Step Duration Effects on Blood Loss in Simulated Designs of Tourniquet Use Procedure

John F. Kragh Jr, MD[1]; James K. Aden 3rd, PhD[2]; Michael A. Dubick, PhD[3]*

ABSTRACT

Background: We sought new knowledge by further developing a model of using calculations in the simulation of a first-aid task. The purpose of this study was to develop the model to investigate the performance of tourniquet use in its component steps. **Methods:** We aimed to design an experiment on a desktop computer by mathematically manipulating simulated data in tourniquet use. A time factor of tourniquet use was ranged widely through time challenges in five degrees from ideal to worst performances. Redesigning the task was assessed by time costs and blood losses. **Results:** The step of tourniquet application took 17% of the trial time and securing the tourniquet after bleeding control took the longest amount of the trial time, 31%. A minority of the time (48% [17% + 31%] to apply tourniquet plus secure it) was spent after the tourniquet touched the patient, whereas most of the time (52%) was spent before the tourniquet touched the patient. The step of tourniquet application lost 14% of the total blood lost, whereas no blood was lost during securing the tourniquet, because that was the moment of bleeding control despite securing the tourniquet taking much time (31%). Most (86%) of blood lost occurred before the tourniquet touched the patient. But blood losses differed 10-fold, with a maximum of 2,434mL, which, when added to a pretask indication blood loss of 177mL, summed to 2,611mL. Before redesigning the task, costs of donning gloves and calling 9-1-1 included uncontrolled bleeding, but gloving mitigated risk of spreading pathogens among people. By step and person, redesigns of the task altered the risk-benefit profile. **Conclusions:** The model was useful because it simulated where most of the bleeding occurred before the tourniquet touched the patient. Modeling simulated redesigns of the task, which showed changes in the task's risk-benefit profile by step and among persons. The model generated hypotheses for future research, including the capability to screen candidate ideas among task designs.

Keywords: *tourniquet; first aid, bleeding control and prevention; emergency; task deconstruction, simulation, modeling*

Introduction

Anyone may have to give first aid in care for an injury.[1,2] First-aid experts recommend tourniquets to help control bleeding from limb wounds.[3–5] However, tourniquet indications and use remain somewhat unclear, partly because most data on emergency use are limited[6–8] and of low certainty.[9]

Tourniquet use comprises component steps ordered routinely by design. Step performance in simulation and clinical care can be assessed using metrics. A common metric is the duration between injury and bleeding control. A long time risks shock and death. An understanding of when a step is performed unsatisfactorily can inform where future developments might improve care.

In 2018, we made calculations to inform our understanding of tourniquet use by including the step of donning medical gloves.[10] Extra blood volume lost in simulation while donning gloves was, on average, 239mL. Before steady bleeding was stopped, a relationship among the steps became clear: step times and blood loss were causally linked. However, after bleeding control, times and losses were unassociated. Donning gloves controlled the risk of infection, but uncontrolled bleeding was prolonged by the donning time. In the task's design, the risk of infection was prevented but inadvertently at a cost of blood loss. The design produced a profile of risks that revealed itself: donning gloves harmed the patient by delaying control of bleeding, yet infection control benefited both the caregiver and the patient. A tradeoff of risks and benefits was seen between the steps and the persons.

Given that unexpected tradeoff, we sought new knowledge of other possible tradeoffs by broadening our way of using calculations in simulation. The purpose of this study was to develop the previous mathematical model to investigate the performance of tourniquet use in its component steps. The focus was on duration effects on bleeding.

Methods

This study was conducted in December 2019 within the limits of protocol guidelines at the US Army Institute of Surgical Research. The design was an experiment of simulated data on a desktop computer of tourniquet use by mathematical manipulations. The study was designed to model a time factor of tourniquet use through a wide spectrum of simulated performances. The spectrum was made large to simulate many emergency caregiving episodes with different degrees of time

*Correspondence to 3698 Chambers Pass, Joint Base San Antonio Fort Sam Houston, TX; *or* john.f.kragh.civ@mail.mil
[1]**Dr Kragh** is a researcher of bleeding control at the Institute of Surgical Research (ISR), Fort Sam Houston, TX, and an associate professor in the Department of Surgery, Uniformed Services University of the Health Sciences, Bethesda, MD. [2]**Dr Aden** is a statistician at the Brooke Army Medical Center, Fort Sam Houston, TX. [3]**Dr Dubick** is a researcher and chairperson of the Department of Hemorrhage Control and Resuscitation at the ISR.

challenges to range from ideal to worst. The design included a test of five speeds in tourniquet use from fastest to slowest in five strata simulating minimal to maximal time challenges, respectively. Time challenges for the four nonminimum strata could include various issues like a user struggling in a step, making an error, and undoing a step then redoing it correctly. Problems tend to beget more problems, which may compound into clusters, which may yield maximum times.

