusion pressure can vary significantly between individuals due to differences in anatomy, physiology, and medical conditions. Consequently, the absence of a universally accurate LOP standard poses a challenge in ensuring safe and effective tourniquet use.

Historically, a standard pressure of 250 mmHg has been applied to upper extremities during tourniquet use [7]. However, this value frequently exceeds the actual requirements for many individuals, often leading to unnecessary complications. Excessive pressures, coupled with prolonged application times, significantly increase the risk of nerve and tissue damage due to elevated pressure levels and steep pressure gradients. Extended application of pressures well above the minimum LOP can result in severe injuries. Muscle damage may occur after 30–60 minutes of tourniquet application, however, this is generally tolerable if the pressure remains near the LOP and evenly distributed across the limb. Ensuring proper pressure management is critical to minimizing the risks associated with tourniquet use [6].

II. Existing Technologies and Drawbacks

Tourniquets can be split into two categories regarding their optimal use environments: emergency and surgical tourniquets. For emergency tourniquets, the tourniquet is tightened until blood flow is visibly cut[9]. In the emergency setting, there are three main emergency tourniquets commonly used: tourniquet straps, elastic tourniquets, and the windlass tourniquet. On the other hand, surgical tourniquets rely on pressure calculations to achieve a bloodless field based on the LOP. The widely used surgical tourniquet is a pneumatic cuff [10].

A. Tourniquet Strap

The tourniquet strap is a prevalent emergency tourniquet, in which blood flow is cut off by applying pressure to the injured area by tightening a durable band around the limb, usually in the form of a buckle[9]. This device does not provide feedback on the pressure used to occlude the limb. In addition, it concentrates the application of pressure to the limb with a small surface area of the strap, leading to higher stress concentrations on the underlying tissue. The high stresses and lack of pressure feedback can cause a greater risk of injury.

B. Elastic Tourniquet

An elastic tourniquet is an emergency setting tourniquet that consists of tightly wrapping an elastic band above the area of blood loss. This method is less than ideal as it is difficult to control the pressure. The Committee on Tactical Combat Casualty Care (COTCCC) has not approved any elastic tourniquets for military use due to its inconsistent nature [11]. Subsequently, elastic tourniquets often result in excessive pressure application, which can lead to nerve, muscle, and vascular injuries due to the lack of pressure control [12]. Specific complications due to the absence of pressure feedback, are the increased risk of venous thromboembolism, neurovascular injury, fracture nonunion, and wound complications including infection [13]. .

C. Windlass Tourniquet

Windlass tourniquets are one of the most trusted and reliable tourniquets in emergency settings. This tourniquet consists of a durable strap and a rod. The medic fastens the strap above the injury point and tightens the tourniquet by twisting the rod until there is no more blood loss, achieving LOP [9]. The rod is then locked, creating a constant pressure to maintain the restraint of blood flow. Although effective in occlusion of blood flow, the lack of pressure application indicators can lead to excessive pressure and major injuries below the application site if left on for prolonged periods of time.

D. Pneumatic Tourniquet

Pneumatic tourniquets are a staple in surgical settings due to their ability to achieve a nearly bloodless surgical field. This tourniquet is in the form of a blood pressure cuff, which has ability to occlude an extremity by inflating a cuff [10]. Pneumatic tourniquets are the standard tourniquet system in surgery as the ideal pressure can be optimized on a patient-to-patient basis, reducing the risk of error found in all other tourniquets. By using systolic blood pressure measurements, and pulse oximetry of the limb under the procedure, pneumatic tourniquets are reliable devices that impede blood flow for surgical settings[2].

Ultimately, fixed pressure systems do not offer real-time adjustments, increasing the risk of complications since they rely on manual tightening without any feedback mechanism. The absence of standardized protocols and the lack of systems to monitor both pressure and application time often result in inconsistent use and overuse, increasing the risk of tissue damage [14]. Additionally, most tourniquet systems require professional expertise, making them easy to misuse in emergencies. These issues highlight the need for cheaper, more accessible, and safer tourniquet technologies.

III. Technical Sections

A. Selected Approach

The proposed system aims to solve the shortcomings of existing devices by incorporating dynamic pressure adjustments though continuous monitoring of the occluded limb with an easy-to-use interface for both medical professionals and untrained users. The core of the smart tourniquet system is the ESP-32 microcontroller, which processes real-time data from a pressure transducer and pulse oximeter to dynamically control cuff pressure. The logic for our control diagram is shown in Figure 2.

Traditionally, a pressure feedback control system continuously monitors the pressure with a pressure transducer. This measured pressure of the inflatable cuff is then used in combination with a safety offset and algorithms to ensure that the LOP is achieved. One cuff pressure setting method that has been used successfully implemented in clinical studies is LOP + 40 mmHg for LOP levels less than 130 mmHg, LOP + 60 mmHg for LOP levels between 131 – 190 mmHg, and LOP + 80 mmHg for LOP levels greater than 190 mmHg [15]. The microcontroller uses the pressure data to manage an

air pump, which inflates the cuff and increases pressure, or to decrease pressure with solenoid valves, which releases air when necessary.

