# Effects of Tourniquet Features on Application Processes

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

## ABSTRACT

**Background:** We investigated emergency-use limb tourniquet design features effects on application processes (this paper) and times to complete those processes (companion paper). **Methods:** Sixty-four appliers watched training videos and 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 were scored from videos. **Results:** Thirty-three appliers had no prior tourniquet experience. All 512 applications were placed proximal to the recipient's simulated distal thigh injury. Thirty-one appliers (13 with no experience) had 66 problem-free applications (18 by no experience appliers). Tightening-system mechanical problems were more frequent with windlass rod systems (26 losing hold of the rod, 27 redoing rod turns, and 58 struggling to secure the rod) versus ratchet systems (3 tooth skips and 16 advance failures). Thirty-five appliers (21 with no experience) had 68 applications (45 by no experience appliers) with an audible Doppler pulse when stating "Done"; causes involved premature stopping (53), inadequate strap pull (1 SOFTTW3, 1 RST), strap/redirect understanding problem (1 SOFTTW5, 1 X8T, 4 Tac RMT, 1 RST), tightening-system understanding problem (2 CAT7, 1 SOFTTW3, 1 TMT, 1 RST), and physical inability to secure (1 SOFTTW3). Fifty-three appliers (32 no experience) had 109 applications (64 by no experience appliers) not correctly secured. Six involved strap/redirect understanding problems: 4 Tac RMT, 1 X8T, 1 SOFTTW5; 103 involved improper securing of non-self-securing design features: 47 CAT7 (8 strap, 45 rod), 31 TMT (17 strap, 19 rod), 22 OMT (strap), and 3 SOFTTW3 (rod). **Conclusion:** Self-securing systems have process advantages. Because most emergent tourniquet recipients require transport, we believe tourniquet security is a critical design aspect. Decisions regarding tourniquet choices may become very different when both occlusion and tourniquet security are considered.

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

## Introduction

Well-designed emergency-use limb tourniquets are lifesaving when correctly used to stop severe bleeding before shock or death.[1–5] The national Stop the Bleed campaign and training emphasize teaching everyone to provide first aid for bleeding injuries, including tourniquet use for severe limb bleeding.[6]

The American College of Surgeons Committee on Trauma and the Committee on Tactical Combat Casualty Care have a track record of preference toward windlass designs,[7–9] but published data shows untrained individuals are not necessarily more successful with a windlass tourniquet than with a ratcheting tourniquet or an elastic tourniquet (195 appliers; all applications on a mannequin; Combat Application Tourniquet, 11 successful of 65 applications; Ratcheting Medical Tourniquet, 15 successful of 64 applications; Stretch Wrap And Tuck Tourniquet, 7 successful of 66 applications; $p$=.149).[10] Additionally, rapid application with one windlass tourniquet design does not necessarily translate to equally rapid application with an alternate windlass design.[11]

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 successfulness of application processes. The companion paper discusses the effects of tourniquet features on process times.[12]

## Methods

The Drake University Institutional Review Board approved this study. Tourniquets were requested (Figure 1, Table 1);

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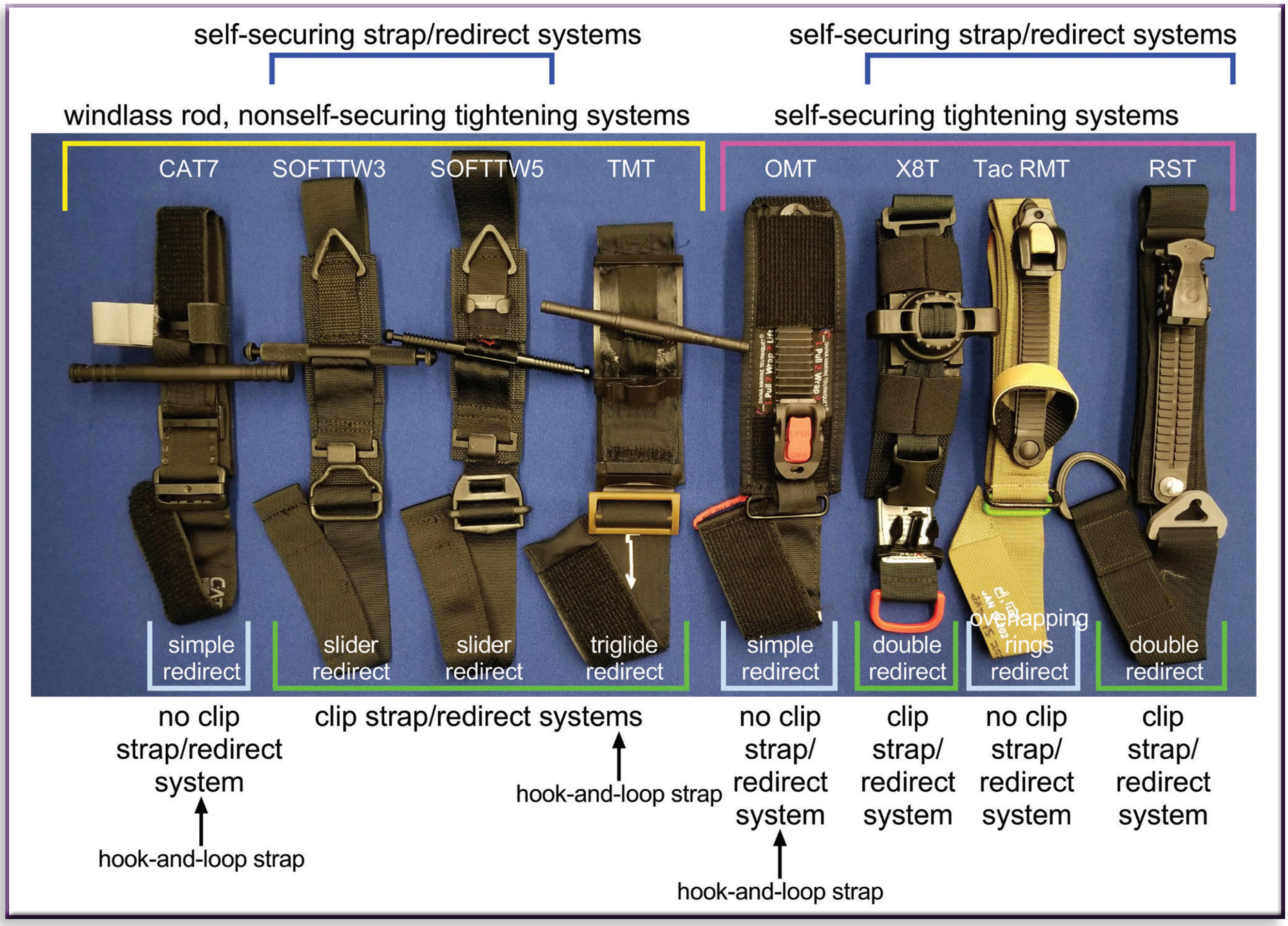
**FIGURE 1** *Tourniquets.* Note all TQs were CoTCCC recommended except the X8T and OMT




Features are indicated above and below the tourniquets (also see Table 1). From left to right the tourniquets are Combat Application Tourniquet Generation 7 (CAT7), SOF® Tactical Tourniquet–Wide Generation 3 (SOFTTW3), SOF® Tactical Tourniquet–Wide Generation 5 prototype (SOFTTW5), Tactical Mechanical Tourniquet (TMT), OMNA Marine Tourniquet Gen 2 (OMT), X8T-Tourniquet (X8T), Tactical Ratcheting Medical Tourniquet (Tac RMT), and RapidStop Tourniquet (RST).

seven models were donated by manufacturers or distributors. TMTs were purchased (two Lot 040517 for a study[13] in 2018 and two MFG April 2019, Lot 45097 for this study). Data collection occurred September–November 2020.

### *Recipients*

Four females and two males were tourniquet recipients (median, minimum–maximum: 22, 20–61 years old, 49.8, 43.5–60cm thigh circumference, 100, 90–128mmHg systolic blood pressure). Each had research tourniquet-recipient experience, audible Doppler dorsal pedal artery pulses (Ultrasonic Doppler Flow Detector Model 811 with 9.5MHz adult flat probe; Parks Medical Electronics, www.parksmed.com), and no contraindications (e.g., no abnormal bleeding or clotting tendencies, circulation problems, pain syndromes, peripheral neuropathies, or connective tissue disorders). As shown in training videos,[14–21] recipients were supine with a flexed receiving leg and a marker-indicated injury one hand-width proximal to the knee.

### *Tourniquets*

See Figure 1 and Table 1. Two tourniquets per design were used in rotation. TMTs used by the first 12 chronological-order appliers (Lot 040517) had prior research use and were changed to a new TMT pair starting with the 13th chronological-order applier (MFG April 2019, Lot 45097). No other tourniquets had prior use.

For study consideration, tourniquet parts and activities were divided into the strap and redirect buckle ("strap/redirect system") and the tightening system (Figure 1 and Table 1). In descriptions, "clip" refers to the clip portion of redirect buckles that can be unclipped instead of requiring strap unthreading for placement around a trapped limb. For dual redirect buckles, the redirect with the clip, at which strap pulling is to occur, is the primary redirect. For windlass rods, each 180° rotation from the rod parallel to the strap equals one turn.

Major design feature differences among tourniquets were the presence or absence of a clip, whether or not strap/redirect systems and tightening systems were self-securing, and the plane of rotation of the tightening system (Figure 1 and Table 1). Among clips, four involved the piece containing the redirection of the strap, hooking over a piece adjacent to the tightening system (SOFTTW3, SOFTTW5, TMT, RST). The other clip was a side-release buckle (X8T). All non-self-securing strap/redirect systems had hook-and-loop: CAT7 and OMT simple redirects depended on the applier engaging hook-and-loop to achieve strap/redirect security. The TMT triglide redirect traded strap-pulling ease for designed-in promotion of hook-and-loop engagement. CAT7 video instructions[14] included securing the remaining limb-encircling strap over the rod in the bracket and then placing the gray hook-and-loop time strap over the bracket opening. Non-self-securing strap/redirect systems could not be