The situation was routine first aid and not care under threat, such as gunfire. The patient had one wound. The caregiver was uninjured, undistracted, at arm's length to the patient, and had at hand a tourniquet, a pair of medical gloves, a smartphone, and a marker. The need for tourniquet use was a clinical indication defined by an externally visible blood loss of 177mL, a threshold used previously as a referent amount in bleeding control.[11] The indication is patient determined whereas its detection is user determined; in self-aid, the patient is the user.

The task of tourniquet use was divided into steps in a set order (Table 1). The task was deconstructed by breaking down the procedure of tourniquet use in first aid into its essential components as discrete psychomotor performance units.[12] The order of the 14 steps was routine as experienced in simulation, teaching, and caregiving. The early steps were helping behaviors and late steps were initial care for an injury. The first step was detecting a hemorrhage. The second step included assessing the bleeding. The third was deciding to intervene. The fourth was initiating an emergency call by phoning 9-1-1, a step that bundled finding and unlocking a phone, turning airplane mode off, opening a telephone application, dialing 9-1-1, and reaching a dispatcher. The fifth step included talking with the dispatcher. The sixth ended the call. The seventh through 10th steps were finding a tourniquet, unwrapping it, putting it down, and getting two gloves, respectively. The 11th, 12th, and 13th steps were donning the gloves, picking the tourniquet back up, and applying the tourniquet, respectively. The tourniquet application bundled placing the tourniquet on the limb, routing the band, removing slack from the band, and turning the rod to stop the bleeding. By definition, tourniquet application ended at a key physiologic moment when bleeding was controlled, whereas that step began when the tourniquet first touched the patient. The 14th and final step was called "secure," which meant the time after bleeding was controlled. Secure bundled clipping the rod, tidying the band under the clips, securing the strap to bridge between the clips, and writing the application's time of day with a marker on the strap.

The data on each step had a duration in seconds. Each step's time was estimated as a minimum. The lead author estimated the minimum for each of the 14 steps from publications[13–21] or his experience in caregiving, teaching, and research.[22–24] Each of the 14 minimums constituted a base stratum of data to represent a fast tourniquet use. From this base stratum, four other strata of data were calculated by multiplying the minimums data by four ordinal factors: 2.5, 5, 7.5, and 10. In this way, durations varied 10-fold. The five strata constituted the data set, and the strata times were named minimum, short, moderate, long, and maximum.

To globally maximize the pertinence of the mathematical model, we simulated a common emergency that was a serious threat to life. An uncontrolled bleeding rate was set at 2.5mL/s. This rate is about one-fourth of what our laboratory has routinely simulated at 10.4mL/s in combat with a thigh amputation injury.[10,11,25] That thigh amputation is an uncommon trauma that is a severe threat to life, whereas the US Navy, on occasion, has simulated a rare trauma that is a critical threat to life at a hemorrhage rate of 25mL/s when the student is to learn about combat-like stress.[26]

TABLE 1 *Step Names With Notes on Step Details*

Step Name	Notes, Including Key Bundled Actions
Detect bleed	See, locate, and recognize the bleeding wound
Assess	Judge bleeding severity, rate, amount, and nature
Decide	Make decision about intervening in this situation
Call 9-1-1	Get and unlock phone, dial, and reach dispatcher
Talk with dispatcher	Discuss the emergency
End call	Close application and put phone away
Find tourniquet	Locate and grasp a tourniquet
Unwrap tourniquet	Unwrap the tourniquet from its plastic wrapper
Table tourniquet	Put the tourniquet down
Get gloves	Find and grasp two medical gloves
Don gloves	Put on the pair of gloves
Grab tourniquet	Pick the tourniquet back up
Apply tourniquet	Loop onto limb in place, pull slack, and turn rod
Secure	Clip rod, tidy band, secure strap, and write time

Step metrics included durations and blood losses. For those steps with uncontrolled bleeding, loss data were calculated as the bleeding rate multiplied by the duration of bleeding. For the final step, when bleeding was controlled, the bleeding rate was 0mL/s and blood loss was 0mL. For the 13th step of tourniquet application, the tightening tourniquet incrementally controlled bleeding from 2.5mL/s to 0mL/s; we split the difference to approximate slowed bleeding at 1.25mL/s. Because we set a bleeding rate for each step, the proportions of times for individual steps were to be identical among all strata. Blood loss proportions were similarly identical among strata, but the time-blood proportions differed by step, due to differences in blood loss rates. A trial was the tourniquet use for a given stratum. There were five trials. Trial duration was the sum of its steps. A trial blood-loss volume was similarly summed from its 14 steps as formulated in Equation 1:

$$trial\ volume = \sum (rate \times time) \qquad \text{[Equation 1]}$$

Summation is from step 1 to step 14. Deconstructing the task into its component steps preceded the redesigning of the task. Manipulations of the steps were compared with the original 14 steps in order. Manipulation categories included step deletions, movements, or their combinations. Movement of a step was from its ordered place to another place. The combination was a deletion with a movement. These manipulations were counterfactual to the unmanipulated steps, which served as a basis of comparison. For example, applying the tourniquet before gloves are donned may stop the hemorrhage quickly, whereas donning gloves after bleeding is controlled would mitigate the risk of pathogen transmission when a wound is dressed or a limb is handled.

