









A low-cost, DIY tourniquet simulator with built-in self-assessment for prehospital providers in Guatemala city

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Abstract

Background: Hemorrhage is the leading cause of preventable death after trauma. In high-income countries first responders are trained in hemorrhage control techniques but this is not the case for developing countries like Guatemala. We present a low-cost training model for tourniquet application using a combination of virtual and physical components.

Methods: The training program includes a mobile application with didactic materials, videos and a gamified virtual reality environment for learning. Additionally, a physical training model of a bleeding lower extremity is developed allowing learners to practice tourniquet application using inexpensive and accessible materials. Validation of the simulator occurred through content and construct validation. Content validation involved subjective assessments by novices and experts, construct validation compared pre-training novices with experts. Training validation compared pre and post training novices for improvement.

Results: Our findings indicate that users found the simulator useful, realistic, and satisfactory. We found significant differences in tourniquet application skills between pre-training novices and experts. When comparing pre- and post-training novices, we found a significantly lower bleeding control time between the groups.

Conclusion: This study suggests that this training approach can enhance access to life-saving skills for prehospital personnel. The inclusion of self-assessment components enables self-regulated learning and reduces the need for continuous instructor presence. Future improvements involve refining the tourniquet model, validating it with first-responder end users, and expanding the training program to include other skills.

KEYWORDS

hemorrhage control, prehospital care, simulator, tourniquet, trauma

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1 | INTRODUCTION

Hemorrhage is the leading cause of preventable death after trauma, responsible for up to 40% of deaths. It only takes minutes for a patient to bleed to death, and decisions on hemorrhage control must be made within seconds. Thus, basic hemorrhage control techniques are among the most effective interventions in early trauma management.^{1–3}

In High Income Countries, first responders (paramedics, police officers, firefighters) and even some laypeople are trained in hemorrhage control techniques,^{4,5} but this is not the current reality in many LMICs. Guatemala, an upper-middle-income country per World Bank grouping,⁶ lacks a formalized EMS system. Three firefighting companies provide emergency prehospital care for the entire country of Guatemala. In total, these three companies are made up of about 8500 firefighters, or “bomberos”, at least half of whom are volunteers. The firefighters of Guatemala attend to every type of emergency, from childbirth to shootings to natural disasters. The medical training the firefighters receive to attend these emergencies is basic, and only one of the three companies provides the option of a formal EMT course which is not mandated. Furthermore, many traumas occur in rural areas where there are no trauma centers, blood banking capability is scarce, and hospital transport times vary dramatically and can be extensive.

Inadequate or incomplete training leads to poor hemorrhage control techniques and, ultimately, ongoing bleeding and preventable death. Practice in hemorrhage control has been shown to be effective, especially for advanced maneuvers which include tourniquet application.⁷ Untrained personnel were found to have unacceptably high rates of tourniquet failure when given tourniquets to deploy without any additional training aside from package instructions. These findings confirm that formalized training and hands-on practice is essential.⁸ Unfortunately, among the barriers to increasing surgical and procedural capacity are the time and financial investments required to train novices, which is often lacking in LMIC settings. In other industries (e.g., aviation),⁹ simulation has been shown to reduce costs and improve outcomes in a crisis. Simulation-based learning in healthcare similarly reflects the potential for reducing errors through skill acquisition and cognitive retention, and is often used in surgical skills training.¹⁰ Furthermore, low-cost training paradigms that include self-assessment are crucial in mitigating the costs of providing in-person training, as the self-assessment allows for independent learning that still results in high-quality education.

In this manuscript, we describe the design and validation of a comprehensive simulator and training platform in hemorrhage control techniques aimed to educate first responders and healthcare personnel in low-resource settings. We report on the validation of the

training platform with novice learners. Our training platform combines a gamified virtual reality system, physical psychomotor training, and built-in self-assessment techniques, obviating the need for expensive, in-person instruction.

