Effects of Tourniquet Features on Application Processes Times

Piper Wall, DVM, PhD[1]; Charisse Buising, PhD[2]; Alex White[3]; JaNiese Jensen[4]; Justin Davis, MD[5]; Catherine Hackett Renner, PhD[6]*

ABSTRACT

Background: We investigated emergency-use limb tourniquet design features effects on application processes (companion paper) and times to complete those processes (this paper). **Methods:** Sixty-four appliers watched training videos then each applied all eight tourniquets: Combat Application Tourniquet Generation 7® (CAT7), SOF® Tactical Tourniquet-Wide Generation 3 (SOFTTW3), SOF® Tactical Tourniquet-Wide Generation 5 (SOFTTW5), Tactical Mechanical Tourniquet™ (TMT), OMNA Marine Tourniquet® (OMT), X8T-Tourniquet (X8T), Tactical Ratcheting Medical Tourniquet® (Tac RMT), and RapidStop™ Tourniquet (RST). Application processes times were captured from videos. **Results:** From "Go" to "touch tightening system" was fastest with clips and self-securing redirect buckles and without strap/redirect application process problems (n, median seconds: CAT7 n=23, 26.89; SOFTTW3 n=11, 20.95; SOFTTW5 n=16, 20.53; TMT n=5, 26.61; OMT n=12, 25.94; X8T n=3, 18.44; Tac RMT n=15, 30.59; RST n=7, 22.80). From "touch tightening system" to "last occlusion" was fastest with windlass rod systems when there were no tightening system understanding or mechanical problems (seconds: CAT7 n=48, 4.21; SOFTTW3 n=47, 5.99; SOFTTW5 n=44, 4.65; TMT n=38, 6.21; OMT n=51, 6.22; X8T n=48, 7.59; Tac RMT n=52, 8.44; RST n=40, 8.02). For occluded, tightening system secure applications, from "touch tightening system" to "Done" was fastest with self-securing tightening systems tightening from a tight strap (occluded, secure time in seconds from a tight strap: CAT7 n=17, 14.47; SOFTTW3 n=22, 10.91; SOFTTW5 n=38, 9.19; TMT n=14, 11.42; OMT n=44, 7.01; X8T n=12 9.82; Tac RMT n=20, 6.45; RST n=23, 8.64). **Conclusions:** Suboptimal processes increase application times. Optimal design features for fast, occlusive, secure tourniquet applications are self-securing strap/redirect systems with an easily identified and easily used clip and self-securing tightening systems.

Keywords: *tourniquet; hemorrhage; first aid; emergency treatment*

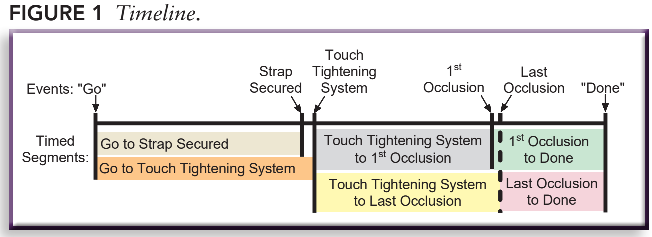
Introduction

The key to lifesaving use of emergency-use limb tourniquets is quickly stopping severe bleeding via arterial occlusion. Different tourniquet design features affect appliers' ability to achieve arterially occlusive, secure applications and the speed of achieving tourniquet-sustainable arterial occlusion. Using scoring and time, we investigated the effects of different tourniquet design features on appliers' ability to correctly and quickly apply emergency-use limb tourniquets. The hypothesis was that different features would have different effects on the successes and times of application processes. This paper discusses the times for application processes. The companion paper earlier in this journal discussed the success of application processes.[1]

Methods

The Drake University Institutional Review Board approved this study. The companion paper[1] details all the methods except those for application timing. In brief, eight tourniquet designs were applied in randomized order. Tourniquet parts and activities were divided into the strap and redirect buckle ("strap/redirect system") and the tightening system. Major design feature differences among tourniquets are shown and described in Figure 1 and Table 1 of the companion paper.[1] The major design feature differences were the presence or absence of a strap/redirect system clip (no clip: CAT7, OMT, Tac RMT; clip: SOFTTW3, SOFTTW5, TMT, X8T, RST), whether or not strap/redirect systems were self-securing (strap/redirect not self-securing: CAT7, TMT, OMT; strap/redirect self-securing: SOFTTW3, SOFTTW5, X8T, Tac RMT, RST), whether or not tightening systems were self-securing (tightening system not self-securing: CAT7, SOFTTW3, SOFTTW5, TMT; tightening system self-securing: OMT, X8T, Tac RMT, RST) and the plane of rotation of the tightening system (parallel to the limb: CAT7, SOFTTW3, SOFTTW5, TMT, X8T; perpendicular to the limb: OMT, Tac RMT, RST).

FIGURE 1 *Timeline.*



The times involved in applying each tourniquet are shown. Of 512 tourniquet applications, 35 never reached occlusion, and 36 had separate first and last occlusions.

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TABLE 1 *Median and Interquartile Times in Seconds According to Tourniquet*

	CAT7	SOFTTW3	SOFTTW5	TMT	OMT	X8T	Tac RMT	RST	*P*-values[1]
"Go" to "Strap Secured" (strap/redirect system) Good Orientation[2]	n=53 23.74 (21.26, 29.15)	n=59 24.12 (19.97, 35.24)	n=60 21.50 (17.81, 28.92)	n=57 43.07 (34.21, 58.39)	n=56 26.03 (22.56, 31.07)	n=56 22.50 (19.77, 29.28)	n=59 36.03 (28.09, 46.91)	n=61 24.50 (21.15, 38.86)	<.050 TMT and Tac RMT versus each of others except *p*=.085 TMT versus SOFTTW3
"Go" to "Strap Secured" (strap/redirect system) Good All Aspects[2]	n=23 25.02 (21.71, 27.37)	n=11 20.45 (16.93, 24.08)	n=16 19.51 (16.20, 21.50)	n=5 26.08 (23.09, 33.23)	n=12 23.41 (18.92, 28.39)	n=3 18.10 (16.04, 22.12)	n=15 30.30 (27.24, 36.12)	n=7 22.17 (20.76, 24.73)	<.008 Tac RMT versus each of others except TMT
"Go" to "Strap Secured" (strap/redirect system) Tight Strap[2]	n=49 23.74 (21.26, 29.15)	n=22 21.35 (17.64, 28.49)	n=39 20.92 (16.57, 26.20)	n=16 38.49 (29.46, 53.85)	n=45 26.20 (22.56, 30.85)	n=14 22.19 (16.31, 34.36)	n=21 30.30 (26.46, 36.82)	n=23 24.73 (21.82, 29.23)	<.010 TMT versus CAT7, SOFTTW5, and OMT; =.094 TMT versus SOFTTW3; =0.113 TMT versus X8T; =0.097 TMT versus RST
"Go" to "Strap Secured" (strap/redirect system) Secure Strap[2]	n=46 24.27 (21.55, 29.05)	n=59 24.12 (19.97, 35.24)	n=59 21.49 (17.81, 28.54)	n=42 39.22 (32.85, 49.55)	n=39 25.62 (22.55, 31.29)	n=56 22.50 (19.77, 29.28)	n=56 35.09 (28.07, 43.37)	n=61 24.50 (21.15, 38.86)	<.030 TMT versus each of others except SOFTTW3 and Tac RMT; =.079 TMT versus SOFTTW3; <.009 Tac RMT versus CAT7, SOFTTW5, OMT, and X8T
"Go" to "Touch Tightening System" (strap/redirect system) Good Orientation[2]	n=53 25.48 (22.30, 30.62)	n=59 25.73 (20.37, 37.55)	n=60 22.65 (18.52, 33.09)	n=57 45.14 (35.29, 60.20)	n=56 28.48 (24.13, 33.38)	n=56 25.62 (21.39, 33.77)	n=59 36.70 (28.90, 48.07)	n=61 25.92 (21.59, 41.72)	<.050 TMT versus SOFTTW5, OMT, and X8T; =.054 TMT versus CAT7; =.109 TMT versus SOFTTW3; =.063 TMT versus RST; <.040 Tac RMT versus each of others except TMT
"Go" to "Touch Tightening System" (strap/redirect system) Good All Aspects[2]	n=23 26.89 (22.47, 28.65)	n=11 20.95 (18.16, 24.94)	n=16 20.53 (16.64, 22.62)	n=5 26.61 (23.80, 33.92)	n=12 25.94 (20.20, 29.39)	n=3 18.44 (16.77, 22.91)	n=15 30.59 (27.89, 36.99)	n=7 22.80 (21.32, 25.92)	<.030 Tac RMT versus each of others except TMT
"Go" to "Touch Tightening System" (strap/redirect system) Tight Strap[2]	n=49 25.48 (22.30, 30.62)	n=22 24.22 (18.94, 31.16)	n=39 21.77 (17.27, 27.62)	n=16 40.34 (33.19, 54.28)	n=45 28.34 (23.98, 33.32)	n=14 26.81 (18.02, 35.48)	n=21 30.71 (27.38, 37.71)	n=23 25.92 (21.87, 29.85)	<.030 TMT versus CAT7, SOFTTW5, and OMT; =.118 TMT versus SOFTTW3; =.088 TMT versus RST
"Go" to "Touch Tightening System" (strap/redirect system) Secure Strap[2]	n=46 25.59 (22.31, 30.06)	n=59 25.73 (20.37, 37.55)	n=59 22.62 (18.51, 31.15)	n=42 42.66 (34.57, 51.97)	n=39 28.63 (24.17, 33.19)	n=56 25.62 (21.39, 33.77)	n=56 36.14 (28.90, 43.89)	n=61 25.92 (21.59, 41.72)	<.050 TMT versus each of others except SOFTTW3 and Tac RMT; =.111 TMT versus SOFTTW3; <.020 Tac RMT versus CAT7, SOFTTW5, and X8T; =.064 Tac RMT versus OMT
"Touch Tightening System" to "First Occlusion" (tightening system) Good Understanding & Good Mechanical[3]	n=48 3.97 (3.12, 6.24)	n=47 5.80 (4.52, 7.95)	n=44 4.25 (3.60, 6.48)	n=38 5.30 (4.64, 7.42)	n=51 6.22 (4.17, 8.12)	n=48 7.13 (4.82, 11.02)	n=52 8.44 (5.75, 12.04)	n=40 8.02 (6.01, 10.28)	<.020 Tac RMT versus CAT7, SOFTTW3, SOFTTW5, and OMT; =.087 Tac RMT versus TMT; <.050 RST versus CAT7, SOFTTW3, SOFTTW5, and OMT; <.008 X8T versus CAT7 and SOFTTW5
"Touch Tightening System" to "First Occlusion" (tightening system) Good Understanding & Good Mechanical from Tight Strap[3,4]	n=47 3.90 (3.12, 5.28)	n=19 4.84 (3.98, 5.70)	n=34 4.18 (3.48, 5.76)	n=12 4.50 (3.49, 5.21)	n=40 5.32 (4.06, 8.01)	n=11 6.70 (4.62, 12.54)	n=19 5.53 (4.55, 8.25)	n=13 6.69 (4.87, 8.44)	<.040 X8T versus CAT7 and SOFTTW5; =.148 X8T versus SOFTTW3; =.110 X8T versus TMT; =.095 Tac RMT versus CAT7; =.078 Tac RMT versus SOFTTW5
	p=.998 versus CAT7 Loose Strap	*p*=.564 versus SOFTTW3 Loose Strap	*p*=.076 versus SOFTTW5 Loose Strap	*p*=.558 versus TMT Loose Strap	*p*=.583 versus OMT Loose Strap	*p*=.999 versus X8T Loose Strap	*p*=.039 versus Tac RMT Loose Strap	*p*=.991 versus RST Loose Strap	
"Touch Tightening System" to "First Occlusion" (tightening system) Good Understanding & Good Mechanical from Loose Strap[3,4]	n=1 12.10	n=28 6.47 (5.01, 8.16)	n=10 6.51 (3.84, 9.63)	n=26 6.39 (5.10, 7.85)	n=11 7.70 (6.40, 8.40)	n=37 7.56 (4.83, 11.00)	n=34 9.80 (7.93, 12.96)	n=27 8.77 (6.45, 11.50)	=.061 Tac RMT versus SOFTTW3, =.109 RST versus SOFTTW3
	p=.998 versus CAT7 Tight Strap	*p*=.564 versus SOFTTW3 Tight Strap	*p*=.076 versus SOFTTW5 Tight Strap	*p*=.558 versus TMT Tight Strap	*p*=.583 versus OMT Tight Strap	*p*=.999 versus X8T Tight Strap	*p*=.039 versus Tac RMT Tight Strap	*p*=.991 versus RST Tight Strap	