We made a spreadsheet (Excel 2016; Microsoft, https://www.microsoft.com/en-us/) with 14 column headers as the step names. Each column had four cells for each stratum: the step duration (seconds), step time proportion ([step duration / trial duration] × 100%), step blood loss (step duration × blood-loss rate for that step), and step blood-loss proportion ([step blood loss / trial blood loss] × 100%). The minimum stratum had its data entered. The data of other strata were multiplied by the data of the base stratum. A pair of pie charts displayed a trial with each of its steps as a slice. One pie was time. Another was blood. To frame the speed of tourniquet use in a practical way for learners, another pair of pie charts lumped results by before and after the tourniquet first touched the patient.

Results

Results of the task trials were divided among 14 steps, which had various durations (Table 2; Figure 1). The step of tourniquet application took 17% of the trial time, whereas securing the tourniquet after bleeding control took the greatest proportion of time, 31%. A minority of the time (48% [17% + 31%, to apply the tourniquet plus secure it, respectively]) was spent after the tourniquet touched the patient. Most of the time (52%) was spent before the tourniquet touched the patient.

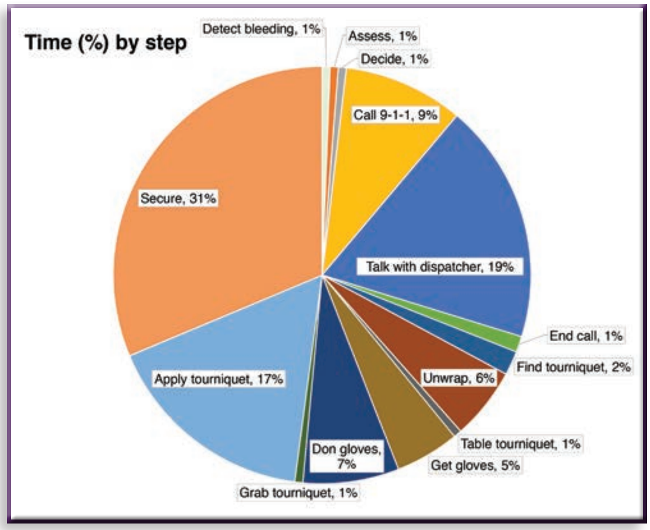
TABLE 2 *Relative Proportion of Time and Blood Loss by Step*

Step	Step Name	Time (%)	Blood Loss (%)
1	Detect bleed	1	1
2	Assess	1	1
3	Decide	1	1
4	Call 9-1-1	9	15
5	Talk with dispatcher	19	31
6	End call	1	2
7	Find tourniquet	2	3
8	Unwrap tourniquet	6	9
9	Table tourniquet	1	1
10	Get gloves	5	8
11	Don gloves	7	12
12	Grab tourniquet	1	1
13	Apply tourniquet	17	14
14	Secure	31	0

Concurrently with time results, the talk with a dispatcher was the step during which the most blood was lost (31%; Table 2; Figure 2). The step of tourniquet application lost 14% of the blood, whereas the secure step resulted in no lost blood because it began at the moment bleeding control began. Secure had no blood loss (0%) but took 31% of the time. The proportion of blood lost before the tourniquet touched the patient was 86%.

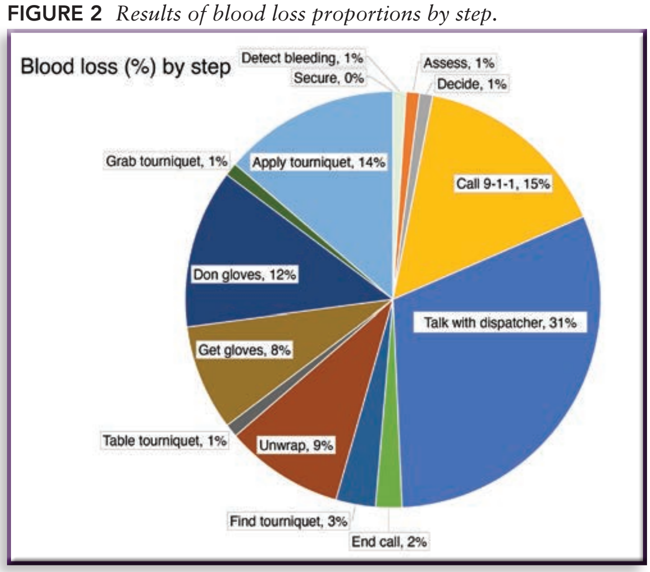
Blood losses accrued over time (Figure 3). From the start of trials at the point of indication, all strata bled linearly at one rate as steady losses occurred. Initially, all plotted lines were superimposed. Over time, each stratum's pathway eventually separated from the others. One by one, each path had a different moment when tourniquet application began to curb losses, to show its pathway making a right turn off the remaining, superimposed lines. The order of each turn was the order of each stratum. The minimum times (faster speed) turned first. The maximum times turned last. Each mapped path had the

FIGURE 1 *Results of time proportions by step.*



The pie chart presents the trial of tourniquet use beginning at the top (12 o'clock); the steps occur in order clockwise. The slices of the pie are labeled with the step name and the proportion of time required at each step.

