

# Producing and testing tourniquets

Michał Chrzanowski      Rafał Ćwiek      Adam Ćwilich  
Mariusz Girguś      Kamila Kotur      Joanna Majsak

Student team project  
Faculty of Physics  
University of Warsaw  
Supervised by prof. Andrzej Wysmołek

July 12, 2022

# Contents

<b>1</b>	<b>Introduction</b>	<b>3</b>
<b>2</b>	<b>Production of tourniquets</b>	<b>3</b>
<b>3</b>	<b>Literature review</b>	<b>4</b>
3.1	Current standards for tourniquets . . . . .	4
3.2	Known methods of tourniquet evaluation . . . . .	4
3.2.1	Gathering data from clinical use . . . . .	4
3.2.2	Laboratory testing with human subjects . . . . .	6
3.2.3	Laboratory testing without human subjects . . . . .	9
3.3	Conclusions from literature review . . . . .	9
<b>4</b>	<b>Testing ideas</b>	<b>9</b>
<b>5</b>	<b>Experimental part</b>	<b>10</b>
5.1	Methodology . . . . .	10
5.2	Results . . . . .	12
5.3	Future plans . . . . .	13

## 1 Introduction

In the face of the invasion of Ukraine by Russia on 24th of February 2022, an idea emerged among some students at the Faculty of Physics at the University of Warsaw. We wanted to use the resources available to us to assist the Ukrainians in any way possible. We were partly inspired by a previous successful project realized in Makerspace@UW. In 2019, in the midst of the COVID-19 pandemic, volunteers from the faculty's community manufactured and distributed to medical personnel over 12 000 face shields. We wondered what supplies we could manufacture this time, which couldn't be obtained otherwise. It quickly turned out that tourniquets used to stop bleeding were largely unavailable for purchase, after a surge in demand caused by the war. We also considered them relatively easy to manufacture with the resources available at Makerspace@UW, with readily available instructions online.

This report summarizes our work on the project. We first detail our work on manufacturing the tourniquets. We describe the problems we encountered and why - after a reality check - we realized that the contribution we would be able to make would be more towards testing, rather than manufacturing tourniquets. The next sections contain a literature review and our chosen testing approach based on it. Our experiment is then discussed. The conclusion suggests further steps to undertake.

## 2 Production of tourniquets

Initially we made an attempt to design and manufacture fully functional tourniquets. We spent 3 months designing, sewing and 3D printing models. The whole enterprise has been very popular at our faculty, dozens of students were coming after lectures to help with sewing prototypes. We decided to simultaneously develop our own model and model created by Glia, a company from Canada. Their design was made available as an open source model and the rationale for its conception was detailed in [1]. The design was successfully used in Gaza. We learned a lot from cooperation with Glia's Medical Director, Tarek Loubani.

We suggested plenty of changes to the Glia's project on GitHub applying everything we've learned. Among others, we noticed that the instructions gave slightly wrong dimensions for one element or we suggested a method for sewing velcro together with the use of masking tape.

After these 3 months, as the production of tourniquets occurred to be more problematic than expected, we needed to change our approach and the goal of



Figure 1: The first tourniquet manufactured by our group.

the project. With many new 3D printed tourniquet designs appearing and with low-quality counterfeits flooding the market, we realized that the main problem with tourniquets availability is not producing them but testing whether they are fit for use. It is a crucial problem, as failing of a tourniquet in most cases means death of a person. But as far as we learned (and documented in the following literature review), there is no official, universal and repeatable way of testing tourniquets in laboratory conditions. That is why the final step was the idea to develop a test that will allow to quickly check tourniquets on field or use that test to evaluate tourniquets available on the market.

### 3 Literature review

#### 3.1 Current standards for tourniquets

The widely accepted standard in the medical community are the recommendations of the Committee on Tactical Combat Casualty Care (CoTCCC). Recently, in 2019, the CoTCCC have updated their recommendations for the first time since 2005 [2]. The recommendations were based on a literature review, using criteria such as arterial occlusion, speed and simplicity of application, optimal occlusion pressure range, width, length, weight, known reported issues of devices, usage reports, logistics. Out of the 1,627 devices approved by the FDA as tourniquets at the time of writing 6 were approved (CAT Gen 6, 7, SOFTT-Wide Gen 3, TMT, RMT-T/TX2, SAM-XT), 2 approved only in the pneumatic category (only as TQ replacements in combat) and 11 were not recommended.

The only studies included in the CoTCCC review where those which for assessing the most critical requirement - arterial occlusion - used Doppler ultrasonography or high-fidelity limb tourniquet simulators. The use of non-Doppler ultrasound, pulse oximetry, or palpable pulse were not considered to be definitive determinants of occlusion. The authors stated those do not definitively assess blood flow.