**TABLE 1** *Tourniquets*

| Tourniquet | Strap/Redirect System | | Tightening System | |
|---|---|---|---|---|
| Combat Application Tourniquet Generation 7 (CAT7, Lot 101K179; C-A-T Resources, LLC, http://combattourniquet.com/) | No clip | Non-self-securing rough, simple redirect buckle with hook-and-loop strap | Non-self-securing windlass, top open bracket for securing windlass rod, two hook-and-loop straps to place over secured rod (limb strap then time strap) | Rod rotation parallel to limb surface |
| SOF® Tactical Tourniquet–Wide Generation 3 (SOFTTW3, MFG Date 010819; Tactical Medical® Solutions, www.tacmedsolutions.com) | Clip | Self-securing slider redirect buckle with smooth strap | Non-self-securing windlass, limited mobility vertical triangle for securing windlass rod | Rod rotation parallel to limb surface |
| SOF® Tactical Tourniquet–Wide Generation 5 prototype (SOFTTW5, MFG Date CS1A; Tactical Medical® Solutions, www.tacmedsolutions.com)[*†] | Clip | Self-securing slider redirect buckle* with smooth strap | Non-self-securing windlass, limited mobility top open bracket for holding and limited mobility vertical triangle for securing windlass rod[†] | Rod rotation parallel to limb surface |
| Tactical Mechanical Tourniquet (TMT, Lot 040517 for appliers 1-12; MFG April 2019, Lot 45097 for appliers 13-64; Combat Medical, https://combatmedicalsystems.com)[‡] | Clip | Non-self-securing triglide redirect buckle with hook-and-loop strap | Non-self-securing windlass, unidirectional side entrance bracket with click-in for securing windlass rod[‡] | Rod rotation parallel to limb surface |
| OMNA Marine Tourniquet Gen 2 (OMT, Manufacture Nov 12, 2019, Lot 0I0015; OMNA, www.omnainc.com) | No clip | Non-self-securing smooth, simple redirect buckle with hook-and-loop strap | Self-securing ratcheting buckle on a toothed ladder | Ratcheting buckle rotation perpendicular to limb surface |
| X8T-Tourniquet (X8T, 2020-05-20; RCR Medical Products, LLC, www.rcrmedic.com) | Clip | Self-securing double redirect system (2 smooth simple redirect buckles with smooth strap trapped against limb) | Self-securing ratcheting dial | Unidirectional dial rotation parallel to limb surface |
| Tactical Ratcheting Medical Tourniquet (Tac RMT, Jan 15 2020; m2®inc., www.m2inc.biz) | No clip | Self-securing overlapping rings redirect buckle with smooth strap | Self-securing ratcheting buckle on a toothed ladder | Ratcheting buckle rotation perpendicular to limb surface |
| RapidStop Tourniquet (RST, Lot 032620; Aero Healthcare, www.rapid-stop.com) | Clip | Self-securing double redirect system (2 smooth simple redirect buckles with smooth strap trapped against limb) | Self-securing ratcheting buckle on a toothed ladder | Ratcheting buckle rotation perpendicular to limb surface |

[*]The redirect buckle of the commercially available SOFTTW5 is slightly changed from the prototype such that the sliding piece of the redirect cannot be dislodged from the buckle.

[†]For this study, appliers were allowed to finish the SOFTTW5 application with the windlass rod only in the bracket, only in the triangle, or in both the bracket and the triangle. This was done specifically to examine the influence of securing the rod in the triangle versus in an open bracket between the two generations of SOFTTW. Correct medical use requires rod securing in the triangle.

[‡]Two TMT design changes were present: 1) The size of strap end increased. The size on the older version allowed strap unthreading and rethreading through the triglide buckle with sufficient applier effort. The increased size of the strap end on the newer version made unthreading impossible. 2) The bracket for securing the windlass rod had some shape change to the non-click-in side. The non-click-in side of the older version was continuous with the top of the bracket and had a rounded corner that was the back side against which the rod would be in contact when fully clicked into the securing bracket (version shown in reference videos[17,26,34]). The non-click-in side of the newer version has an extension of the top of the bracket as a separate wing past the vertical aspect of the bracket against which the rod would be in contact when fully clicked into the securing bracket (version shown in Figure 1).

pulled tighter with additional pulls, whereas this was possible for self-securing strap/redirect systems.

### *Appliers*

Appliers were a convenience sample of adults. Appliers were given printed instructions (Appendix A). Each watched a 6 minute, 13 second training video[22] with opportunity to take notes and replay. Appliers wrote answers to seven questions (Table 2) presented at the video start, answered during the video, and re-answered in summary form at the video end,[22] then watched 35 to 56 second training videos[14–21] for each tourniquet in assigned order with opportunity to take notes and replay before moving to the next video. Then the applier went to the tourniquet application room.

### *Tourniquet Applications*

The dorsal pedal artery Doppler signal was audible before starting applications. Recipients remained as non-responsive and relaxed as possible. Each application was videoed from two angles at 90 frames per second with GoPro Hero 5 Sessions (GoPro Inc., www.gopro.com).

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 approximate quarters, with the (primary) redirect buckle as the location of the center fold.[23–30] 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.[13–20] 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 had stated "Done," or the director stopped the application 5 minutes from saying "Go," or the recipient called for a halt. A researcher released

**TABLE 2** *Answers to Seven Questions in Training Video*

| Question | Answer Elements Required | Applier-Tourniquet Experience (Any or No) with Answers Scored as Incorrect/Inadequate |
|---|---|---|
| Why would you apply an emergency-use limb tourniquet? | Serious or life-threatening or severe bleeding or to stop blood loss | Any Experience "to prevent further injury to a life-threatening injury on a limb"<br>No Experience "3 to 4 finger widths above the heart of the injury" |
| Where would you place an emergency-use limb tourniquet? | Proximal to injury or closer to the heart or body than the injury or 3–4 fingers or 2–3 inches closer to the heart or body than the injury | No Experience "You would place an emergency-use limb tourniquet 3–4 finger widths closer to the heart than the injury and not on a limb." |
| How tight should you pull the strap of an emergency-use limb tourniquet? | As tight as possible or very tight | Any Experience "to stop all blood flow to the limb – should indent the skin and then lose Doppler when fully secured and tightened."<br>Any Experience "till blood flow to the limb has stopped"<br>No Experience "tight enough to stop all blood flow" |
| What are two good techniques to use when pulling the strap? | Any two of: prevent slipping, pull parallel to limb surface at redirect, pull using body weight, and secure the strap if needed | Any Experience "pull the strap tight"<br>No Experience "pull perpendicular to the leg, straight"<br>No Experience "secure and hold" |
| What indication should be visible when the strap is secured? | Limb indentation or skin indentation | Any Experience "bleeding has stopped"<br>No Experience "__"<br>No Experience "no slippage/rod secured/latch click 3 times" |
| When your hands are off a completed application of an emergency-use limb tourniquet, how tight should the tourniquet be? | Tighter than when all blood flow stopped or no bleeding or no pulse | 3 Any Experience and 4 No Experience had some version of: as tight as possible<br>No Experience "there should be an indentation of the skin where the tourniquet is"<br>No Experience "very" |
| What is a research indicator of blood flow? | Doppler or audible pulse | Any Experience "color/indented leg"<br>No Experience "?" |

and removed each tourniquet[31–38] and placed the next assigned tourniquet.

This study occurred early in the COVID-19 pandemic. Everyone wore face masks. Clear plastic curtains separated appliers from recipients' upper bodies and from researchers.

### *Application Process Scoring*

Videos were used for scoring application processes (Appendix B). Research assistant pairs provided consensus scores; final scores were determined by a researcher (PW). Major groupings from scoring are shown as the x-axis labels in Figure 2 and are defined in Appendix C.

### *Statistical Analysis*

To control for order effects, the orders of watching application videos[14–21] and of tourniquet applications were separately randomized with 8 × 8 Latin squares using hamsterandwheel.com.

Process scores 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). Fisher exact and chi-square tests were used for contingency data with statistical significance set at $p \leq .05$.

## Results

The results are complex and discrete. The discussion section will synthesize information from the results into messages regarding tourniquet use in the field.

### *Applier Information*

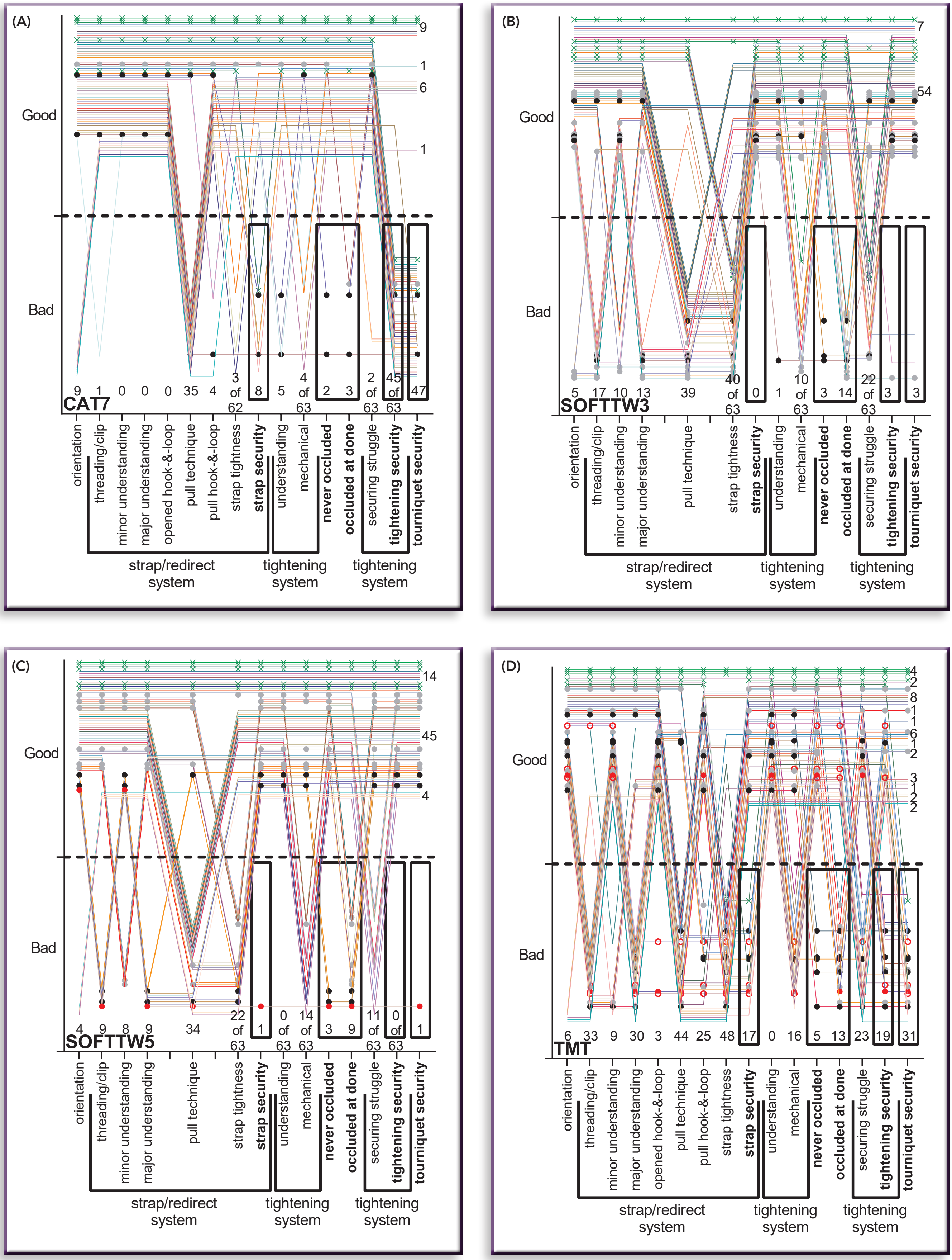
Sixty-four appliers with varying previous tourniquet experience (Figure 3A) were predominantly right-handed (n=61), female (n=46), and 18–22 years of age (n=59; remaining 5 were aged 28, 40, 55, 60, and 62 years). Answers to the questions (Table 2) indicated appliers remembered information presented in the training video.[22] Of the 5.1% of answers missing the required elements (Table 2), some had correct information for variations of the questions.

