

Single versus Double Routing of the Band in the Combat Application Tourniquet

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ABSTRACT

Background: Common first aid tourniquets, like the Combat Application Tourniquet (CAT) of a windlass and band design, can have the band routed through the buckle in three different ways, and recent evidence indicates users may be confused with complex doctrine. **Objective:** The purpose of the present study is to measure the differential performance of the three possible routings in order to better understand good tourniquet practice. **Methods:** A training manikin was used by two investigators to measure tourniquet effectiveness, time to stop bleeding, and blood loss. **Results:** The effectiveness rate was 99.6% (239/240) overall. Results were similar for both single-slit routings (inside vs. outside, $p > 0.05$). Effectiveness rates (yes-no results for hemorrhage control expressed as a proportion of iterations) were not statistically different between single and double routing. However, the time to stop bleeding and blood loss were statistically different ($p < 0.05$). **Conclusions:** CAT band routing, through the buckle either singly or doubly, affects two key performance criteria: time to stop bleeding and volume of blood lost. Single routing proved to be faster, thereby saving more blood. Learning curves required to optimize user performance varied over 30-fold depending on which variable was selected (e.g., effectiveness vs. blood loss).

KEYWORDS: hemorrhage; first aid; trauma; damage control; emergency medical services

Introduction

Tourniquets, in particular the standard issue Combat Application Tourniquet (CAT, Composite Resources, Rock Hill, SC), are currently in the first aid kits of deployed soldiers.^{1,2} The CAT has a band that goes around a limb, passes through a buckle, and, after slack removal, secures to itself.³⁻⁵ This band is then tightened by windlass turns

to stop wound bleeding. The band can be passed through the double-slit buckle in three ways — singly through either one of the two slits or through both slits. Single and double routings have been advised for one-handed and two-handed application, respectively.³⁻⁵ Recently, evidence emerged that CATs applied in the field had patterns of single and double routing at rates that mismatched doctrinal expectations.^{1,6-8} Single routing was used 41% of the time (18% in upper extremity, 23% in lower extremity); all three of these proportions exceeded expectations of doctrinal use one-handed self-application (about 1% of use) or application by anyone including other users to upper extremities (about 16%).^{1,2} Because 17% was the maximum expectation (1% + 16%), single routing use of 41% doubled (41%/17%, 2-fold) the expectation.¹ Users may be confused by complex instructions (multiple pages, multiple slits to choose in the buckle) or complicated doctrine (one- vs. two-handed application, upper vs. lower extremity use, and Care Under Fire vs. Tactical Field Care).

The present buckle configuration and its routing instructions were based on a field experience of a CAT inventor (co-author T.W.) who related a case of slippage of the band that led to redesign and double routing. However, the cause of that slip was unclear as it slid distal over the cone-shaped part of the mid-thigh due to aggressive transport of the casualty away from gunfire. In more than a decade of war, with thousands of CAT uses, slippage of the self-adhering band along the line of pull has been neither reported nor confirmed. Given this information, does it make a difference whether the band is single-routed or double-routed? Also, single routing of the band was first compared to answer a minor question posed from the field: Does it make a difference if single routing is done through the inside or outside slit? To answer the questions, an experiment was designed to measure the differential performance of the three possible

Note: Study performed at U.S. Army Institute of Surgical Research (USAISR).

routings in order to better understand good tourniquet practice.

Methods

The protocol was approved by the U.S. Army Institute of Surgical Research Regulatory Office as a laboratory protocol (Practical Biomedical Engineering Research of Tourniquet Application and Use, L-12-009). The present study was executed in May through August 2012. This study was conducted under a protocol reviewed and approved by the regulatory office and in accordance with good clinical practices. Investigators included a pair of cadets and a tourniquet researcher. The iterations of tourniquet testing were performed by two users: a cadet who had entry-level tourniquet training and a clinician-scientist who was a tourniquet expert. Both users were oriented to correct CAT use and manikin testing.