"Touch Tightening System" to "Last Occlusion" (tightening system) Good Understanding & Good Mechanical[3]	n=48 4.21 (3.15, 7.30)	n=47 5.99 (4.52, 8.04)	n=44 4.65 (3.88, 7.38)	n=38 6.21 (4.97, 8.24)	n=51 6.22 (4.17, 8.12)	n=48 7.59 (4.87, 11.02)	n=52 8.44 (5.75, 12.04)	n=40 8.02 (6.01, 10.28)	<.040 Tac RMT versus CAT7, SOFTTW3, SOFTTW5, and OMT; <.009 RST versus CAT7 and SOFTTW5; =.054 RST versus SOFTTW3; =.084 RST versus OMT; =.041 X8T versus CAT7; =.124 X8T versus SOFTTW5
"Touch Tightening System" to "Last Occlusion" (tightening system) Good Understanding & Good Mechanical from Tight Strap[3,5]	n=47 4.17 (3.14, 7.28)	n=19 5.00 (3.98, 7.76)	n=34 4.25 (3.87, 6.46)	n=12 4.50 (3.49, 5.21)	n=40 5.32 (4.06, 8.01)	n=11 7.83 (5.22, 12.54)	n=19 5.53 (4.55, 8.25)	n=13 6.69 (4.87, 8.44)	=.107 X8T versus CAT7; =.082 X8T versus SOFTTW5; =.092 X8T versus TMT
	p=.998 versus Loose Strap	*p*=.993 versus Loose Strap	*p*=.527 versus Loose Strap	*p*=.389 versus Loose Strap	*p*=.583 versus Loose Strap	*p*=.982 versus Loose Strap	*p*=.039 versus Loose Strap	*p*=.991 versus Loose Strap	
"Touch Tightening System" to "Last Occlusion" (tightening system) Good Understanding & Good Mechanical from Loose Strap[3,5]	n=1 12.10	n=28 6.47 (5.01, 8.16)	n=10 8.37 (5.14, 11.61)	n=26 6.68 (5.15, 9.99)	n=11 7.70 (6.40, 8.40)	n=37 7.56 (4.83, 11.00)	n=34 9.80 (7.93, 12.96)	n=27 8.77 (6.45, 11.50)	=.089 Tac RMT versus SOFTTW3; =.148 RST versus SOFTTW3
	p=.998 versus Tight Strap	*p*=.993 versus Tight Strap	*p*=.527 versus Tight Strap	*p*=.389 versus Tight Strap	*p*=.583 versus Tight Strap	*p*=.982 versus Tight Strap	*p*=.039 versus Tight Strap	*p*=.991 versus Tight Strap	
"Touch Tightening System" to Done (tightening system) Occluded at Done[3]	n=52 12.26 (8.70, 15.71)	n=48 13.16 (10.22, 24.45)	n=51 10.55 (7.87, 16.69)	n=45 17.08 (11.42, 28.70)	n=55 7.67 (5.72, 10.43)	n=48 8.94 (5.70, 13.43)	n=53 9.74 (6.71, 12.95)	n=57 9.87 (7.66, 12.75)	<.030 TMT versus all except SOFTTW3; <.030 SOFTTW3 versus all except TMT
"Touch Tightening System" to "Done" (tightening system) Occluded at Done & Tightening System Secure[3]	n=17 14.47 (10.47, 18.12)	n=46 13.16 (10.09, 25.15)	n=51 10.55 (7.87, 16.69)	n=34 16.81 (11.26, 30.65)	n=55 7.67 (5.72, 10.43)	n=48 8.94 (5.70, 13.43)	n=53 9.74 (6.71, 12.95)	n=57 9.87 (7.66, 12.75)	<.030 TMT versus OMT, X8T, Tac RMT, and RST; <.040 SOFTTW3 versus SOFTTW5, OMT, X8T, Tac RMT, and RST
"Touch Tightening System" to "Done" (tightening system) Occluded at Done & Tightening System Secure from Tight Strap[3,6]	n=17 14.47 (10.47, 18.12)	n=22 10.91 (8.36, 17.90)	n=38 9.19 (7.00, 11.58)	n=14 11.42 (8.08, 15.29)	n=44 7.01 (5.56, 9.76)	n=12 9.82 (6.01, 14.39)	n=20 6.45 (5.56, 9.63)	n=23 8.64 (7.47, 11.66)	=.048 SOFTTW3 versus OMT; =.149 SOFTTW3 versus Tac RMT
		p=.025 versus Loose Strap	*p*<.0001 versus Loose Strap	*p*=0.003 versus Loose Strap	*p*=.400 versus Loose Strap	*p*=.153 versus Loose Strap	*p*=.018 versus Loose Strap	*p*=.177 versus Loose Strap	
"Touch Tightening System" to "Done" (tightening system) Occluded at Done & Tightening System Secure from Loose Strap[3,6]	n=0	n=24 17.10 (11.49, 31.16)	n=13 18.08 (14.76, 25.76)	n=20 22.68 (15.71, 34.10)	n=11 8.92 (8.07, 13.48)	n=36 8.83 (5.70, 12.66)	n=33 11.36 (9.34, 14.30)	n=34 10.68 (8.00, 13.80)	<.040 TMT versus OMT, X8T, and Tac RMT; =.051 TMT versus RST; <0.030 SOFTTW3 versus OMT, X8T, Tac RMT, and RST; =.054 SOFTTW5 versus X8T
		p=.025 versus Tight Strap	*p*<.0001 versus Tight Strap	*p*=.003 versus Tight Strap	*p*=.400 versus Tight Strap	*p*=.153 versus Tight Strap	*p*=.018 versus Tight Strap	*p*=.177 versus Tight Strap	

1. All *p*-values for tight versus loose tourniquet comparisons within a specific tourniquet are reported; otherwise, *p*-values >.150 are not reported. *P*-values >.050 to .150 are individually reported. Comparisons with *p*-values ≤.050 are grouped with only a *p*-value greater than each individual *p*-value reported.
2. Times starting at "Go" are for applications initially placed in the good orientation as defined by the video-shown orientation[2-10] with the redirect buckle lateral and the tightening system located above the redirect (optimal strap pulling would be downward).
3. Times starting at "Touch Tightening System" are for applications in the good orientation when secured.
4. *P*-values for comparisons within specific tourniquets are for "Touch Tightening System" to "First Occlusion" for Good Understanding & Good Mechanical from Tight Strap versus Good Understanding & Good Mechanical from Loose Strap.
5. *P*-values for comparisons within specific tourniquets are for "Touch Tightening System" to "Last Occlusion" for Good Understanding & Good Mechanical from Tight Strap versus Good Understanding & Good Mechanical from Loose Strap.
6. *P*-values for comparisons within specific tourniquets are for "Touch Tightening System" to "Done" times for Occluded at Done & Tightening System Secure from Tight Strap versus Occluded at Done & Tightening System Secure from Loose strap.

