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TiMON: a real-time integrated monitor for improving the placement and wear of emergency tourniquets

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Abstract

Background The use of emergency tourniquets among military personnel has helped to dramatically reduce battlefield deaths and has recently gained popularity in the civilian sector. Yet, even well-trained individuals can find it difficult to assess proper tourniquet application. Emergency tourniquets are typically deemed sufficiently tightened through cursory visual confirmation or pulse assessment. These indicators are not always accurate and are difficult to assess during chaotic events where fast and effective tourniquet application by both trained and untrained personnel can contribute significantly to saving lives. Towards addressing these issues, we have developed the Tourniquet Integrated Monitor (TiMON) as an easy-to-use real-time pressure sensing device designed to seamlessly integrate with pre-existing emergency tourniquets. Here, we present the results of two studies in which the TiMON was tested among a group of soldiers participating in the Army Expeditionary Warrior Experiments (AEWE) as well as in a group of untrained civilians from Massachusetts General Hospital.

Methods In the first study, 30 soldiers with prior tourniqueting experience were asked to apply a TiMON equipped CAT tourniquet onto a leg mannequin with (unblinded) and without (blinded) assistance from the TiMON's output. In the second study, 30 lay volunteers from Massachusetts General Hospital with no prior tourniquet training were recruited and taught how to apply a tourniquet under normal conditions prior to being asked to perform the same exercises as the soldiers. In both studies, data collected for statistical analysis consisted of the real-time applied pressure along with the elapsed time for each subject to finish applying the emergency tourniquet.

Results Subjects in both groups utilizing the TiMON had greater success in applying emergency tourniquets at the civilian clinically recommended occlusion range of 180 to 300 mmHg (soldiers: 86.67% assisted vs 33.33% unassisted; untrained volunteers: 93.33% assisted vs 40.00% unassisted). In terms of applied pressure, no significant mean differences were observed in either group (soldiers p-value = 0.13; untrained volunteers p-value = 0.26), however the unblinded subjects were found to exhibit significantly lower variances in applied pressure compared to those who were blinded (soldiers p-value < 0.0001; untrained volunteers p-value < 0.0001). In terms of application speeds, no significant differences in means and variances were observed in the soldiers (p-values = 0.85 and 0.61, respectively), while mildly significant increases in application times were observed in the untrained volunteers (p-value = 0.036).

Conclusion Trained soldiers and lay volunteers using the TiMON were able to consistently apply tourniquets at clinically recommended occlusion pressures between 180 and 300 mmHg with significantly less under and

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over tightening while minimizing any negative effects to their application speeds. Despite it being their first time using the TiMON, both groups were able to quickly apply emergency tourniquets at significantly improved and consistent success rates regardless of prior training and experience.

Keywords Emergency tourniquet, Combat casualty care, Bleeding, Hemorrhage

Introduction

Emergency tourniquets are used to stop severe arterial bleeding via the application of uniform circumferential pressure around traumatic limb injuries until definitive medical attention is available [1]. The use of tourniquets within the military has helped to dramatically reduce battlefield incidences of preventable death related to rapid compressible hemorrhaging. They have also recently gained traction in the civilian sector with just-in-time and point-of-injury pre-hospital use increasing for accidents, natural disasters, acts of violence, and mass casualty incidents [2–6]. The most commonly used emergency tourniquet design is based on a windlass mechanism in which a rod is manually twisted in order to tighten a band around the region-of-interest [7]. This particular tourniquet design is recommended by both military and civilian first responders for its mechanical simplicity, reliability, and ability to be quickly and easily applied. Additionally, it has proven to be effective under austere conditions and can be self-applied with one hand without the need of external power. In theory, emergency tourniquets can be utilized by anyone, even individuals with little to no formal training.

However, in practice, even trained individuals can find it difficult to properly apply emergency tourniquets [8, 9]. Emergency tourniquets are typically deemed sufficiently tightened through cursory pulsatile assessment or visual confirmation that bleeding has stopped. These indicators are not always accurate and can be difficult to assess during chaotic battlefield and mass casualty incidents where fast and effective tourniquet application can contribute significantly to saving lives prior to definitive care. In a large-scale longitudinal study involving 465 laypersons, it was observed that only 54% of Bleeding Control Basic participants where able to successfully apply a tourniquet 3 to 9 months following initial training without a refresher course [10]. For laypersons without any prior training whatsoever, success rates have been observed to be as low as 14.4% [11]. These numbers are less than satisfactory when considering the potential of civilian bystanders as immediate responders to life-threatening emergencies.