No appliers had a problem-free application of every tourniquet. There were 66 problem-free applications by 31 appliers (Figure 2 and Figure 3B). As shown in Figure 3B, more appliers (18 of 31 versus 13 of 33; $p$=.21) with any tourniquet experience had more problem-free applications (48 of 248 versus 18 of 264; $p$<.0001). Critical application problems were considered "Not Occluded at Done" and "Not Correctly Secured at Done" (Figure 3C, 3D). In 3C, more appliers (17 versus 12; $p$=.21) with any tourniquet experience had more occluded applications (225 versus 219; $p$=.013). In Figure 3D, more appliers (10 versus 1; $p$=.0023) with any tourniquet experience correctly secured tourniquets in more applications (203 versus 200; $p$=.11).

### *Design-Related Mechanical Problems*

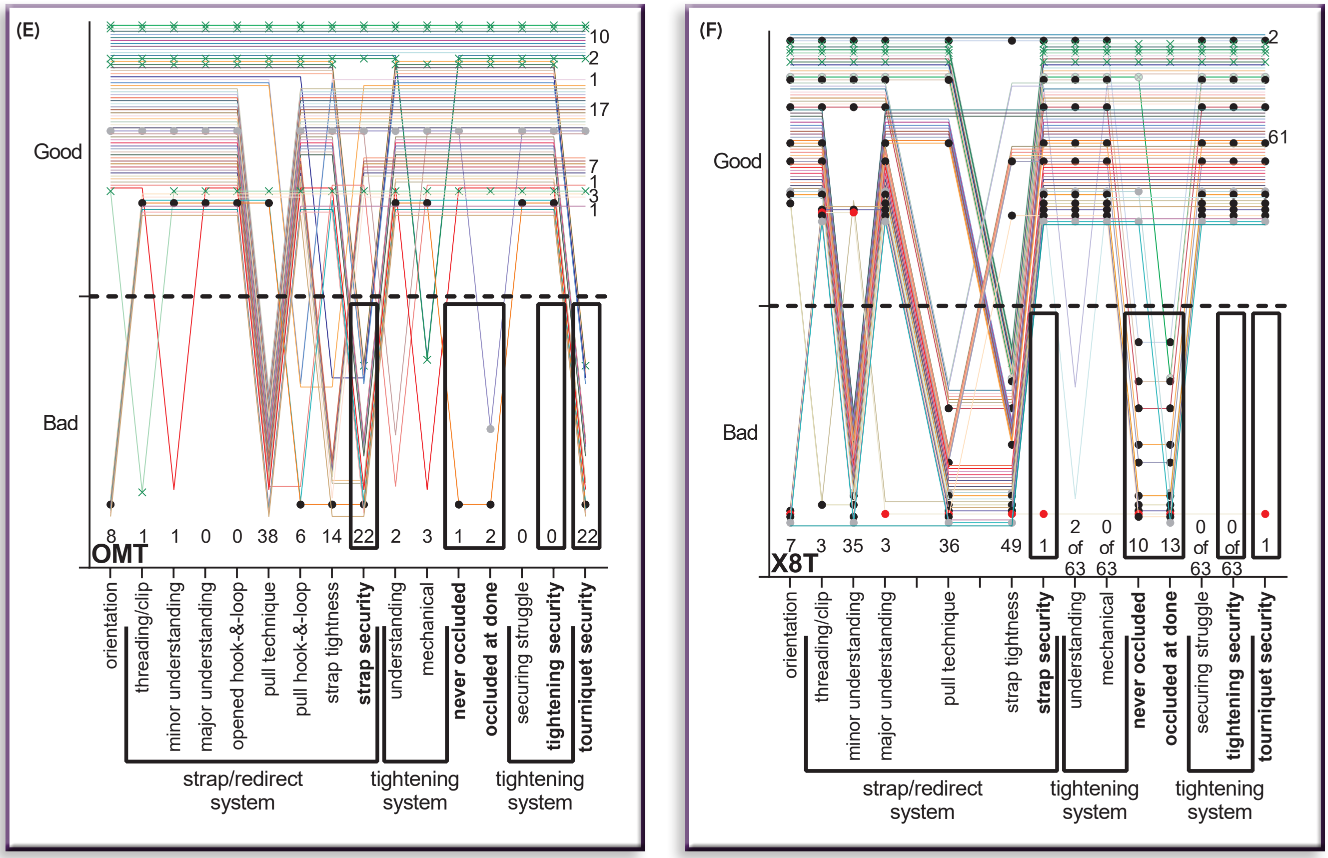
Most application problems belonged to the applier (Figure 2), but design-related mechanical problems occurred in 22 applications by 21 appliers (Figure 3E). Design-related problems were similarly frequent in appliers with and without experience (11 versus 10 appliers, $p$=.79; and 11 versus 11 applications $p$>.9999, Figure 3E). The SOFTTW5 problem related to mis-threading (Figure 2 filled red circles); the applier dislodged the sliding piece from the redirect buckle, preventing strap

FIGURE 2 *Tourniquet application scores flow diagrams.*




*(continues)*

**FIGURE 2** *Cont.*




See page 22 about the non-occluded

*(continues)*

security, occlusion, and tourniquet security. Between the study prototype and the commercially available SOFTTW5, a small slider buckle change now prevents the possibility of this problem. The TMT problem related to poor strap pulling, resulting in four rod turns creating a rod angle that precluded full rod securing (Figure 2 open red circles). Considering the frequency of poor strap tightness, this is a rod-security problem that could easily reoccur. The OMT problem was an instance of tooth skipping,[39] which can be disconcerting but does not preclude tightening and is avoidable with appropriate pressure on the advancing part of the ratcheting buckle toward the ladder. The RST problem that occurred 16 times was failure of the locking pawl to advance a full tooth despite correct, full rotation of the lever arm of the ratcheting buckle. The problem did not involve tooth skipping. In each instance, the applier reset and re-rotated the RST ratcheting buckle lever arm with successful advances of the locking pawl over the ladder teeth. We don't know what caused this problem. The second RST problem occurred during two applications and was inadvertent activation of the releasing mechanism during ratcheting buckle advancement (Figure 2 red circles). The problem occurred because the releasing mechanism is located under the buckle lever arm and is activated by lifting.

### *Application Process Scoring*

Training videos[14–22] showed applications 2–3 inches (3–4 finger widths) proximal to the simulated injury and strap/redirect orientations with redirect buckles lateral with downward, optimal strap pulling. All 512 tourniquet applications were placed proximal to the simulated injury: 6 applications <1 inch proximal, 490 applications 2–3inches proximal, 16 applications >3 inches proximal.

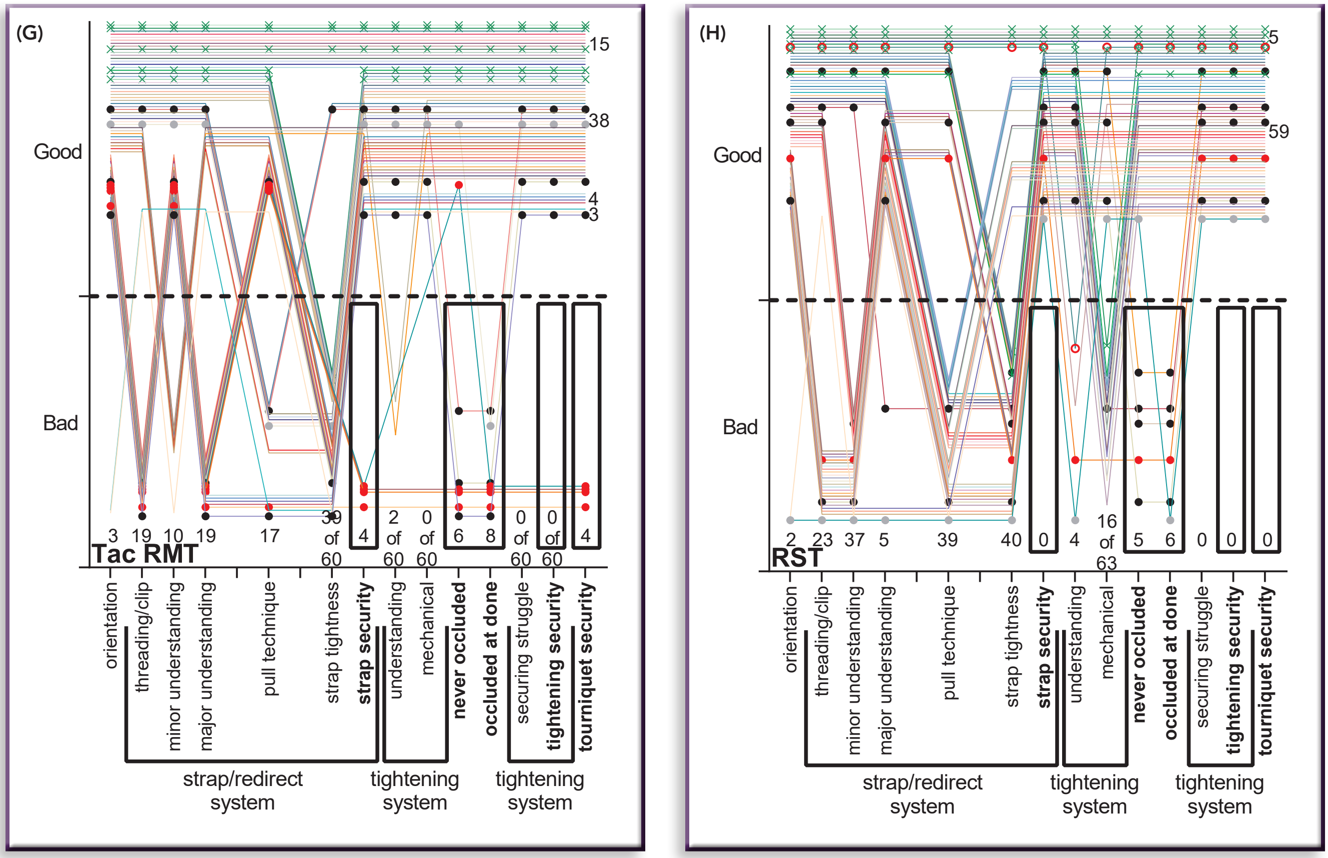
### *Application Process Scoring: Orientation*

Fifty-one applications (10.0%) started with strap/redirect orientations other than shown.[14–22] In seven, appliers changed to the video-shown orientation. The other 44 are indicated as bad orientation in Figure 2. Forty-two had strap/redirect-system problems (95.5% versus 80.6% for video shown, good orientation; $p$=.013); 15 had tightening-system problems (34.9% versus 31.3% for good orientation; $p$=.61); 5 were never occluded (11.4% versus 7.5% for good orientation; $p$=.37) and 10 were not occluded at "Done" (22.7% versus 14.5% for good orientation; $p$=.18). Bad orientation did not have a significantly greater incidence of less-than-optimal strap tightness (59.1% versus 49.8% for shown orientation; $p$=.27) and did not appear to cause other problems so much as to be one of several problems in those 44 applications.