2 | METHODS

The Crashsavers team consists of trauma surgeons, doctors, and engineers located in Guatemala, Chile, United States, and Brazil who collectively designed all parts of the methodology and collaborated in execution. The CrashSavers platform uses virtual and physical components to teach hemorrhage control theory, techniques, and self-assessment. Funding for materials, research and development, and salary support was obtained through the Intuitive Foundation's Global Surgical Training Challenge.

2.1 | App and model design

2.1.1 | Mobile application and didactics

We created a mobile application, available for free on both Android and iOS platforms, consisting of didactic materials, videos, and a gamified VR environment for learning and user engagement (see Appendix 1 for QR code to download). The app contains reference resources such as instructional text and links to online resources, as well as instructional videos created by the team to teach hemorrhage control techniques. Completion and review of didactic materials on anatomical knowledge and hemorrhage control techniques are required before the user can progress to virtual reality case scenarios that assess clinical decision-making in hemorrhage scenarios. In virtual reality case scenarios, knowledge checkpoints ensure that users can only advance after accurately completing all tasks (Figure 1). All didactic material was provided in Spanish. The content was either written in Spanish initially, or written in English, translated to Spanish, and then back-translated to English to ensure consistency.

2.1.2 | Physical training model

We developed a physical training model of a lower extremity with active bleeding that learners can use to practice tourniquet application. The model was built using inexpensive materials that are easily accessible. A list of these materials is provided in the supplementary content. The building process was improved through multiple iterations, and instructions on how to build the model are also included in the supplementary content. The user can build the simulator from step-by-step instructions provided in the application (Figure 2).



FIGURE 1 Representative screenshots from mobile application. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/yns.12158)]

A blood pressure cuff is used to calibrate the flow of blood through the model to simulate physiologic pressure and blood flow that can be stopped using reasonable force from tourniquet application. Standard CAT tourniquets were used in this validation as they are widely available for online order at relatively low-cost in Guatemala. In the event that a CAT tourniquet cannot be obtained, the training didactics show the learners that it is possible to create tourniquets out of sheets and boards, or other materials.

2.2 | Study design

We validated the physical training simulator in two phases. The first assessed content validation, meaning an assessment of whether the simulator is representative of

the task at hand, and the second assessed construct validation, meaning whether the simulator adequately teaches the task. Content validation was undertaken to evaluate the experience, realism, and quality of tourniquet placement on the model. Fourteen novices (defined as Guatemalan medical students without prior tourniquet or hemorrhage control experience) and seven experts (defined as Guatemalan trainees or surgeons with experience in in vivo tourniquet application) completed a subjective validation questionnaire tool (Appendix 2).

Construct validation was performed via assessment of 10 pre-training novices and 10 experts using a tourniquet application checklist (Appendix 3). After completion of both content and construct validation, training validation was performed by comparing novice performance of tourniquet application on the physical simulator pre- and post-training on the gamified app. All participants were volunteers. The same novices were used for all validation steps, and the same experts plus an additional three were used for construct validation. The intention behind these initial phases of testing was to achieve response saturation prior to moving on to training validation. This was done so that we could demonstrate a clear benefit of the training system before expanding to testing with end users, the bomb-eros, which is underway.

3 | ETHICS APPROVAL

The study design was reviewed and approved by a Guatemalan national ethics review board, Zugueme. Informed consent was obtained from all individual participants included in the study. IRB submission and approval was not required by the Harvard IRB as this project was considered educational quality improvement.

3.1 | Statistical analysis

Analysis of data was performed using Student's *t*-test through the pooled method for interval variables and Fisher exact test for proportions. All data was processed in Epi Info 7.¹¹

4 | RESULTS

4.1 | Content validation

All participants found the tool useful for training in general and for hemorrhage-treating protocols. All participants agreed that the simulator appropriately motivates learning, and it stimulated critical thinking and decision-making skills. Regarding the simulator tool characteristics, 78.6% of novices versus 85.71% of experts found the tool realistic. 79% of novices and all experts found the blood flux on the simulator realistic. All participants