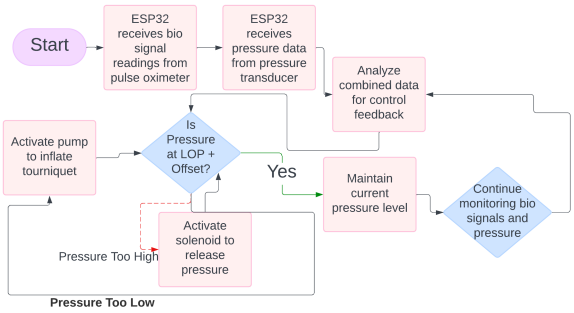

Fig. 2: Control Diagram for maintaining optimal tourniquet pressure using bio-signal (heart rate) and pressure feedback.

The hardware used in our automatic tourniquet consists of a closed solenoid valve by WSDMAVIS [16], electric pump by Eilumduo [17], and a Stryker 5921218135 pneumatic tourniquet [18]. The sensors we used are a MAX30102 integrated circuit by Analog Electronics [19], accelerometers by Analog Devices [20] and TDK InvenSense [21], and a MP3V5050GC6U pressure transducer by nxp semiconductors [22]. The sensors and hardware components are controlled by one ESP32 microcrontroller by espressif [23]. The entire device is powered by 11.1V Lithium-Polymer battery pack, which is stepped-down to 5V using a LM2956 voltage regulator board to power lower-power devices on the board. When a pulse is detected using the pulse oximeter, the ESP32 allows current to flow through the pump and NPN transistor circuits, inflating the pneumatic tourniquet. Power is cutoff from the pump when a pulse is no longer detected in the patient. The microcontroller allows power to flow to the solenoid valve, through a separate NPN transistor, to release air pressure if the pressure transducer detects a pressure level too high for the patient. The circuits that control the respective systems of the device are shown in Figure 3.

There are four sensors in the overall device that are crucial to its successful operation. The first of these is the pulse oximeter, which tracks the patient's pulse. If there is no pulse distal to the area of tourniquet application, the tourniquet no longer needs to be inflated. The second of these sensors is the pressure transducer, which along with the ability to give an accurate reading of the pressure values, it can detect small perturbations in pressure along the tourniquet membrane due to blood flow. The signal is filtered using infinite impulse response (IIR) filtering in combination with external RC filtering to ensure clean signals and accuracy in peak-detection. If blood flow is detected proximal to the area of tourniquet application, the tourniquet will continue to inflate. The third and fourth of these sensors are the accelerometers, which detect patient movement. Motion can easily distort the outputs of the pressure transducer and pulse oximeter, causing the reading of a false positive that could lead to an unnecessary or even dangerous increase in tourniquet pressure. If motion is detected in the accelerometer, then the tourniquet will not inflate to reduce risk of TRNI. As such, we incorporated one accelerometer in the finger pulse detection encasement and one in the encasement which houses the pneumatic components.

The device features OLED displays that show the patient's pulse graph, allowing verification of proper operation. The display also provides readings for tourniquet pressure and alerts for anomalies, such as the absence of a finger or the presence of rapid patient movement. Additionally, a three-color LED indicator is integrated into the pneumatic encasement to notify the user of the patient's status, including pulse detection or movement. In the event of a malfunction, the user can activate a mechanical emergency switch to deflate the pneumatic system, preventing tourniquet-related nerve injury (TRNI).

B. System Architecture and Hardware

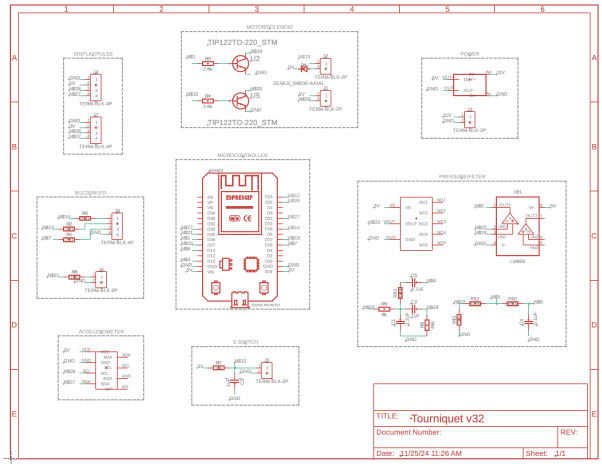

Fig. 3: Circuit Schematic for Smart Tourniquet System. The diagram is sectioned into Microcontroller, Buzzer/Led, Accelerometer, E-Switch, Display/Pulse, Motor/Solenoid, Power, and Pressure/Filer groups for readability.