Tourniquet Applications

The dorsal pedal artery Doppler signal was audible before starting applications. Each application was videoed from two angles at 90 frames per second with GoPro Hero 5 Sessions (GoPro Inc., www.gopro.com).

After watching training videos, [2,3–10] appliers knelt beside the recipient's leg and waited for the director to say "Go" before picking up the tourniquet. Each tourniquet was presented threaded or clipped in a closed loop and folded in approximately quarters with the (primary) redirect buckle as the location of the center fold.[11–18] Each tourniquet was on the same side of the applier as the recipient's feet and oriented with the (primary) redirect buckle away from the recipient's leg.[3–10] Appliers had to unthread or unclip the tourniquet to place it around the limb; lifting the recipient's foot to slide an intact tourniquet loop up the leg was not allowed (considered a trapped limb). Applications were considered complete when the applier was hands off and stated "Done" or the director stopped the application 5 minutes after saying "Go."

Application Timing

Total times were determined real time with a stopwatch started by the director when saying "Go" and stopped when the applier removed his or her hands from the tourniquet and said "Done" or at 300 seconds (5 minutes). Application-step-related times (described in Appendix A) were determined later from a video-captured online stopwatch display (minutes to thousandths of a second displayed on a screen with a 60Hz refresh rate). VLC media player version 3.0.16 (VideoLan, www.videolan.org) was used for playback (60 frames per second, interactive zoom, and the ability to play at 0.25 speed with audio or advance frame-by-frame). Research assistant pairs provided consensus times; a researcher, CB, determined final application-step-related times from videos.

The timed segments in the application process are shown in Figure 1 and relate to the y-axis times in Figures 2–5 and to the x-axis events shown in Figure 2 of the companion paper.[1] The scoring criteria and definitions of major groupings are detailed in Appendices B and C of the companion paper.[1]

Times of 300 seconds were used for strap/redirect system event failures and for tightening system event failures with no times assigned to events following the failure: 1) The six applications that did not reach strap security because of a broken (SOFTTW5) or incorrectly threaded (4 Tac RMT) redirect buckle or pulling at the wrong strap redirect (X8T) received "Go" to "strap secured" and "Go" to "touch tightening system" times of 300 seconds. 2) The CAT7 application that never went to rod rotation received a "Go" to "touch tightening system" time of 300 seconds. 3) The two CAT7, one SOFTTW3, and one RST applications that never reached occlusion because of failure to understand the tightening system received "touch tightening system" to "occlusion" times of 300 seconds and did not receive "occlusion" to "Done" times. Applications that never reached occlusion because the applier simply stopped tightening prematurely did not receive "touch tightening system" to "occlusion" times.

Statistical Analysis

To control for order effects, the orders of watching application videos[3–10] and of tourniquet applications were separately randomized with 8x8 Latin Squares using www.hamsterandwheel.com.

Time data were organized in Microsoft® Office Excel 2003 (Microsoft Corp., www.microsoft.com). Graphing and statistical analyses were performed with GraphPad Prism, version 7.04 for Windows (GraphPad Software Inc., www.graphpad.com). One-way analysis of variance (ANOVA) with Tukey's or Sidak's multiple comparisons tests and unpaired, two-tailed t tests were used for time comparisons. P-values of .15 or less are reported.

Results

Applier and application process information is detailed in the companion paper.[1] In brief, 33 of 64 appliers had no prior tourniquet experience of any sort, 33 appliers (13 appliers with some prior tourniquet experience and 20 appliers with no prior tourniquet experience) had at least one application process problem in each of their eight tourniquet applications (only 66 applications had no application process problems), 68 of 512 applications were not occluded at "Done" (55 because the applier stopped use of the tightening system prematurely), and 109 applications were not correctly secured at "Done."

Orientation

Times to "strap secured" and to "touch tightening system" are shown for each orientation in Figure 2 and for only the good orientation in Table 1. Fifty-one applications (10.0%) started with strap/redirect orientations other than those shown.[2–10] In seven, appliers took time to change to the video-shown orientation. Times from these seven are included in tightening system-related figures and analyses. Times from the 44 applications that remained in the alternate orientation are not included in tightening system-related figures and analyses.

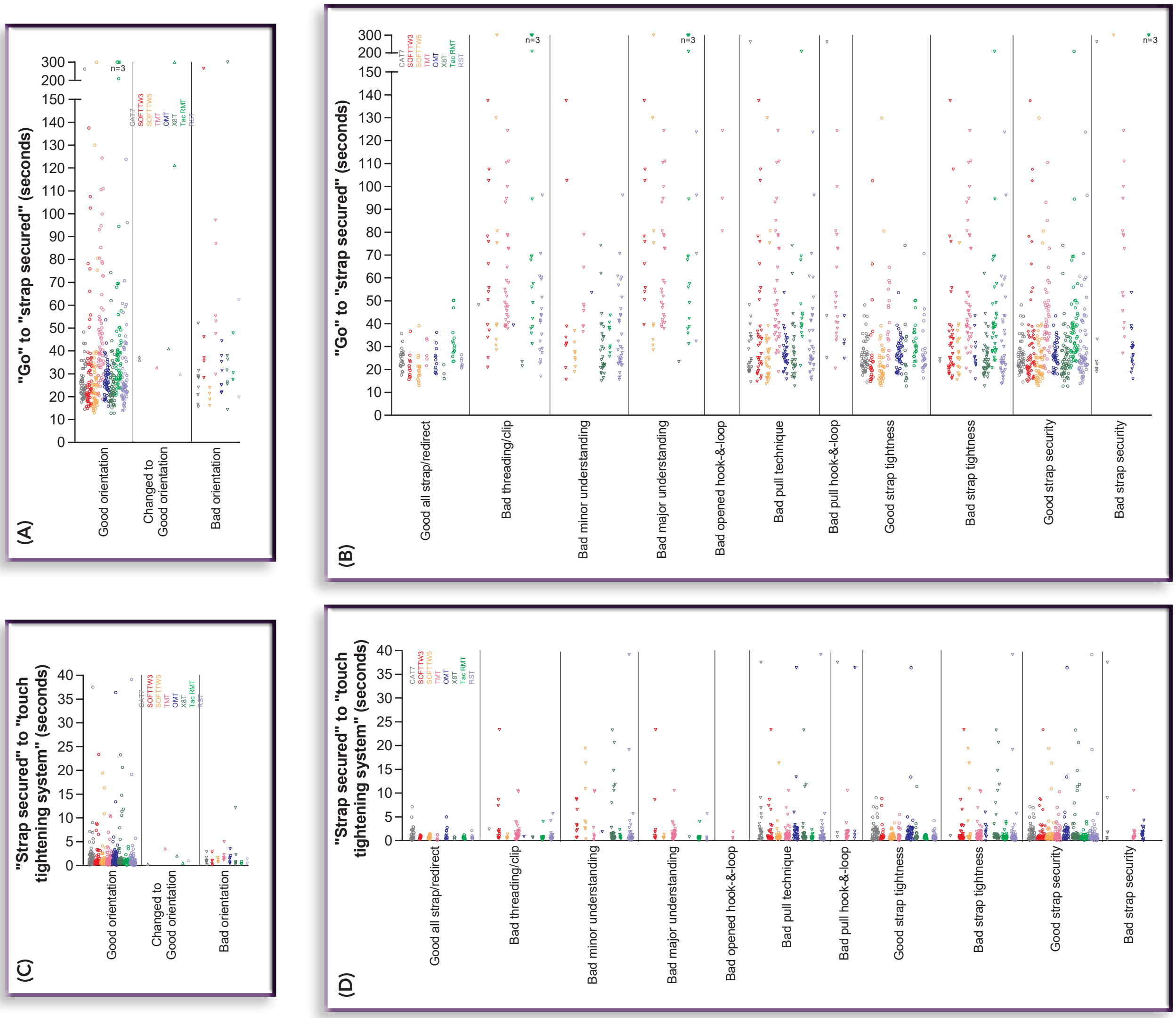
Strap/Redirect System

For each tourniquet, applications without strap/redirect problems generally reached "strap secured" and "touch tightening system" faster than applications with problems (Figure 2). Among applications without strap/redirect problems, self-securing redirect systems had the fastest (clip and slider of SOFTTW5) and slowest (no clip and overlapping rectangles Tac RMT) "strap secured" and "touch tightening system" times. Threading/clip problems, minor and major understanding problems, opening hook-and-loop problems, and hook-and-loop interference during pulling ("bad pull hook-and-loop") resulted in slower "strap secured" and "touch tightening system" times. Bad pull technique had slower median times for all tourniquets except the CAT7, but the p-values were all >.15. Tight applications were not slower than loose applications of the same tourniquet. Applications with bad strap security were generally slower than applications with good strap security.