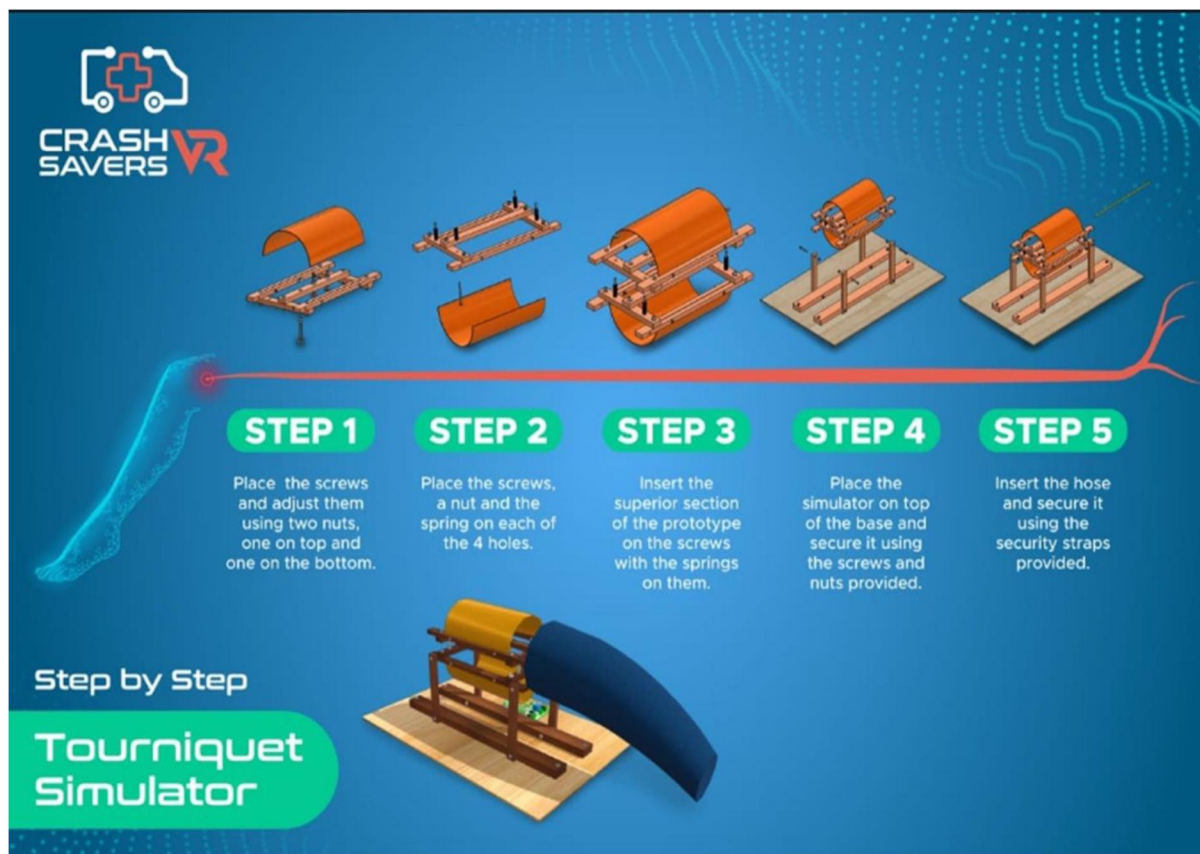


FIGURE 2 Stepwise assembly of the tourniquet simulator. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/wjs.12158)]

responded “Yes” to the question “Are you satisfied with the simulator?” Overall, there were no significant differences between the novice and expert experience with the simulator, including the average scores each group rated the simulator ($p = 0.16$) (Table 1).