FIGURE 2 *Results of blood loss proportions by step.*

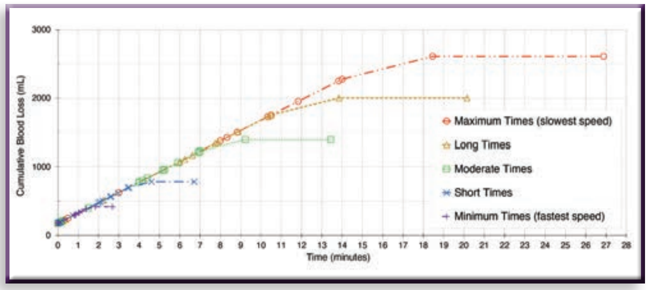


The pie chart shows the tourniquet trial starting at the top; the steps occur in clockwise order. Each pie slice is labeled with the step name and its proportion of blood loss. The greatest volume of loss was during the "Talk with a dispatcher" step. Because bleeding control was the moment secure began, the secure step had no loss. In comparison with Figure 1, where secure time was the maximum (31%) result for the trial, secure blood loss in Figure 2 dropped to the minimum, zero. Comparisons between steps other than apply tourniquet and secure show only two trace differences, which were due to rounding.

same shape: concave downward, which connoted decelerating loss rates as the bleeding was being controlled. When bleeding was stopped, each path reached its plateau.

Results of blood loss by step name, as ordinal data, showed different results than when results were plotted by scaled time. All strata pathways diverged immediately from the point of indication, albeit initially by tiny degrees representing tiny differences in blood-loss volumes. Each path had steps of a different slope than those of other strata, but all strata had a zero slope in the final step, secure. Excepting secure, steps were associated with incrementally widening interstrata results.

FIGURE 3 *Time-course study of blood loss.*



The graph depicts gradual blood loss over time. Cumulative blood loss is shown among five strata of performances, with minimum times connoting fastest speed of first aid and maximum times connoting slowest speed. All strata originate at the bottom left at the point of indication: 177mL of blood loss was the clinical need for tourniquet use in first aid. The graphed simulation results allowed its total blood loss to be seen as the height of the plateau. Each path had a different, scalable height (loss) and length (time). By framing cumulative bleeding by time, the explanatory power is clear that benefits among performance strata for time and blood are by both their amounts and when they occur. Notably, a user with minimum times finishes 10-fold earlier than one with maximum times. The chart shows benefits by increments of speed but also implies that acquired increments of speed may have consumed user time and effort in practice to acquire it beforehand. A return on investment looks promising. By respective stratum in a path metaphor, the differences between sprint, run, trot, hike, or walk made five different mesas to climb. Tracing one's eye backward along the paths, one imagines watching a movie in reverse to see regression to the trailhead at the edge of the pool of blood (177mL), the indication. If the down climb was to be made in forward direction and forward time, the return trip would end in a bloody puddle (420mL to 2,460mL).

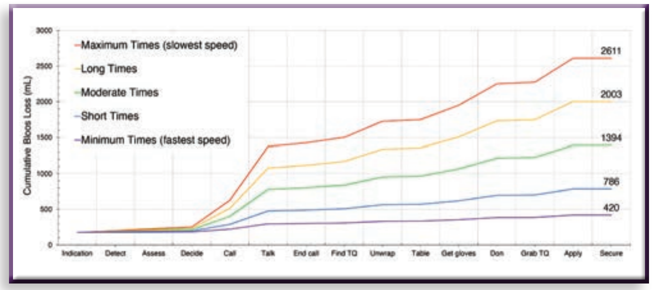
The largest accrual of blood loss in this stepwise plot occurred during the talk with the dispatcher (Figure 4).

Results of time and blood loss by step name showed proportionate results for each stratum of performance as set by the math (Tables 3 and 4). The 10-fold differences in duration and blood loss ranged widely, and the maximum blood loss was 2,434mL. When a 2,434mL loss was added to the prestep indication of 177mL, the sum was 2,611mL.

Next, the results of task manipulation showed potential value by redesigning the task. Users may unwrap tourniquets beforehand to save time by deleting that step from first aid. If one unwrapped a tourniquet beforehand, the deletion of that step shortened trial time by 6% and prevented 9% of blood loss. Because the deleted step preceded putting the tourniquet down to table it, the deletion now makes that tabling step nonsense. An added value of the deletion was that its consequence naturally made some following steps less relevant or superfluous. In manipulating the task by reordering steps, if one moves the step of "find tourniquet" to after donning gloves, then another two steps, table tourniquet and grab tourniquet, may also be deleted. The deletion of these two steps sum to 1% of time and 2% of blood loss, after rounding. The net savings of deleting all three steps in trialing this redesigned task are 7% of time and 11% of blood loss.

