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# Design of a system to detect the force applied by tourniquets in a manikin's limb

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*Abstract*— **Massive hemorrhage remains the number one cause of preventable death in trauma worldwide. However, immediate intervention by a bystander can significantly improve the survival of the injured person. In this context, the tourniquets represent the most quick and effective devices for stopping arterial and venous blood flow. The aim of this study was to implement a system to detect the force applied by a tourniquet on a simulated limb, without blood flow. The system we designed is characterized by four low-cost force sensing resistors placed on each lower limb of a manikin, below the groin. Tests on 21 tourniquets, revealed that our system is able to detect the force applied for 60 minutes, also discriminating between turns. Hence, this system can be used to compare the performance of different types of devices, but also to assess proper tourniquet placement in trainees and trauma care providers, thus making it a versatile low-cost device.**

*Clinical Relevance*— **This system allows to test the efficacy and performance of tourniquets for an extensive period of time in a riskless way.**

## I. Introduction

To this day, the first cause of preventable deaths in trauma is massive external bleeding [1], [2]. In fact, hemorrhage accounts for an estimated 35% of civilian prehospital trauma deaths and 40% of deaths in the first 24 hours post-injury [3]. A proper management of the trauma can significantly reduce the risk of mortality of the injured person [4]. Particularly, in these situations, the 'time' factor plays a fundamental role: the shorter the time between the acute event and the qualifying treatment, the greater the chances of survival. Therefore, the immediate application of devices creating a circumferential pressure that occludes arterial vessels, such as tourniquets upstream of the bleeding point can be essential to stop perfusion and save a life.

In order to increase the general population awareness and training, various courses have been presented over the years, such as ATLS (Advanced Trauma Life Support), PHTLS (Pre Hospital Trauma Life Support), giving safe and reliable methods for the management of injured patients [5]–[7]. Also, in 2015, the White House call to action launched a national awareness campaign entitled "Stop the Bleed". Such program is aimed at educating the population on the use of techniques and devices that could control external bleeding in an extra hospital setting, thus allowing for the time needed for trained professionals to intervene [8]–[12]. Since 2017 over 85 thousand Stop the Bleed courses have been held all over the globe, with 1.5 million people certified [13]. This widespread campaign, as well as the popularization of the tourniquet device through the media, has led to an increase in the availability to the general public of Committee on Tactical Combat Casualty Care (CoTCCC) approved tourniquets, such as the Combat Application Tourniquet (C.A.T), SOFT-T, etc. [14].

Tourniquets are often used in extreme and remote situations, such as mass casualty events, remote settings and non-permissive environments, where their employment can be prolonged [15]. The efficacy and performance of tourniquets for an extensive period of time cannot be tested on human volunteers due to risk of ischemic tissue injury and nerve injury [15]. Furthermore, animal models are expensive and difficult to implement in places with limited resources. Conversely, the use of systems as manikins allows for prolonged measurement time, as well as the measurement of the complete range of forces that can be applied by the tourniquet population. Yet, manikins generally do not have a blood flow, thus making it impossible to measure the pressure applied on the limb by using traditional methods such as cuffs or ultrasound Doppler.

Within this framework, the aim of this study was to design and implement a system to detect the force applied by a tourniquet on a manikin's limb, that does not have any blood flow. The system we designed should meet the following criteria: (i) ability to quantify the force applied for at least one hour; (ii) reduced dimension to not alter the positioning of the

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tourniquet; (iii) ease to use by non-technical users; (iv) limited cost, which allows for the system to be eventually used in remote or low-resource areas.

## II. Methods

### A. *Setup*

The setup includes eight FSR 402 force sensors (FSR, Interlink Electronics, CA, USA) connected to an Arduino Mega 2560 board with a 10 kΩ resistor. Each sensor has a diameter of 18.22 mm, an active area of 12.7, a thickness of 0.45 mm, and works up to 100N with an accuracy of ± 2N. In order to collect data from two tourniquets simultaneously, the sensors are equally positioned in the two lower limbs of a full-body manikin, immediately below the groin (Fig. 1). In particular, each limb includes four sensors covering the entire circumference (i.e., the angle between two consecutive sensors is 90 degrees). Analog data from the sensors have been converted into force by considering the manufacturer force curve and output function, and then sent to a computer via serial (Data Streamer for Microsoft Excel; Fig. 1; Sampling Frequency 1Hz).