It is worth noting that CoTCCC looks specifically for applicability in the military. This does not include civilian use, in particular on smaller limbs, such as those of children.

It is also worth noting that even the highest ranked tourniquets don't achieve occlusion in 100% cases. In some studies included in the CoTCCC review some of the recommended tourniquets reached occlusion in only around 70% of cases, as measured with the aforementioned Doppler method.

#### 3.2 Known methods of tourniquet evaluation

##### 3.2.1 Gathering data from clinical use

Probably the most trusted method of assessing if a tourniquet is appropriate is if it proved effective clinically - deployed in the field or in the ambulance. Because there is a feedback loop between how trusted a product is and how

often in is used by medics, the vast majority of clinical use studies available are for the tourniquets used by the US military and recommended by the ToCCC.

Useful studies of this kind included those which gathered tourniquet units already deployed in the field and looked at what effect use or just exposure to environment had on the units. A few of these studies are briefly summarized below.

In [3] in 2011 efficacy and breakage of 166 Afghanistan-exposed CAT tourniquets compared to 166 unexposed CAT tourniquets were studied. The exposure lasted approximately 6 months. In a controlled environment in the United States, a previously exposed tourniquet was tested on one thigh of each subject, while an unexposed tourniquet was tested on the opposite thigh. Efficacy was defined as absence of distal pedal pulse for at least 30 seconds. Breakage and the number of turns required to stop the distal pedal pulse were also recorded. Tourniquets exposed to the environment broke more often (14/166 versus 0/166) and had decreased efficacy (63% versus 91%). Three turns were required for most tourniquets to be efficacious. It was interestingly noted that of the 14 tourniquets that broke, five still stopped the distal pulse. Among the 14 tourniquets, 12 broke at the stabilization plate slot, one at the self-adhering band, and one at the friction adaptor.

A similar study ([4]) was conducted in 2013. It compared three groups of Afghanistan-exposed CAT tourniquets to unexposed CAT tourniquets. The three groups were: Afghan-exposed tourniquets worn on the plate carrier, Afghan-exposed tourniquets carried in the Individual First Aid Kit (IFAK) and wrapped in manufacturer plastic wrapping, and Afghan-exposed tourniquets carried in the IFAK without the manufacturer plastic wrapping. The mean time that each tourniquet was exposed to the Afghan environment was around 212 days. Efficacy was evaluated by ability to stop distal pulse for at least 30 seconds without causing unbearable pain, regardless of tourniquet breakage, measured with a Doppler ultrasound stethoscope. Tourniquets worn on the plate carrier had an efficacy of 57%. When compared to the control group, there were no significant differences in efficacy between the tourniquets stored in the IFAK with or without manufacturing packaging. No control tourniquets or tourniquets stored in IFAKs broke; however, 46 (12%) of the plate carrier-exposed tourniquets did break. Of those 46 tourniquets, 40 broke at the stabilization plate slot and 6 broke at the friction adaptor. None of the 46 tourniquets that broke were able to stop the distal pulse.

A slightly different approach was adopted in [5] in 2013. Tourniquets were recovered from deceased service members serving in support of recent combat operations. Device makes and models, breakage, deformation, band routing, and windlass turn numbers were counted. 824 tourniquets were recovered, of which 390 were used in care and 434 were carried unused. 95% of the tourniquets were CAT (70%) and SOFTT (25%). For tourniquets with data, the windlass turn number averaged 3.2. The CAT windlass turn number was associated positively with tourniquet deformation. Moderate or severe deformation began at 2 turns and at 3 turns appeared in 25% of the units. Moderate deformation was defined as less than severe and included any device that could be made to

be effective (e.g., twisted plastic parts like the normally flat stabilization plates under the windlass). Severe deformation made effectiveness impossible (catastrophic failure or disruption of any component, severely burned components, or device destruction by explosion).

Aside from studies conducted on tourniquets used in the military, an observation worth noting was also made in [6]. The study was conducted on around 1000 tourniquets gathered from prehospital clinical use on civilians between 2015 and 2020. High tourniquet effectiveness was found. What was interesting was that absence of distal pulse recorded with the Doppler method was not synonymous with adequate haemorrhage control. While only 59% of patients for whom distal pulse presence/absence was documented had absence of distal pulse measured with Doppler method, nearly 88% of patients did have documentation that the injured limb had adequate haemorrhage control as determined by the receiving physician. However, this was not very well documented and further research is needed.