If one not only deletes the step of unwrapping the tourniquet but also moves the step of don gloves to after the moment bleeding is controlled, another reordering of steps may further improve results; donning gloves may benefit a tourniquet user during other first-aid actions like splinting or handling the limb to which the tourniquet has been applied, working

FIGURE 4 *Cumulative blood loss by step among five strata of performances.*



The graph depicts cumulative blood loss. The 14 steps are on the horizontal axis and are preceded by indication. Indication is a prestep as onset point of clinical need after which task steps are to be performed. All performance strata originate at the bottom left at the point of indication at 177mL of blood loss. Cumulative blood loss including that 177mL is plotted on the vertical axis among strata with minimum times as the fastest speed and maximum times as the slowest speed. Steps are ordinal, not time scaled.

TABLE 3 *Time Results Among Performance Strata by Step Order*

	Time (s)				
Step Name	Minimum	Short	Moderate	Long	Maximum
Detect bleed	1	3	5	8	10
Assess	1	3	5	8	10
Decide	1	3	5	8	10
Call 9-1-1	15	18	75	113	150
Talk with dispatcher	30	75	150	225	300
End call	2	5	10	15	20
Find tourniquet	3	8	15	23	30
Unwrap tourniquet	9	23	45	68	90
Table tourniquet	1	3	5	8	10
Get gloves	8	20	40	60	80
Don gloves	12	30	60	90	120
Grab tourniquet	1	3	5	8	10
Apply tourniquet	27	67	134	201	267
Secure	51	126	253	379	505
Total	161	403	806	1,209	1,612

in a bloody scene, moving or positioning the patient, or performing other lifesaving interventions. Reordering the steps of getting gloves (5% of time) and donning gloves (7% of time) to when no bleeding occurs results in faster control of bleeding by moving 12% (5% + 7%) of task duration from before bleeding control to after secure. Such reordering necessarily prolongs postcontrol time by that 12%. Such a reordering eliminates blood losses of those two steps (with their losses of 8% and 12%, respectively), thereby additionally lessening task blood loss by 21%, after rounding. The net savings of deleting all the three steps and moving two in trialing this redesigned task are 21% plus the 11% saved previously, to yield 32% blood saved.

Taking redesigns further may improve results more if, altogether, one unwraps a tourniquet beforehand, dons gloves after secure, and moves the call to dispatch to postcontrol time. Those manipulations additionally reorder the steps of "call 9-1-1," "talk with dispatcher," and "end call" (9%, 19%, and

TABLE 4 *Blood Loss Results Among Performance Strata by Step Order*

	Blood Loss (mL)				
Step Name	Minimum	Short	Moderate	Long	Maximum
Detect bleed	3	6	13	19	25
Assess	3	6	13	19	25
Decide	3	6	13	19	25
Call 9-1-1	38	94	188	281	375
Talk with dispatcher	75	188	375	563	750
End call	5	13	25	38	50
Find tourniquet	8	19	38	56	75
Unwrap tourniquet	23	56	113	169	225
Table tourniquet	3	6	13	19	25
Get gloves	20	50	100	150	200
Don gloves	30	75	150	225	300
Grab tourniquet	3	6	13	19	25
Apply tourniquet	33	84	167	251	334
Secure	0	0	0	0	0
Sum	243	609	1,217	1,826	2,434
Sum + indication (177mL)	420	786	1,394	2,003	2,611

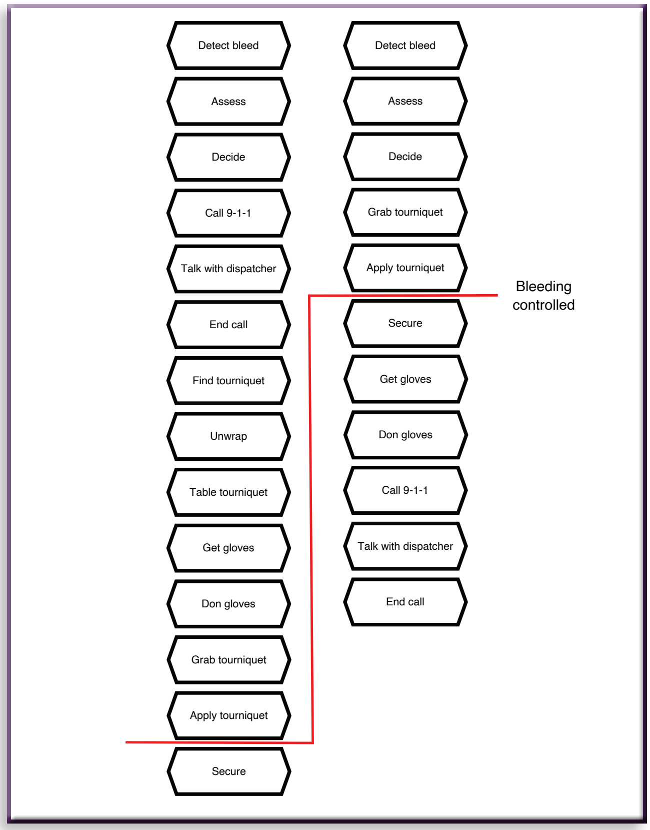
1% of time, with 15%, 31%, and 2% of blood loss, respectively), which sum to save no time yet save 48% more blood (Figure 5). This 48% adds to 32% saved, as explained in the previous paragraph, to a total of 80%. In trialing these manipulations in the redesigned task, bleeding during its steps was reduced by 80% (e.g., [2,434mL–484mL] / 2,434mL] × 100%), as framed by the task performed (Figure 6). To frame by the patient's need, including the 177mL prestep indication, adding that amount to the numerators and denominators changed the savings to 73% (e.g., [2,434mL–661mL] / 2,434mL] × 100%).