The HapMed Leg Tourniquet Trainer (CHI Systems, Fort Washington, PA), a simulated right-thigh body segment (leg number 000F) with an amputation injury just proximal to the knee, was selected as the testing device. The medial hip-pelvic area had an embedded computer interface that included a cellular telephone-like touchpad. The software (version 1.9) allowed the leg to stand-alone and be operated by user input through finger touch on the pad. Scenario 1 was used (the casualty had a small build and the setting was Tactical Field Care, a setting that resembles civilian emergency care). The thigh was laid on a desk in the laboratory and was operated in accordance with the manufacturer's instructions. The manikin had no fluids to simulate blood, but bleeding was represented by red lights that transilluminated the wound. The number of lights illuminated represented the intensity of bleeding. All lights on meant no control of bleeding; no lights on meant bleeding had stopped. The arterial pulse was noted when palpable in the popliteal and femoral artery areas. The user tightened the tourniquets, CAT Generation 6 (e.g., windlass turned) until simulated bleeding stopped. The system reports the blood loss volume as calculated using a linear equation from the arterial capacity and number of pulses before hemorrhage control. Tourniquet devices, users, test iterations, and outcomes were uniquely identified. The iteration began with a device on the desk-top and not applied to the thigh and ended when the user touched the touchpad button. The touchpad readout included iteration bleeding control or not, the time to stop bleeding, and blood loss. The measurement of the time to stop bleeding started when the iteration began and stopped when the manikin sensed that the thigh was losing no more blood. Effectiveness was defined as the stoppage of blood loss and the termination of distal pulse.

The CAT has a band that goes around the limb, passes through a buckle, and secures with hook-and-loop

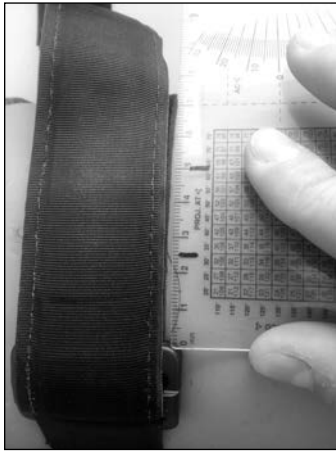
fasteners on one side of the band by self-adhering on contact in order to hold the removal of all slack. This band is then tightened by windlass turns to stop wound bleeding. The band can be passed through the double slit buckle (referred to by the manufacturer as the friction adapter) in three ways. It can be routed singly through either one of the two slits or through both slits. Single and double routings are instructed for one-handed and two-handed application, respectively. The one-handed configuration allows a casualty to self-apply the CAT if an upper extremity is incapacitated. To facilitate this self-care option, the manufacturer packaged the CAT is packaged in a single-routed configuration and recommends that the CAT be carried this way in the field. Double routing is intended primarily to stop the self-adhering band from having its hook-and-loop fasteners slip along the line of pull; i.e., the longitudinal axis of the band. The band has a surface material called Omni-Tape (a Velcro brand) of hook-and-loop fasteners woven on a single side of the band. When the band is folded back onto itself, the hooks-and-loops face each other and engage on contact. This single-component closure offers the benefits of reduced lint contamination and a softer feel against the skin compared to traditional hook-and-loop fasteners. The number of turns was recorded. One windlass turn was a 180° excursion arc, the limit of wrist supination in turning of the windlass. The user, by convention, re-grips the windlass after each 180° arc; so 180° is considered one turn.

An assessment was also conducted of how easy it is to make the device ineffective (a surrogate of device slippage or malfunction; e.g., the self-adhering band is peeled back or the CAT is knocked off in casualty transport). To test the required contact area of the self-adhering band, a CAT was secured around the manikin as described above. The self-adhering band was placed directly on top of itself, with no folds or overlaps to ensure that the entire width of the band was in contact.

A ruler was placed alongside the band to measure self-adhering band contact with itself, with the zero measurement beginning at the outside end of the buckle (Figure 1). The self-adhering band was then slowly peeled back off itself until the self-adhering band slipped. Slippage was defined as visible loosening of the self-adhering band. The length of the contact area was recorded in millimeters. Iterations ended when the tourniquet loosened (e.g., the band lost its tension when it slipped through the buckle).

