ABSTRACT

Background: In emergencies when commercially designed tourniquets are unavailable, hemorrhage may need to be controlled with improvised tourniquets. In the aftermath of the Boston Marathon bombing, no improvised strap-and-windlass tourniquets were used to treat casualties; tourniquets without windlasses were used. The purpose of the present study is to determine the effectiveness of improvised tourniquets with and without a windlass to better understand the role of the windlass in tightening the tourniquet strap.

Methods: An experiment was designed to test the effectiveness of improvised strap-and-windlass tourniquets fashioned out of a tee shirt on a manikin thigh. Two users conducted 40 tests each with and without the use of a windlass. Results: Without a windlass, improvised tourniquets failed to stop bleeding in 99% of tests (79 of 80 tests). With a windlass, improvised tourniquets failed to stop bleeding in 32% of tests (p < .0001). In tests with no windlass, attempts to stop the pulse completely failed (100%, 80 of 80 tests). With a windlass, however, attempts to stop the pulse failed 31% of the time (25 of 80 tests); the difference in proportions was significant (p < .0001). Conclusions: Improvised strap-and-windlass tourniquets were more effective than those with no windlass, as a windlass allowed the user to gain mechanical advantage. However, improvised strap-and-windlass tourniquets failed to control hemorrhage in 32% of tests.

Keywords: first aid; hemorrhage; tourniquets; shock; damage control; tourniquet, makeshift; tourniquet, homemade; strap-and-windlass

Introduction

Explosions on Boylston Street near the crowded finish line of the 2013 Boston Marathon caused more than 260 casualties, which, in turn, spurred nearby people to improvise tourniquets to stop limb bleeding. These first people to respond made tourniquets fashioned out of clothing such as shirts from nearby runners or from blast-damaged storefronts, for use on casualties who were at risk of death by wound exsanguination. No longer bystanders, these responders gave first aid by wrapping and tightening a shirt around a limb, and these makeshift tourniquets reportedly helped save lives. Such field tourniquets were replaced at the hospitals with dressings, commercial tourniquets, or blood pressure cuffs; observers noted that tourniquets improvised by first responders were ineffective, as hemorrhage was not controlled. The lifesaving–ineffective contradiction indicates confusion and a need to better understand improvised tourniquets. The confusion and contradiction exist fundamentally because there is essentially no substantial research into the optimal use of improvised tourniquets. This lack of research leaves knowledge gaps unfilled regarding best tourniquet practices.

A strap-and-windlass design is an ancient way to use a rod to wind a strap more tightly around a limb; a key step in improvising tourniquets is to twist a strap with a windlass to gain mechanical advantage in tightening. However, to our knowledge, no one in Boston reported windlass use with an improvised tourniquet. If the role of the windlass was made clear, then tourniquet practice might be improved. A theory is that an inadequately tightened strap can occlude limb veins but not arteries; venous tourniquets control venous bleeding while arterial tourniquets control both venous and arterial bleeding. If so, then a venous tourniquet may be effective only for venous bleeding and not for arterial bleeding. Furthermore, such effectiveness for venous hemorrhage may be only brief since paradoxical bleeding may soon occur.

The purpose of the present study is to determine the effectiveness of improvised tourniquets with and without a windlass to better understand the role of the windlass in gaining mechanical advantage in tightening the tourniquet strap.

Methods

This study was conducted under a protocol reviewed and approved by the Regulatory Compliance Division.
**Role of the Windlass in Improvised Tourniquet Use on a Manikin Hemorrhage Model**

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Approved for public release, distribution unlimited
of the US Army Institute of Surgical Research. A laboratory experiment was designed to compare the function of improvised tourniquets with and without windlass use. The study design was based on first responder actions in Boston.

The study group was a set of tests of an improvised tourniquet design with a windlass. The strap-and-windlass design included a strap that was a cotton tee shirt; the shirt was used for each test. For this experiment, a set of standard bamboo chopsticks was used as the windlass mechanism; we used six chopsticks taped together into a functionally single windlass. The windlass reliably kept itself in a bundle. The windlass, after insertion into the tourniquet knot, was twisted by the user in 180° turns, thereby tightening the tourniquet strap. The control group was constituted similarly to the study group except there was no windlass used.

There were two tourniquet users—one experienced and one inexperienced in tourniquet use. The experienced user always preceded the inexperienced user, and the control group was tested by each user before the study group was tested. There were 40 tests per group per user; hence, each user had 80 tests (40 tests times two groups times two users), or 160 tests altogether for the experiment.