4.2 | Construct validation

Results of our program's construct validation are shown in Table 2. We found a difference of 46 s ($p = 0.01$) to control bleeding between pre-training novices and experts. While there were some differences between groups in the following categories, none were statistically significant: “positions the tourniquet in the proper location,” “pulls the self-adhering back tight and securely fastened back on itself as tight as possible,” “secures strap so as not to adhere the band past the windlass clip,” “twists the windlass rod until bleeding stops,” “secures/locks windlass in windlass clip,” “secures the windlass time tag across the clip,” “verbalized need to note time of application of tourniquet,” and “application of the tourniquet resulted in control of bleeding.” Finally, the following tasks showed no difference between groups: “Identified uncontrollable external bleeding,” and “applied the tourniquet to the extremity (inserts through loops or fastens around extremity).”

4.3 | Training validation

When comparing novice performance pre- and post-training, there was an improvement in their ability to apply tourniquets, and the average time to successfully control bleeding was reduced to almost half from 96.3 to 49.5 s ($p < 0.05$). No other skill showed a statistically significant improvement (Table 3).

There was no significant difference in the performance of the experts and post-training novices in successful tourniquet deployment ($p = 0.9$) however, a significantly higher proportion of post-training novices secured the windlass in the windlass clip ($p = 0.02$) and the time tag across the clip than experts ($p = 0.02$). There was no difference found in the performance of the other skills when comparing experts to post-training novices.

5 | DISCUSSION

In this manuscript, we describe a low-cost model for training in tourniquet application that includes both hands-on training combined with virtual case-based, gamified simulation software and in-built self-assessment. Our results show that novices who complete the training curriculum achieve performance

TABLE 1 Content validation questionnaire of novice and expert experiences with tourniquet simulator.

Agree or totally agree with the following statements	% novices (n)	% experts (n)	p-value ^a
This tool is useful for training in hemorrhage treating protocols	100% (14)	100% (7)	-
This tool is useful for training	100% (14)	100% (7)	-
The simulator stimulates learning	100% (14)	100% (7)	-
Average simulator score (SD)	4.85 (0.43)	4.57 (0.52)	0.16
This tool helps with critical thinking and decision making	100% (14)	100% (7)	-
The tool is realistic enough	78.6% (11)	85.71% (6)	0.1
Blood flux is realistic in the simulator	85.7% (12)	85.7% (7)	0.1
I am satisfied with the simulator	100% (14)	100% (7)	-

^aT student test through the pooled method for interval variables and Fisher exact test for proportions.

TABLE 2 Construct validation of tourniquet simulator; pre-training novice versus expert performance.

Participants completed the following tasks	% novices pre-training (n)	% experts (n)	p-value ^a
Identified uncontrollable external bleeding	100% (10)	100% (10)	-
Applies the TQ to the extremity (inserts through loops or fastens around extremity)	100% (10)	100% (10)	-
Positions the TQ in the proper location	80% (8)	100% (10)	0.47
Pulls the self-adhering back tight and securely fastens back on itself as tight as possible	80% (8)	67% (6)	0.63
Secures strap so as not to adhere the band past the windlass clip	90% (9)	67% (6)	0.63
Twists the windlass rod until bleeding stopped	40% (4)	70% (7)	0.37
Secures/locks windlass in windlass clip	80% (8)	40% (4)	0.17
Secures the windlass time tag across the clip	80% (8)	40% (4)	0.17
Verbalized need to note time of application of TQ	20% (2)	0% (0)	0.47
Application of the TQ resulted in control of bleeding	40% (4)	60% (6)	0.66
Average seconds to control bleeding (SD)	96.3 (40.95)	50.3 (20.4)	0.01
Average seconds to verbalize they finished (SD)	102.3 (41.45)	53.9 (23.8)	0.01

^aT student test through the pooled method for interval variables and Fisher exact test for proportions.

equivalent to experts in tourniquet application. Simple but effective manual skills like tourniquet application and wound packing are especially amenable to simulation training. This is true for users in multiple settings,³ and in the case of our trainer, evident in the acceptability of this model shown by the initial phase of testing where expert and novice learners both found the model to be satisfactory and representative of tourniquet application. In terms of our model's ability to discriminate between those who have prior knowledge of tourniquet application (experts) from those who are new to the task (novices), we saw that pre-training novices were unable to complete tourniquet application as efficiently and effectively as experts. This validates that we were able to create a trainer that is sufficiently appropriate and reflective of real-time challenges. Finally, with regards to training validation, the performance of post-training novices was not found to be significantly

different from the experts' performance, even including completion of very specific skills such as securing the windlass time tag across a clip. These findings show that in this sample, our training module was successful in teaching novices a new skill.