Emergency tourniquets are not effective unless they are tightened enough to achieve complete arterial occlusion to the region-of-interest. Under-tightened tourniquets will fail at stopping life-threatening hemorrhages and can further exacerbate hemorrhaging from damaged arteries, which can lead to significant injuries to the underlying and distal tissues [7]. Further complicating the issue is that over-tightened and/or prolonged use of tourniquets can also promote additional injuries, and after two hours, the risk of acute muscle injury and nerve palsy increases greatly due to a buildup of lactic acid, pH, glucose, and reactive oxygen metabolites such as hypoxanthine and xanthine [12–14]. The pressure required for occlusion can vary greatly from person-to-person and anatomical location, with the lower extremities requiring higher pressures to occlude since blood flow increases exponentially with limb circumference [15]. In the case of intraoperative tourniquet use, it is generally recommended to apply pressures that are 50 to 150 mmHg above systolic blood pressure, using the lower end of the range for upper extremities and the high end for the lower extremities [16, 17]. For normotensive persons of average build, it is generally recommended that 200 mmHg in the upper extremity and 250 mmHg in the lower extremity will be adequate to induce complete arterial occlusion [18]. It is important to keep in mind that these are only general guidelines and are expected to vary greatly in practice.

In 2015, following several decades of notable mass shootings including the Sandy Hook Elementary School shooting [19–21], the White House National Security Council staff and its Office of Medical Preparedness Policy launched a national campaign titled "Stop the Bleed" that was intended to raise awareness and empower the general public to stop life-threatening bleeds by increasing access to bleeding control kits and training [22]. From this initiative, various curricula were developed aimed at converting the general public into "immediate responders" capable of providing point-of-injury hemorrhage control. Apart from traditional classroom training that suffer from long-term challenges related to knowledge retention, various methods have been developed for augmenting a layperson's ability to successfully apply an emergency tourniquet. These include just-in-time instructions via notes [23, 24], phone instructions from emergency medical dispatchers [9], and pre-recorded instructions [25]. While many of these methods do indeed improve emergency tourniquet application by laymen in a controlled environment, it is difficult to gauge their efficacy during real-life scenarios where attention spans may be critically diminished. Moreover, these

methods cannot be readily extended to military and combat environments where such visual, auditory, or other guidance would likely interfere with operational capabilities. Importantly, none of these methods ensure that the emergency tourniquet is applied tight enough to induce arterial occlusion. Advanced emergency tourniquets with pressure sensing and self-tightening capabilities are currently in development [26], but these tend to incorporate many costly components which limit their potential for widespread adoption beyond the tried-and-true windlass design that is so ubiquitously utilized by militaries and EMTs across the world.

Towards addressing these barriers surrounding proper emergency tourniquet application, we developed the Tourniquet Integrated Monitor (TiMON) as a real-time force sensing toolkit that is designed to seamlessly integrate with pre-existing standard-of-care military tourniquets. The TiMON is easy-to-use and allows for the real-time monitoring of applied pressure and occlusion duration in order to assess adequate tourniquet application along with tracking patients for conversion, replacement, or triage. Importantly, the TiMON is an add-on that is built from regularly-available consumer electronic components and can be made inexpensively for widespread use. Here, we will describe the development of the TiMON and present results from two separate studies: one involving soldiers with tactical combat casualty care (TCCC) and combat lifesaver (CLS) training who were participating in the Army Expeditionary Warrior Experiments (AEWE) and another involving untrained volunteers from Massachusetts General Hospital.

Methods

Tourniquet integrated monitor (TiMON)

As seen in Fig. 1, the TiMON is a 3D printed device developed to integrate with pre-existing windlass tourniquets that are commonly used within the U.S. Military such as the Combat Application Tourniquet (CAT) (North American Rescue, Greer, SC). Real-time applied pressure is measured by a calibrated capacitive force sensor and is visually displayed to the user via an onboard OLED display. When the applied pressure is within a predetermined range, a timer on the TiMON is activated to indicate the time elapsed since achieving and maintaining a clinically recommended occlusion pressure. The device is relatively compact with a dimension of 48 × 48 × 32 mm^3 and a weight of 30 g. The TiMON, along with its enclosure, were built and tested to with the goal of reaching MIL-STD 810H standards and IP67 ratings for withstanding specific environmental conditions related to physical shocks and liquid immersion [27, 28].