The configuration of the project's pneumatic system is as follows: The pump is connected to the tourniquet directly. Using the same tubing on the opposite side, the pressure transducer is plugged in to detect air pressure, followed by the solenoid in parallel to release pressure. When the normally-closed solenoid is not powered, the pneumatic system is closed. When the solenoid is powered, the system opens, allowing air to escape and tourniquet pressure to decrease.

C. Printable Circuit Board

The printed circuit board (PCB) design is shown in the figure above. The ciruits were designed using Fusion360 and EagleCAD, creating custom footprints for components as needed. For 3D models the group did not create, we used electronic footprints and libraries from SnapEDA, GrabCAD, and UltraLibrarian. In terms of optimizing the board layout, over 30 design iterations were completed, focusing on decreasing trace routing length, decreasing board size, refining component placement for efficiency, and ensuring correct orientation of

footprints. The ECAD model of our PCB is shown in Figure 4.

For prototyping, the group used a Wegst mini CNC mill with copper-platted fiberglass for PCB fabrication. Tool paths were created for traces using a pocket cut at 20° and 0.07 mm depth, through holes with a 90° drill at 0.9 mm, and board outlines with a profile cut at 1.6 mm depth. Soldering was a challenge since de-soldering mistakes could strip the copper, but this method of fabrication was great for proof-of-concept designs as it was cheap and quick to complete.

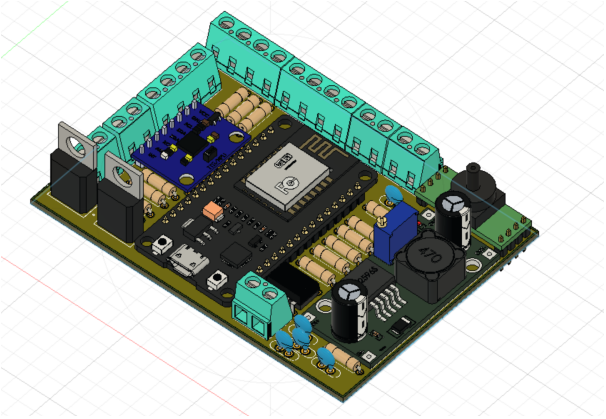

Fig. 4: Top of the PCB Design. The modular components are all placed on one side of the board for efficiency.

The PCBs were professionally manufactured by JLCPCB. These are double-sided FR-4 boards, measuring 90.9 mm by 66.5 mm, with a 1.6 mm thickness. The designs are 2-layer with a green solder mask and minimum via hole diameter of 0.3 mm. Through-hole type components were used for their ease in replacement in the case of overload damaging . Ultimately, the PCB design process was very much a learning process for the team in this project. One challenge the group faced was dealing with flipped footprints on some components, which was resolved though trial and error in the manufacturing process.

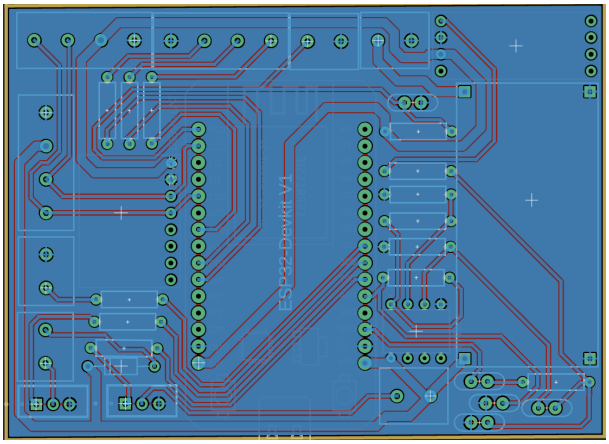

Fig. 5: Bottom of the PCB Design. The thick power traces are of 0.4 mm width while the signal traces are 0.16 mm width. The top and bottom of the two-sided board functions as the ground plane.

D. System Software and Algorithm

The pressure transducer's voltage output was calibrated using an Analog Discovery 2 (AD2) to map voltage levels to corresponding pressure levels in the tourniquet. Calibration was conducted safely and ethically by applying pressure to the arms of our group members with the Stryker tourniquet. An analog mechanical blood pressure gauge by McKesson [24] was used as a reference to determine the relationship between voltage and pressure. The transducer's maximum output of 3.3 volts was mapped to the maximum pressure value, with intermediate pressures linearly scaled between 0 and 3.3 volts.

In terms of the control system, the tourniquet pressure is initially set to 180 mmHg. If a pulse is detected, the device incrementally increases the pressure by 10 mmHg until no pulse is detected, signaling adequate blood flow occlusion. To safeguard against excessive pressure, the system integrates a solenoid valve that releases pressure when the maximum allowable limit of 300 mmHg is exceeded. This process is governed by the ESP-32 microcontroller, which continuously analyzes real-time data from the pressure transducer. Pressure adjustments are made only under specific conditions, such as the detection of a pulse and the absence of patient movement, to ensure safe and controlled operation.