### *Application Process Scoring: Strap/Redirect System*

Problems with threading/clipping aspects of redirects were uncommon with the simple redirects and the side-release buckle (Figure 2 threading/clip). Threading/clip problems were most prevalent with the clip of the TMT (51.6% of applications; $p$<.0001), but only acted as the cause of failure to achieve occlusion with one SOFTTW5 application (misthreading, Figure 2, major understanding problem, filled red circles, never occluded) and four Tac RMT applications (misthreadings, Figure 2, major understanding problem, red circles, not occluded at "Done"). Despite a non-secured strap, one Tac RMT applier still managed to achieve sufficient pressure with continuous strap holding to achieve occlusion, but none of the incorrectly threaded applications were occluded at "Done."

**FIGURE 2** *Cont.*



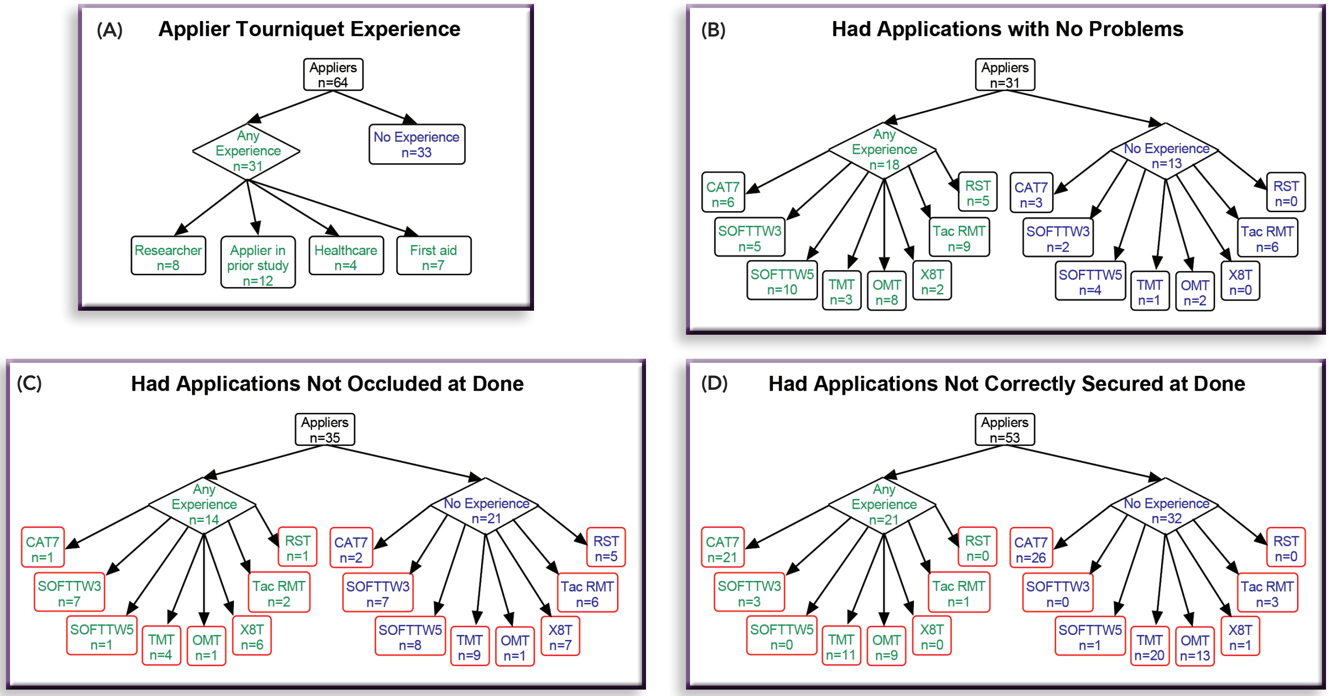

The tourniquets in the panels are in the same order as the pictures in Figure 1 and are as follows: **(A)** CAT7, **(B)** SOFTTW3, **(C)** SOFTTW5, **(D)** TMT, **(E)** OMT, **(F)** X8T, **(G)** Tac RMT, **(H)** RST.

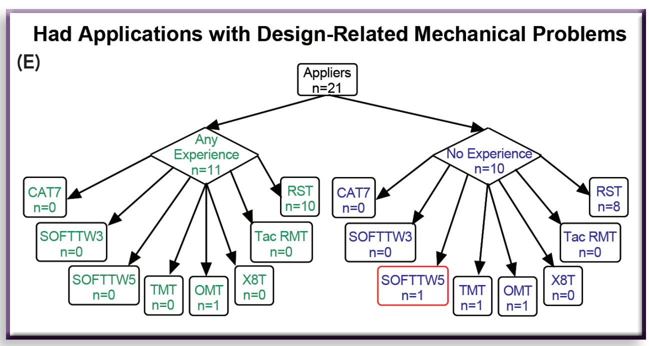
- A video orientation for the graphs can be accessed at https://vimeo.com/799980540.
- The graph in each panel is a flow diagram for every application of the tourniquet indicated in the lower left corner of each graph.
- The line color for each applier is the same in every graph. Every graph contains one line for each application of the tourniquet specified in the lower left corner of the graph.
- Green x's are present at scorable points of applications by five highly experienced tourniquet appliers. Filled black circles are present at scorable points of applications that never occluded. Filled gray circles are present at scorable points of applications that occluded at some point but were not occluded when the applier stated "Done." Red circles are present for scorable points for applications involving serious applier problems with the design of the tourniquet (1 SOFTTW5, 4 TMT, 1 X8T, 4 Tac RMT, 2 RST). Filled red circles indicate non-occlusive applications. Open red circles indicate occlusive applications.
- All points in the upper "Good" half of each graph indicate the event listed on the x-axis did not have a problem. All points in the lower "Bad" half of each graph indicate the x-axis event had a problem.
- The top number along the right side of each graph above the "Good" divider line indicates the number of applications with no problems. The other numbers along the right side and above the divider line sum to indicate the number of applications that finished with both strap and tightening-system security but had some problems (more than one number is present when there were interrupted groupings of lines). The numbers immediately above the x-axis indicate the number of applications with a problem with the respective x-axis event. When an event could not be scored for all 64 applications, the number of scored applications is included with the number having a problem. For example, "3 of 62" for strap tightness for the CAT7 indicates only 62 had scorable strap tightness and three of those 62 had bad strap tightness.
- The order of events on the x-axis is by time of occurrence. For the strap/redirect-system events and the tightening-system events, brackets below the events are labeled with the system to which the events belong. For the events determining the security of the application and the events indicating the effectiveness of the application, the event labels are bold, and the scored points below the "Bad" divider line are captured within four vertical black rectangles.
- The vertical x-axis labels have the definitions indicated in Appendix C.

Among clip tourniquets (Figure 1 and Table 1), the first common problem was clip finding/recognition: 33 TMT, 19 RST, 11 SOFTTW3, and 8 SOFTTW5 ($p$<.0001; see Figure 2 minor understanding problem). This led to trying to unthread the redirect, even while holding the unrecognized clip: 27 tried/2 unthreaded TMT (unthreading only possible with the older version and that took considerable struggling), 13 tried/10 unthreaded SOFTTW3, 8 tried/6 unthreaded SOFTTW5, 3 tried/0 unthreaded RST, and 0 tried X8T ($p$<.0001; Figure 2 major understanding problem). Those who managed to unthread a slider redirect had problems rethreading: 6 of 10 SOFTTW3 and 3 of 6 SOFTTW5. Besides clip recognition and unthreading-related problems, appliers also sometimes had problems with unclipping/reclipping: 7 SOFTTW3, 6 RST, 3 TMT, 3 X8T, and 1 SOFTTW5 ($p$=.15). Strap/redirect system major understanding problems did not occur with the simple redirects and were not common with the X8T and RST, two clip tourniquets that could not be unthreaded, but were common with the TMT (0 CAT7, 0 OMT, 3 X8T, 5 RST, 9 SOFTTW5, 13 SOFTTW3, 19 Tac RMT, 30 TMT, $p$<.0001; see Figure 2 major understanding).

Following reclipping or rethreading, 18 appliers (28.1%) had some difficulty determining where to pull on the X8T (Figure 2 minor understanding problem, only X8T; <.0001). After

**FIGURE 3** *Applier experience and tourniquet application outcomes.*




In each panel, the n values for "Appliers," "Any Experience," and "No Experience" are for the number of appliers, and the n values associated with the name of a tourniquet are for the number of applications of that tourniquet. Text related to "Any Experience" is in green. Text related to "No Experience" is in blue. Red boxes indicate applications that were not occluded or were not correctly secured when the applier stated "Done." **(A)** Any Experience/No Experience refers to whether or not appliers had any experience with emergency-use limb tourniquets. Two researcher appliers had hands-on research tourniquet experience with all of the tourniquets; three with the CAT7, SOFTTW3, OMT, and Tac RMT; and three with the OMT. Appliers who had taken part in a prior study had experience with the OMT. Healthcare appliers were a trauma nurse and EMTs. First aid appliers had tourniquet experience limited to first aid training such as Stop the Bleed, general first aid, Boy Scouts, and high school health science. **(B)** The applier numbers are for appliers who had at least one tourniquet application that had no problems. The specific tourniquet numbers are for how many applications of that tourniquet occurred with no problems. **(C)** The applier numbers are for appliers who had at least one tourniquet application that was not occluded when the applier stated "Done." The specific tourniquet numbers are for how many applications of that tourniquet were not occluded when the applier stated "Done." **(D)** The applier numbers are for appliers who had at least one tourniquet application that was not correctly secured when the applier stated "Done." The specific tourniquet numbers are for how many applications of that tourniquet were not correctly secured when the applier stated "Done." **(E)** The applier numbers are for appliers who had at least one tourniquet application with a design-related mechanical problem. The specific tourniquet numbers are for how many applications of that tourniquet had a design-related mechanical problem. The SOFTTW5 problem precluded strap securing and occlusion and cannot occur in the production model. The TMT problem precluded correct rod securing. The OMT problem was an instance of tooth skipping in two applications, which does not preclude occlusion or securing. Sixteen of the RST problem applications involved an instance of failure of the ratcheting buckle to correctly advance on the ladder. This did not relate to a detected suboptimal application technique. The other two RST problem applications involved inadvertent activation of the releasing mechanism during ratcheting buckle advancing. One of these RST applications did not reach occlusion.

pulling, 17 appliers in 30 applications wasted time wanting to do something with the amount of strap length present (Figure 2 minor understanding problem: 11 X8T, 6 SOFTTW5, 5 SOFTTW3, 4 RST, 2 TMT, 1 OMT, 1 Tac RMT). Excluding the misthreaded SOFTTW5 and four Tac RMTs, and the failure to ever pull in the correct location X8T (Figure 2 filled red circles), 32 appliers in 60 applications held the strap while using the tightening system (Figure 2 minor understanding problem: 22 RST, 15 X8T, 11 Tac RMT, 7 SOFTTW3, 3 SOFTTW5, 1 TMT, and 1 OMT).