A notable effort was also made to measure tourniquet functioning simultaneously to clinical use. In 1990 in [7] the authors measured the pressure exerted by wrist tourniquets used in surgery. 25 patients' cases were studied. The method used here inspired a number of consecutive studies, so it is worth describing. A neonatal-sized blood pressure cuff was initially applied to each patient's wrist and inflated to approximately 30 mm Hg. Then the tourniquet was applied over it and used normally for surgery. The tourniquet pressure was determined to be the recorded reading from the wrist pressure cuff minus the initial 30 mm Hg pressure inflated into the cuff. Pressures generated with this technique ranged from 110 mm Hg to 260 mm Hg, with a mean pressure of 158 mm Hg

### 3.2.2 Laboratory testing with human subjects

Already in 1952 the author of [8] gave recommendations on what pressures exerted by tourniquets would be needed for successful use of them in surgery of the hand. He claimed that the only safe tourniquets were blood pressure cuffs attached to mercury manometers. He recommended pressures of 270-300 mm Hg for adults and 250 mm Hg for children. When pneumatic tourniquets of this sort were used, measuring pressures was a natural way to quantify and standardize their functioning. It also appeared for example in a study on animals, looking into effect of tourniquet usage on nerves ([9]). Further extensive literature on the subject, including safe time of usage, potential damage etc. can be seen e.g. in the literature review in [ochoa] or references in [10]. In this review we'll focus on studies relevant to testing tourniquets. We'll briefly summarize some studies attempting to quantify their effectiveness without using them in a clinical context, while still using human subjects.

In [11] in 1986 the pressures under the three digital tourniquets most commonly used clinically were measured. A miniature pressure transducer (1.5 mm in diameter and 0.3 mm in thickness) and a digital strain indicator were used to measure pressures generated by the various tourniquets. Out of the three, the rolled glove tourniquet had the lowest mean pressure of  $355 \pm 100$  mm Hg.

Penrose drain ( $675 \pm 165$  mm Hg) and the rubber band tourniquet ( $1080 \pm 400$  mm Hg). The uncertainty is the standard deviation for 10 tries by each of the 5 participants. A relevant observation was made in the preliminary phase of this study. It was found that the position of the pressure transducer on the circumference of the digit did not affect the documented pressure. However, there was an error range of 100 mg Hg in the monitoring system because of temperature, stability, and electric drifts. It was thus recommended that the numerical values of each studied system should be compared with relative rather than absolute values.

Another study examining tourniquets commonly used in extremity surgery was [10] published in 1993. The pressures under the Esmarch tourniquet were measured using a modification of the aforementioned method used in [7]. An 8- to 13-cm infant blood pressure cuff was attached to a pressure monitor and inflated to 5 mm Hg of pressure to avoid collapse during testing. The cuff was then secured horizontally on a volunteer's leg. The infant blood pressure cuff now served as a pressure sensor. The accuracy of the system was verified by comparing the readings obtained to those from an adult blood pressure cuff, attached to a mercury manometer, placed circumferentially around the leg centered over the infant cuff. The adult cuff was inflated in increments of 10 mm Hg from 100 mm Hg to 300 mm Hg. For each increment of 10 mm Hg, an infant cuff pressure was recorded. This sequence was repeated for a total of four series. The data demonstrated that the final infant cuff pressure minus the initial infant cuff pressure was equal to the mercury manometer attached to the adult cuff (the known pressure) to  $\pm 5$  mm Hg throughout a range of 100 to 300 mm Hg. The author claimed that statistical analysis demonstrated a linear correlation between the known pressures and the pressure readings obtained by our sensor. Interestingly they also claimed that statistical analysis also showed that the values could be extrapolated to a value of 600 mm Hg within a reasonable degree of certainty. After ensuring the accuracy of the measuring system, pressures underneath a normally applied Esmarch tourniquet were then measured. The obtained values of the average pressure for 3 or 4 inch tourniquets, with 3 or 4 wraps were all in the range 200-300 mm Hg.

The methods in the two studies mentioned above, [7] and [10], were also used in [12]. The authors also used a rubber bladder from an infant blood pressure cuff placed on the subject's leg, connected to a digital pressure monitor. Before the actual test the system was then checked for accuracy with a blood pressure cuff, as in the study described above. The average pressure of the 10 participating surgeons' trials for three wraps with a tuck was 222 mm Hg (range, 146–319 mm Hg); four wraps with a tuck averaged 288 mm Hg (range, 202–405 mm Hg).