A black tee shirt (lightly worn, cotton, short sleeve, large men’s size; Lands End, Inc.; www.landsend.com) was used in the trials. The shirt was folded into a strap to encircle the limb. The line of folding was diagonal from one sleeve to the opposite waist to maximize circumferential length around the thigh. Users wrapped the shirt around the manikin at the proximal thigh, tying a half-knot and pulling tightly to maintain tension in the strap and create pressure on the underlying skin. The user terminated the test when one of three conditions existed: (1) hemorrhage was controlled; (2) there was futility after repeated efforts to generate sufficient tension (repeated efforts led only to unceasing failure); or (3) when unsafe use occurred (e.g., lacerated skin of the manikin).

When a windlass was tested, the same procedure was used, except the user put the windlass atop the half-knot and then tied another half-knot atop the windlass before twisting it to wind the knot and supposedly create more strap tension.

The tourniquets were tested on a manikin in the laboratory. The investigators used a HapMed™ Leg Tourniquet Trainer (CHI Systems Inc.; www.chisystems.com/index.php)—a simulated right-thigh (leg number 000F) with an above-knee amputation injury was the testing apparatus. The medial hip had an embedded computer that included a smartphone-like touchpad. Software (version 1.9, CHI Systems Inc.; www.chisystems.com/index.php) integral to the thigh allowed the manikin to stand alone and be operated by user input through finger touch on the pad. The thigh had no blood, but bleeding was represented by red lights that transilluminated the wound. The number of lights illuminated represented the rate of bleeding—all 26 lights on meant maximal bleeding; no lights on meant bleeding had stopped. Users tightened tourniquets until they perceived that simulated bleeding stopped or until efforts proved futile. Arterial pulses were palpable in the popliteal artery area behind the knee. The time for hemorrhage control was that interval from iteration initiation until cessation of bleeding, as evidenced by the absence of lights. Effectiveness was defined as cessation of blood loss. When hemostasis was achieved, users stopped turning the windlasses. The manikin settings included a constant hemorrhage rate (635mL/min); the resulting bleed-out time in this scenario was 4 minutes—240 seconds in which to successfully apply the tourniquet. The system reported blood loss volume as calculated from the product of hemorrhage rate and time until hemorrhage control. The casualty had a medium build and the setting was Care Under Fire, a setting resembling emergency care when under gunfire.

The critical outcome was effectiveness (hemorrhage controlled: yes or no). An important outcome was absence of palpable pulse distal to the tourniquet (yes or no). Minor outcomes included time to cessation of bleeding (seconds), pressure applied to the skin by the tourniquet (mmHg), and the volume of blood loss (mL). Effectiveness, time to stop bleeding, and pressure were measured by the manikin, while pulse stoppage was measured by the user. Historically, a threshold has been used as a rough guide to tourniquet effectiveness such that when 80% or more of uses are successfully effective, then the tourniquet has reached a minimal level of reliability—a so-called 80% solution. Descriptive statistics were used to analyze results. For categorical variables, a chi-squared test was used and the likelihood ratio \( p \) values were reported (SAS Institute Inc.; www.sas.com). For continuous variables, a mixed model was used with user as a random effect, as there was a clear user difference in the results. Confidence limits were adjusted Wald 95% confidence intervals (CIs). Significance for results was established when \( p \) values were less than .05.

Results

The Role of the Windlass in Improvised Strap-and-Windlass Tourniquet Use

Without a windlass, improvised tourniquets failed to stop bleeding 79 times out of 80 tests (99%; 95% CI,
93%–100%) (Table 1). With a windlass, improvised tourniquets failed to stop bleeding 26 times out of 80 tests (32%; 95% CI, 23%–43%) (Table 1). The difference in proportions, 99% versus 32%, was statistically significant ($p < .0001$). However, neither group was reliably effective: Both with and without a windlass, improvised tourniquets did not achieve 80% effectiveness, the minimum threshold of reliable effectiveness.

### Table 1  Hemorrhage Control Results by Windlass or No Windlass

<table>
<thead>
<tr>
<th>Windlass Used</th>
<th>Failed Hemorrhage Control</th>
<th>Total Tests, No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>79 (99)</td>
<td>80</td>
</tr>
<tr>
<td>Yes</td>
<td>26 (32)</td>
<td>80</td>
</tr>
</tbody>
</table>

Note: CI, confidence interval.

Pulse results were nearly the same as the hemorrhage control results in that the windlass played a major role in improvised tourniquet performance (Table 2). In tests with no windlass, attempts to stop the pulse failed every time (80 of 80 tests, 100%; 95% CI, 96%–100%). With a windlass, however, attempts to stop the pulse failed 31% (95% CI, 22%–42%) of the time (25 of 80 tests); the difference in proportions was significant ($p < .0001$). The similarity between results of pulse stoppage and hemorrhage control indicated that the two phenomena were closely related.