For applications without strap/redirect problems, the median times from strap secured to "touch tightening system" were <1.2 seconds. A bad, minor understanding problem, that resulted in slower times from "strap secured" to "touch tightening system" was appliers wondering what to do with what they perceived as extra strap length.

Among applications with good orientation, the fastest median time from "Go" to "touch tightening system" was with the SOFTTW5, as was the fastest median time for tight strap applications and secure strap applications (Table 1). The slowest median times for good orientation applications, tight strap applications, and secure strap applications were with the TMT (Table 1).

FIGURE 2 *Times to reach a secured strap and touch the tightening system.*



A video orientation for the graphs can be accessed at https://vimeo.com/799927371. The x-axis has application processes and process quality (good/bad) for processes that occur between picking the tourniquet up and achieving a secured tourniquet strap. Symbols for applications with the good version of the indicated processes have open circles. Symbols for applications with a bad version have downward-pointing open triangles. Applications with an orientation process that started bad and changed to good have upward-pointing open triangles. The colors on the graphs are linked with the tourniquets as follows: CAT7 = gray, SOFTTW3 = red, SOFTTW5 = orange, TMT = magenta, OMT = dark blue, X8T = dark green, Tac RMT = light green, RST = lavender. The "n=3" at the top of the Tac RMT columns indicates three applications with event failures and the corresponding time assignments for the process of 300 seconds.

(A) Times from "Go" to "strap secured" for all applications according to placement orientation around the leg. Good was defined as the video-shown orientation[2-10] with the redirect buckle lateral and the tightening system located above the redirect (optimal strap pulling would be downward). Among the 461 applications with good orientation, the TMT and Tac RMT were slower to secured than each of the other six tourniquets ($p<.050$ for each versus each of the other tourniquets except TMT versus SOFTTW3 $p=.085$).

(B) Times from "Go" to "strap secured" for only applications with good orientation. *P*-values for time comparisons between each of the tourniquets are as follows:

- Good all strap/redirect (meaning no bad strap or redirect processes), n=92, $p<.008$ Tac RMT versus each other tourniquet except TMT
- Good strap tightness; n=229; $p<.010$ TMT versus CAT7, SOFTTW5, and OMT; $p=.094$ TMT versus SOFTTW3; $p=.097$ TMT versus RST
- Good strap security; n=418; $p<.030$ TMT versus each other tourniquet except SOFTTW3 and Tac RMT; $p=.079$ TMT versus SOFTTW3; $p<.009$ Tac RMT versus CAT7, SOFTTW5, OMT, and X8T.

P-values for Good all strap/redirect time comparisons within a specific tourniquet are as follows:

- CAT7 (n=23) $p=.0001$ versus Bad pull hook-&-loop (n=3), $p=.117$ versus Bad strap security (n=7)
- SOFTTW3 (n=11) $p<.0009$ versus Bad threading/clip (n=14) and Bad major understanding (n=10), $p=.125$ versus Bad minor understanding (n=9)
- SOFTTW5 (n=16) $p<.0001$ versus Bad threading/clip (n=9), Bad major understanding (n=9), and Bad strap security (n=1)
- TMT (n=5) $p<.040$ versus Bad threading/clip (n=30), Bad major understanding (n=27), Bad opened all hook-&-loop (n=3), and Bad strap security (n=15)
- OMT (n=12) $p=.0008$ versus Bad minor understanding (n=1)
- X8T (n=3) no *p*-values <.560
- Tac RMT (n=15) $p<.0003$ versus Bad threading/clip (n=16), Bad major understanding (n=16), Bad strap security (n=3)
- RST (n=7) $p<.0001$ versus Bad major understanding (n=4), $p=.137$ Bad threading/clip (n=21).

No *p*-values <.150 for Good strap tightness versus Bad strap tightness within a specific tourniquet.

P-values for Good strap security versus Bad strap security within a specific tourniquet are as follows:

- CAT7 (n=46) $p=.107$ (n=7 Bad strap security)
- SOFTTW5 (n=59) $p<.0001$ (n=1 Bad strap security because broke redirect)
- TMT (n=42) $p=.008$ (n=15 Bad strap security)
- Tac RMT $p<.0001$ (n=3 Bad strap security because never correctly rethreaded).

(C) Time differences from "Go" to "strap secured" versus "Go" to "touch tightening system" for all applications according to placement orientation around the leg. Among the 461 applications with good orientation, the TMT and Tac RMT were slower from "Go" to "touch tightening system" than each of the other six tourniquets ($p<.050$ TMT versus SOFTTW5, OMT, and X8T; $p=.054$ TMT versus CAT7; $p=.109$ TMT versus SOFTTW3; $p=.063$ TMT versus RST; $p<.040$ Tac RMT versus each other tourniquet except TMT).

(D) Time differences from "Go" to "strap secured" versus "Go" to "touch tightening system" for only applications with good orientation. *P*-values for time comparisons from "Go" to "touch tightening" between each of the tourniquets are as follows:

- Good all strap/redirect (meaning no bad strap or redirect processes), n=92, $p<.030$ Tac RMT versus each other tourniquet except TMT
- Good strap tightness; n=229; $p<.030$ TMT versus CAT7, SOFTTW5, and OMT; $p=.118$ TMT versus SOFTTW3; $p=.088$ TMT versus RST
- Good strap security; n=418; $p<.050$ TMT versus each other tourniquet except SOFTTW3 and Tac RMT; $p=.111$ TMT versus SOFTTW3; $p<.020$ Tac RMT versus CAT7, SOFTTW5, and X8T; $p=.064$ Tac RMT versus OMT.

P-values for Good all strap/redirect time comparisons within a specific tourniquet are as follows:

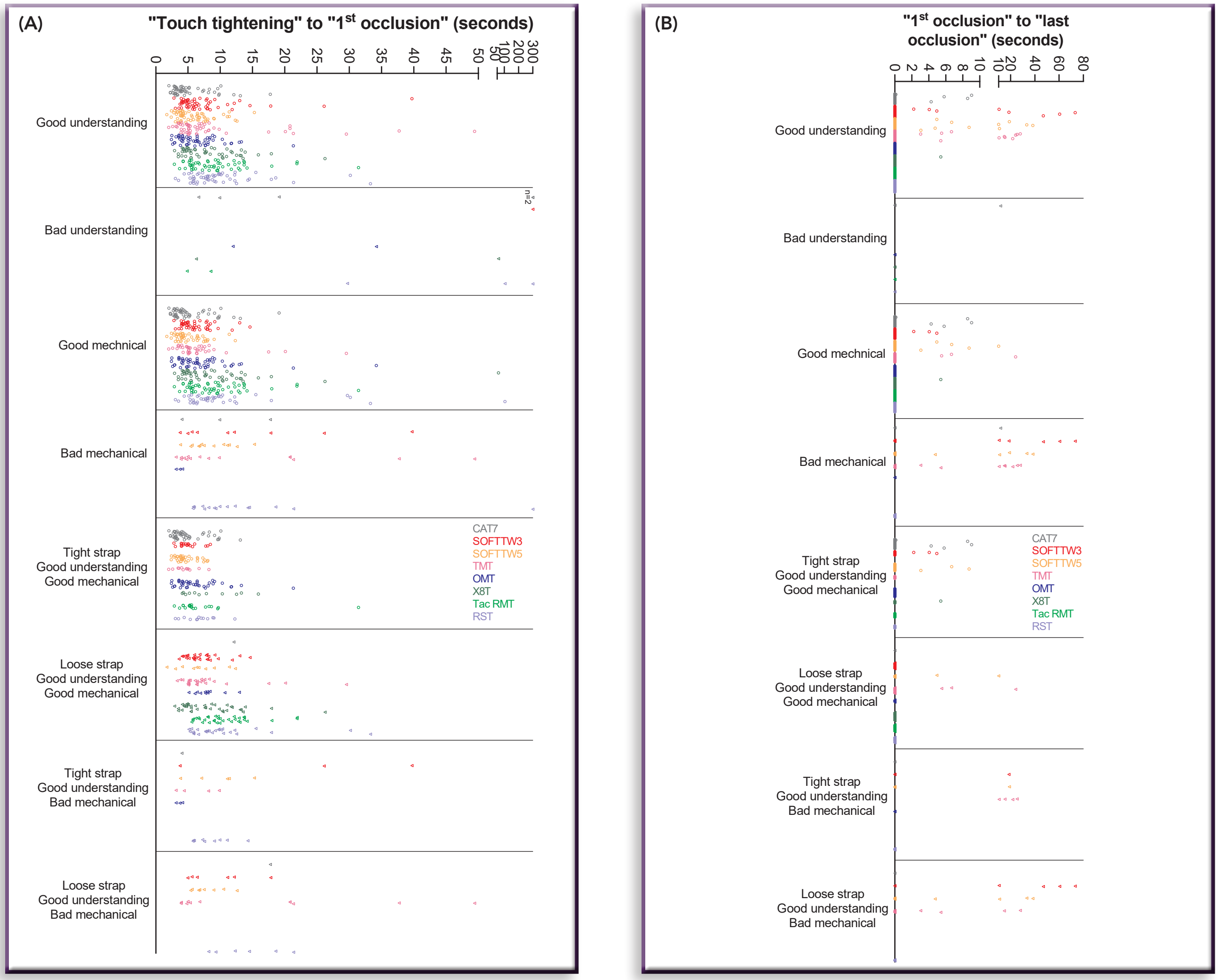
- CAT7 (n=23) $p=.0001$ versus Bad pull hook-&-loop (n=3), $p=.102$ versus Bad strap security (n=7)
- SOFTTW3 (n=11) $p<.001$ versus Bad threading/clip (n=14) and Bad major understanding (n=10), $p=.103$ versus Bad minor understanding (n=9)
- SOFTTW5 (n=16) $p<.0001$ versus Bad threading/clip (n=9) and Bad major understanding (n=9)
- TMT (n=5) $p<.030$ versus Bad threading/clip (n=30), Bad major understanding (n=27), Bad opened all hook-&-loop (n=3), and Bad strap security (n=15); $p=.144$ versus Bad pull technique (n=38); $p=.130$ versus Bad pull hook-&loop (n=19)
- OMT (n=12) $p<.030$ versus Bad minor understanding (n=1) and Bad pull hook-&-loop (n=4)
- X8T (n=3) no *p*-values <.330
- Tac RMT (n=15) $p<.0003$ versus Bad threading/clip (n=16), Bad major understanding (n=16), Bad strap security (n=3)
- RST (n=7) $p<.0001$ versus Bad major understanding (n=4).