To achieve precise and stable control, a proportional-integral-derivative (PID) controller is employed to manage the tourniquet pressure smoothly, with parameters$K_p = 1.5$, $K_i = 0.05$, and $K_d = 0.1$. Hysteresis is incorporated into the control logic to prevent oscillations between activating the pump and opening the solenoid valve. The maximum allowable pressure is capped at 300 mmHg, based on the team's research into safe tourniquet application [25]. A first-order Butterworth filter, with a 20 Hz cutoff frequency, is applied as a finite impulse response (FIR) filter to smooth transducer data and improve the precision of pressure control.

The ESP32 utilizes multiple filtered pressure metrics to account for subtle pressure changes, which may be caused by residual blood flow beneath the tourniquet. These ripples are processed electronically through a low-pass filter followed by a high-pass filter to remove high-frequency noise and eliminate direct current (DC) bias. The filtered signals are then amplified using an operational amplifier (OP AMP) circuit, serving as a secondary indicator of pulse presence. Further, digital low-pass filtering was applied to average the pulse data, enhancing the accuracy and reliability of the readings which could be impacted.

Pulse detection in the device utilizes a combination of a pulse oximeter and the pressure transducer. The pulse oximeter measures user pulse via photoplethysmography, using an infrared light emitting diode (LED) to detect fluctuations in reflected light captured by the integrated circuit. These fluctuations correspond to changes in blood flow volume, allowing the microcontroller to measure the user's pulse.

The MAX30102 pulse oximeter data was extracted and processed using C++ within the Arduino IDE. The provided library code was modified to optimize pulse detection for the specific requirements of this application. While the original library was designed to calculate precise digital heart rate

values, our device only needs to determine the binary presence or absence of a pulse. This simplification reduces reliance on continuous heart rate measurements during operation, making the device more robust against potential perturbations or noise.

During testing, the MAX30102 faced challenges detecting peaks in infrared light due to signal fluctuations. A high-pass filter with a cutoff frequency of 0.5 Hz was implemented to eliminate the DC component, stabilizing the signal. After filtering, the pulse waveform appeared more consistent, unaffected by variable finger pressure. A new detection algorithm was written to identify a pulse only when a finger was detected (infrared value above 50,000 digital counts). The algorithm monitored zero crossings in the filtered signal—transitions where the signal value changed from negative to positive—to reliably detect pulses. The pulse rate could then be calculated by measuring the time intervals between consecutive zero crossings.

One issue encountered was the presence of small divots in the pulse graph that occasionally caused false positives that can be seen in Figure 6. To address this, a minimum time threshold was implemented to ensure that pulses were not counted if they occurred too quickly. Additionally, constraints were set to reject unrealistic heart rate values outside the range of 30–200 bpm.

To determine when no pulse was present, tests were conducted using a windlass tourniquet safely applied to a group member's arm. The algorithm determined the absence of a pulse if no detection occurred within 2000 ms, corresponding to a heart rate below 40 bpm. This threshold was chosen as it represents an unlikely scenario for a patient in this context. Testing consistently ensured accurate detection of pulse absent conditions once the tourniquet reached sufficient pressure. An example pulse waveform, collected with a Criticare pulse oximeter, is shown in Figure 6 and is consistent with the MAX30102 pulse signal waveform shape.

Overall, the pulse oximeter refinements ensured reliable pulse detection, even under varying conditions, and contributed to the overall functionality of the system.

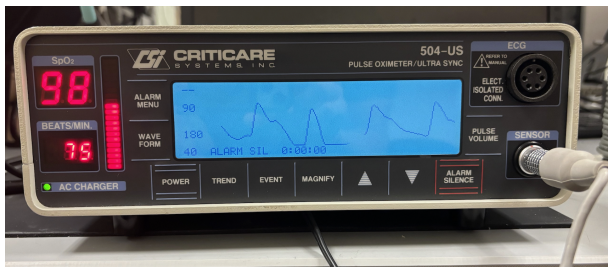

Fig. 6: Example pulse waveform shown by external pulse oximeter. The Criticare device was utilized for validation of the pulse oximeter readings from the MAX30102. When the tourniquet inflated to the minimum occlusion pressure, there was no pulse waveform, indicating that the LOP was reached.

The system also incorporates an accelerometer with a sensitivity threshold to detect patient movement. This prevents false positives caused by motion, ensuring pressure adjustments are paused during movement. By halting adjustments in such scenarios, the risk of over-inflation or inaccurate pressure readings is minimized. The combination of accelerometers and motion-reduction-filtering algorithms provides reliable tourniquet operation, addressing both clinical and emergency use cases.

E. Mechanical Encasement

The device is housed in an encasement with dimensions of 120 x 90 x 60 mm, shown in Figure 7. The dimensions of the encasement were determined with respect to the size of the inflatable tourniquet cuff, ensuring that the encasement did not extend 10 mm beyond of the edge of the cuff. The design accommodates all components while prioritizing portability and minimal interference with a fully inflated cuff.