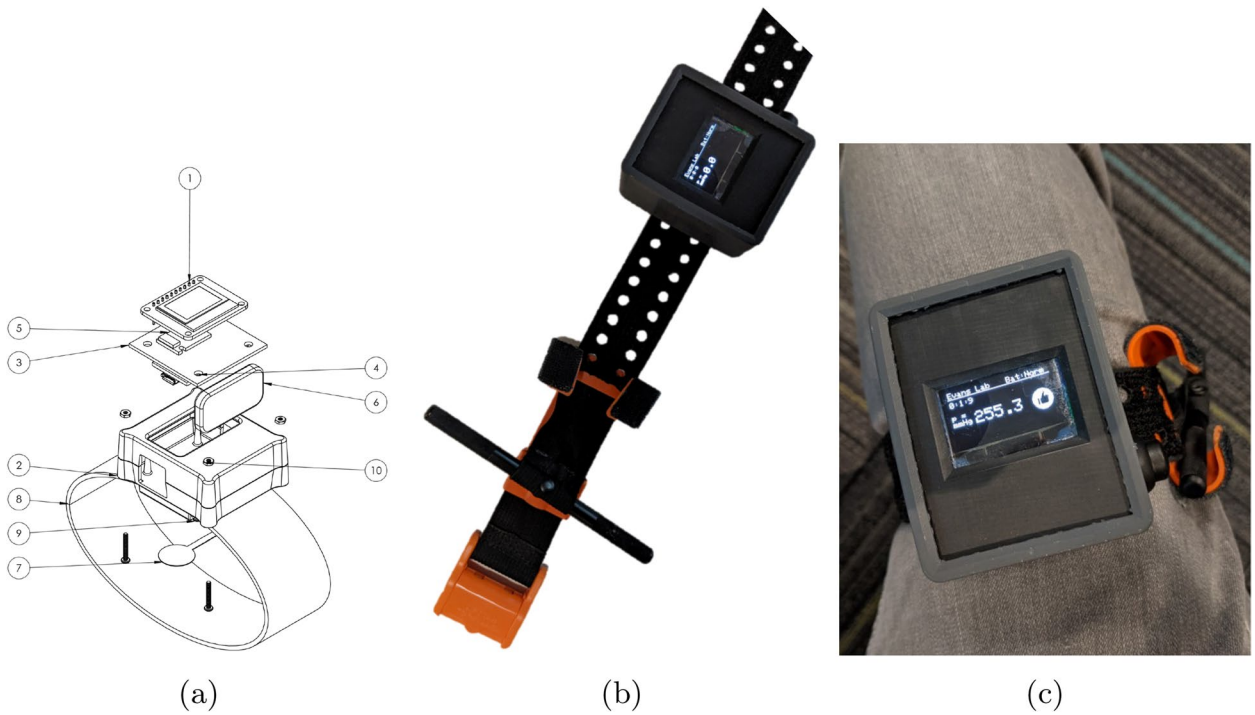

Fig. 1 **a** Blowout schematic of the TiMON. Descriptions of each component can be found inline. **b** Example of the TiMON attached to an emergency tourniquet. **c** Example of a TiMON equipped emergency tourniquet applied to the thigh. When the applied pressure is between 180 and 300 mmHg, a visual thumbs-up indicator is activated along with a timer in the top left corner of the display

In terms of components, the TiMON's main enclosure was fabricated using a Form 3 3D printer (Formlabs, USA) and its general purpose black resin. A protective outer shell was 3D printed from Flexible 80A black resin. (Formlabs, USA) The TiMON is controlled by a single-board microcontroller (Argon, Particle Industries, USA) that includes Bluetooth connectivity, a WiFi network co-processor, and a USB port for charging and data transfer (Fig. 1a.④). This was soldered onto a custom-designed printed circuit board (Fig. 1a.③) along with a monochrome OLED display (938, Adafruit Industries, USA) (Fig. 1a.①), micro SD card reader (Adafruit 254, Adafruit Industries, USA) for expanded data storage (Fig. 1a.⑤), a push button switch (RP8201B2M1CEBLKBLKNIL, E-Switch Inc., USA) for turning the device on/off, and a rechargeable lithium polymer battery (2750, Adafruit Industries, USA) (Fig. 1a.⑥).