No *p*-values <0.150 for Good strap tightness versus Bad strap tightness within a specific tourniquet.

P-values for Good strap security versus Bad strap security within a specific tourniquet are as follows:

- CAT7 (n=46) $p=.091$ (n=7 Bad strap security)
- TMT (n=42) $p=.010$ (n=15 Bad strap security)
- Tac RMT $p<.0001$ (n=3 Bad strap security because appliers never correctly rethreaded the redirect buckle.)

FIGURE 3 *Times from Touching the Tightening System to Occlusion.*



A video orientation for the graphs can be accessed at https://vimeo.com/799936785. The x-axis has application processes and process quality (good/bad) for processes that occur between touching the tightening system after achieving a secured strap to reaching occlusion. Symbols for applications with the good version of the indicated processes have open circles. Symbols for applications with a bad version have downward-pointing open triangles. The colors on the graphs are linked with the tourniquets as follows: CAT7 = gray, SOFTTW3 = red, SOFTTW5 = orange, TMT = magenta, OMT = dark blue, X8T = dark green, Tac RMT = light green, RST = lavender. The "n=2" at the top of one CAT7 column indicates two applications with event failures and the corresponding time assignments for the process of 300 seconds. Times and *p*-values are for applications with good orientation when the strap was secured (good orientation defined as the video-shown orientation[2-10] with the redirect buckle lateral and the tightening system located above the redirect).

(A) Times from "touch tightening system" to "first occlusion". *P*-values for time comparisons between each of the tourniquets are as follows:

- Good understanding (of the tightening system); n=424; *p*<.040 RST versus CAT7, SOFTTW5, and OMT; *p*<.020 Tac RMT versus CAT7 and SOFTTW5; *p*=.084 Tac RMT versus OMT; *p*=.014 TMT versus CAT7; *p*=.078 TMT versus SOFTTW5
- Good mechanical (no windlass rod slipping, windlass rod resetting, tooth skipping, or buckle advance failures); n=377; *p*<.030 RST versus CAT7, SOFTTW3, SOFTTW5, TMT, and OMT; *p*=.079 and 0.074 Tac RMT versus CAT7 and SOFTTW5; *p*=.107 and 0.100 X8T versus CAT7 and SOFTTW5
- Good understanding and Good mechanical combined; n=368; *p*<.008 X8T versus CAT7 and OMT; *p*<.020 Tac RMT versus CAT7, SOFTTW3, SOFTTW5, and OMT; *p*<.050 RST versus CAT7, SOFTTW3, SOFTTW5, and OMT
- Tight strap Good understanding Good mechanical, n=195, *p*<.040 X8T versus CAT7 and SOFTTW5; *p*=.148 and 0.110 X8T versus SOFTTW3 and TMT; *p*=.095 and 0.078 Tac RMT versus CAT7 and SOFTTW5
- Loose strap Good understanding Good mechanical; n=174, *p*=.061 Tac RMT versus SOFTTW3; *p*=.109 RST versus SOFTTW3.

P-values for time comparisons within a specific tourniquet are as follows:

- CAT7 *p*<.0001 Good understanding (n=50) versus Bad understanding (n=5)
- SOFTTW3 *p*<.001 Good understanding (n=56) versus Bad understanding (n=1), Good mechanical (n=47) versus Bad mechanical (n=9), and Tight strap Good understanding Bad mechanical (n=3) versus Loose strap Good understanding Bad mechanical (n=6)
- SOFTTW5 *p*=.0001 Good mechanical (n=44) versus Bad mechanical (n=13), *p*=.076 Tight strap Good understanding Good mechanical (n=34) versus Loose strap Good understanding Good mechanical (n=10)
- TMT *p*=.033 Good mechanical (n=38) versus Bad mechanical (n=15); *p*=.138 Tight strap Good understanding Bad mechanical (n=4) versus Loose strap Good understanding Bad mechanical (n=11)
- OMT *p*<.0001 Good understanding (n=54) versus Bad understanding (n=2)
- X8T *p*<.0001 Good understanding (n=48) versus Bad understanding (n=2)
- Tac RMT *p*=.039 Tight strap Good understanding Good mechanical (n=19) versus Loose strap Good understanding Good mechanical (n=34)
- RST *p*<.0001 Good understanding (n=54) versus Bad understanding (n=3).

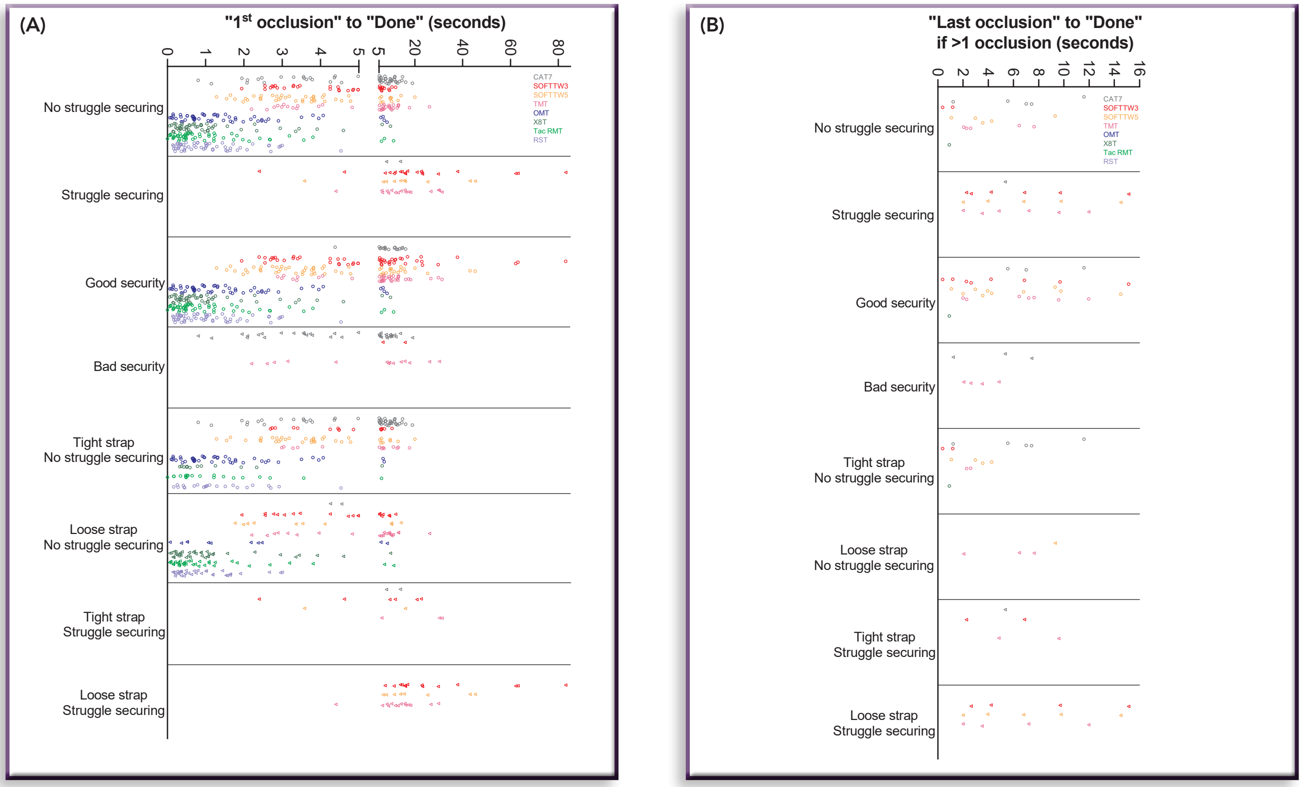
(B) Time differences from "touch tightening system" to "first occlusion" versus "touch tightening system" to "last occlusion". *P*-values for time comparisons from "touch tightening system" to "last occlusion" between each of the tourniquets are as follows:

- Good understanding (of the tightening system), n=424, *p*<.030 TMT versus CAT7 and OMT; *p*<.050 SOFTTW3 versus CAT7 and OMT
- Good mechanical (no windlass rod slipping, windlass rod resetting, tooth skipping, or buckle advance failures); n=377; *p*<.030 RST versus CAT7, SOFTTW3, SOFTTW5, and OMT; *p*=.146 RST versus TMT
- Good understanding and Good mechanical combined; n=368; *p*=.041 X8T versus CAT7; *p*=.124 X8T versus SOFTTW5; *p*<.040 Tac RMT versus CAT7, SOFTTW3, SOFTTW5, and OMT; *p*<.009 RST versus CAT7 and SOFTTW5; *p*=.054 RST versus SOFTTW3; *p*=.084 RST versus OMT
- Tight strap Good understanding Good mechanical, n=195, *p*=.107 X8T versus CAT7; *p*=.082 X8T versus SOFTTW5; and *p*=.092 X8T versus TMT
- Loose strap Good understanding Good mechanical, n=174, *p*=.089 Tac RMT versus SOFTTW3; *p*=.148 RST versus SOFTTW3.