The centerpiece of the present study was a comparison of single versus double routing for differential time to stop bleeding and blood loss volume. Because there are two slits in the buckle, the comparison for single routing by each of its two options was made. One slit is the near

Figure 1 Procedure for Measuring Contact Area



Note: Photograph showing an arm tourniquet being measured for distance. The ruler was placed alongside the Combat Application Tourniquet's self-adhering band (black strap) to measure the distance of surface area contact between the two faces of the band's hook-and-loop fasteners.

slit (also called the inside opening or slit) because it is nearer the working end of the tourniquet, with its stabilization plate and windlass, whereas the outside (or far) slit is farther away (Figure 2). The double routing trials had the band go through both the inside and the outside slit in that order.

Statistical analysis included use of descriptive statistics (means, medians, standard deviation, minimum, maximum, percentiles), χ^2 test for comparison of turn number data, and Wilcoxon's two-sample test for comparison of means among continuous data. Significance level was set at $p = 0.05$.

Results

Effectiveness rates were 99.6% (239/240) overall for both users pooled in that these iterations had hemorrhage controlled. Each individual user's effectiveness rate was not statistically different from the other's rate.

Single routing of the band was first compared to determine whether it makes a difference if single routing is done through the inside or the outside slit. Eighty single-routed iterations in both options, inside and outside, were completed: 159 of 160 iterations were effective. Additionally, all measured performance parameters were not statistically different. Performance included time to stop bleeding, blood loss, and band contact length (Table 1, $p < 0.05$). Because the two results were similar and the inside and outside routings were both single routings, the two data sets (inside and outside single routing) were pooled for the next comparison: single routing versus double routing.

Effectiveness rates (i.e., yes-no results for hemorrhage control expressed as a proportion of iterations) were not statistically different between single and double routing. However, the time to stop bleeding, blood loss, and

Figure 2 Inside vs. Outside Slit in CAT Buckle



Note: Photograph shows the tourniquet's buckle inside and outside slits. The tourniquet's inner strap is within the outer self-adhering band and has creases as it passes through the windlass and then dives into and out of the stabilization plate's two slits before reentering the self-adhering band.

Table 1 Results of Single Band Routing Through the Inside or Outside Buckle Slit

Single Routing by Slit	Parameters	Time to Stop Bleeding (sec)	Blood Loss (mL)	Contact Length (mm)
Near slit	Mean	19	93	25
	± SD	± 6.2	± 19.3	± 5.2
	Median	17	91	26
	Minimum	11	33	18
	Maximum	39	162	33
	(N)	(80)	(80)	(10)
Outside slit	Mean	19	92	27
	± SD	± 6.6	± 25.7	± 7.2
	Median	19	86	25.5
	Minimum	11	46	18
	Maximum	39	161	41
	(N)	(80)	(80)	(10)
Comparison of means, p value		0.9999	0.7812	0.4861

Note: N is number, sec is seconds, mL is milliliters, and mm is millimeters.

required contact length were statistically different (Table 2; all p values < 0.05 ; Figure 3). Time to stop bleeding increased from a mean of 19 seconds with single routing to a mean of 26 seconds with double routing. This was associated with an increase in blood loss from a mean of 93mL to 144mL. Band contact was not a factor in any double-routed iteration because no slippage occurred even when there was no hook-and-loop fastener contact.