Aside from measuring pressures under tourniquets which were commonly clinically used, a need was also seen to evaluate if a tourniquet is effective at all. A very popular method for this is checking for elimination of detectable distal pulse. One study which examined this was [13] from 2005. Seven tourniquets were tested on the thigh for elimination of detectable distal pulse by Doppler auscultation on 10-20 subjects (depending on experiment phase). Fail-

ure of tourniquets to eliminate distal Doppler pulse signal was due to inadequate mechanical advantage for tightening, device failure (breakage), or intolerable pinching or circumferential pain prior to pulse elimination. Doppler detection is now often used to assess tourniquet designs, e.g. in [14], [15]. Other methods, including palpation and pulse oximetry can be used for detecting elimination of pulse. In [16], effectiveness of pulse oximetry versus Doppler for tourniquet monitoring is discussed. Doppler signal is found to be more sensitive. There also exists at least one specialised mannequin leg for assessing if occlusion can be reached with a tourniquet, HapMed Leg Tourniquet Trainer. It was used in [17] to compare two tourniquets used in the Israeli armed forces - IST and CAT. It was found that the with the IST occlusion was reached more often than for CAT (91 vs 73.1%, of 78 participants). Occlusion was declared to be reached if the HapMed sensor detected at least 200 mm Hg of pressure exerted by a tourniquet.

A combination of pressure measurement and Doppler occlusion detection was used in [18]. The objective was to determine arterial occlusion and completion pressures with the CAT and the SWAT-T tourniquets. Sixteen volunteers self-applied and had tourniquets applied to their thighs and arms (CAT, SWAT-T and pneumatic - standard adult blood pressure cuffs). For measuring pressure under a tourniquet, a neonatal pressure cuff was used, just as in the studies mentioned above. Occlusion pressures were recorded when the distal arterial Doppler pulse signal became inaudible. Completion pressures were recorded when the applier's hands were off the secured tourniquet. Loss of occlusion pressures were recorded if the Doppler pulse signal became audible after occlusion but before the 1-minute-after-completion removal. Prerelease pressures were recorded just before removal. Occlusion pressures were higher than predicted and often lower than completion pressures (completion median, range: CAT 360, 147–745 mm Hg; SWAT-T 290, 136–449 mm Hg; cuff 184, 108–281 mm Hg). Three CAT thigh and 9 CAT arm completion pressures were >500 mm Hg. Pressure decreases and occlusion losses occurred over 1 minute (pressure decrease: CAT  $44 \pm 33$  mm Hg; SWAT-T  $6 \pm 8$  mm Hg; cuff  $14 \pm 19$  mm Hg;  $p < 0.0001$ ; loss/initially occluded: CAT 17 of 61, SWAT-T 5 of 61, cuff 40 of 64,  $p < 0.01$ ). CAT pressures before turn did not have a clear relationship with turns to occlusion.

There were also studies into how the mechanical elements of a design affect its effectiveness. In [19] in 2018 effects of buckle and strap features on converting pulling force to strap pressure were examined. Twenty-two buckle and strap combinations were evaluated using a thigh-diameter, ballistic gel cylinder and 3 thighs. Weights of 14.11, 27.60, and 41.11 kg provided pulling force. The contribution of buckle movement was evaluated: all buckles on gel and 12 on thighs allowed limited vertical movement, 12 on gel and 4 on thighs held static. The conclusions were that buckle design and strap fabric affect the conversion of pulling force to tourniquet strap pressure. Low-friction, smooth, round redirects allow the best conversion. An interesting side observation from this study was a comparison of how ballistic gel and real thigh react to applied force. Among setups used on the gel and the thighs, the pressures developed for each pulling

force were similar for gel applications and thigh applications.

### 3.2.3 Laboratory testing without human subjects

A complementary approach to evaluating tourniquets forgoes the use of human subjects. From what we've found, it is mostly used by manufacturing companies to prove the validity of their product. Some examples are summarized below.

In [20] the manufacturer of RECON Medical GEN 4 tourniquets tested the tensile strength of their units. A tourniquet was fastened between two pulling elements, with the windlass rotated by 450 degrees. Then it was pulled by a machine in two opposite directions. The force at point of failure was recorded by a dynamometer. The average force for the 53 tourniquets tested was 2319 pound-force (10kN). The most frequently occurring failure mode was the internal webbing, followed by Velcro delamination, heat weld, and lastly the buckle.

[21] from 2020 contains a report commissioned by the manufacturer of tourniquets, HALO LLC, on computer modelling, analytical methods and physical testing undertaken to validate strength requirements and determine safety factors of tourniquets.

## 3.3 Conclusions from literature review

Testing just mechanical properties of a design's elements may be useful but doesn't seem sufficient. In fact, tests can be devised which can look impressive but not really be informative. In [20] even the authors themselves claim: *we have designed and manufactured our tourniquets to carry an arbitrary yet impressive tensile strength...* and then proceed to measure that arbitrary strength. Clinical testing is the most reliable but hard to implement. An intermediate test is needed. A promising direction is obtaining from literature pressures needed to reach occlusion and then testing if a design can reach them reliably.