P-values for time comparisons within a specific tourniquet are as follows:

- CAT7 *p*<.0001 Good understanding (n=50) versus Bad understanding (n=5)
- SOFTTW3 *p*<.0001 Good understanding (n=56) versus Bad understanding (n=1), Good mechanical (n=47) versus Bad mechanical (n=9)
- SOFTTW5 *p*<.0001 Good mechanical (n=44) versus Bad mechanical (n=13)
- TMT *p*<.0001 Good mechanical (n=38) versus Bad mechanical (n=15)
- OMT *p*<.0001 Good understanding (n=54) versus Bad understanding (n=2)
- X8T *p*<.0001 Good understanding (n=48) versus Bad understanding (n=2)
- Tac RMT *p*=.039 Tight strap Good understanding Good mechanical (n=19) versus Loose strap Good understanding Good mechanical (n=34)
- RST *p*<.0001 Good understanding (n=54) versus Bad understanding (n=3).

FIGURE 4 *Times from "Occlusion" to "Done."*



A video orientation for the graphs can be accessed at https://vimeo.com/799944365. The x-axis has application processes and process quality for processes that occur between occlusion and a completed application with hands off the tourniquet. Symbols for applications with the good version of the indicated processes have open circles. Symbols for applications with a bad version have downward-pointing open triangles. The colors on the graphs are linked with the tourniquets as follows: CAT7 = gray, SOFTTW3 = red, SOFTTW5 = orange, TMT = magenta, OMT = dark blue, X8T = dark green, Tac RMT = light green, RST = lavender. Times are for applications with good orientation when the strap was secured (good orientation defined as the video-shown orientation[2-10] with the redirect buckle lateral and the tightening system located above the redirect).

(A) Times from "first occlusion" to "Done." *P*-values for time comparisons between each of the tourniquets are as follows:

- No struggle securing (the tightening system), n=386, $p<.030$ CAT7 versus all except TMT; $p<.030$ SOFTTW3 versus all except SOFTTW5; $p<.003$ SOFTTW5 versus all except SOFTTW3; $p<.005$ TMT versus all except CAT7; each $p<.0001$ for each windlass rod tourniquet versus each self-securing tightening system tourniquet
- Good security (tightening system according to study instructions); n=383; $p<.003$ CAT7 versus OMT, X8T, Tac RMT, and RST; $p<.020$ SOFTTW3 versus SOFTTW5, OMT, X8T, Tac RMT, and RST; $p<.003$ SOFTTW5 versus OMT, X8T, Tac RMT, and RST; $p<.0001$ TMT versus OMT, X8T, Tac RMT, and RST
- Tight strap No struggle securing; n=215; $p<.004$ CAT7 versus SOFTTW5, OMT, X8T, Tac RMT, and RST; $p<.050$ SOFTTW3 versus OMT, X8T, Tac RMT, and RST; $p<.040$ SOFTTW5 versus OMT, X8T, Tac RMT, and RST; $p<.0001$ TMT versus OMT, X8T, Tac RMT, and RST; $p=.079$ TMT versus SOFTTW5; each $p<.050$ for each windlass rod tourniquet versus each self-securing tightening system tourniquet
- Loose strap No struggle securing; n=173; $p<.0003$ SOFTTW3 versus X8T, Tac RMT, and RST; $p<.003$ SOFTTW5 versus X8T, Tac RMT, and RST; $p=.040$ TMT versus SOFTTW3; $p<.0001$ TMT versus OMT, X8T, Tac RMT, and RST.

P-values for time comparisons within a specific tourniquet are as follows:

- CAT7 $p=.008$ Good security (n=17) versus Bad security (n=36)
- SOFTTW3 $p<.040$ No struggle securing (n=36) versus Struggle securing (n=20), Tight strap Struggle securing (n=6) versus Loose strap Struggle securing (n=14)
- SOFTTW5 $p<.0001$ No struggle securing (n=47) versus Struggle securing (n=10)
- TMT $p=.0002$ No struggle securing (n=36) versus Struggle securing (n=17)
- RST $p=.069$ Tight strap No struggle securing (n=23) versus Loose strap No struggle securing (n=34).

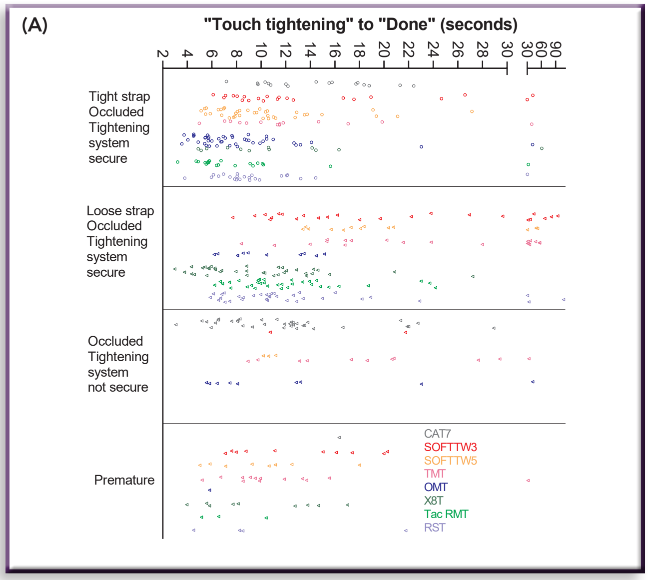
(B) Time differences from "last occlusion" to "Done" versus "first occlusion" to "Done" if the "last occlusion" was not the same as the "first occlusion". *P*-values for time comparisons from "last occlusion" to "Done" between all the tourniquets are as follows:

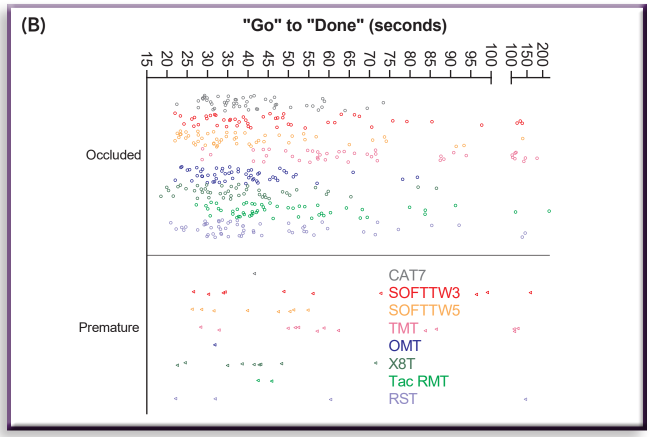
- No struggle securing (the tightening system); n=386; $p<.030$ CAT7 versus SOFTTW3, SOFTTW5, OMT, X8T, Tac RMT, and RST; $p<.0001$ SOFTTW3 versus OMT, X8T, Tac RMT, and RST; $p<.003$ SOFTTW5 versus TMT, OMT, X8T, Tac RMT, and RST; $p<.0001$ TMT versus OMT, X8T, Tac RMT, and RST; each $p<.0003$ for each windlass rod tourniquet versus each self-securing tightening system tourniquet
- Good security (tightening system according to study instructions); n=383; $p<.002$ CAT7 versus SOFTTW5, OMT, X8T, Tac RMT, and RST; $p<.0004$ SOFTTW3 versus SOFTTW5, OMT, X8T, Tac RMT, and RST; $p<.007$ SOFTTW5 versus TMT, OMT, X8T, Tac RMT, and RST; $p<.007$ TMT versus SOFTTW5, OMT, X8T, Tac RMT, and RST; $p<.0005$ for each windlass rod tourniquet versus each self-securing tightening system tourniquet
- Tight strap No struggle securing; n=215; $p<.0001$ CAT7 versus SOFTTW5, OMT, X8T, Tac RMT, and RST; $p=.083$ CAT7 versus SOFTTW3; $p<.003$ SOFTTW3 versus OMT, X8T, Tac RMT, and RST; $p<.030$ SOFTTW5 versus OMT, X8T, Tac RMT, and RST; $p<.0002$ TMT versus OMT, X8T, Tac RMT, and RST; each $p<.030$ for each windlass rod tourniquet versus each self-securing tightening system tourniquet
- Loose strap No struggle securing; n=173; $p<.030$ SOFTTW3 versus OMT, X8T, Tac RMT, and RST; $p<.0005$ SOFTTW5 versus X8T, Tac RMT, and RST; $p=.124$ SOFTTW5 versus OMT; $p<.0002$ TMT versus OMT, X8T, Tac RMT, and RST.