Training for tourniquet application and other hemorrhage control techniques do exist—the most widely utilized of these is the Stop the Bleed program created by the American College of Surgeons.⁵ This training program is similar to the program we have created in that it combines didactic education as well as hands-on training on simulators to teach wound pressure, packing, and tourniquet application. However, the simulators created and used by Stop the Bleed are prohibitively expensive for many LMIC learners. Further, the training is delivered in centralized courses that are led by volunteer instructors. Although these courses can be led by any qualified volunteer, this is still an extra step

TABLE 3 Training validation comparing novice performance pre- and post-training and post-training novices versus expert task performance.

Participants completed the following tasks	% pre training (n)	% post training (n)	% pre- and post- training p-value ^a	% experts (n)	% post-training versus experts p-value
Identified uncontrollable external bleeding	100% (10)	100% (10)	-	100% (10)	-
Applies the TQ to the extremity (inserts through loops or fastens around the extremity)	100% (10)	100% (10)	-	100% (10)	-
Positions the TQ in the proper location	80% (8)	100% (10)	0.47	100% (10)	0.47
Pulls the self-adhering back tight and securely fastens back on itself as tight as possible ^a	80% (8)	40% (4)	0.17	67% (6)	0.37
Secures strap so as not to adhere the band past the windlass clip ^a	90% (9)	100% (10)	0.99	67% (6)	0.09
Twists the windlass rod until bleeding stopped	40% (4)	80% (8)	0.17	70% (7)	0.99
Secures/locks windlass in windlass clip	80% (8)	100% (10)	0.47	40% (4)	0.02
Secures the windlass time tag across the clip	80% (8)	100% (10)	0.47	40% (4)	0.02
Verbalized need to note time of application of TQ	20% (1)	10% (1)	1	0% (0)	1
Application of the TQ resulted in control of bleeding	40% (4)	80% (8)	0.17	60% (4)	0.63
Average seconds to control de bleeding (SD)	96.3 (40.96)	49.5 (13.84)	0.003	50.3 (20.4)	0.9
Average seconds to verbalize they finished (SD)	102.30 (41.45)	53.60 (15.76)	0.003	53.9 (22.78)	0.85

^aPercentages may vary due to missing values.

that may be difficult to execute in low-resource settings and requires an educator in a supervisory role—which also incurs higher costs required for infrastructure and instructor reimbursement.

These types of resources to train pre-hospital care providers in hemorrhage control are scarce in Guatemala, as is true in many other low-and-middle-income countries. The particular challenges of training first responders in these settings include barriers particular to the type and level of formal education first responders have, issues of cost, personnel shortages for in-person training, and lack of infrastructure to host centralized training sessions. The completion of this suite of training devices that are self-constructed and self-directed can expand the timely deployment of these techniques by a wide variety of learners, including volunteers, first responders, and hospital-based healthcare personnel in low-resource settings. The impact of this type of self-led skills training is especially valuable in LMICs where costs of training courses and materials are expensive and oftentimes prohibitive.¹² Simulation technology that is based on virtual learning platforms and easily-available products to build psychomotor skills simulators, such as our freely available smartphone application and DIY tourniquet model, presents an alternative to expert-led, in-person training.^{13,14} These technologies may increase access to learning skills that have broad implications in reducing prehospital morbidity and mortality, especially in the setting of traumatic hemorrhage given the burden of injury worldwide.