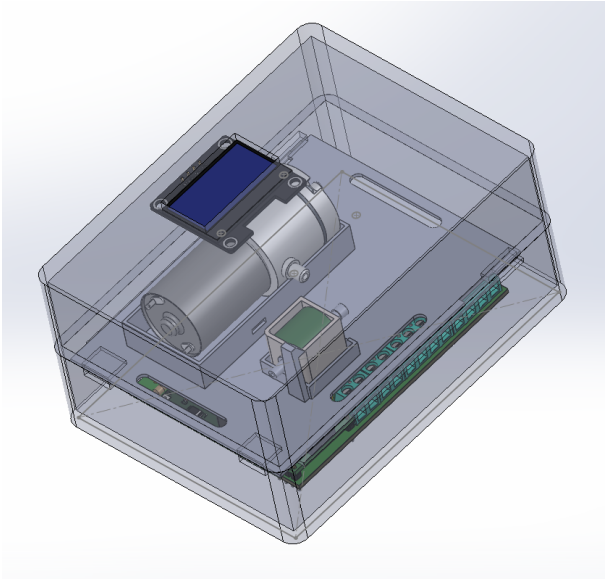

Fig. 7: 3-D Encasement Assembly. It includes parts downloaded online: pump, solenoid, and display[26][27]

Reducing the opacity of the encasement reveals the arrangement of the internal components. The top layer features a digital display, the solenoid, the pump, and a designated hole for an LED indicator. Post-printing modifications made with a Dremel, such as additional holes for wiring, ventilation, and access to ports, further enhance functionality. These adjustments, not visible in the 3D model, allow for integration with external components and improve the device's overall compactness. A middle layer separates the PCB from other components, providing structural support and reducing potential electronic interference. The PCB itself is mounted at the base of the encasement to ensure stable connections for wiring and sensors.

Externally, the pulse oximeter and accelerometer connect to the PCB via wires extending from the encasement. These components are housed in a finger clip, which secures the patient's finger during operation, the design for the pulse oxmiter encasement was obtained online [28]. The clip minimizes movement and external light interference, improving the accuracy of the pulse oximeter's readings while enabling the accelerometer to effectively detect finger motion. This design,

shown in Figure 8 ensures reliability and precision in various operational contexts.

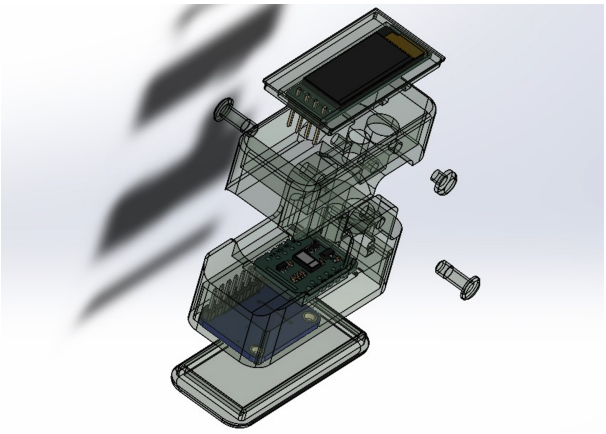

Fig. 8: 3-D Finger Encasement Exploded view. It includes parts downloaded online: MAX30102 pulse oximeter, ADXL345 accelerometer, and the B08L7QW7SR digital display[26][27].

In addition, there is a small hole design on the side of the shell for the installation of the valve connector. It is used to connect the internal pump and the external cuff. The cuff and the device can be placed separately without affecting the system. The system can be easily assembled by connecting the cuff tubing with the valve connector.

The encasement was constructed and assembled in the lab to prove the viability of the idea as seen in Figure 9. The housing for the electronics, both the device and the pulse oximter, were 3D printed in PLA using a Creality K1 3d printer. The print was done at 15 percent infill and printed with tree supports.

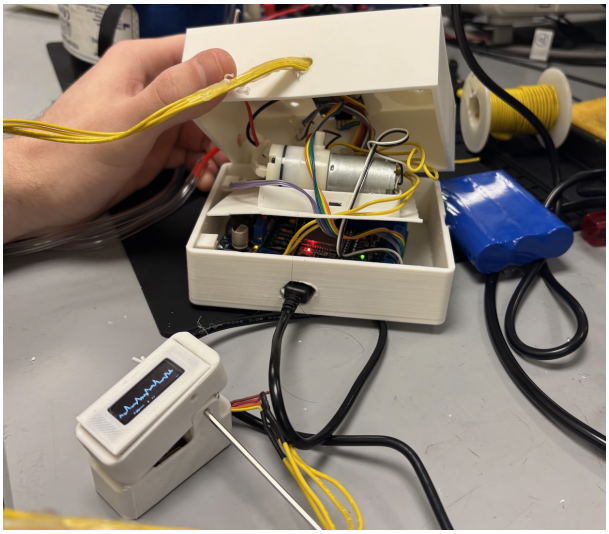

Fig. 9: Inside the assembled 3D encasement and the finger clip pulse oximeter. We utilized groups of colored jumper wires for organization.