Forty-four appliers had 72 applications with one or more hook-and-loop problems (35 TMT, 26 OMT, and 11 CAT7 applications; $p<.0001$). Failure to completely open all the hook-and-loop happened three times and only with the TMT (Figure 2 opened hook & loop red circles). One applier fixed the problem after tightening system first use (Figure 2 filled red circles). The others had trapped, folded strap present at completion (Figure 2 open red circles). The TMT also had the highest incidence of hook-and-loop interference when pulling the strap through the redirect: 25 applications versus 6 OMT and 4 CAT7 ($p<.0001$). TMT good strap-pull tightness was more common when hook-and-loop interference did not occur (3 of 25 good strap-pull tightness with interference versus 13 of 39 good strap-pull tightness without interference, $p=.077$).

Excluding hook-and-loop failure to fully open and pulling interference, seven appliers had eight applications with other hook-and-loop difficulties before securing the strap: 6 TMT and 2 OMT. TMT difficulties were the following hook-and-loop interactions: while setting up to pull; during placement around the leg (two applications); side-to-side engagement during pulling; repeated strap engagement distal to the pulling hand requiring strap disconnection for the next pull; and major side-to-side folding of the strap together during pulling so that <2/3 overlap during strap securing. OMT difficulties were strap side-to-side engagement during pulling.

Tourniquet slipping around the limb during strap pulling was indicated by a major change in the redirect buckle location in 30 applications (5.9% of all applications: 7 RST, 6 Tac RMT, 5 X8T, 3 CAT7, 3 OMT, 2 SOFTTW3, 2 SOFTTW5, 2 TMT; slipping not shown in Figure 2). Only 10 of 30 applications with slipping reached optimal strap tightness ($p$=.089) versus 239 reached optimal tightness of 474 scorable for strap tightness with no slipping. Many applications with slipping involved more than one holding-against-slipping location: 12 involved locations pre-defined as bad (redirect buckle or rod), 8 involved no holding location, and 22 involved locations pre-defined as good (rod-securing bracket, hand flat on tourniquet above the redirect buckle, the X8T dial, or the Tac RMT holding loop).

Strap-pulling effort (strong 352/weak 160 applications), major body weight engagement during pulling (major body weight 175/primarily arms 337 applications), and visual assessment of strap tightness (tight 284/not very tight 228 applications) before tightening-system use were all deemed difficult to score consistently, and therefore were not used for assigning good or bad pull technique in Figure 2. Assigning a single angle of strap pulling was also difficult because the angle sometimes changed during pulling, and some applications had more than one pull, so pulling angle information was grouped into applications with any pulls >45° away from the limb (208, 40.6%) and those with only pulls ≤45° from the limb (304, 59.4%). Applications with any pulls >45° were considered bad pull technique (Figure 2 pull technique). Pull technique was also assigned bad if the redirect buckle or windlass rod was used as a holding location during pulling (redirect holding in 148, 28.9% of applications; rod holding in 42, 8.2% of 256 windlass rod applications).

Forty-two CAT7 and 38 OMT applications involved one effortful strap pull, and five CAT7 and nine OMT involved more than two effortful strap pulls. The TMT had 25 applications involving one effortful pull and 16 involving more than two effortful pulls ($p$=.0050 versus CAT7 and OMT). Self-securing strap/redirect-system applications involving one effortful strap pull were 28 SOFTTW5, 22 X8T, 16 SOFTTW3, 13 Tac RMT, and 13 RST; applications involving more than two effortful pulls were 28 Tac RMT, 25 RST, 25 SOFTTW3, 17 SOFTTW5, and 15 X8T.

Optimal pull-related strap tightness (Figure 2 strap tightness and Figure 4) was not reached in 255 (50.6%) of 504 applications in which it could be scored. Applications with optimal pull-related strap tightness were more common with appliers with any tourniquet experience ($p$=.0024 across all tourniquets, Figure 4). Applications with bad pull technique (Figure 2 pull technique) reached pull-related optimal strap tightness less frequently than those with good technique (45.3% versus 54.4%; $p$=.049). Bad pull technique was most common with the TMT and least common with the Tac RMT ($p$=.0002 for differences across all tourniquets; Figure 2 pull technique). Among applications with bad pull technique, simple redirects had the highest number reaching optimal pull-related strap tightness (32 of 34 CAT7, 28 of 38 OMT, 20 of 33 SOFTTW5, 16 of 39 RST, 10 of 38 SOFTTW3, 9 of 36 X8T, 3 of 16 Tac RMT, and 8 of 44 TMT; $p$<.0001 for differences across all tourniquets [Figure 2 pull technique and strap tightness]). Among applications with good pull technique, simple redirects had the highest number reaching optimal pull-related strap tightness (27 of 28 CAT7, 22 of 26 OMT, 21 of 30 SOFTTW5, 13 of 25 SOFTTW3, 18 of 44 Tac RMT, 8 of 20 TMT, 8 of 25 RST, and 6 of 28 X8T; $p$<.0001 for differences across all tourniquets [Figure 2 pull technique and strap tightness]). Not reaching optimal pull-related strap tightness was associated with never reaching occlusion (24 of 28 never occluded versus 231 of 476 occluded at some point in time; $p$=.0001) and with not being occluded at "Done" (53 of 60 not occluded at "Done" versus 202 of 444 occluded at "Done"; $p$<.0001 [Figure 4]).

No clip problems and no strap backsliding occurred during tightening-system use. When correctly threaded, self-securing redirects successfully secured straps ($p$<.0001 versus non-self-securing redirects; Figure 2 strap security). Twenty-eight appliers failed to fully adhere hook-and-loop straps in 47 applications (Figure 2 strap security and Figure 4). Failure to fully adhere consisted of not securing the entire circumference of exposed hook-and-loop (14 OMT, 7 TMT, and 5 CAT7), <2/3 side-to-side overlap of hook-and-loop (12 TMT, 11 OMT, and 4 CAT7), or failure to fully open the hook-and-loop (2 TMT; Figure 2 open red circles). Audible hook-and-loop releasing noise during tightening-system use occurred in the two never fully opened TMT applications and one OMT application that lacked full circumferential and side-to-side hook-and-loop overlap. In the OMT application, the noise was slight with no visible strap movement.

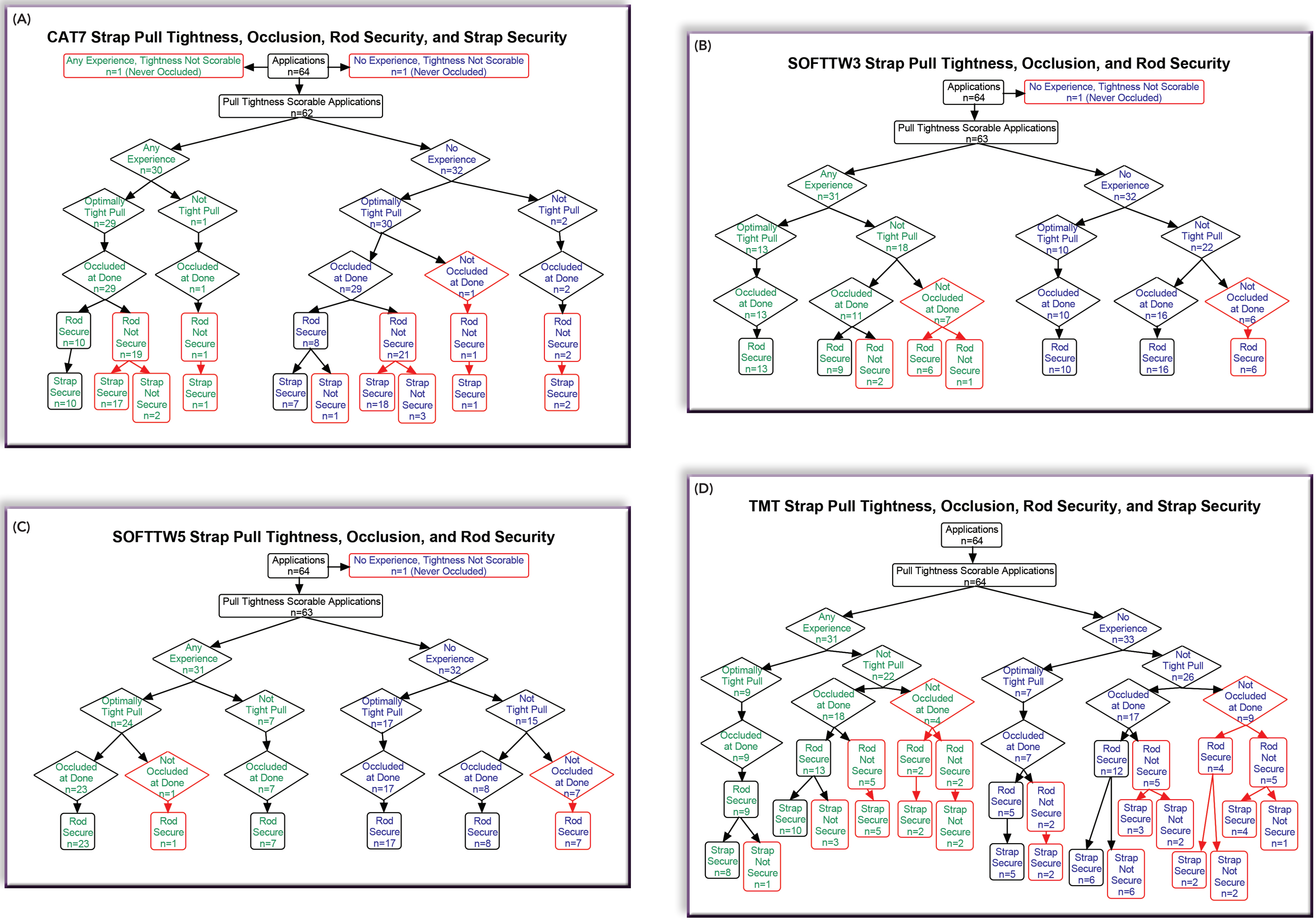
After engaging the tightening system, in 37 applications, 22 appliers returned to the strap/redirect system to do additional strap pulls or to disengage and completely redo strap pulls (9 SOFTTW3, 7 TMT, 6 RST, 5 SOFTTW5, 3 X8T, 3 Tac RMT, 2 CAT, and 2 OMT). Both consume time, and pulls with an engaged tightening system are unlikely to gain strap tightness beyond initial pulling.