Pressure sensing is accomplished through the use of a 15 mm diameter capacitive force sensor (SingleTact 15 mm, PPS UK Ltd, UK) with a full scale range of 45 N attached to a soldered I^2C interface board for data acquisition (Fig. 1a.⑦). The capacitive sensor measures at 16-bit precision which was then scaled down to a 10-bit digital signal for conversion to applied pressure via a calibration technique described below. The internal capacitance to digital converter operates at a sampling rate of 140 Hz which was then downsampled into a 100 Hz readout. Further signal averaging was also performed on the microcontroller in order to reduce the effects of noise and impulse response, from which the pressure displayed to the user updates at a rate of 1 Hz.

In order to facilitate the TiMON's operation and features, a custom firmware was written in the C programming language. Coded features include built-in calibrations for converting digital signals to pressure and a schema for displaying immediate pressure changes, threshold achievement, and application time.

Pressure Calibration The capacitive force sensor and I^2C interface board outputs a digital signal that corresponds to a 0 to 2 V analog output range. For our particular application, this signal needs to be converted into an applied pressure value. Due to inherent variabilities in sensor response for these prototypes, each sensor requires its own unique calibration curve for converting the digital signal into applied pressure measurements. This was accomplished through the use of 11 calibration weights each weighing 100 grams towards spanning a summed range of 0 to 1100 g. Assuming constant gravity and that the capacitive sensor has a diameter of 15 mm, each calibration weight contributes approximately 5.55 kPa of applied pressure, which further converts to approximately 41.96 mmHg per calibration weight. In total, the calibration range was 0 to 461.56 mmHg. This was then fit to a 2nd order polynomial as exemplified in Fig. 2 in order to generate a unique calibration curve for each TiMON unit's embedded firmware.

Operation The TiMON is designed in such a way that it can be easily slid or clipped onto the belt of a windlass emergency tourniquet as exemplified by Fig. 1b. Once attached, the TiMON can be activated by pressing the on/off switch on the side of the device. While the tourniquet is positioned on the intended body part and tightened according to the manufacturer's instructions, the applied pressure will be reported in real-time on the

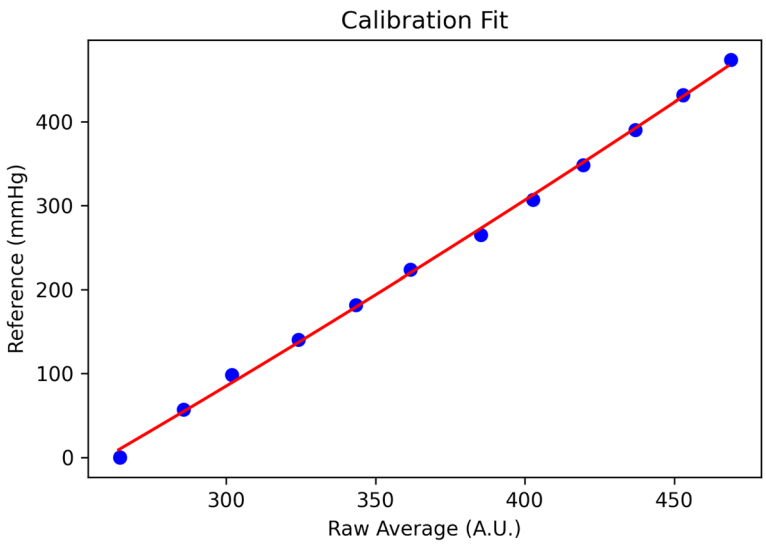

Fig. 2 Example of a TiMON calibration curve

OLED display. For these studies, when the applied pressure was recorded to be between 180 and 300 mmHg, an icon would be displayed and a timer would be activated in the top right corner as seen in Fig. 1c. This clinically-recommended range was based on physician opinions and literature as described in the Introduction section prior [15–18]. Due to the importance of time in tourniquet conversion and replacement prior to definitive care, the timer does not turn off or reset after its initial setting unless manually powered off.