Additionally, each user exhibited a clear learning curve for time to stop bleeding and blood loss (Figures 4 and 5). Much learning was evidenced as a change in performance

Table 2 Tourniquet Data by Whether Band Routing Was Single or Double

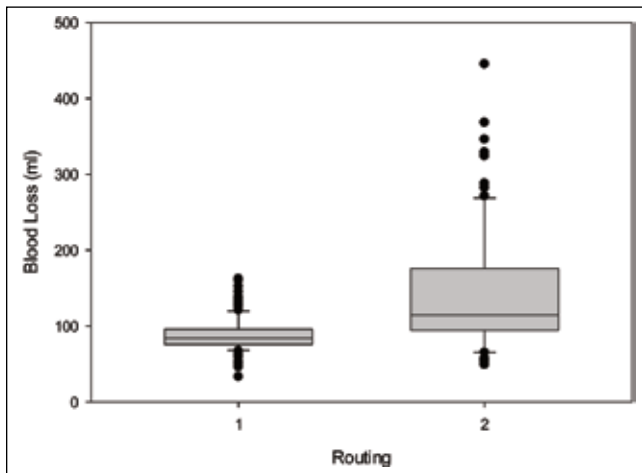
Routing: Single Versus Double	Parameters	Time to Stop Bleeding (sec)	Blood Loss (mL)	Contact Length (mm)
Single (inside and outside slit data pooled)*	Mean ± SD	19 ± 6.4	93 ± 22.7	26 ± 6.2
	Median	18	87.5	26
	Minimum	11	33	18
	Maximum	39	162	41
	(N)	(160)	(160)	(20)
Double	Mean ± SD	26 ± 11.0	144 ±	0 ± 0*
	Median	21.5	79.7	0*
	Minimum	13	114.5	0*
	Maximum	63	49	0*
	(N)	(80)	445 (80)	(10)*
Comparison of means, <i>p</i> value		< 0.0001	< 0.0001	

Notes: N is number, sec is seconds, mL is milliliters, and mm is millimeters.

*When double-routed, the tourniquet did not loosen when the self-adhering band was completely peeled back from itself.

*Pooled indicates that the two single routing data sets (each set consisting of 80 iterations) were combined to create one, joint data set (of 160 iterations) of all single routed tests.

Figure 3 Blood Loss Results in Single vs. Double Routing for Two Users



Notes: Plot shows the blood loss volume by single (1) vs. double (2) band routing. The gray box bottom and top represent the 25th and 75th percentiles, respectively. The median is a straight black line across a box.

over time in a steep slope of the trend line, and constant performance, indicating no learning, was represented by a slope of zero (i.e., a flat line). The number of iterations required to achieve constant performance varied from 1 to 35, depending mainly on the outcome selected (effectiveness, time, and blood loss) and little on the user (two individuals). Effectiveness, a yes-no binary variable, was yes on the first iteration for each user and remained yes for nearly every iteration thereafter—steep learning

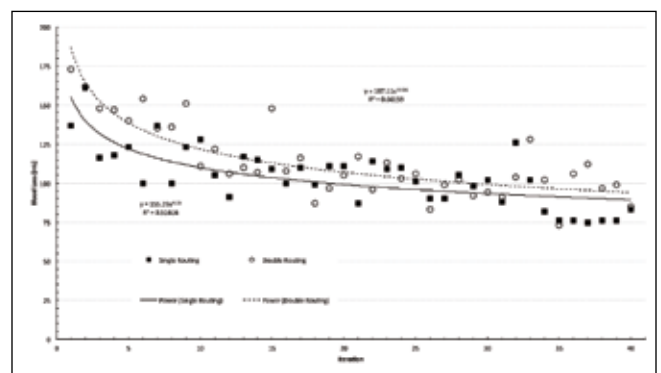
curves with flat performance at and after iteration 1. For time and blood loss, continuous variables, performance became constant at or about 35 iterations. Learning curves by iteration ranged greater than 30-fold.

When comparing the two users for inter-user performance differences, there were no statistically significant differences except that the cadet, not the expert, had better performance for time to stop bleeding and blood loss in the double routing ($p < 0.0001$ and $p = 0.034$, respectively) and for time to stop bleeding in the single routing ($p < 0.0001$). The differences in means were 16 seconds, 59 ml, and 8 seconds, respectively.