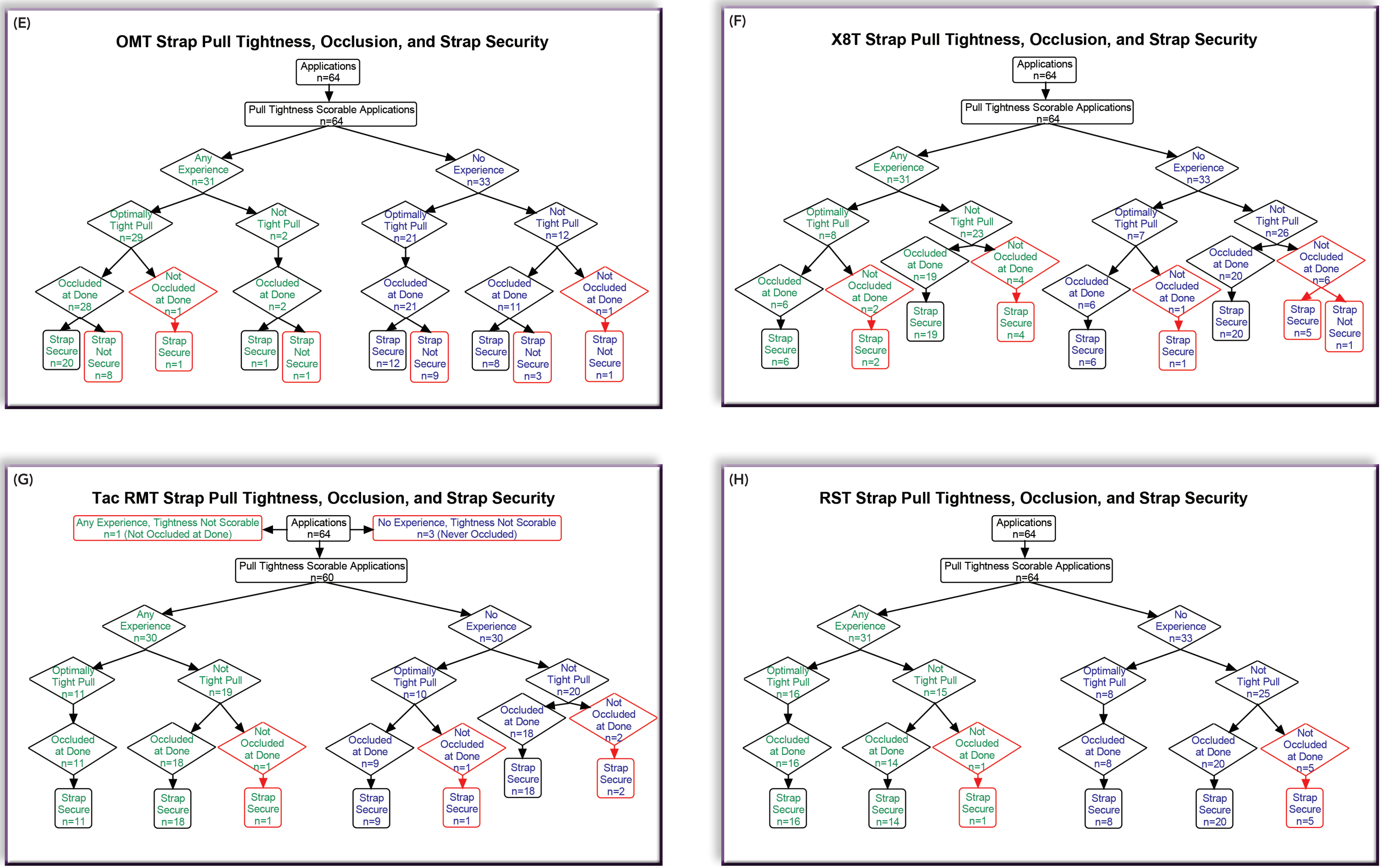
### *Application Process Scoring: Tightening System*

Tightening-system understanding problems (Figure 2 understanding) were uncommon for rotation-parallel-to-limb windlass rods (5 CAT7 and 1 SOFTTW3 of 255 scorable), rotation-perpendicular-to-limb ratcheting buckles (4 RST, 2 OMT, and 2 Tac RMT of 188 scoreable), and rotation-parallel-to-limb ratcheting dial (2 of 63 X8T, $p$=.53). One applier never understood the tightening systems of the CAT7, SOFTTW3, OMT, and RST but still managed to achieve occlusion with the OMT and RST. Another applier had problems understanding the CAT7 and X8T tightening systems but achieved occlusion with both. No other appliers had understanding problems with more than one tourniquet. Failure to ever understand the windlass rod tightening system caused occlusion never to be achieved in two CAT7 and one SOFTTW3 application. Failure to ever understand the ratcheting-buckle tightening system did not prevent appliers achieving occlusion (one OMT and one RST).

Some appliers with ratcheting-buckle understanding problems pulled on the ladder while holding the ratcheting buckle. Ladder pulling alone was ineffective, but holding the ratcheting buckle during ladder pulling sometimes resulted in buckle

FIGURE 4 *Tourniquet strap pull tightness, occlusion, and security.*






In each panel, the number of applications that had scorable pull tightness (“Pull Tightness Scorable Applications”) are split into applications by appliers with any tourniquet experience (green text) and applications by appliers with no tourniquet experience (blue text). Red boxes indicate applications that were not occluded or were not correctly secured when the applier stated “Done.” Connecting arrows become red when departing from a red box. Each panel is for a separate tourniquet. Tourniquets with a self-securing tightening or strap system do not have a separate level of diamonds/boxes for the self-securing system. **(A)** CAT7, **(B)** SOFTTW3, **(C)** SOFTTW5, **(D)** TMT, **(E)** OMT, **(F)** X8T, **(G)** Tac RMT, **(H)** RST.

advancement. Another understanding problem was two appliers lifting the releasing mechanism of the RST while lifting the ratcheting buckle lever arm (Figure 3E).

Other windlass rod-tightening system problems (Figure 2 mechanical) were losing hold of the windlass rod (11 TMT, 9 SOFTTW5, 3 SOFTTW3, and 4 CAT7) or intentionally redoing windlass rod rotations (9 TMT – 4 also lost hold, 9 SOFTTW3 – 2 also lost hold, 8 SOFFTW5 – 3 also lost hold, and 1 CAT7).

The other ratchet-tightening-system problems (Figure 2 mechanical) were one OMT lever arm slipping from the lifting thumb and the previously detailed tooth skipping (2 OMT, Figure 3E), and failures of the RST to advance (16 RST, Figure 3E).

Median (minimum, maximum) tightening-system use at occlusion was CAT7 0.75 (0.25, 2.5) turns, SOFTTW3 2 (0.75, 5) turns, SOFTTW5 1.5 (1, 3.25) turns, TMT 2 (0.75, 4.5) turns, OMT 5 (2, 10) clicks, X8T 13 (4, 23) clicks, Tac RMT 8 (3, 16) clicks, RST 7 (3, 12) clicks. Tightening-system use at "Done" for not occluded applications was CAT7 0.5 turns (0, 1, and one applier did not understand the system sufficiently to even turn the rod to 0 turns), SOFTTW3 2 (2, 5) turns, SOFTTW5 2 (1, 3) turns, TMT 2 (1, 3) turns, OMT 9.5 (4, 15) clicks, X8T 11 (7, 19), Tac RMT 9.5 (4, 14) clicks, RST 7.5 (5, 18) clicks. Tightening-system use at "Done" for occluded applications was CAT7 1 (1, 3) turns, SOFTTW3 3 (1, 4) turns, SOFTTW5 2 (1, 4) turns, TMT 3 (2, 5) turns, OMT 5 (2, 11) clicks, X8T 13 (4, 23) clicks, Tac RMT 8.5 (3, 17) clicks, RST 7 (3, 12) clicks.

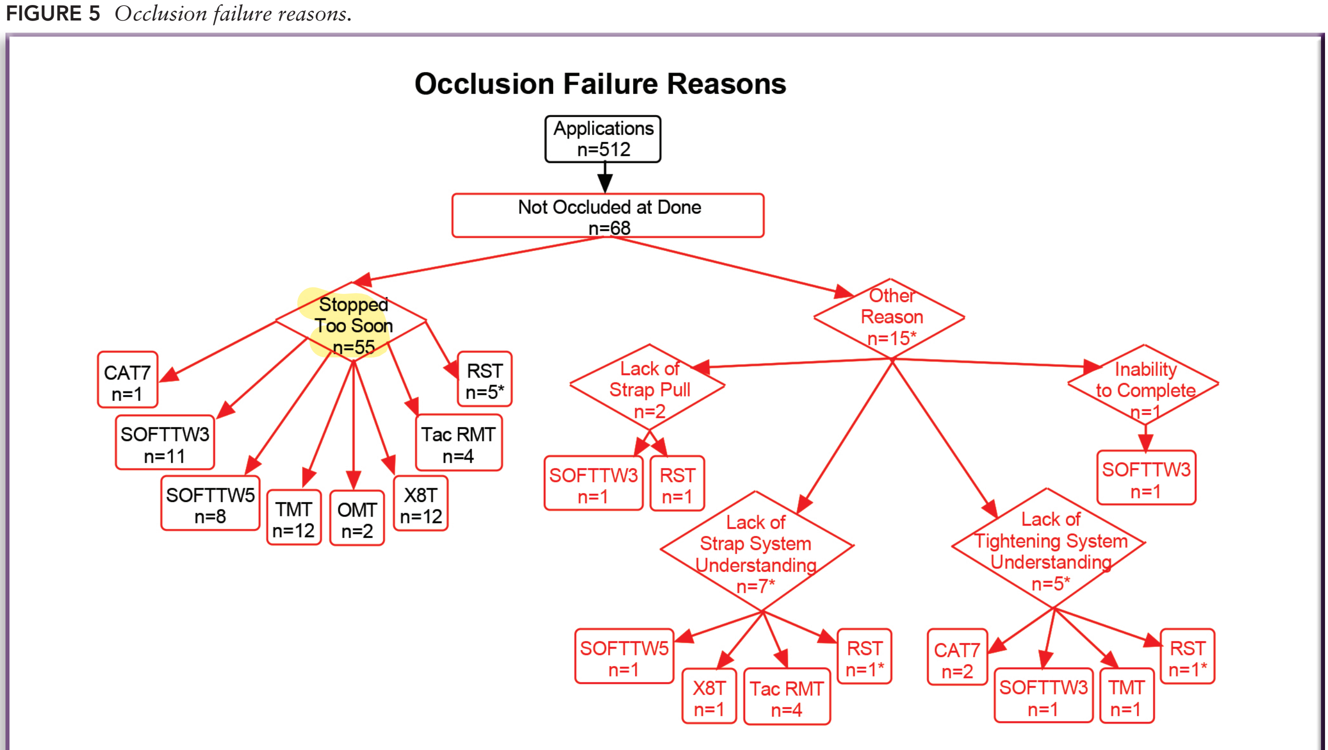
### *Application Process Scoring: Occlusion*

Twenty appliers had 35 applications that never reached occlusion (Figure 2 never occluded, $p$=.057 across all tourniquets), and an additional 15 appliers had an additional 33 applications that were not occluded when the applier said "Done" (Figure 2 occluded at "Done" and Figure 3C; $p$=.0041 across all tourniquets). A few applications achieved such quiet Doppler signals when the applier had finished that an inexperienced applier may not have realized a pulse was still present. In many of the 33 applications that reached occlusion but had a pulse return before the applier said "Done," the applier clearly realized the mistake but had already committed to being finished with the application.