The encasement integrates all components into a compact and functional design. The bottom layer, containing the PCB, can be removed via a sliding mechanism, allowing for easy access during maintenance or component replacement. A display, located on the top surface, provides real-time data, while an LED indicator and an emergency switch enhance the usability and safety of the system. The overall encasement design ensures durability, portability, and integration with a tourniquet cuff through the air port.

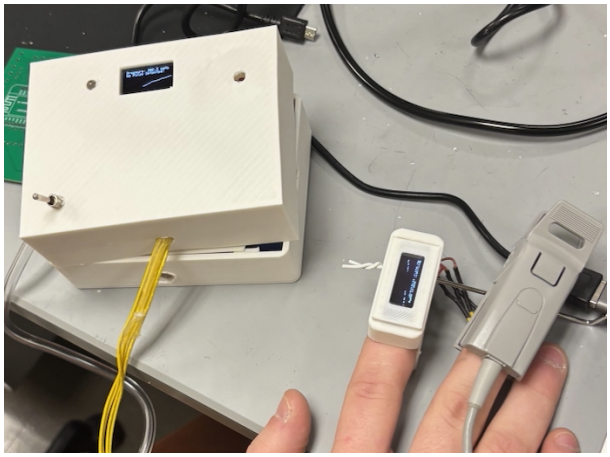

Fig. 10: Testing arrangement with both pulse oximeters and tourniquet. Upon detection of a pulse, the tourniquet inflates until a pulse is no longer detected.

IV. Results

The smart tourniquet system was tested on group members under controlled conditions. During testing, the tourniquet was applied to the upper arm, while the device's pulse oximeter clip was attached to the forefinger of the same arm, shown in Figure 10. To validate the accuracy of the device, a second, external pulse oximeter was clipped onto the middle finger of the same arm to provide independent measurements.

The external pulse oximeter monitored the subject's pulse as the device inflated the tourniquet. This served as a reference to confirm the functionality of the integrated oximeter. A loss of pulse detection, as seen in Figure 6, on the external device indicated that the tourniquet had successfully occluded blood flow to the distal part of the arm. This method ensured the device could reliably achieve and maintain the required pressure for limb occlusion while validating its performance against a standard measurement tool.

Testing was conducted multiple times on different group members, yielding consistently positive results. The device successfully occluded blood flow for each individual, as confirmed by the external pulse oximeter, despite variations in LOP among the test subjects. After each test, the system was reset to ensure it did not retain the previous test subject's LOP data, maintaining accuracy and reliability for subsequent trials. The testing configuration with the tourniquet is shown in Figure 10.

The device's graphical output on its display closely matched or exceeded the level of detail provided by the external oximeter, further validating its performance. Additionally, a group member manually verified the absence of a pulse in each test subject by palpating the occluded area, confirming the

device's effectiveness in achieving and maintaining occlusion. This thorough testing demonstrated the device's capability to adapt to individual LOPs and its reliability in monitoring and controlling tourniquet pressure.

The device was also tested in special case scenarios. Each subject moved their body to trigger the accelerometer to stop the inflation of the tourniquet. The pulse oximeter of the smart tourniquet device was also placed on the opposite arm to test if the tourniquet would not exceed the set limit (which it did not). The testing configuration is shown in Figure 11.

Figure 11 illustrates the tourniquet and device in operation, achieving a Limb Occlusion Pressure (LOP) of approximately 180 mmHg. The pressure was calibrated using an external pressure gauge from a blood pressure monitor to ensure the device's readings were accurate. The LOP was validated through manual palpation and cross-checked with a secondary pulse oximeter, confirming the system's accuracy.

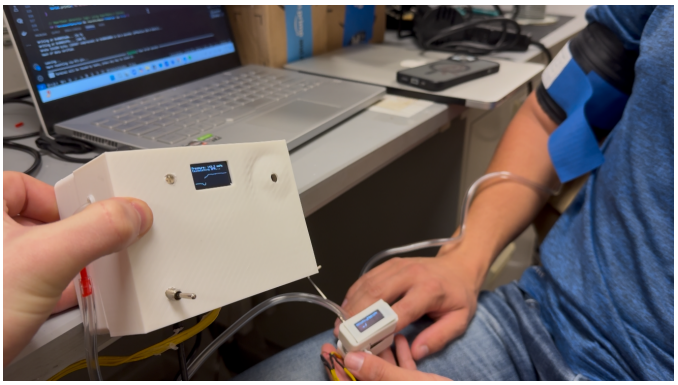

Fig. 11: The device and tourniquet during usage. The tourniquet is attached to the bicep where it inflates to restrict the bracial artery.