AEWE study design

The study was performed on 30 subjects consisting of soldiers from the United States Army's 1st Battalion, 29th Infantry Regiment and the British Army's 1st Battalion, Royal Irish Regiment participating in the AEWE at Fort Moore, GA. These soldiers regularly participate in combat lifesaver (CLS) and TCCC courses and are considered well-trained at applying emergency tourniquets in battlefield environments. Each soldier was asked to apply a TiMON equipped CAT tourniquet onto a silicone leg mannequin (TrueClot PCT3 Leg Trainer, Rescue Essentials, USA) without ("Blinded") and with ("Unblinded") assistance from the TiMON's output. Data collected for statistical analysis consisted of the applied pressure over time along with the time required for each soldier to completely apply the tourniquet. The study was reviewed by the Partners Healthcare (now known as Mass General Brigham) IRB and approved under IRB 2019P001686.

Untrained volunteer study design

Thirty lay subjects with no prior tourniquet training were recruited and consented under approval from Mass General Brigham's IRB (#2019P001686). During this study, a medical doctor with extensive experience in trauma and wound care would demonstrate how to apply an emergency tourniquet under normal circumstances without the TiMON attached. The subjects were encouraged to ask questions, but were not allowed any hands-on practice. Afterwards, the subject would then be instructed to apply the TiMON-equipped tourniquet onto the same silicone leg mannequin that was used in the AEWE study described in the previous section. The first measurement was "blinded" in which the TiMON's display was covered and obscured from view from the participant. The following measurement was "unblinded" in which the TiMON's display was uncovered and the participant was encouraged to use the real-time pressure measurements while applying the tourniquet. Data recorded for analysis included the amount of time it took the subject to apply and lock-in the tourniquet, and the TiMON's recording of applied pressure.

Results

Testing and validation

The TiMON devices were initially tested on the HapMed Tourniquet Trainer (CHI Systems, USA), which is an electronic leg mannequin aimed at simulating a traumatic lower-extremity amputation. As a training device, the HapMed itself incorporates sensors for measuring applied pressure and bleeding status, and has been utilized in various studies involving tourniquet usage in the past [29–31]. An example of the TiMON's applied pressure output can be seen in Fig. 3 during each phase of tourniquet application. Both the TiMON and HapMed simultaneously indicated a proper tourniquet application at the HapMed's 250 mmHg threshold pressure as indicated by the orange horizontal line.

Soldiers with prior tourniqueting experience

Thirty soldiers participated in the AEWE study where the TiMON was attached to a CAT tourniquet for testing on a silicone leg mannequin. Data was recorded by the TiMON devices, half of which displayed feedback (unblinded) and the other half which were configured to not display information (blinded). Time vs pressure traces were analyzed using Python and R routines for quantitative and statistical analysis.

The analysis found that soldiers assisted by the TiMON were significantly more successful (binomial test, p-value < 0.0001) in applying an emergency tourniquet at the clinically recommended occlusion range of 180 to 300 mmHg (86.67% assisted vs 33.33% unassisted). Of the failures during the blinded phase, 15 were over-tightened and 5 were under-tightened. When unblinded, all four failed tourniquet applications were found to be over-tightened.

Distributions were found to be non-parametric, thus Wilcoxon-Signed Rank and Brown-Forsythe tests were used to compare the means and variances, respectively. As seen in the bar plots in Fig. 4, no significant mean differences were observed in applied pressure (p-value $= 0.13$) and application times (p-value $= 0.85$) between the blinded and unblinded groups. However, the degree of variance was found to be significantly lower (p-value < 0.0001) in the unblinded application where the TiMON's visual feedback was provided during tourniquet application. Mildly significant mean and variance differences between blinded and unblinded applications were also observed in achieving the minimum threshold pressure of 180 mmHg (p-values $= 0.012$ and 0.0078, respectively.).

Even though it was their first time using the TiMON, the soldier's tourniquet application speeds were