The most frequent reason for occlusion failure was premature stopping of tightening-system use (Figure 5); all 55 such applications could have been taken to occlusion. Applications with the X8T, TMT, and SOFTTW3 had the most frequent premature stopping ($p$=.0017 for differences across all tourniquets [Figure 5]). Reasons for occlusion failure other than premature stopping were predominantly related to system understanding problems (Figure 5). In Figure 5, fewer appliers ($p$=.13) with any tourniquet experience had fewer "Stopped Too Soon" not occluded applications ($p$=.0065), and fewer appliers ($p$=.15) with any tourniquet experience had fewer "Other Reason" not occluded applications ($p$=.18).

The 15 applications with occlusion failure for reasons other than stopping tightening too soon, were by nine appliers. One applier with some tourniquet experience had three occlusion failures: physical inability to complete rod securing with two rod turns with a SOFTTW3; lack of strap rethreading

**FIGURE 5** *Occlusion failure reasons.*




The number of applications not occluded when the applier stated "Done" are split into applications that only needed achievable additional tightening to be occluded ("Stopped Too Soon") and applications that had other reasons ("Other Reason") for not reaching occlusion. One RST application ("*") is counted in the "Stopped Too Soon" and in the "Other Reason" because the applier stopped too soon because of a failure to understand the strap system ("Lack of Strap System Understanding") and a failure to understand the tightening system ("Lack of Tightening System Understanding").

understanding with a Tac RMT; and a combination of not fully understanding the strap system and the tightening system and giving up on tightening too soon with an RST. One applier with some experience had one occlusion failure: a lack of SOFTTW3 strap pulling leading to six turns of the windlass without occlusion; with this many windlass turns, it is unclear that anyone could have increased the number of turns to reach occlusion and then secured the rod. Three appliers with no experience had two occlusion failures each: one applier lack of tightening-system understanding with a CAT7 and SOFTTW3; one applier lack of tightening-system understanding with a CAT7 and TMT; and one applier lack of strap-system understanding with a Tac RMT and lack of strap pull leading to running out of ladder teeth with an RST. Four appliers with no experience had one occlusion failure each: lack of strap-system understanding with one SOFTTW5 (broke slider with rethreading failure), two Tac RMTs (rethreading failures), and one X8T (pulled at the secondary redirect).

### *Application Process Scoring: Tightening-System Securing Struggle*

Self-securing tightening systems had no securing struggles ($p$<.0001 versus non-self-securing tightening systems, Figure 2 securing struggle). Forty appliers struggled securing windlass rods in 58 of 254 applications: 23 TMT, 22 SOFTTW3, 11 SOFTTW5, and 2 CAT7 ($p$<.0001 across windlass rod tourniquets, Figure 2 securing struggle). Use of the SOFTTW3 triangle was associated with more rod-securing difficulties than use of the SOFTTW5 bracket ($p$=.0385). (Bracket-only securing is not medically appropriate and was only allowed to assess difficulty imposed by the triangle; only 10 struggled of 59 appliers who just used the SOFTTW5 bracket.) Across all windlass rod tourniquets, suboptimal strap tightness was associated with struggling to secure the rod ($p$<.0001). Struggling frequency was not significantly different by applier-tourniquet experience (18 any experience versus 22 no experience appliers [$p$=.61] with 24 versus 34 applications [$p$=.23]).

### *Application Process Scoring: Tightening-System Security*

Self-securing tightening systems had no security problems ($p$<.0001 versus non-self-securing tightening systems, Figure 2 tightening security). Only two of the 45 CAT7 rod-security problems involved failure to put the rod into the bracket (one applier used the time strap to attach the rod to the bracket top, another rested the rod against the edge of the bracket opening), two involved placing the limb-encircling strap in the bracket before the rod, 18 involved placing neither the limb-encircling strap nor the time strap over the rod, six involved placing only the limb-encircling strap over the rod, 11 involved placing only the time strap over the rod, and nine involved placing the time strap over the rod and then trying to place the limb-encircling strap over the time strap. With the SOFTTW3, one applier was physically unable to secure the rod in the triangle with two rod turns (Figure 5); one rested the rod on the edge of the triangle with three rod turns; and one rested the rod on the redirect clip with three rod turns. With the TMT, 13 appliers placed the rod under the first part of the bracket without clicking it into the secure location; one balanced the rod on the open side of the bracket without placing it under the first part of the bracket, four balanced the rod on the wrong side of the bracket, and a design problem prevented one applier from correctly securing the rod in the bracket with four rod turns (Figure 2 open red circles and Figure 3E).

### *Application Process Scoring: Tourniquet Security*

Tourniquets that involved applier actions for strap/redirect and/or tightening-system security had higher rates of security problems than did tourniquets with both self-securing strap/redirect and self-securing tightening systems ($p$<.0001; Figure 2 tourniquet security, Figure 3D, and Figure 4).

### *Application Process Scoring: Combined and Critical Strap/Redirect-System, Tightening-System, and Tourniquet Problems*

Problems were frequent with strap/redirect systems (Figure 6A; $p$<.0001), but not all problems had the same importance. The frequency of strap/redirect major understanding problems varied (Figure 6B; $p$<.0001). The two strap/redirect-system outcomes associated with the critical final outcomes of occlusion and tourniquet security varied across tourniquets (Figure 6C; $p$<.0001) and did not match the frequency of either any strap/redirect-system problems or strap/redirect-system major understanding problems ($p$<.0001 for each tourniquet). Despite conceptual similarities such as a clip, a simple redirect buckle, a slider redirect buckle, or a hook-and-loop strap, conceptually similar strap/redirect systems did not match each other regarding strap/redirect problem frequencies (for example, compare CAT7 and OMT and SOFTTW3 and SOFTTW5 in Figure 6C).

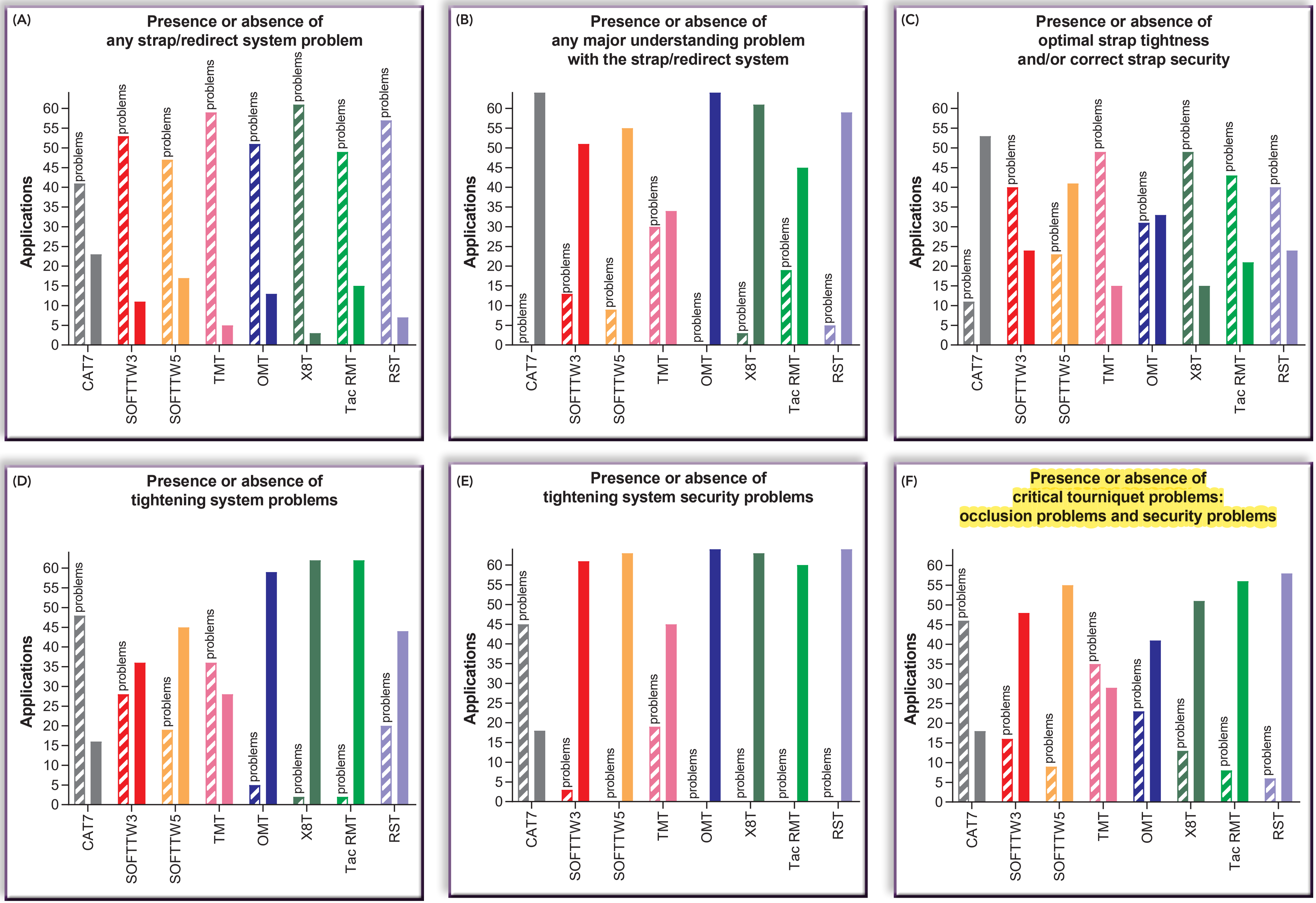
Tightening-system problem frequencies varied (Figure 6D; $p$<.0001). Despite conceptual similarities such as a ratcheting buckle advancing on a ladder, conceptually similar tightening systems did not match each other regarding tightening-system problems (for example, compare OMT, Tac RMT, and RST in Figure 6D). The tightening-system problem associated with the critical final outcome of tourniquet security varied across non-self-securing windlass rod tourniquets and did not exist with self-securing ratcheting tourniquets (Figure 6E; $p$<.0001). The frequency of system-security problems was not significantly different from the frequency of the combined tightening-system problems for the CAT7, X8T, and Tac RMT (each $p$ >.50) but was different for the other tourniquets (SOFTTW3, SOFTTW5, and RST each $p$<.0001; TMT $p$=.0041, OMT $p$=.058).