Future refinements may aim to reduce the LOP floor, but 180 mmHg was selected as a safe baseline to closely approximate most patients' LOP without requiring unnecessary measurement stages at lower pressures. This value is significantly lower than the typical excess pressure of 250 mmHg often employed, thus prioritizing patient safety while maintaining effective functionality [7]. We would also like to statistically test the numerical differences for the live pulse oximtery readings between the MAX30102 and Criticare device, shown in Figure 6, for further validation

V. Conclusion

The automated pneumatic tourniquet system provides an innovative solution to the widespread issue of TRNI associated with emergency and surgical tourniquet use. Unlike current emergency tourniquets, this device offers the capability to modulate pressure during use dynamically. Its compact, lightweight, and self-sustaining design makes it an ideal alternative, effectively addressing the limitations of conventional tourniquets and significantly reducing the risk of TRNI.

The team successfully designed and implemented a smart pneumatic tourniquet system, controlled automatically by a microcontroller and vital signs sensors. The project also included the development of a custom PCB to integrate all electronic components and a 3D-printed encasement to house the entire system. Due to time constraints, the assembly and testing of the system were completed toward the end of the project period, leaving limited time for iterative improvements to the design.

Future enhancements could address both the physical and software aspects of the device. The current design is costly, limiting its practicality as a low-cost emergency-use item. Conducting additional research to identify more affordable components could significantly reduce production costs. On the software side, implementing more advanced multi-stage filtering techniques could improve the isolation of patient pulse signals, simplifying detection and increasing reliability.

Further testing is also necessary to verify the accuracy of the MAX30102 in detecting pulse rates and to validate the system's pressure calibration using external reference systems. Incorporating additional vital sign measurements, such as blood oxygen levels, could further enhance the device's ability to monitor and prevent tourniquet-related nerve injury (TRNI).

Despite its current limitations, the team believes that the device reliably detects blood flow in a patient's limb and accurately controls tourniquet pressure. These features significantly reduce the risk of TRNI, demonstrating the system's potential for future refinement and broader application.

Abbreviations

AD2, Analog Discovery 2; COTCCC, Committee on Tactical Combat Casualty Care; DC, Direct Current; FIR, Finite Impulse Response; IIR, Infinite Impulse Response; LED, Light Emitting Diode; LOP, Limb Occlusion Pressure; OP AMP, Operational Amplifier; PID, Proportional-Integral-Derivative; TRNI, Tourniquet Related Nerve Injury;

AI Usage Statement

AI was used for text refinement and coding assistance, with all content remaining original to the authors.

References

[1] J. Chang, L. Bhandari, J. Messana, S. Alkabbaa, A. H. Jahromi, and P. Konofaos, "Management of tourniquet-related nerve injury (trni): A systematic review," *Cureus*, vol. 14, no. 8, e27685, Aug. 2022. DOI: 10.7759/cureus.27685.

[2] *Tourniquet injuries: Mechanisms and prevention*, Tourniquets.org, Available: https://tourniquets.org/tourniquet-injuries-mechanisms-and-prevention/, Sep. 2024.

[3] A. Saied, A. A. Mousavi, F. Arabnejad, and A. A. Heshmati, "Tourniquet in surgery of the limbs: A review of history, types and complications," *Iran Red Crescent Med. J.*, vol. 17, no. 2, e9588, Feb. 2015, Accessed: Sep. 10, 2024. DOI: 10.5812/ircmj.9588. [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4353220/.

[4] J. F. Kragh *et al.*, "Survival with emergency tourniquet use to stop bleeding in major limb trauma," *Annals of Surgery*, vol. 249, no. 1, pp. 1–7, 2009. DOI: 10.1097/sla.0b013e31818842ba.

[5] C. Lee, K. M. Porter, and T. J. Hodgetts. "Tourniquet use in the civilian prehospital setting." (2007).

[6] B. A. Masri, A. Eisen, C. P. Duncan, and J. A. McEwen, "Tourniquet-induced nerve compression injuries are caused by high pressure levels and gradients – a review of the evidence to guide safe surgical, pre-hospital and blood flow restriction usage," *BMC Biomed. Eng.*, vol. 2, no. 1, p. 7, May 2020, Accessed: Sep. 10, 2024. DOI: 10.1186/s42490-020-00041-5. [Online]. Available: https://doi.org/10.1186/s42490-020-00041-5.

[7] J. P. Sharma and R. Salhotra, "Tourniquets in orthopedic surgery," *Indian J. Orthop.*, vol. 46, no. 4, pp. 377–383, 2012, Accessed: Sep. 10, 2024. DOI: 10.4103/0019-5413.98824. [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3421924/.

[8] "Tourniquet traffic light." [Online; accessed 18-Sep-2024], The Cove, Australian Army. (2024), [Online]. Available: https://cove.army.gov.au/article/tourniquet-traffic-light.

[9] J. Ward. "Breaking down the parts of a tourniquet for better first aid skills." [Online; accessed 18-Sep-2024]. (2023), [Online]. Available: https://tacticon.com/tactical-products-know-how/breaking-down-the-parts-of-a-tourniquet-for-better-first-aid-skills/.