Self-assessment is also necessary for self-regulated learning. Building in checks for self-assessment (failure and need to restart a clinical case scenario in the gamified VR component, inability to stop blood flow in the physical model using the tourniquet) helps teach proper technique from the initial stages of learning and removes the requirement of instructors to be physically present at all times of assessment.^{15,16} In order to expand upon the self-assessment component of this training tool, we had initially included a pressure sensor in the building of the tourniquet simulator that could more accurately reflect the amount of pressure required to stop flow and give the learner a sense of how it feels to apply appropriate pressure with a tourniquet. However, the cost of purchasing this sensor was prohibitive and required slightly more experience with electronics to properly integrate the sensor with the model, which conflicts with our aim of creating a simulator that does not require an expert to build. Further, we considered conducting a knowledge-based exam as a method of assessing readiness for practice on the tourniquet model, but we found that our target learners, firefighters who often have not had formal higher education, were not well equipped to perform on written or multiple choice exams; thus this method of examination did not accurately reflect their knowledge that they were able to demonstrate in verbal communication.

After this primary training validation was completed, we conducted the same model of training validation within the target training demographic: Guatemalan bomberos. This is underway, and we aim to perform

secondary validation of the tourniquet model to include a greater number of trainees. This step will provide a larger sample size to more precisely refine the training program. In addition to refining the tourniquet model, we plan to create additional simulators and VR training cases for other forms of immediate hemorrhage control; namely, direct pressure, wound packing, pelvic binder placement, and balloon tamponade. Finally, we intend to conduct 1-year followup testing to ascertain knowledge and skill retention.

6 | LIMITATIONS

It is worth noting that with this model, there is a risk of test-retest bias in which the participant may remember or be more familiar with the test when taking it multiple times. This would overestimate the effect of the course on the participant's performance. Additionally, given that the simulators are meant to be created by the trainees themselves with materials found at a local hardware shop, it is difficult to precisely regulate the materials used and their technical characteristics. For example, variations in the tubing used for the "vessel" and springs used for the model can lead to variations in calibration of the device, so that it may not accurately represent physiological blood pressure, or the pressure required to stop bleeding. However, these technical variations may ultimately not confer too significant of a setback, as the goal of the simulation is to teach tourniquet placement techniques and steps of the procedure,^{17,18} which remain unchanged by slight variations in the model.

7 | CONCLUSIONS

We describe the design and validation of a low-cost, do-it-yourself tourniquet simulator and virtual reality app-based training platform. We performed validation of the physical simulator with experts and novices in tourniquet application and real-time hemorrhage control. Novice medical students who used our training program demonstrated improvement in ability to apply a tourniquet and their performance matched that of experts in tourniquet application. Further, trainees showed significant improvement in their tourniquet application skills and time to stop bleeding after completing the training. High quality, low-cost simulation teaching decision-making and psychomotor skills with built-in self-assessment can be used to improve hemorrhage control training in prehospital personnel.

AUTHOR CONTRIBUTIONS

Rashi Jhunjunwala: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; validation; writing –

original draft; writing – review & editing. **Jose Monzon:** Data curation; formal analysis; funding acquisition; investigation; methodology; validation; writing – original draft; writing – review & editing. **Isabella Faria:** Data curation; formal analysis; investigation; methodology; resources; visualization; writing – review & editing. **Gabriel Escalona:** Conceptualization; formal analysis; funding acquisition; investigation; methodology; project administration; software; validation; writing – review & editing. **Analia Zinco:** Data curation; investigation; methodology; project administration; writing – review & editing. **Pablo Ottolino:** Funding acquisition; methodology; supervision; validation; writing – review & editing. **Favio Reyna:** Conceptualization; data curation; formal analysis; investigation; methodology; software; supervision; validation; visualization; writing – review & editing. **Nakul Raykar:** Conceptualization; data curation; funding acquisition; investigation; methodology; project administration; resources; supervision; validation; writing – review & editing. **Sabrina Asturias:** Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; supervision; visualization; writing – review & editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ETHICS STATEMENT

This study was reviewed and approved by an independent ethics committee.

INFORMED CONSENT

Informed consent was obtained from all individual participants included in the study.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.