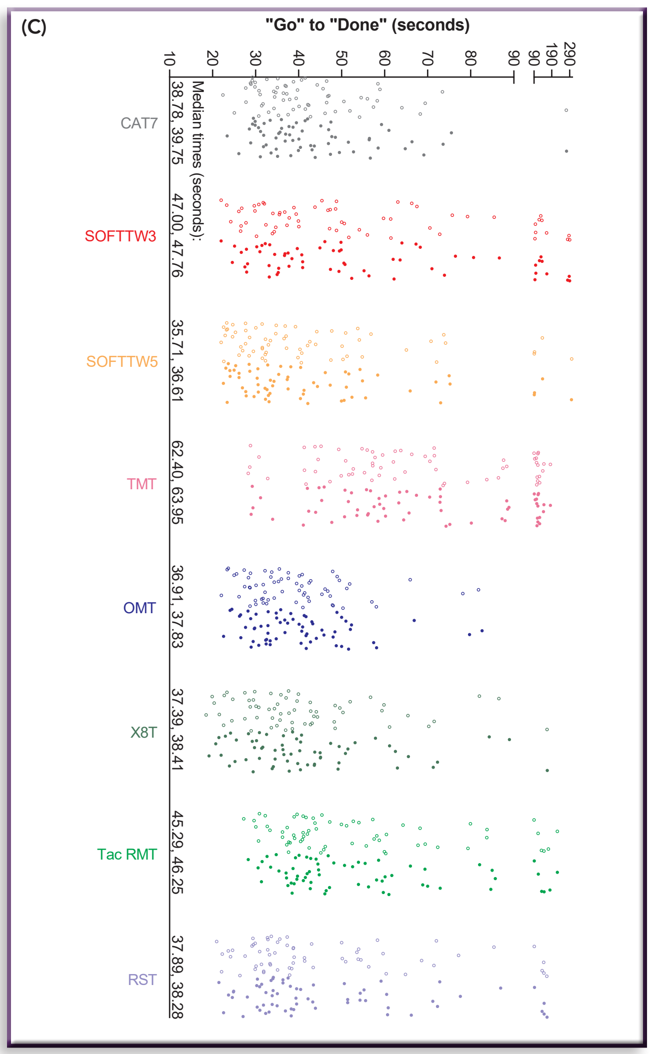
P-values for time comparisons within a specific tourniquet are as follows:

- CAT7 $p=.003$ Good security (n=17) versus Bad security (n=36)
- SOFTTW3 $p<.050$ No struggle securing (n=36) versus Struggle securing (n=20), Tight strap Struggle securing (n=6) versus Loose strap Struggle securing (n=14)
- SOFTTW5 $p<.0001$ No struggle securing (n=47) versus Struggle securing (n=10)
- TMT $p=.002$ No struggle securing (n=36) versus Struggle securing (n=17)
- RST $p=.069$ Tight strap No struggle securing (n=23) versus Loose strap No struggle securing (n=34).

FIGURE 5 *Times from "Touch Tightening" to "Done" and "Go" to "Done."*







A video orientation for the graphs can be accessed at https://vimeo.com/799965802. In **(A)** and **(B)**, the x-axis has application processes and process quality for processes that occur between touching the tightening system or picking up the tourniquet and a completed application with hands off the tourniquet; symbols for applications with the good version of the indicated processes have open circles; and symbols for applications with a bad version have downward-pointing open triangles. The colors on the graphs are linked with the tourniquets as follows: CAT7 = gray, SOFTTW3 = red, SOFTTW5 = orange, TMT = magenta, OMT = dark blue, X8T = dark green, Tac RMT = light green, RST = lavender. In **(A)**, times are for applications with good orientation when the strap was secured (good orientation defined as the video-shown orientation[2-10] with the redirect buckle lateral and the tightening system located above the redirect). In **(B)**, times are for applications with good orientation at initial placement. In **(C)**, the x-axis has the tourniquet; symbols for video frame-by-frame determined times have open circles; symbols for real time stopwatch times have filled circles; and times are for all applications regardless of orientation.

(A) Times from "touch tightening system" to "Done." *P*-values for time comparisons between each of the tourniquets are as follows:

- Occluded at "Done" applications, n=409, $p<.030$ TMT versus all except SOFTTW3; $p<.030$ SOFTTW3 versus all except TMT
- Occluded and tightening system secure at "Done" applications; n=361; $p<.030$ TMT versus OMT, X8T, Tac RMT, and RST; $p=.054$ TMT versus SOFTTW5; $p<.040$ SOFTTW3 versus SOFTTW5, OMT, X8T, Tac RMT, and RST
- Tight strap Occluded Tightening system secure, n=190, $p=.048$ SOFTTW3 versus OMT; $p=.149$ SOFTTW3 versus Tac RMT; $p=.098$ CAT7 versus OMT
- Loose strap Occluded Tightening system secure; n=171; $p<.040$ TMT versus OMT, X8T, and Tac RMT; $p=.051$ TMT versus RST; $p<.030$ SOFTTW3 versus OMT, X8T, Tac RMT, and RST; $p=.054$ SOFTTW5 versus X8T
- Occluded Tightening system not secure, n=48, $p=.005$ TMT versus CAT7
- Time comparisons were not done among applications with tightening system use stopped prematurely.

P-values for time comparisons within a specific tourniquet are as follows:

- TMT $p=.017$ Premature (n=13) versus Occluded at "Done" (n=45)
- SOFTTW3 $p=.025$ Tight strap Occluded Tightening system secure (n=22) versus Loose strap Occluded Tightening system secure (n=24)
- SOFTTW5 $p<.0001$ Tight strap Occluded Tightening system secure (n=38) versus Loose strap Occluded Tightening system secure (n=13)
- TMT $p=.003$ Tight strap Occluded Tightening system secure (n=14) versus Loose strap Occluded Tightening system secure (n=20)
- Tac RMT $p=.018$ Tight strap Occluded Tightening system secure (n=20) versus Loose strap Occluded Tightening system secure (n=33).

(B) Times from "Go" to "Done." *P*-values for time comparisons between each of the tourniquets are as follows:

- Occluded at "Done" applications, n=404, $p<.002$ TMT versus all; $p=.040$ Tac RMT versus OMT; $p=.056$ Tac RMT versus X8T.

P-values for time comparisons within a specific tourniquet are as follows:

- SOFTTW3 $p=.132$ Occluded (n=48) versus Premature (n=10).

(C) Times for each tourniquet from "Go" to "Done" from video frame-by-frame and from real time stopwatch. Median times are shown just above the x-axis. For each tourniquet, frame-by-frame versus real time stopwatch $p<.0001$, $r>0.9988$, and median difference <0.91 seconds.

Tightening System

The fastest times from "touch tightening system" to "first occlusion" were applications that achieved a tight strap during the strap/redirect system part of the application (Figure 3 and Table 1). Understanding the tightening system and not having problems such as losing hold of the windlass rod were also associated with faster times to "first occlusion." Separate first and last occlusions happened with windlass rod tourniquets (6 CAT7, 8 SOFTTW3, 10 SOFTTW5, and 11 TMT) and one X8T application. Separate first and last occlusions were not restricted to applications that lost hold of the windlass rod or redid windlass rod turning.

Only windlass rod tourniquets had tightening system securing struggles and a lack of tightening system security (Figure 4). Times from "touch tightening system" to "Done" and from "occlusion" to "Done" were faster for each of the self-securing tightening systems than for any of the windlass rod tightening systems, even when only comparing windlass rod tourniquet applications without rod securing struggles (Figure 4, Figure 5, and Table 1). Among applications that were occluded at "Done" and had secure tightening systems, those that achieved a tight strap during the strap/redirect system part of the application generally had faster "touch tightening system" to "Done" times than applications that did not achieve a tight strap during the strap/redirect system part of the application (Figure 5 and Table 1).

Among good orientation applications that were not occluded at "Done" because the applier prematurely stopped using the tightening system, median times from "touch tightening system" to "Done" were not significantly faster than occluded at "Done" times for all tourniquet applications except those of the TMT (Figure 5).

Among the windlass rod tourniquet applications that had the tightening system secured as directed and were occluded at "Done," "touch tightening system" to "Done" times were significantly faster for the SOFTTW5 (median 10.55, interquartile range [IQR] 7.87–16.69 seconds) than the SOFTTW3 (median 13.16, IQR 10.22–24.45 seconds, p=.036). Tightening system secured as directed for the SOFTTW5 in this study was placement of the windlass rod in the bracket and did not require rod securing in the triangle. (Bracket only securing is not medically appropriate and was only allowed to assess difficulty imposed by the triangle; securing in the triangle is required for clinical applications.) In addition to differences in the incidence of struggling to secure the rod,[1] the time difference between the SOFTTW3 and SOFTTW5 supports placement of the rod in the securing triangle as less easy and more time-consuming than placement in an open-top bracket. Among applications that were occluded at "Done," the longest "touch tightening system" to "Done" times belonged to the unidirectional, side-opening bracket of the TMT (median 16.81, IQR 11.26–30.65 seconds, n=34 tightening system secured and 18.61, 13.12–27.66 seconds, n=11 not secured). Times from "touch tightening system" to "Done" for the CAT7 were longer when the windlass rod was correctly secured in the top-open bracket with overlying hook-and-loop straps than when it was not correctly secured (median 14.47, IQR 10.47–18.12 seconds, n=17 tightening system secured and 11.90, IQR 8.08–13.53 seconds, n=35 not secured).

Total Times

Total stopwatch times for each tourniquet during applications were well matched with total times as determined via frame-by-frame capture from video (Figure 5, each tourniquet correlation coefficient >0.99). Stopwatch times were always slightly longer, with <0.91 seconds as median differences from frame-by-frame for each tourniquet.