Discussion

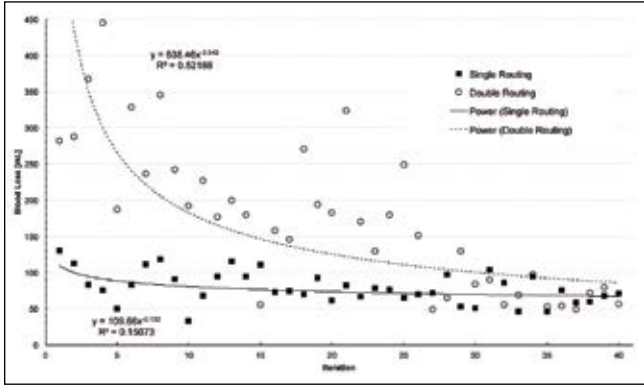
The main finding of the present study is that the Combat Application Tourniquet (CAT) band routing, either through the buckle singly or doubly, affects two key performance criteria: time to stop bleeding and volume of blood lost. It is not unexpected that single routing proved to be faster, therefore saving more blood. It is relevant that no differences were noted in the routing through the inside or outside slit; trainers may now elect to consider either as acceptable in practice or testing. Effectiveness rates were similar for single routing and double routing. Single routing proved simpler and easier to apply than double routing, as indicated by the high variability of data points for double routing in comparison to single routing (Figures 3 and 4). Along with the faster speed of the single routing were fewer mistakes or problems, when compared to double routing. Double routing was susceptible to complications because it had more steps in which to err; one complication noted by both users was the ease with which the self-adhering band unintentionally stuck to itself at contact, causing delays in application during double-routing.

Figure 4 Differential Learning Curves for Single vs. Double Routing for Blood Loss in One User



Notes: Learning by changes in behavior during the 40 iterations of tourniquet use for a cadet user is shown. The volume of blood lost is the outcome of learning, and double routing (white circles and dashed trendline) had similar learning as single routing (black boxes and black solid trendline).

Figure 5 Differential Learning Curves for Single vs. Double Routing for Blood Loss in One User



Notes: Learning for an expert user. Double routing had more learning than single routing until the final iterations where performance became similar. The data collection order for this user was the double before single routing; so order of learning may have affected results.

Users generally assumed that the single routing can come undone more easily than double routing (Table 4). We found this to be true, but our results were surprising. The minimum length of 41 mm (1.6 in.) was required to keep the tourniquet secure (Table 2). The self-adhering band is a 35mm (1.4 in.) wide; therefore, the minimum contact area was found to be 1435mm² (2.2 in²). This area represents the minimum acceptable contact area required to keep the tourniquet secure during laboratory testing. No folds were present in the band, no mud was present, and no clothing or other obstructions were in the way. This area is much smaller than expected. The hook-and-loop fasteners, when self-engaged, resist loads applied along the line of pull. The mechanism through which the self-adhering band is loosened is perpendicular force; akin to peeling the band back off from itself. Because of the engagement of the hook-and-loop fasteners, the CAT in this leg simulation model is able to apply the required pressure to stop arterial blood flow with minimal contact area.

The experimental evidence indicates a performance advantage for single routing, initially unexpected, that may have field advantages; e.g., users and casualties may spend less time in Care Under Fire applying tourniquets during what may be called an unforgiving minute. Gun-fire rates of dozens of rounds fired from one weapon per minute are common in war and occasional in civilian settings such as the violent incidents at Virginia Tech and Aurora, Colorado. The above information that indicates improved performance may prompt discussion among instructors and policy developers on the use of single-slit routing for initial application of all CATs. This also has design implications, specifically for a possible redesign of the buckle to include only one slit, thereby simplifying use (Table 3).