[10] Epomedicine. "Bruner's ten rules of pneumatic tourniquet use." [Online; accessed 18-Sep-2024]. (2019), [Online]. Available: https://epomedicine.com/medical-students/bruners-ten-rules-of-pneumatic-tourniquet-use/.

[11] S. Curtis. "New tccc guidelines provide officers more tourniquet choices." [Online; accessed 19-Sep-2024]. (2020), [Online]. Available: https://www.police1.com/police-products/tactical/tactical-medical/articles/new-tccc-guidelines-provide-officers-more-tourniquet-choices-IU8xxdD00eMCpp9z/.

[12] M. Mccunn *et al.*, "Chapter 17 - trauma and acute care," in *Anesthesia and Uncommon Diseases*, 6th, Elsevier Inc, 2012, pp. 488–525.

[13] M. M. Farhan-Alanie *et al.*, "The risks associated with tourniquet use in lower limb trauma surgery: A systematic review and meta-analysis," *European Journal of Orthopaedic Surgery & Traumatology*, vol. 31, no. 5, pp. 967–979, 2021. DOI: 10.1007/s00590-021-02957-7.

[14] R. Vaishya, A. K. Agarwal, V. Vijay, and M. K. Tiwari, "Short term outcomes of long duration versus short duration tourniquet in primary total knee arthroplasty: A randomized controlled trial," *J. Clin. Orthop. Trauma*, vol. 9, no. 1, pp. 46–50, Jan. 2018, PMID: 29628683; PMCID: PMC5884052. DOI: 10.1016/j.jcot.2017.11.016.

[15] A. S. E. Younger, J. A. McEwen, and K. Inkpen, "Wide contoured thigh cuffs and automated limb occlusion measurement allow lower tourniquet pressures," *Clin. Orthop. Relat. Res.*, vol. 428, pp. 286–293, Nov. 2004. DOI: 10.1097/01.blo.0000142625.82654.b3.

[16] "1 pcs mini micro electric solenoid valve dc 12v normally closed magnetic water air control valve tools 0-450mmhg." (), [Online]. Available: https://www.amazon.com/WSDMAVIS-Electric-Solenoid-Normally-0-450mmHG/dp/B08NWZ2KH5?source=ps-sl-shoppingads-lpcontext&ref_=fplfs&psc=1&smid=A2S7F3O8N742PI#.

[17] "Air pump - dc 6v micro vacuum pump, electric mini air pumping booster for treatment instrument and aquarium oxygen tank 1.5l-3.2l/minute." (), [Online]. Available: https://www.digikey.com/en/products.

[18] "Stryker 5921218135 color cuff, cylindrical tourniquet cuff 18 inch length single port, single bladder, quick connect." [Online; accessed 02-Dec-2024]. (2024), [Online]. Available: https://hs770.com/product/stryker-5921218135-ccolor-cuff-cylindrical-tourniquet-cuff-18-inch-length-single-port-single-bladder-quick-connect/?srsltid=AfmBOopycs34Y1aVEqBwHP-3LRKeRX2qOn526dNVQGSm_YZAy2CpC8MM.

[19] "High-sensitivity pulse oximeter and heart-rate sensor for wearable health." (), [Online]. Available: https://www.analog.com/media/en/technical-documentation/data-sheets/MAX30102.pdf.

[20] "Adxl345." (), [Online]. Available: https://www.analog.com/en/products/adxl345.html#part-details.

[21] "Mpu-6050." (), [Online]. Available: https://invensense.tdk.com/products/motion-tracking/6-axis/mpu-6050/.

[22] "Mp3v5050gc6u." (), [Online]. Available: https://www.nxp.com/part/MP3V5050GC6U.

[23] "Join us at ces 2025." (), [Online]. Available: https://www.espressif.com/.

[24] "Blood pressure gauge mckesson brand." (), [Online]. Available: https://mms.mckesson.com/product/363783/McKesson-Brand-01-809GM.

[25] M. M. E. T. Z. T. Zhelun S. Zhijian *et al.*, "Personalized tourniquet pressure versus uniform tourniquet pressure in trauma orthopedic surgery of extremities: A prospective randomized controlled study," *Journal of Orthopaedic Surgery and Research*, vol. 19, p. 721, 2024. DOI: 10.1186/s13018-024-05217-6. [Online]. Available: https://doi.org/10.1186/s13018-024-05217-6.

[26] "Vacuum pump 370a." (2022), [Online]. Available: https://grabcad.com/library/vacuum-pump-370a-1.

[27] "Ssd1315 zhongjingyuan 1.29" oled module." (2024), [Online]. Available: https://grabcad.com/library/ssd1315-zhongjingyuan-1-29-oled-module-1.

[28] "Finger pulse oximeter max30102." (2021), [Online]. Available: https://www.thingiverse.com/thing:4847827.