Discussion

Key findings were as follows: 1) Process problems (see companion paper[1]) were associated with slower strap/redirect system times and slower tightening system times. 2) Achieving good strap tightness in the strap/redirect system part of the application process is not slower than achieving bad strap tightness. 3) Achieving good strap tightness in the strap/redirect system part of the application process is associated with a shorter duration of tightening system use. 4) The fastest strap/redirect systems had clips and were self-securing. 5) The fastest tightening systems were self-securing.

Our data support the expectation that understanding problems and physical problems during the strap/redirect system part and the tightening system part of the application process slow applications down. This increases the time from picking up a tourniquet to stopping bleeding and therefore to doing any other tasks such as managing other injuries or helping other casualties. This means understanding and physical process problems that are not necessarily directly associated with lower rates of reaching occlusion[1] or tourniquet security[1] are still important to consider when making tourniquet choices.

The strap tightness from strap/redirect system use affects the results of tightening system use. This was already shown with prior generations of CATs with regards to tourniquet damage and the amount of tightening system use required for occlusion.[19-22] Data in the companion to this paper show not achieving good strap tightness in the strap/redirect system part of the application process is associated with tightening system failure to achieve occlusion and problems with tightening system security for tourniquets besides the CAT7.[1] Our time data indicate not achieving good strap tightness also lengthens the duration of tightening system use. Because not achieving good strap tightness is not faster than achieving good strap tightness, not achieving good strap tightness increases time to occlusion and to application completion. Therefore, any tourniquet application instruction should include the importance of achieving good strap tightness before using the tightening system,[1,19-22] optimal pulling technique concepts for achieving good strap tightness,[23,24] and achieving visible skin indentation as a necessary marker of good strap tightness.[24]

A high rate of good strap tightness is a positive aspect of simple redirects;[1] however, current simple redirect designs involve hook-and-loop straps and are not self-securing. Self-securing strap redirect buckles have the benefits of not requiring appliers to properly secure the strap (one less step and one less possible problem[1]), allowing additional pulling to potentially incrementally tighten the strap, no need for hook-and-loop on the strap with its opening and pulling interference potential (two fewer possible problems[1]), and, at least when combined with a clip, faster times from picking up a tourniquet to use of the tightening system.

Regarding clips versus strap rethreading through the redirect buckle, clip systems had the fastest "Go" to "touch tightening system" individual and median times for all and problem-free applications. Not all clips are equivalent: clip recognition problems were prevalent with the TMT and non-existent with the X8T, and unclipping/reclipping problems were the least frequent with the SOFTTW5, though the most frequent with the similar clip of the SOFTTW3.[1] Unthreading and rethreading of a self-securing redirect buckle was not as fast as unclipping and reclipping a self-securing redirect buckle and offered the unfortunate opportunity for rethreading problems.[1]

Time from "touch tightening system" to "occlusion" was faster with windlass rod systems, but "touch tightening system" to "Done" was faster with self-securing systems by a larger margin and avoided questionable rod security issues. Additionally, 34 windlass rod system applications that did not involve a tightening system understanding problem had variable length occlusion losses between achieving occlusion and completing the application. These occlusion losses are indicated by separate first and last occlusion times (Figure 3, differences from 0.13 to 73.41 seconds). In 18 applications, the occlusion losses were associated with losing hold of the rod or resetting the rod. Other causes of these occlusion losses were the backward movement of the rod during the securing process and the time spent achieving rod securing.[25] Beyond the faster tightening system completion times and prevention of rod security issues, two additional advantages to the self-securing tightening systems would be the finer resolution securable pressure increments and the ease of additional tightening whenever indicated with no need to un-secure and then resecure a windlass rod with the additional risk of releasing the tightening system because of rod slippage.

From our results concerning scoring[1] and timing the processes involved in tourniquet application around a "trapped" limb, we conclude the following: 1) For nonelastic, non-pneumatic emergency-use limb tourniquets, the best combination of design features for most frequently achieving the fastest occluded and secure tourniquet applications would be an easily identified and used clip, a self-securing strap redirect buckle (unidirectional friction would be preferred but is not a current tourniquet option to our knowledge), and a self-securing tightening system (either parallel to the limb dial rotation or perpendicular to the limb buckle advancement on a ladder). 2) Tourniquet training for the public should include tourniquets with clips, self-securing redirect buckles, and self-securing tightening systems. Teaching and supplying only windlass rod style tourniquets for public "Stop the Bleed" kits is suboptimal if maximizing the percentage of applications that are occlusive, secure, and fast is desired. 3) When strap rethreading can happen, a diagram of the rethreading should be placed on the strap because once the strap has been unthreaded, the threading pattern can no longer be seen to be copied. 4) For individuals supplied with a specific tourniquet, training should include avoiding errors that are easy, common, or important with that specific tourniquet (examples, failure to open all the hook-and-loop of the TMT, [1] failure to correctly secure the windlass rod of the CAT7, [1] or grasping the releasing mechanism of the RST during tightening[1]). 5) Training for people who might encounter any type of tourniquet should emphasize key concepts.[1] Educating potential tourniquet users on key concepts and optimal techniques is more likely to allow users to achieve the best applications allowed by the circumstances encountered. Failure to understand key concepts and optimal techniques does not generally equate with the best outcomes when people are faced with physical tasks that require some deviation from how the task was done in a controlled setting.

Limitations

This study has the limitations associated with the pre-study decisions detailed in the discussion section of the companion paper.[1] In addition to the shared limitations,[1] collecting time data related to specific design features requires discrete, identifiable starting and stopping actions for those features. This resulted in times for use of the entire strap/redirect system without separate times for clip use. Another limitation-imposing choice was what to do regarding times for event failures. Not including a time for an event failure would result in misleadingly fast times for that tourniquet for that event; therefore, we chose to use 300 seconds, the maximum allowable application time as the time for event failures.

Conclusions

Suboptimal tourniquet application processes increase application times. Suboptimal strap tightness from the strap/redirect system part of the application process negatively affects all aspects of the tightening system use part of the application process. Among nonelastic, non-pneumatic emergency-use limb tourniquets, optimal design features for fast, occlusive, secure tourniquet applications are self-securing strap/redirect systems with an easily identifiable and easily used clip and self-securing tightening systems.

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Author Contributions

PW and CB contributed to concept development and project design. All authors contributed to the acquisition, analysis, and interpretation of data and the drafting and revising of the article. All authors had final approval of the manuscript.

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APPENDIX A.
APPLICATION-STEP-RELATED TIMES FROM DISPLAYED TIMER

Times Points
1. "Go"
2. Strap/redirect secured
3. Touch tightening system
4. First Doppler signal loss
5. Last Doppler signal loss before hands off
6. Hands off for Done

Instructions Regarding Time Points
1. Start of "Go"
2. Strap/redirect secured
   a. If applier only puts the tourniquet on the limb once and goes from placing the tourniquet around the limb to securing the tourniquet to using the tightening system with additional attempts to pull the strap tighter mixed in with use of the tightening system, "strap/redirect secured" is first time at which applier stops securing strap to go to tightening system. If applier continues to pull on the strap while using the tightening system, time of "strap/redirect secured" will match time of "touch tightening system."
   b. If applier never secures strap/redirect system, no other times recorded.
   c. If applier puts the tourniquet on the limb and works on securing or even on tightening but then undoes the tourniquet and restarts the securing process, then "strap/redirect secured" is not the very first time at which applier stops securing the strap. Instead, "strap/redirect secured" is the "strap/redirect secured" time within the last set of secured to tightening system use. "List other" in the "Problems with or without arterial occlusion at Done" receives the explanation.
3. Touch tightening system
   a. "Touch tightening system" time is when applier touches tightening system with purpose to use the tightening system, for example not hand resting on tightening system while still wondering what to do with rest of strap.
   b. If applier only puts the tourniquet on the limb once and goes from placing the tourniquet around the limb to securing the tourniquet to using the tightening system with additional attempts to pull the strap tighter mixed in with use of the tightening system, "touch tightening system" is the first time at which applier touches tightening system as part of starting to use tightening system. If the holding location includes part of the tightening system, then the time to touch tightening system is to when applier starts to use the tightening system.
   c. If applier puts the tourniquet on the limb and works on securing and on tightening but then undoes the tourniquet and restarts the securing process, then "touch tightening system" is not the very first time at which applier touches tightening system as part of starting to use tightening system. Instead, "touch tightening system" is the "touch tightening system" time within the last set of secured to tightening system use. "List other" in the "Problems with or without failure" receives the explanation.
4. First Doppler signal loss
   a. With ratcheting buckle tourniquets, this is the time with no pulse with the buckle in its flat resting position. With tightening systems that rotate in a plane parallel to the limb (windlass and X8T), this is the time of the missing beat that is the first of the missing beats of occlusion. If the applier fails to achieve a Doppler signal loss, there will not be a time.
5. Last Doppler signal loss before hands off
   a. For applications with only one Doppler signal loss, this is the same time as first Doppler signal loss.
   b. For applications with more than one Doppler signal loss, this is the time of the last Doppler signal loss prior to hands off and "Done."
6. Hands off
   a. Applier is done touching the tourniquet.
   b. If the applier takes hands off but then realizes the Doppler signal isn't gone and does additional tightening before saying "Done," then "hands off" is not the first time but the last time with hands off the tourniquet.

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