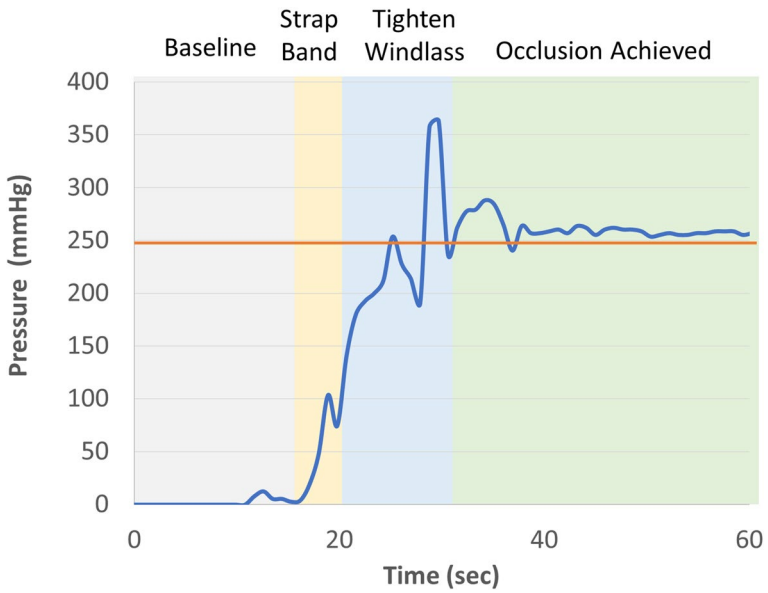

Fig. 3 Example of TiMON measurements of applied pressure while testing with the HapMed tourniquet trainer. The orange horizontal line indicates the HapMed's 250 mmHg threshold pressure for successful tourniquet application

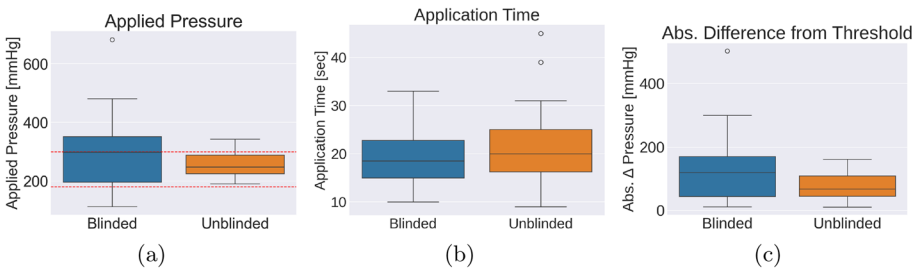

Fig. 4 Blinded and unblinded results from soldiers utilizing the TiMON for emergency tourniquet applications. **a** Applied pressure, where mean comparison *p*-value = 0.13 and variance comparison *p*-value < 0.0001. Red dashed lines indicate the 180 to 300 mmHg range considered for successful tourniquet application. **b** Application time, where mean comparison *p*-value = 0.85 and variance comparison *p*-value = 0.61. **c** Absolute difference from minimum threshold pressure of 180 mmHg, where mean comparison *p*-value = 0.012 and variance comparison *p*-value = 0.0078

statistically indistinguishable from their normal speeds but with the added benefit of a significantly improved and consistent success rate. While no significant differences in overall applied pressure was observed between the blinded and unblinded groups, soldiers using the TiMON were able to consistently apply tourniquets at the clinically recommended occlusion pressures with significantly less under and over tightening compared to their original applications.

Untrained volunteers

The TiMON was further tested in a group of 30 lay civilians who had never received tourniquet training. Under the clinically recommended range of 180 to 300 mmHg, untrained volunteers using the TiMON were significantly more successful (binomial test, p-value < 0.0001) in applying an emergency tourniquet (93.33% assisted vs 40% unassisted). Of the failures during the blinded phase, 10 were over-tightened and 8 were under-tightened. When unblinded, both failed tourniquet applications were found to be over-tightened.

From the results seen in Fig. 5, no significant differences between the blinded and unblinded mean application pressures were observed (p-value = 0.26), but a significant reduction in applied pressure variance was observed (p-value < 0.0001). A mildly significant increase in the means related to application time was observed between blinded and unblinded applications (p-value = 0.036). Additionally, significant improvements in the mean and variance were also observed in achieving the