## 4 Testing ideas

Our first idea for testing tourniquets was building a model of a human leg and measure pressure needed to stop the blood flow. We considered the following materials

- PVA

Poly(vinyl alcohol) cryogel (PVA-C) is a composite hydrogel. It is formulated using solutions of poly(vinyl alcohol). These solutions become a solid gel when they are successively submitted to freezing and thawing. The mechanical properties of PVA-C are influenced by many parameters, for example rate of thawing and number of cycles. This makes it hard to use when reproducibility is required [22].

- Gelatin and agar

They have good mechanical properties. However, they have a short dura-

bility and are not rigid at room temperature, which makes them impractical [22].

- Silicone

The silicone based models have many advantages. They are easy to manipulate, nontoxic and stable for a long time [23].

- Polyurethane

The properties of polyurethane can be influenced by using elastomers with different soft to hard phase ratio, polyurethane sponges, or by incorporating reinforcing particles. They have a long shelf life and stability [23].

However, building a model of a human leg turned out to be too complicated. We also feared it would not be repeatable. Instead, we decided to use a strain gauge, for measuring the pressures exerted by a tourniquet and comparing them to the values available in literature.

## 5 Experimental part

### 5.1 Methodology

The first step of the new plan was the selection of the strain gauges. Several factors have been considered. First of all, the selected strain gauge had to be of a small size. Otherwise, it might not fit (i.e. it had to be smaller than the tourniquet itself) or even be damaged, as it is an inflexible device that was supposed to be placed between pseudo-spherical objects exerting high pressure. An additional factor was, of course, the cost, which in our case could not be relatively high.

Taking into account all the factors, it was decided to choose the RA18P-DIY<sup>1</sup> model from the Botland company.

According to the information from the manufacturer, the strain gauge can withstand a pressure equivalent to 4 kilograms, which gives the pressure equal to:

$$p = \frac{mg}{S} \approx \frac{40N}{177mm^2} = 226kPa = 1695mmHg, \quad (1)$$

which is more than enough for our purposes.

In order to measure the pressure using the strain gauge, one has to first calibrate it (i.e. find the electric resistance of the strain gauge as a function of the pressure exerted on it). Simple electric circuit was used to calibrate the device. Arduino Leonardo board was used as a 5 V voltage source and as a gauge of a voltage drop across the strain gauge.



Figure 2: The RA18P-DIY model.

---

<sup>1</sup><https://botland.com.pl/czujniki-nacisku/12157-czujnik-sily-nacisku-ra18p-diy-4kg-okragly-18mm-5904422318789.html>

The constructed system for measuring the voltage on a strain gauge as a function of the pressure exerted on it, is shown in Fig. 3. The strain gauge is located between a glass bottle with a radius similar to that of a typical human arm and a blood pressure cuff. The strain gauge is connected to the Arduino module which allows to measure the voltage on the strain gauge. The cuff is connected to a pump and a blood pressure monitor.

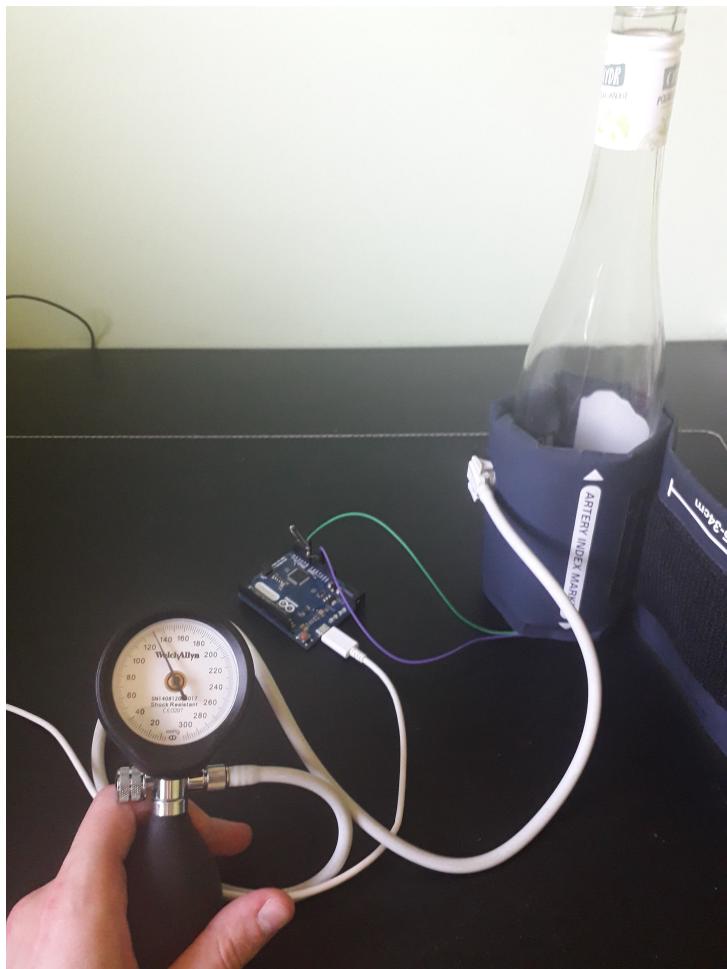


Figure 3: The system for measuring the voltage on a strain gauge as a function of the pressure exerted on it.