### Time to Bleeding Cessation, Pressure, and Blood-Loss Volume Results

The mean time to bleeding cessation with no windlass was 59 seconds (95% CI, 54–64 seconds), and all but one test with no windlass ended in failure (79 of 80 tests; 95% CI, 93%–100%). On the other hand, the mean time to bleeding cessation with a windlass was 98 seconds (95% CI, 90–105 seconds), and 32% (26 of 80 tests; 95% CI, 23%–43%) of tests ended in failure. The difference in mean times was significant ($p < .0001$; 95% CI for difference, 28–48).

### Table 2  Pulse Stoppage Results by Windlass or No Windlass

<table>
<thead>
<tr>
<th>Windlass Used</th>
<th>Failed Pulse Cessation</th>
<th>Total Tests, No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>80 (100)</td>
<td>80</td>
</tr>
<tr>
<td>Yes</td>
<td>25 (31)</td>
<td>80</td>
</tr>
</tbody>
</table>

Note: CI, confidence interval.

The mean pressure applied with no windlass was 46mmHg (95% CI, 35mmHg–58mmHg), whereas with a windlass, it was 114mmHg (95% CI, 92mmHg–136mmHg; $p < 0.0001$; 95% CI for difference, 42mmHg–92mmHg). Windlass use increased the pressure under the tourniquet compared to no windlass use.

The mean blood loss volume with no windlass was 415mL (95% CI, 383mL–446mL) and with a windlass it was 648mL (95% CI, 596mL–700mL; $p < .0001$; 95% CI for difference, 172mL–294mL). When blood loss was measured as volume per time, the windlass tests bled at an average of 6.7mL/s (95% CI, 6.5mL/s–6.9mL/s) until bleeding was stopped, while the tests without a windlass bled at an average of 7.1mL/s (95% CI, 6.9mL/s–7.3mL/s) throughout the test period.

### The Role of the User

There were interesting results that varied by user. Even with the user effect taken into account in the statistical methods, there was a very significant windlass use effect. For both users, the results of tests with no windlass were similar in that almost every test failed. However, tests with a windlass varied by user.

The user with more experience had faster tests (mean time, 70 seconds vs. 87 seconds, $p < .0001$; 95% CI for difference, 6–27 seconds). With these shorter times to stopping bleeding, the mean blood loss was also less for the user with more experience (mean volume, 458mL vs. 604mL; $p < .0001$; 95% CI for difference, 78mL–213mL). However, the users differed greatly in pressure. The mean pressure applied by the experienced user was 15mmHg, while the less-experienced user applied a mean pressure of 145mmHg ($p < .0001$; 95% CI for difference, 111mmHg–148mmHg). Based on these results, we decided it was necessary to consider the user a random effect in the mixed statistical modeling when comparing windlass type for the factors of interest: time to stop bleeding, pressure, blood loss, and blood loss per second.

### Discussion

The first major finding of the present study is that the performance of improvised tourniquets varied by design, with the strap-and-windlass method performing substantially better than the strap with no windlass. Tourniquets with a windlass had higher proportions of tests with hemorrhage control, higher proportions of tests with suitable pressures, and lower rates of blood loss. Mean blood loss volumes with a windlass were more because such tests were reliably effective and lasted longer while tests with no windlass were not reliably effective and ended earlier. Use of a windlass is historically intended to gain a mechanical advantage in tightening a tourniquet. As a matter of fact, this windlass role is not specific to tourniquets but applies to hauling and lifting.
Windlass in Improvised Tourniquet Use

The limitations of the present study are based in its experimental design. The results were gathered through an experiment and not through patient care. Therefore,
the results are based on an assumption that the manikin acted like a bleeding patient, but the manikin has no pain response. If the inexperienced user’s excessive force skewed the results toward higher effectiveness, then when patients feel pain, real-world results may be more like that of the experienced user. A controlled experiment is not as chaotic as mass casualty situations that entail other considerations such as human factors, various levels of healthcare, and tourniquet-user performance under stressful situations with associated distractions. Given these limitations, the current understanding of improvised tourniquets does not permit a definitive recommendation regarding the optimal design or best technique of use.

Future directions for research include study of other purposes, such as looking at more users to better understand user variability in skill level, looking at bystander capacity to use tourniquets, looking at learning curves of users with increasing experience by numbers of uses, and progressing to fill the many other empiric gaps in knowledge regarding improvised tourniquet use, such as which techniques are better, which device designs are better, and which training programs are better. A search for better designs of improvised tourniquets appears worthwhile. Better understanding of the effectiveness–safety relationship is needed. Once these gaps are filled by research, the user’s understanding of tourniquets and of their mechanical use in first aid may be improved to move current care toward best care.

In summary, the improvised strap-and-windlass tourniquet was more effective than the same strap tourniquet with no windlass, as a windlass allowed the user to gain mechanical advantage. However, the improvised strap-and-windlass tourniquet was only 68% effective and this rate did not achieve the minimum threshold of reliability of 80%.

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Disclosure

The authors declare no conflicts of interest.

References


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