Discussion

The main finding of this study was that the developed mathematical model generated new knowledge in simulated redesigning of the first-aid task of tourniquet use. As developed so far, the model worked to vet ideas in a screening process while generating data on which to better characterize or understand the issue of emergency caregiving for limb-wound hemorrhage. The model calculations used introduce a way to screen hypotheses in what managers of research have named "knowledge readiness" at a level 2, screening hypotheses or ideas, on a scale of maturation from 1 to 9, from observation and literature reporting to validation of the knowledge after its translation into teaching or caregiving.[27] Roughly paralleling technology readiness levels for materiel, knowledge readiness levels designate the stage of development of knowledge products such as the model used here. Whereas level 2 is immature, level 3 could include a consensus among several unrelated manikin studies showing a limited proof of concept in the use of the model.

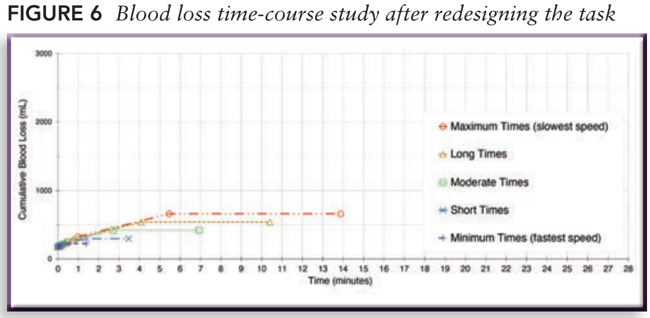
Two minor findings of this study dealt with redesigning the task and its consequences. Redesigns showed usefulness in the model by its demonstrated ability to measure risk-benefit

FIGURE 5 *The step structure before and after redesigning the task.*



The two step structures have the moment of bleeding that is controlled at the end of the step called "Apply tourniquet." The redesigned task has fewer steps to stop the bleed. The redesign may save time and blood yet increase risk of exposure to pathogens. The red lines denote bleeding control, the time of which differs by the left and right task designs. Control at left is late, right is early.

FIGURE 6 *Blood loss time-course study after redesigning the task*



This graph is scaled the same as the chart in Figure 3 and both plot blood loss scaled to time. However, this chart has five performance strata plotted for the final manipulation reported in the results section. The steps "unwrap tourniquet," "table tourniquet," and "grab tourniquet" were deleted. After the secure step, the steps moved to "get gloves," "don gloves," "call 9-1-1," "talk with dispatcher," and "end call." This redesigned task led to less blood loss and shorter tasks but more postcontrol time. Although changes are proportionally equal by strata, the visual display of quantitative information includes a narrowed spectrum of performance indicating increased speed and raw changes are greater for longer times and larger blood losses. The findings typify improved performance. Preparation to do first aid by unwrapping a tourniquet and designing the task, as done here, appear to promise improved results for time and blood.

tradeoffs between steps and people. Much blood loss occurred early in the emergency, when bleeding was uncontrolled, and the largest loss found in these trials risked death from hemorrhagic shock. The task of tourniquet use, among its 14 steps, had 52% of its time spent and 86% of blood loss ocurring before the tourniquet touched the patient. The finding of how much bleeding occurred before the tourniquet touched the patient was coherent with the research of the initial model,[10] where that amount was 406mL of 508mL, or 80%. Here, extra steps added time and bleeding. Because bleeding rates differed 4.16-fold between the prior and present studies yet bleeding proportions differed only 1.15-fold, the idea of proportionate loss before the moment of bleeding control may be more robust than we previously thought. The present findings consolidated with those of its predecessor,[10] because patient bleeding came at the cost of steps such as donning gloves and calling 9-1-1 while gloving mitigated risk of pathogen transmission among people. The step of greatest accrual of simulated blood loss, 31%, was in talking with a dispatcher, and this step is sometimes recommended to be done before bleeding is controlled. Speed in controlling hemorrhage matters. The design of the task also matters. In this study, the last redesign saved little time but much blood. This method of redesigning a task added a tool to the simulation toolkit.