Table 3 Windlass TurnNumber Results by Single vs. Double Routing

Type of Routing	Windlass Turn Number					Total
	1	2	3	4	5	
Single	22	39	18	1	0	80
Double	0	33	5	0	2	40
Total	22	72	23	1	2	120

Table 4 Clinical Use Pearls and Pitfalls of Single vs. Double Routing

Single Routing	Double Routing
<p>Pearls</p> <ul style="list-style-type: none"> • This routing is storage configuration • Slack removal is easier • Fastening band is easier and faster • Windlass turning begins sooner • Placing tourniquet on limb is easier • Self-application takes less time • One-handed use is easier and faster 	
<p>Pitfalls</p> <ul style="list-style-type: none"> • Users confuse which of two slits to use • May lose tension before band secured • Band secured only by hooks-and-loops 	
	<ul style="list-style-type: none"> • Hooks-and-loops and buckle secure band • Storage after use requires reconfiguration • Slack removal requires buckle manipulation • Band may stick to itself inadvertently • Fastening band requires added slit routing • Windlass turning begins later • Added slit routing loses tension giving slack • Added slit routing adds to application time • One-handed use is harder and slower • Added slit adds second slack removal step • More steps risk more errors

A minor finding of the present study is the learning curve required to optimize performance of the task. Performance can be considered stabilized for a user by a slope near zero on a chart of performance parameter versus iteration. The learning curve stabilized at or about 35 iterations for both users (Figures 4 and 5). Prior to the experiment, performance was thought to stabilize at around four iterations since tourniquets were thought simple, and previous research evidenced performance up to four iterations.⁴ Tourniquet use is simpler than

surgery where learning curves stabilize at around 65 iterations. However, the task was not so simple, and the learning curve was not as steep as projected. One other observation noted was that the learning process of routing the band through the buckle was similar for both single routing and double routing. Routing the band through one slit was able to help the user learn to route the band through two slits and vice versa. One user who completed all 40 iterations of double routing first, followed by 80 iterations of single routing, showed this learning transference clearly. When plotting the user's performance, the learning curve for double routing flattened out near 35 iterations (Figures 4 and 5). However, the learning curve for single routing was almost flat, as performance was constant for all iterations. This steady performance came after the user's familiarity with the routing and the practice derived from the prior double routing iterations.

Another minor finding associated with the experiment was the advent of hybrid intervention: the combination of a manual maneuver with the use of a device in order to stop blood flow (Figures 4 and 5). The use of hybrid intervention slowed the application of the tourniquet but decreased the amount of blood lost by the casualty. User 1, an orthopedic surgeon familiar with the anatomical location of the popliteal artery and the superficial femoral artery, was able to apply hand pressure through the applied tourniquet targeting an underlying artery before buckle routing. This user's technique slowed overall application but reduced the total amount of blood lost by slowing the blood loss earlier before even buckle routing. Additionally, this user's method relied on the self-adhering band for the initial pressure by assertive removal of all possible slack and used the windlass only for the final stoppage of bleeding. User 2, unfamiliar with the location of the artery, spent less time manually tightening the self-adhering band and relied on the windlass to apply the required pressure on the limb. Hybrid intervention resulted in a slower time to stop bleeding but a lesser volume of blood lost. The two users' disparate results may stem from disparate approaches to the experiment. One aimed at speed to minimize bleeding time by replicating rhythmic iterations consistently listening to music, whereas the other aimed to minimize blood loss by trying novel techniques and allowing more variation as to maximize new knowledge generation among iterations. Both strategies had merit in the game-like experiment.

The findings stated above invite a discussion of decision-making and available options. As the CAT is manufactured currently, empirically there are three routing options. A soldier can route the band through the inside slit, the outside slit, or both slits. As Hick's Law states,