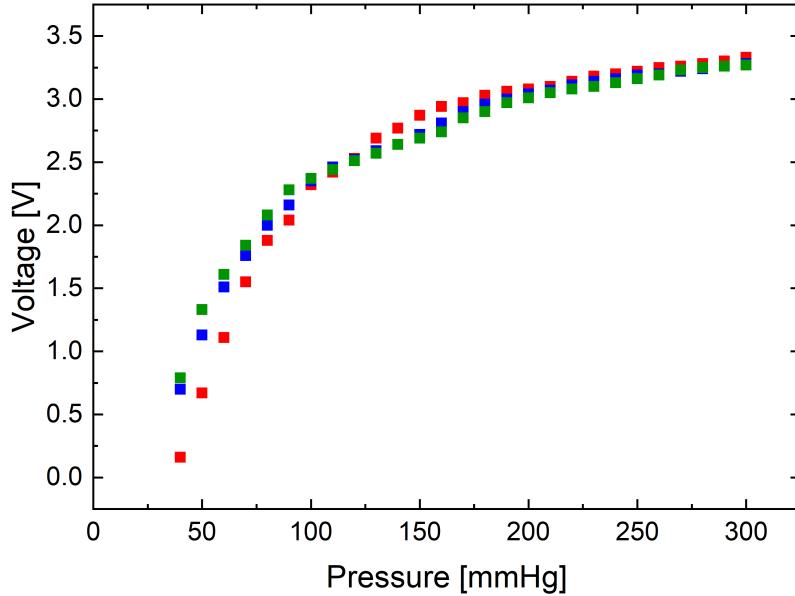


Figure 4: The results of three measurements of the dependence of the voltage on the strain gauge on the pressure exerted on it.

## 5.2 Results

The measurement data is shown on the graph 4. In order to obtain calibration of the system, the results of three measurement series were averaged and the relation  $U(P)$  needed to be reversed to  $P(U)$ . Obtained data was fitted with a following function:

$$y = \frac{b + c \cdot x}{1 + a \cdot x}, \quad (2)$$

where the parameters are  $a = -0.2653 \pm 0.00128$ ,  $b = 44.16594 \pm 1.97764$ ,  $c = -2.52546 \pm 0.87145$ . This way we obtained a calibration, where measured voltage  $x$  corresponds to the pressure exerted on the surface of the cylinder. The averaged data with the fitting is shown in the figure 5. However the fitting is not very accurate at low voltages, we expect pressures above 100 mmHg [24] where the fitting is more accurate. Unfortunately, as can be seen in figure 4, the measurement is burdened with a human error related to reading the results and inaccuracy caused by the setting of the measuring system. The main problem is probably the possibility of shifting the strain gauge during the measurement, which can be corrected by fixing it at the surface of the cylinder.

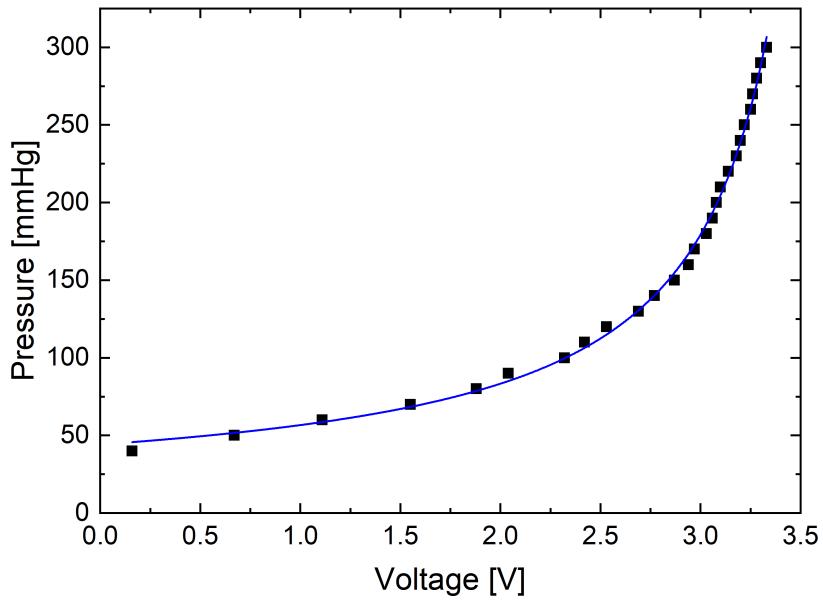


Figure 5: The averaged data from figure 4 is presented as a  $P(U)$  relation. The blue line was fitted using the formula (2).