### B. *Test*

To test our system, we collected data from 21 tourniquets (CAT Gen7). Specifically, 12 testing sets have been performed: nine with two tourniquets simultaneously, (as in Fig. 1) and three with a single one (2 in the left leg, 1 in the right one).
Briefly, an instructed experimenter placed the tourniquet in the upper part of the thigh (Fig. 2), ensuring that all the sensors detected the device. Once placed in the correct position, the lace is tightened by performing three 180 degrees turns and secured. Each session lasted around one hour, and force was recorded through the entire session.

### C. *Data analysis*

For each tourniquet, we computed the force by averaging the values of three sensors positioned under the device, i.e., we excluded the sensor positioned under the stabilization plate, to avoid incorrect measurements. Then, we computed the average force of all sessions (i.e., measurements of all the tourniquets), in order to remove outliers. Specifically, sessions having values above or below 2 standard deviations from the mean have been removed from the dataset. This resulted in two outliers and 19 sessions used for the data analysis.

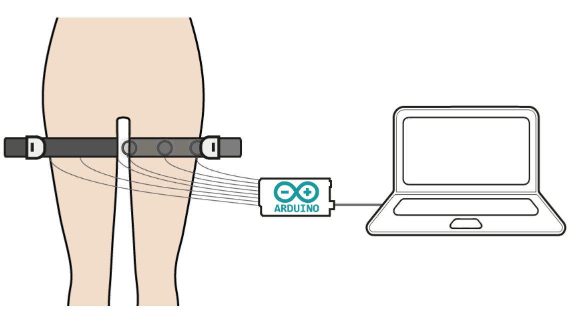


Figure 1: Setup. Eight FSR sensors are positioned in two limbs and connected to an Arduino Mega board which sends data to a computer via serial

Figure 2. Testing session. An experimenter is positioning a tourniquet on a simulated limb

To compute the force applied in the turns and at the beginning of the steady phase, namely the period after the third turn, we considered the first 4 minutes of each session (an example is reported in Fig. 3). In those intervals, we fitted the force data with a series of segmented lines [16], and we found changes in the slope and intercept. Indeed, we looked for lines with absolute slope lower than 3 N/s and we used them to identify the starting and ending point of each turn. Within this interval, we computed the mean force applied. Concerning the steady phase, we considered the first line longer than 10 s after the third turn whose slope is lower than 3 N/s. If no lines are detectable the steady phase starts 10 s after the third turn.
Subsequently, each recording was divided in two segments: turns and steady phase. In the steady phase we averaged the data in 12 5-minute time windows, and we assessed whether the first and last time points showed any statistical difference. In the turns phase, we computed the mean force applied during the placement and at the three turns in all the sessions to verify whether the force applied is significantly different among turns. In four out of 19 sessions the recording started after the tourniquet was positioned; hence, it was impossible to distinguish between turns; and these sessions have not been included in the analysis.

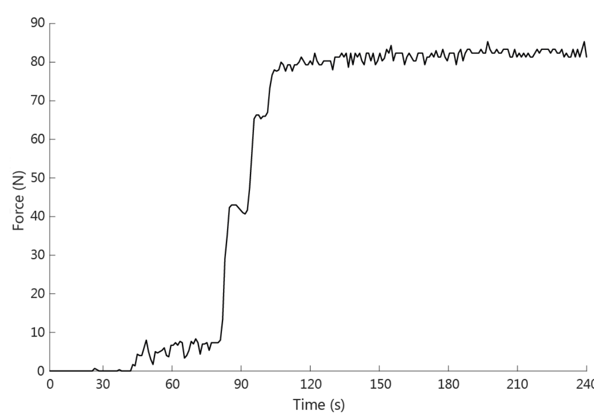


Figure 3. Example of force applied by a tourniquet during the first four minutes of test.

## D. *Statistical Analysis*

The raw force data recorded by the sensors were analyzed offline using Matlab (MathWorks inc.). We tested the normality of the data using Kolmogorov-Smirnov test and since the null hypothesis was rejected, we tested both the steady phase data and the turns force values by the Wilcoxon rank sum test.

# III. Results

Visual inspection of the data shows that the setup we built is able to detect the force applied by the tourniquet for at least 60 minutes (Fig. 3). Also, we found that our system provides repeatable measures in static conditions. Indeed, averaged data (Fig. 4) showed that the force applied by the tourniquets remains constant for one hour ($p=0.43$). Furthermore, the system can detect force variations corresponding to either tourniquet positioning or subsequent turns. In particular, the average force applied by the tourniquet at positioning (i.e., before any turn) was equal to (mean ± S.E.) 7.2 ± 0.6 % the maximum force reached at steady phase, while in the three turns it reached respectively 45.6 ± 3.2%, 73.4 ± 1.8% and 93.7 ± 1.3%. In order to assess whether our system was able to discriminate between different turns, we compared the force values finding significative differences (Positioning vs Turn1 $p<0.001$; Turn1 vs Turn2 $p=0.007$; Turn2 vs Turn3 $p=0.032$; Bonferroni Corrected).