the time required to make a decision increases logarithmically in relation to the number of options available.⁸ This increase in reaction time equates to time on the battlefield where the individual applying the tourniquet is often in danger. Though taught not to use the outside slit for single routing (by any legitimate doctrine), users are to use only the inside slit for self-application; the soldier must decide these options.³⁻⁵ Recently, of 23 single-routed CATs, 16 were near and 7 outside (30%, 7/23) indicating a problem, perhaps user confusion.¹ Nondocctrinal use may indicate that users are confused by the training or doctrine. Confusion sources include instructions which have shown outside slit single routing—the opposite of what is supposed to be taught today.^{3-5,9} Actually, when one looks at the versions of written or video instructions by the military services, academicians, and corporations, these points of confusion are often unspecified, outdated, unclear, or mixed.³⁻⁵ Further complicating the options of the user is that single routing is taught for upper extremity use whether self-aid or buddy aid, but lower extremity use is double-routed whether self-aid or buddy aid. There appears to be no specific instruction for self-aid, one-handed to the lower extremity, perhaps because it is similar to self-aid to the upper extremity (however, it is difficult and slow to double-route one-handed). Additionally, not only is user reaction time slower with more options, but decision making abilities are also diminished. Compounding these problems in decision making, education research has shown that subjects tend toward “choosing the disadvantageous options more frequently” when placed under stress in games with established rules.¹⁰ Such research is applicable to CAT use, as each CAT comes with packaged instructions, and tourniquet training is structured. When individuals place a tourniquet in a stressful situation, they appear more likely to select the wrong routing option than during training. This educational theory and its supportive data are confirmed by the evidence reported from the field.³ The expected maximum rate of single-routed CATs was 17% (1% self-applied and 16% applied to the upper extremity); but when measured in actuality, 41% of tourniquets were single-routed, a 2-fold increase of real-world data vs. doctrinal compliance.¹ Last, during stressful conditions, individuals are less likely to adjust their course of action.¹¹ Less adjustment could partly explain the two-fold increase in single-routed tourniquets. An individual may have noticed the mistake but was under duress and did not take the time to correct the mistake. The 2-fold increase indicates either a flaw with doctrine, training, or a tendency to select the fastest option when under stress. Since the CAT has three different routing possibilities, the user should be able to explain when each routing option is indicated. Additionally, users ideally must be able to select the correct option under stress.

There are several limitations to the present study. The experimental design did not include actual human body parts or blood but rather surrogates. Additionally, the experiment was conducted in a well-lighted laboratory, without dirt, without casualty movement, without noise, and without clothing on the limb. The scenario selected on the HapMed™ Leg Tourniquet Trainer modeled the casualty as a small-build individual who needed only one tourniquet; the manikin findings from three investigators have obvious limitations and it remains unknown if the findings apply well to real world care. The investigators (two cadets with only prior entry-level tourniquet training and a tourniquet researcher [clinician–scientist]) do not mirror the user population. Also, the tourniquet was pre-placed on the desktop, not in its wrapping in the first-aid kit of the casualty. Furthermore, the parameter of time to stop bleeding does not take into account any work done after blood flow stops. This could exclude extra turns, securing the windlass, writing the time, or assessing the casualty. All events excluded required extra time and thus leave the subject vulnerable in combat. Last, the experiment did not include stress. Stress would likely impair the user's motor function, which would highlight difficult steps in CAT application.^{12,13} The inverted-U hypothesis states that performance increases with stress up until a certain point, where performance begins to decrease. This inverted-U relationship also applies to motor function.¹⁴ The increased stress of combat could be enough to maximize performance or, as is more likely, may prove too stressful and may decrease motor function. Because double routing is a more tedious task than single, it is expected that added stress will emphasize the differences between single and double routing. To design a tourniquet to be perfect in all situations, it will be complex and complicated; if one empirically de-emphasized the worst-case scenario for its rarity to favor the common, then one may cut the Gordian knot. If the buckle is remade to one slit only, then training and doctrine are simplified as to routing; and training is harmonized across the board to one routing for all situations. This option is open for future research.

Several improvements can be incorporated into future experiments. Real humans (e.g., volunteers or cadavers) may be used in lieu of a simulator for confirmatory field testing with induced stress. Field testing could assess the impact of dirt, debris, clothes, smoke, noise, and blood on tourniquet application. Medic student use of tourniquets on manikins may be useful. Field assessments likely would allow deeper and broader understanding of the topic beyond the present laboratory experiment. By focusing on a fundamental and common task in care, the present work draws new attention to an important set of ideas in first aid; further research may advance on the present work.

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