Another consequence of redesigning the task was that the user became hands-free of the tourniquet by earlier control of bleeding. A benefit of being hands-free sooner is that those first-aid providers may attend more patients or perform additional lifesaving tasks sooner, such as packing another wound or holding compression on another bleeding wound. Also, hands-free first-aid providers are mobile, such as among mass casualties or around an accident scene, whereas those still applying a tourniquet remain at the patient's limb. Faster tourniquet use may help more people than the first patient and the tourniquet user. On the other hand, a good time to learn how to pull up your global positioning system (GPS) coordinates to report them to the dispatcher is not when you are talking on the phone with the dispatcher. There are many ways to slow aid, and there are very few ways to speed aid. Both are true because there are multiple essentials to skill. Speed is one.[28] The 9-1-1 call is part of the civilian task that makes the call findings more relevant to the public than to military personnel, whereas the savings of time and blood loss are more relevant to the military.

Limitations of this study are numerous, due to its design. The knowledge generated is of a low certainty because it tested a hypothesis in a mathematical model that may be implementable in manikin research. Within the model itself, only in a perfect world are the onset of clinical indication and its detection coincidental, yet that is how we train most learners. Coincidence negates bleeding for the onset-to-detection interval to bias feedback as if users perform optimally. For the tourniquet task, it is unclear how well first-aid providers appreciate the number and types of steps. In the present model, every step and trial was mechanically successful without error. Control achieved was never lost. Research simulations are not real clinical performances, and readers of research reports should not apply the present findings directly to the real world. The math model remains in the idea incubator and is not ready for implementation, such as in teaching. The math model used has limited breadth and depth so far, and such limitations beg additional work.

Future directions of scholarly work are numerous. By simulating a redesign of the first-aid task of tourniquet use by manipulating its steps, some promising findings may be worthy of additional research and development. Tests in manikin exercises may screen promising ideas for additional development toward improving care. For example, if first-aid providers unwrap their tourniquet in preparation for emergencies, the deletion of that step may save certain amounts of time and blood, which may inform decisions of doctrine. Geolocation technology awareness among the public, use rates, and application skills in pulling up GPS coordinates may help inform best instructional practices. Knowing that the largest accrual of losses in this model occurred during the phone-call step may inform the development of dispatching best practices.[29] Dispatch time-segment data or its summary estimates could inform the selection of data for entry into math models. Time data for performances among user cohorts, consensus for operational definitions of steps, bleeding-rate data for limb wounds or specific lesions (e.g., artery, vein, muscle, bone, or combinations), and bleeding-rate models may aid investigators in developing ideas of how math models may be refined for improved validity and reliability by being better grounded in real data and by making the assumptions of the models better understood. A limited proof-of-concept type of work may be routinely expected next in developing candidate designs, such as in a study of manually performed steps upon a manikin comparing results of differently designed tasks tested in a randomized order. The development of an autonomous tourniquet may help.[30] Ongoing coordination between dispatchers and other caregivers may aid in developing doctrinal refinements.

Conclusions

In this study, we developed a mathematical model that generated new knowledge in simulated redesigning the first-aid task of tourniquet use. Modeled redesigns of the task revealed risk-benefit tradeoffs between steps and people. Most blood loss occurred before the tourniquet touched the patient, when patient bleeding came at the cost of donning gloves and calling 9-1-1, whereas gloving mitigated risk of pathogen transmission among people.

Funding

This project was funded by the US Army Medical Research and Development Command.

Disclaimer

The views expressed in this article are those of the authors and do not reflect the official policy or position of the US Army Medical Department, Department of the Army, Department of Defense, or the US Government. The authors are employees of the US Government. This work was prepared as part of their official duties and, as such, there is no copyright to be transferred.

Disclosure

The authors have indicated that they have no financial relationships relevant to this article to disclose.

Author Contributions

All authors participated in study conception and design. J.F.K. resourced, managed, and oversaw the study. J.F.K. generated the study data, and J.F.K. and J.K.A. analyzed the data. All authors participated in writing the manuscript and approved the final version.

References

1. **Gates JD, Arabian S, Biddinger P, et al.** The initial response to the Boston marathon bombing: lessons learned to prepare for the next disaster. *Ann Surg*. 2014;260(6):960–966.