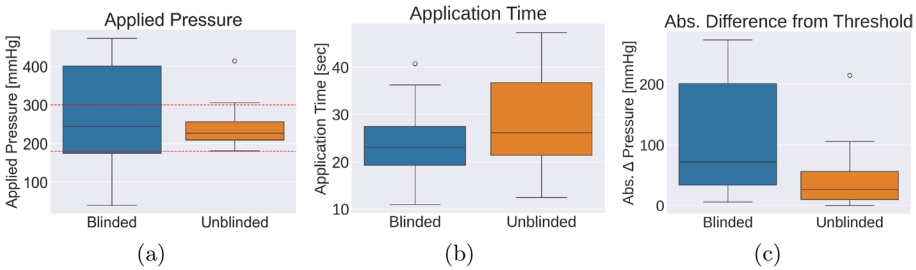

Fig. 5 Blinded and unblinded results from untrained volunteers utilizing the TiMON for emergency tourniquet applications. Red dashed lines indicate the 180 to 300 mmHg range considered for successful tourniquet application. **a** Applied pressure, where mean comparison p-value = 0.26 and variance comparison p-value < 0.0001. **b** Application time, where mean comparison p-value = 0.036 and variance comparison p-value = 0.063. **c** Absolute difference from minimum threshold pressure of 180 mmHg, where mean comparison p-value < 0.0001 and variance comparison p-value < 0.0001

minimum threshold pressure of 180 mmHg (both p-values < 0.0001).

In general, volunteers with no prior experience with emergency tourniquets were found to greatly benefit from the TiMON's assistance. Compared to the briefly trained blinded application, volunteers using the TiMON were able to consistently apply emergency tourniquets at the clinically recommended range of 180 to 300 mmHg albeit with a slightly significant increase in application time.

Discussion

This study described the construction and validation of the TiMON, a real-time force sensing toolkit designed as a simple and intuitive aid for emergency tourniquet applications. The TiMON can be readily attached to many existing emergency tourniquets and allows for straightforward visual assessment of tourniquet tightness. From the results, it can be seen that there is a direct correlation between improved success rates and the decrease of variance that enabled both the military and lay groups to significantly improve their tourniquet application accuracies when using the TiMON, with the civilian group experiencing the greatest improvement. Interestingly, the application speed for trained military personnel was found to be similar with and without the TiMON's visual feedback, however, with soldiers now being able to hit the study's target pressure range with significantly higher rates of success and less variability. Civilian participants also benefited from higher success rates and decreased variability albeit at a slightly significant increase in application time due to the additional readjustments required to reach occlusion pressures. These initial studies demonstrate the TiMON's potential for improving emergency tourniquet applications across both battlefield and civilian settings by reducing the variance and cognitive load required to approximate adequate occlusion pressures.

Scenarios requiring tourniquets are rarely simple, with both military and mass casualty events often taking place in loud, distracting, and highly complex environments. Providing casualty care in such settings is highly challenging, especially when there may be multiple injured soldiers or civilians each requiring individual attention. We envision the TiMON to be helpful in such scenarios through cognitive offloading [32], as use of a TiMON-equipped tourniquet provides rapid, visual, and intuitive feedback of application success, thereby allowing the caregiver to move on to the next individual in need. The inclusion of a timer on the TiMON is also important in the context cognitive offloading, as the TiMON itself can keep track of tourniquet wear time and provide feedback for when the tourniquet must be updated or converted to prevent co-morbidities such as soft tissue injury, compartment syndrome, and amputation [33].

As encouraging as the results are, it is important to highlight some limitations of this study and the TiMON itself. The first is that training on a silicone leg mannequin in a controlled setting will always be vastly different from applying a tourniquet during an actual emergency. Thus it can not be assumed that the improvements seen in this study will be directly transferable to real-life scenarios. For example in real life, there is a high likelihood that the wound may be covered in clothes, armor, or filled pockets which would alter the amount of pressure required to stop the bleed. While it is common protocol to remove these articles of clothing, this may not be possible while under duress. Another limitation of our study is that the silicone mannequins used do not properly simulate bleeding, and despite the TiMON being an excellent tool for tracking applied pressure, it is ultimately the caregiver who must still check for signs of continued bleeding. Finally, in terms of military usage, it is important to note that the TiMON itself represents an additional equipment with its own volume and weight that soldiers must take into account when planning their

loadouts. Future iterations are planned to be smaller and lighter, and we plan to continue working closely with our military collaborators to meet their rigorous standards.

Despite these limitations, future development of the TiMON is expected to offer additional utility as a platform for post-application monitoring of the tourniqueted limb. In current military and civilian settings, once an emergency tourniquet is applied to the injured individual, they are then triaged and transported to definitive care. One challenge that was noted by military medics at AEWE is slippage of the tourniquet, which can occur due to compression of the limb by the tourniquet over time. This soft tissue compression will eventually lead to reductions in the tourniquet's applied pressure, which can result in the tourniquet slipping from the limb since it no longer provides enough pressure to stop bleeding. The TiMON can be used in this setting to ensure that the tourniquet remains at optimal tightness, and it can be configured to provide a wireless, visual, or auditory indicator of reduced applied pressure during triage and transport.