# IV. Discussion

The goal of this study was to design, implement and test a system to detect the force applied by a tourniquet on a manikin's limb, which is characterized by no blood flow. To do so we installed four FSR sensor on two manikin's limbs which record the force applied by a tourniquet for 60 minutes. Even though, FSR are not as accurate as other force sensors (e.g., load cells, strain gauge) in providing absolute force measures, their repeatability make them a good choice for many applications. Specifically, FSR are small, low-cost and versatile sensors usable for performance assessment [17], force evaluation [18], or touch detection [19].

In the specific case of measuring the force applied by a tourniquet, a few research groups have used FSR in different ways, which however do not include installing them in a manikin lacking blood flow: [20] measured the instantaneous surface pressure of digit tourniquets in vivo, and 2-hour continuous pressure on a silicone model; [21] wanted to quantify in-vivo surface pressure distribution of a tourniquet during surgery; [22] used a slightly different sensor (i.e., capacitive-based) to compare different tourniquets, in terms of maximal force generated in vivo. Altogether, these studies indicate that FSR, and more generally force sensors, are reliable for measuring the force generated by a tourniquet.

Tests on commercial tourniquets revealed that our device is stable and consistent across measures, as indicated by low deviations of the measurements (Fig. 4). Indeed, it is particularly suitable to compare the efficacy of different types of devices such as: commercial versus improvised; Committee on Tactical Combat Casualty Care (CoTCCC) approved versus unapproved; surgical versus emergency tools. Another useful application of our device concerns the analysis of used tourniquets, in order to assess their residual outcomes [23]. Also, as our system is designed to be used on manikins, tests for extended periods of time can be performed without any risk. This feature could be particularly useful for assessing extended use efficacy and wear, as this might be required in remote or tactical environments, where extrication and centralization of the patients may be severely prolonged. Altogether, these applications can support manufacturers, investigators, organizations and instructors to further improve the efficacy of tourniquets, as well as to select the best models and techniques to train learners [23]–[25]. Quality of training is crucial to have skilled people who can quickly and properly face emergency situations. In this context, our system can be used as a training tool. In particular, learners can practice multiple times in a riskless environment, eventually receiving a real time feedback on their performance. In addition, instructors can assess performance in an objective way [26], [27].

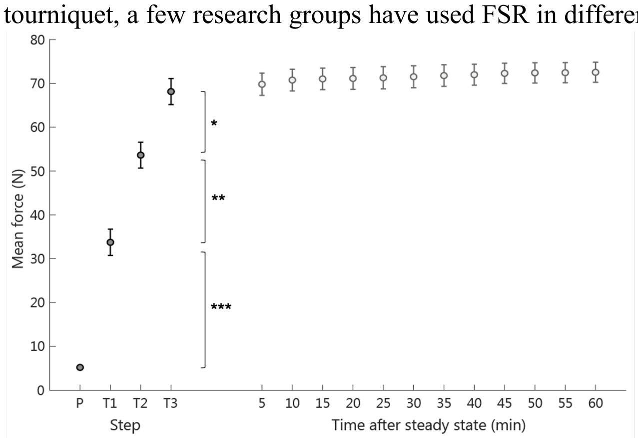


Figure 4. Average across all sessions of the force applied by the tourniquets at turns (black) and at steady phase (gray) by averaging data in 5-minute windows. Dots: mean; bars standard errors of the mean. *$p<0.05$; **$p<0.01$; ***$p<0.001$

# V. Conclusion

The system we designed is able to detect the force applied by a tourniquet on a manikin's lower limb for one hour. Furthermore, force values recorded during placement revealed that our tool can discriminate between different turns.

Future studies will be aimed at: (i) assessing whether the system can collect force data for a longer period of time (i.e., up to six hours); (ii) comparing the performance of different types of tourniquets.

In conclusion, the tool we implement can be used both as an instrument to investigate tourniquets features, and as an educational device to increase the trauma care provider proficiency. Both scenarios would ultimately lead to a safer trauma management and a lower mortality risk.

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