### 5.3 Future plans

Direct measurements of tourniquets, under which strain gauges will be placed, are also planned. The crucial information will be what pressures can be reached with specific types of tourniquets and how long does it take to obtain deserved pressure with different types of tourniquets.

## References

- [1] Tarek Loubani. *Glia's Gaza Tourniquet is ready for emergency use in Ukraine. Make some if you can.* en. Mar. 2022. URL: <https://trklou.medium.com/glias-gaza-tourniquet-is-ready-for-emergency-use-in-ukraine-make-some-if-you-can-ef5f83260b7c> (visited on 07/11/2022).
- [2] Harold R. Montgomery et al. "2019 Recommended Limb Tourniquets in Tactical Combat Casualty Care". eng. In: *Journal of special operations medicine: a peer reviewed journal for SOF medical professionals* 19.4 (2019), pp. 27–50. ISSN: 1553-9768.
- [3] Richard Childers et al. "Tourniquets Exposed to the Afghanistan Combat Environment Have Decreased Efficacy and Increased Breakage Compared to Unexposed Tourniquets". en. In: *Military Medicine* 176.12 (Dec. 2011), pp. 1400–1403. ISSN: 0026-4075, 1930-613X. DOI: 10.7205/MILMED-D-11-00212. URL: <https://academic.oup.com/milmed/article/176/12/1400-1403/4318856> (visited on 05/15/2022).
- [4] Justin Weppner et al. "Efficacy of Tourniquets Exposed to the Afghanistan Combat Environment Stored in Individual First Aid Kits Versus on the Exterior of Plate Carriers". en. In: *Military Medicine* 178.3 (Mar. 2013), pp. 334–337. ISSN: 0026-4075, 1930-613X. DOI: 10.7205/MILMED-D-12-00454. URL: <https://academic.oup.com/milmed/article/178/3/334-337/4210870> (visited on 05/15/2022).
- [5] John F. Kragh et al. "Analysis of Recovered Tourniquets From Casualties of Operation Enduring Freedom and Operation New Dawn". en. In: *Military Medicine* 178.7 (July 2013), pp. 806–810. ISSN: 0026-4075, 1930-613X. DOI: 10.7205/MILMED-D-12-00491. URL: <https://academic.oup.com/milmed/article/178/7/806-810/4243570> (visited on 05/15/2022).
- [6] Rebecca Schroll et al. "AAST multicenter prospective analysis of prehospital tourniquet use for extremity trauma". en-US. In: *Journal of Trauma and Acute Care Surgery* 92.6 (June 2022), pp. 997–1004. ISSN: 2163-0755. DOI: 10.1097/TA.0000000000003555. URL: [http://journals.lww.com/jtrauma/Fulltext/2022/06000/AAST\\_multicenter\\_prospective\\_analysis\\_of.7.aspx](http://journals.lww.com/jtrauma/Fulltext/2022/06000/AAST_multicenter_prospective_analysis_of.7.aspx) (visited on 06/06/2022).
- [7] Emad M. Guirguis and Michael S.G. Bell. "The wrist tourniquet: An alternative technique in hand surgery". en. In: *The Journal of Hand Surgery* 15.3 (May 1990), pp. 516–519. ISSN: 03635023. DOI: 10.1016/0363-5023(90)90076-4. URL: <https://linkinghub.elsevier.com/retrieve/pii/0363502390900764> (visited on 07/10/2022).
- [8] JM BRUNER. "Safety factors in the use of the pneumatic tourniquet for hemostasis in surgery of the hand". In: *The Journal of bone and joint surgery. American volume* 33 A (Jan. 1951), pp. 221–4.