The TiMON device tested in this study was designed with the purpose of measuring both applied pressure and wear time, but can readily be supplemented with additional functionality. For example, the microcontroller used in the TiMON can be configured to drive a speaker towards providing just-in-time auditory prompts and instructions based on the current pressure measurements and guiding otherwise untrained individuals in the accurate application of the tourniquet. If configured with a screen, as in this study, the device can also provide similar and/or simultaneous written guidance, which can be of potential importance in loud environments or situations following blasts where normal hearing may be significantly disrupted. Though not used in this study, additional sensors for motion, blood oximetry, and tissue oxygen concentration [34] can be added to the TiMON to provide acute care information that can be interpreted on-device for triage, transport, and definitive care guidance. Such information may also be important in prolonged critical care scenarios, where definitive care may not be readily obtained within two hours of injury [13, 35]. In this way, devices like the TiMON can provide decision support for tourniquet conversion or replacement, even under challenging settings.

Outside of use at the point of injury, the TiMON provides important value in training settings. Current emergency tourniquet training methods are focused on mannequin applications, which often do not provide quantitative feedback regarding applied tightness. The HapM-ed device is an good training system in that it provides feedback to when a desired pressure is achieved, but unfortunately it does not entirely simulate a real limb. With the TiMON, it is possible to carry out on-human and buddy-on-buddy tourniquet training sessions that better simulate real-life scenarios while incorporating real-time feedback. Such training would be valuable to the individual applying the tourniquet as well as the recipient since both will be able to experience what an adequately applied tourniquet pressure feels like. Additionally, training can be carried out on both the upper and lower extremities. Furthermore, as the TiMON clips on to most emergency tourniquet currently in use, it can be used for training outside of the classroom in complex environments and weather conditions in addition to being used over clothes or uniforms. As demonstrated in our study, it is also possible to use the TiMON in a blinded fashion to monitor tourniquet application during training examinations. This application for guided training and knowledge retainment may be just as important as its use at the point-of-injury.

Next step development of the TiMON device will involve significant miniaturization and ruggedization of the prototype. The initial study device was engineered specifically to validate the proof-of-concept of a tourniquet monitor, but it was not necessarily designed to be small, lightweight, and versatile. The electronics, in particular, can be significantly miniaturized and a switch to low power microcontrollers will allow for years of potential battery life. These engineering steps will require close collaboration with electrical and mechanical engineers, as well as input from military combat medics and emergency medical staff to customize the TiMON for caregiver needs. We anticipate that this collaborative approach will enable a new generation of TiMON devices for training and point-of-injury use to significantly improve the care of wounded soldiers and civilians.

Conclusions

We developed the TiMON as a real-time force sensing toolkit that is designed to seamlessly integrate with pre-existing standard-of-care emergency tourniquets. The TiMON is easy-to-use and allows for the real-time monitoring of applied pressure and occlusion duration in order to assess adequate tourniquet application along with tracking patients for conversion, replacement, or triage.

Trained soldiers and lay volunteers using the TiMON were able to consistently apply emergency tourniquets within a clinically recommended occlusion pressure range with significantly less under and over tightening while minimizing hindrance to their their application speeds. Despite it being their first time using the TiMON, both groups were able to apply emergency tourniquets at significantly improved and consistent success rates compared to their prior training and experience.

Abbreviations

AEWE	Army expeditionary warrior experiments
CAT	Combat application tourniquet
CLS	Combat lifesaver
TCCC	Tactical combat casualty care
TiMON	Tourniquet integrated monitor

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Authors' contributions
The study was designed by JQN, AG, HK, and CLE with clinical input from JP. The TiMON devices were designed, prototyped, and built by JQN, AG, and FB. Subject recruitment and consenting was performed by AG and HK, while IRB documentation was performed by HK. Data collection was performed by JQN, AG, HK, and JP while data analysis was performed by JQN. JQN and CLE wrote the manuscript and editing was performed by JQN, CLE, and HK. All authors have read and approved the manuscript.

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Data availability
Data and analysis for this study is available upon request.

Declarations

Ethics approval and consent to participate
All participants were recruited with informed consent under approval from Mass General Brigham's IRB (2019P001686).

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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