2. **Markenson D, Ferguson JD, Chameides L, et al.** Part 13: First aid: 2010 American Heart Association and American Red Cross International consensus on first aid science with treatment recommendations. *Circulation*. 2010;122(16S2):582–605.
3. **Bulger EM, Snyder D, Schoelles K, et al.** An evidence-based prehospital guideline for external hemorrhage control: American College of Surgeons Committee on Trauma. *Prehosp Emerg Care*. 2014;18(2):163–173.
4. **Rossaint R, Bouillon B, Cerny V, et al.** The European guideline on management of major bleeding and coagulopathy following trauma: fourth edition. *Crit Care*. 2016;20:100.
5. **Spahn DR, Bouillon B, Cerny V, et al.** The European guideline on management of major bleeding and coagulopathy following trauma: fifth edition. *Crit Care*. 2019;23(1):98.
6. **Singletary EM, Charlton NP, Epstein JL, et al.** Part 15: First Aid: 2015 American Heart Association and American Red Cross guidelines update for first aid. *Circulation*. 2015;132(18S2):574–589.
7. **Zideman DA, Singletary EM, De Buck ED, et al.** Part 9: First aid: 2015 international consensus on first aid science with treatment recommendations. *Resuscitation*. 2015;95:e225–261.
8. **Kauvar DS, Dubick MA, Walters TJ, et al.** Systematic review of prehospital tourniquet use in civilian limb trauma. *J Trauma Acute Care Surg*. 2018;84(5):819–825.
9. **Charlton NP, Swain JM, Brozek JL, et al.** Control of severe, life-threatening external bleeding in the out-of-hospital setting: a systematic review. *Prehosp Emerg Care*. 2020 Mar 24:1–49.
10. **Kragh JF Jr, Newton NJ, Tan AR, et al.** New and established models of limb tourniquet compared in simulated first aid. *J Spec Oper Med*. 2018;18(2):36–41.
11. **Kragh JF Jr, Aden JK 3rd, Lambert CD, et al.** Assessment of user, glove, and device effects on performance of tourniquet use in simulated first aid. *J Spec Oper Med*. 2017;17(4):36–42.
12. **Gallagher AG, Ritter EM, Champion H, et al.** Virtual reality simulation for the operating room: proficiency-based training as a paradigm shift in surgical skills training. *Ann Surg*. 2005;241: 364–372.
13. **Schreckengaust R, Littlejohn L, Zarow GJ.** Effects of training and simulated combat stress on leg tourniquet application accuracy, time, and effectiveness. *Mil Med*. 2014;179(2):114–120.
14. **Sanko S, Mindlin D, Eckstein M.** Abstract 74 Tourniquet use in a civilian out-of-hospital setting: the Los Angeles experience. *Ann Emerg Med*. 2015;66(4S):26.
15. **Heldenberg E, Aharony S, Wolf T, et al.** Evaluating new types of tourniquets by the Israeli naval special warfare unit. *Disaster Mil Med*. 2015;1:1.
16. **Higgs AR, Maughon MJ, Ruland RT, et al.** Effect of uniform design on the speed of Combat Tourniquet Application: a simulation study. *Mil Med*. 2016;181(8):753–755.
17. **Baruch EN, Kragh JF, Berg AL, et al.** Confidence-competence mismatch and reasons for failure of non-medical tourniquet users. *Prehosp Emerg Care*. 2017;21(1):39–45.
18. **Moussa M, Dugan J, Jones C, et al.** How competent are emergency medicine residents in applying commercial tourniquets? A pilot study. Research Forum Abstract 33. *Ann Emerg Med*. 2018;72(4S):16.
19. **Pasley AM, Parker BM, Levy MJ, et al.** Stop the bleed: does the training work one month out? *Am Surg*. 2018;84(10):1635–1638.
20. **Tsur AM, Binyamin Y, Koren L, et al.** High tourniquet failure rates among non-medical personnel do not improve with tourniquet training, including combat stress inoculation: a randomized controlled trial. *Prehosp Disaster Med*. 2019;34(3):282–287.
21. **Orlas CP, Parra MW, Herrera-Escobar JP, et al.** The challenge of implementing the "Stop the Bleed" campaign in Latin America. *J Surg Res*. 2020;246:591–598.
22. **Kragh JF Jr, Walters TJ, Baer DG, et al.** Practical use of emergency tourniquets to stop bleeding in major limb trauma. *J Trauma*. 2008;64(2S):38–49.
23. **Kragh JF Jr, Walters TJ, Baer DG, et al.** Survival with emergency tourniquet use to stop bleeding in major limb trauma. *Ann Surg*. 2009;249(1):1–7.
24. **Kragh JF Jr, Beebe DF, O'Neill ML, et al.** Performance improvement in emergency tourniquet use during the Baghdad surge. *Am J Emerg Med*. 2013;31(5):873–875.
25. **O'Conor DK, Kragh JF Jr, Aden JK 3rd, et al.** Cat on a hot tin roof: mechanical testing of models of tourniquets after environmental exposure. *J Spec Oper Med*. 2017;17(1):27–35.
26. **Roach M.** Chapter 6. Carnage under fire: how do combat medics cope. In: Roach M. *Grunt: the Curious Science of Humans at War*. New York, NY: W. W. Norton & Company; 2016: 111.
27. **Engel CC, Silberglitt R, Chow BG, et al.** Development of a knowledge readiness level framework for medical research. Santa Monica, CA: RAND Corporation; 2019.
28. **Johnson HW.** Skill = speed × accuracy × form × adaptability. *Percept Mot Skills*. 1961;13(2):163–170.
29. **McFadden J.** Cellphone trouble. *J Emergency Dispatch*. July 11, 2018. https://iaedjournal.org/cellphone-trouble/. Accessed 16 January 2020.
30. **Kragh JF Jr, Darrah M, Gradilla C, et al.** An intelligent tourniquet system to stop traumatic extremity bleeding. *Am J Emerg Med*. 2014;32(11):1419–1421.