- [9] J. Ochoa, T. J. Fowler, and R. W. Gillatt. “Anatomical changes in peripheral nerves compressed by a pneumatic tourniquet”. eng. In: *Journal of Anatomy* 113.Pt 3 (Dec. 1972), pp. 433–455. ISSN: 0021-8782.
- [10] William C. Biehl et al. “The Safety of the Esmarch Tourniquet”. en. In: *Foot & Ankle* 14.5 (June 1993), pp. 278–283. ISSN: 0198-0211. DOI: 10.1177/107110079301400508. URL: <http://journals.sagepub.com/doi/10.1177/107110079301400508> (visited on 06/08/2022).
- [11] F. Peter Hixson et al. “Digital tourniquets: A pressure study with clinical relevance”. en. In: *The Journal of Hand Surgery* 11.6 (Nov. 1986), pp. 865–868. ISSN: 03635023. DOI: 10.1016/S0363-5023(86)80239-8. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0363502386802398> (visited on 05/25/2022).
- [12] Brett R. Grebing and Michael J. Coughlin. “Evaluation of the Esmark Bandage as a Tourniquet for Forefoot Surgery”. en. In: *Foot & Ankle International* 25.6 (June 2004), pp. 397–405. ISSN: 1071-1007, 1944-7876. DOI: 10.1177/107110070402500606. URL: <http://journals.sagepub.com/doi/10.1177/107110070402500606> (visited on 05/15/2022).
- [13] Thomas J. Walters et al. “Effectiveness of self-applied tourniquets in human volunteers”. eng. In: *Prehospital Emergency Care* 9.4 (Dec. 2005), pp. 416–422. ISSN: 1090-3127. DOI: 10.1080/10903120500255123.
- [14] Eitan Heldenberg et al. “Evaluating new types of tourniquets by the Israeli Naval special warfare unit”. eng. In: *Disaster and Military Medicine* 1 (2015), p. 1. ISSN: 2054-314X. DOI: 10.1186/2054-314X-1-1.
- [15] Christopher Treager et al. “A comparison of efficacy, efficiency, and durability in novel tourniquet designs”. eng. In: *The Journal of Trauma and Acute Care Surgery* 91.2S Suppl 2 (Aug. 2021), S139–S145. ISSN: 2163-0763. DOI: 10.1097/TA.0000000000003216.
- [16] Piper L. Wall et al. “Effectiveness of Pulse Oximetry Versus Doppler for Tourniquet Monitoring”. eng. In: *Journal of special operations medicine: a peer reviewed journal for SOF medical professionals* 17.1 (2017), pp. 36–44. ISSN: 1553-9768. DOI: 10.55460/XSOP-5MDO.
- [17] CPT Yuval Glick et al. “Comparison of Two Tourniquets on a Mid-Thigh Model: The Israeli Silicone Stretch and Wrap Tourniquet vs. The Combat Application Tourniquet”. In: *Military Medicine* 183.suppl\_1 (Mar. 2018), pp. 157–161. ISSN: 0026-4075. DOI: 10.1093/milmed/usx169. URL: <https://doi.org/10.1093/milmed/usx169> (visited on 06/22/2022).
- [18] Piper L. Wall et al. “Tourniquets and Occlusion: The Pressure of Design”. en. In: *Military Medicine* 178.5 (May 2013), pp. 578–587. ISSN: 0026-4075, 1930-613X. DOI: 10.7205/MILMED-D-12-00490. URL: <https://academic.oup.com/milmed/article/178/5/578-587/4222877> (visited on 05/15/2022).

- [19] Michael J. Valliere, Piper L. Wall, and Charisse M. Busing. “From Pull to Pressure: Effects of Tourniquet Buckles and Straps”. en. In: *Journal of the American College of Surgeons* 227.3 (Sept. 2018), pp. 332–345. ISSN: 1072-7515. DOI: 10.1016/j.jamcollsurg.2018.06.005. URL: <https://journals.lww.com/00019464-201809000-00004> (visited on 05/15/2022).
- [20] Asher Holland. *RECON MEDICAL GEN 4 TRAUMA TOURNIQUET TENSILE STRENGTH QUALITY CONTROL TESTING*.
- [21] LLC Blew Consulting. *Tourniquet Modeling, Analysis and Physical Testing*. 2020.
- [22] Guy Lamouche et al. “Review of tissue simulating phantoms with controllable optical, mechanical and structural properties for use in optical coherence tomography”. en. In: *Biomed. Opt. Express* 3.6 (June 2012), pp. 1381–1398.
- [23] A. K. Dąbrowska et al. “Materials used to simulate physical properties of human skin”. In: *Skin Research and Technology* 22.1 (2016), pp. 3–14. DOI: <https://doi.org/10.1111/srt.12235>. eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1111/srt.12235>. URL: <https://onlinelibrary.wiley.com/doi/abs/10.1111/srt.12235>.
- [24] Piper L. Wall et al. “Tourniquet pressures: strap width and tensioning system widths”. eng. In: *Journal of special operations medicine: a peer reviewed journal for SOF medical professionals* 14.4 (2014), pp. 19–29. ISSN: 1553-9768.