The critical tourniquet application problems of lack of occlusion or lack of security are combined in Figure 6F ($p$<.0001). Tourniquets relying on applier actions for strap/redirect-system security have a higher frequency of security problems. For each tourniquet other than the CAT7, the problem frequencies were different for critical tourniquet application problems (Figure 6F), strap tightness and/or security problems (Figure 6C), and tightening-system security problems (Figure 6E; $p$<.0001). For the CAT7, the frequency of critical tourniquet application problems (Figure 6E) was different from strap tightness and/or security problems (Figure 6C; $p$<.0001) but was almost the same as that for tightening-system security problems (Figure 6E).

## Discussion

The key findings were as follows: 1) Conceptually similar design features did not result in matching problem frequencies; 2) Because the initial occlusion can be transient,[40,41] not allowing timed appliers to do any additional tightening after they have called "Done" is likely to result in quite a few non-occlusive applications that could easily be tightened to

**FIGURE 6** *Strap/redirect- and tightening-system problems.*




In each panel, the tourniquets are shown in the same order. Applications with the problems indicated in the figure title are shown with a diagonal slash pattern. Applications without the problems indicated in the figure title are shown with a solid color. The panels show applications according to the presence or absence of the following: **(A)** any strap/redirect-system problem, **(B)** any major understanding problem with the strap/redirect system, **(C)** optimal strap tightness and/or correct strap security, **(D)** tightening-system problems, **(E)** tightening-system security problems, and **(F)** critical tourniquet problems: occlusion problems and security problems.

occlusion; 3) Self-securing systems lead to fewer opportunities for tourniquet security problems; 4) Including tourniquet security rather than only evaluating occlusion results in major differences in how ideal a tourniquet would be considered. The time-related aspects of this study will be discussed in the companion paper[12] following this article in this journal.

Before discussing the key findings, it is important to note that we made several pre-study decisions related to what questions we wanted to explore:

1) We showed only one orientation for tourniquet application: lateral redirect buckle with strap pulling downward. We consider this orientation preferable because it provides more applier working space than does working between the recipient's legs, it also offers the opportunity to engage the applier's body weight in strap pulling, and it puts tightening systems in an accessible location.
2) We folded and oriented each tourniquet as similarly to each other as possible rather than presenting each tourniquet as packaged by the manufacturer. This was to compare the impact of design feature differences rather than the impact of manufacturer-presentation choice differences.
3) We showed SOFTTW5 application completion as windlass rod placement in the bracket without adding the triangle.[16] This allowed investigation of securing-difficulty differences between the triangle (SOFTTW3) and open-top bracket (SOFTTW5) of two very similar tourniquets but is not a clinically appropriate application completion; in real use, the rod of the SOFTTW5 should be secured in the triangle. Our results indicate that placement of a windlass rod in an open-top bracket (CAT7 and SOFTTW5) is physically much easier than placement in a securing triangle (SOFTTW3) or the side opening of a unidirectional bracket (TMT). However, an open-top bracket may require an additional step for security.
4) We used a tightening-system-use-at-occlusion threshold to define optimal pull-related strap tightness. The need for fewer than three 180° rod turns as optimal has been established for the CAT for structural reasons[42-44] and appears reasonable for SOFTTWs[45] and TMTs for rod securability reasons. Defining optimal pull-related tightness with the X8T, OMT, Tac RMT, and RST is harder. Each has finite tightening capacity. With the X8T, we chose less-than-or-equal-to one 180° dial rotation from the starting position as optimal (10 clicks). With the Tac RMT, fewer than eight tooth advances for occlusion corresponds with pull-related strap pressures that would be acceptable for the CAT[44] and are achievable.[45] Because the tooth advances of the OMT and RST are larger than those of the Tac RMT, we set the definition of optimal tightness for those two tourniquets at one click less than for the Tac RMT.
5) We did not instruct appliers to advance ratcheting-tightening systems an additional click past occlusion. This allowed instructional consistency across tightening systems: tighten to Doppler signal loss then secure the tightening system, which means stop tightening when using a self-securing system. For clinical use, we strongly recommend at least one additional advance beyond occlusion with any fine-resolution, self-securing tightening system.[40,41]
6) We decided "Done" would be a final statement with no additional applier-tourniquet interaction allowed after stating "Done."

*Key Finding 1*

Tourniquets can be grouped according to design features (Figure 1), but differences among conceptually similar features have substantial impacts on how successful appliers with limited training will be. For example, the seemingly minor differences in strap materials and slider redirect buckles between the SOFTTW3 and SOFTTW5 resulted in significant differences in strap tightness before tightening-system use. Among the different styles of clips, the TMT clip was much harder for appliers to recognize than other clips. Between the two double redirect tourniquets, some appliers seemed confused regarding where to pull the X8T but not the RST. Therefore, while conceptually grouping tourniquets has its uses, it must be done with caution and consideration of the finer points and end goals of the discussion for which the groupings are made. For example, grouping all tourniquets into either windlass rod or non-windlass rod tightening systems is likely to be inappropriate for reaching optimal decisions regarding what tourniquets are ideal for community-accessible bleeding-control kits and classes. Additionally, when exploring if training with one windlass rod tourniquet, such as the CAT, assists with use of a different windlass rod tourniquet, such as the SOFTTW3,[11] one should consider differences in how easily optimal strap-pull-related tightness is reached and how easily the windlass rods are secured, otherwise one risks mistaking differences in physical properties for failure to learn generalizable knowledge.

*Key Finding 2*

Appliers knew applications were being timed and were instructed to "do your best to be quickly correct with each of your tourniquet applications" (Appendix A). Appliers clearly wanted to finish applications as quickly as possible. In some of the 55 applications in Figure 5 in which tightening stopped too soon, occlusion was present when active tightening stopped but did not persist through "hands off the tourniquet" and stating "Done." In many of those instances, appliers clearly wanted to recall the utterance and perform additional tightening. This may have been most common with the X8T because appliers tended to maintain some hand pressure on the dial between clicks. The best approach for avoiding the problem was full "hands off," followed by a listening pause, then either resumption of tightening or stating "Done." Such an approach traded adding time for assurance of occlusion and was not common. Even one very experienced applier made the "stopped too soon" mistake with an X8T application. Fewer applications would have failed to be occluded at "Done" if appliers had been allowed to change their minds regarding being done. We believe being timed influenced some appliers against taking the time for a listening pause (most inexperienced appliers probably would not have known the usefulness of a listening pause).

Before using the tightening system, appliers interacted with the strap/redirect system. Appliers demonstrated a variety of mistakes with strap/redirect systems. Only a few problems precluded occlusive applications: pulling at the wrong location, improper rethreading, and pulling so poorly that a finite tightening system could not overcome the bad pull. Unexpected strap problems were two appliers managing to unthread the earlier generation TMT and two appliers managing to have occlusive TMT applications without ever opening all the interior strap hook-and-loop.

*Key Finding 3*

The frequency of strap/redirect-system problems impacting tourniquet security was high for hook-and-loop systems. The triglide redirect buckle of the TMT makes its strap less likely to accidentally be successfully released than that of the CAT7 or OMT. Appropriate finishing of CAT7 applications makes its strap more secure than that of the OMT. We lack data regarding how frequently hook-and-loop straps are accidentally released in real tourniquet use, but we find releasing inadequately secured CAT7 applications (no "Time" strap over limb strap) and OMT applications very easy and fast in the laboratory via pulling open the strap hook-and-loop. Failure to do appropriate hook-and-loop overlapping makes strap opening even easier. The five self-securing strap/redirect systems of the tourniquets in this study are very difficult or impossible to release while the tourniquet is tightened to occlusion, so they are considerably more secure than hook-and-loop systems.

As with strap/redirect systems, self-securing tightening systems avoided opportunities for application errors to result in a lack of tourniquet security. The frequency of securing problems with windlass rod tightening systems was high. We even noted a "training scar" when a research-experienced applier called "Done" with the CAT7 without securing the time strap over the bracket opening. Self-securing tightening systems did not have physical securing struggles or errors regarding appropriate securing.

*Key Finding 4*

Most studies examining tourniquet effectiveness consider occlusion. Most, but not all,[46] require occlusion with appliers able to take their hands off the tourniquet. Explicit discussion of the security of occlusive applications is rare in the emergency-use limb-tourniquet literature. Because most patients who receive an emergency tourniquet application require some transport to definitive care, we believe tourniquet security is a critical design aspect. Decisions regarding tourniquet choices may become very different when both occlusion and tourniquet security are considered. This should be especially true in situations potentially involving appliers with little to no tourniquet training.

*Limitations*

This study had the expected laboratory-setting limitations of no actual injuries and substitution of an audible Doppler signal for bleeding as a cue for appliers. Appliers received minimal training, but it occurred directly before tourniquet applications. Additionally, the convenience sample of appliers was recruited predominantly on a college campus by undergraduate students pursuing degrees in biological sciences. We believe the frequency of bad process techniques would likely be higher with the stress of real injuries, no fresh training, and fewer science-inclined appliers.

## Conclusions

Training for a specific tourniquet should include emphasis on problem processes for that tourniquet; for example: correct CAT rod securing and strap securing, the presence of the TMT clip, full hook-and-loop opening with the TMT, correct TMT rod securing, where to pull the X8T, how to rethread the Tac RMT, and how not to engage the RST release mechanism while advancing the RST ratcheting buckle. All general tourniquet training should include the important general concepts of proximal placement, sufficient circumferential tightness to stop all arterial flow (all bleeding), and application security to prevent accidental release. Other important general concepts for most tourniquets are that strap/redirect systems use unthreading/rethreading or unclipping/reclipping for placement around a trapped limb; the techniques, importance, and indicators of good strap pulling before use of the tightening system; recognition of strap security; that most tightening systems involve rotation of some part, which shortens the amount of strap around the limb via strap twisting or strap bunching; and recognition of tightening-system security.

In contrast, when tourniquets may be used by appliers with limited training, designs that diminish opportunities for critical application problems will have fewer critical application problems. Self-securing systems, especially self-securing tightening systems, have serious process advantages for use by appliers with limited training.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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 gave final approval of the manuscript.

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# APPENDIX A. APPLIER INSTRUCTIONS AND APPLIER TRAINER INSTRUCTIONS

## Applier Instructions

Tourniquet applications are not a race and are not a competition. Simply do your best to be quickly correct with each of your tourniquet applications.

Pass the "I don't have any COVID symptoms" verbal quiz.

1) Enter the research training room.
2) Wash your hands.
3) Sign the informed consent form.
4) Watch the general tourniquet use video. You can use pause, and you can rewatch any portions of the video. You can take notes.
5) Answer the post-video questions.
6) Watch the eight individual tourniquet application videos in the assigned order. You can use pause, and you can rewatch any portions of any of the videos so long as you stay in sequence order (in other words, once you have moved to the next video, you can't go back).
7) Go to the tourniquets application room.
8) Wash and thoroughly dry hands.
9) Go to the "apply tourniquets" location.
10) Kneel on the mat beside the indicated Recipient leg.
11) Keep your hands on your thighs until the Director says "Go."
12) Let the Director know if you are or are not ready when he/she asks.
13) When the Director says "Go," pick up and apply the tourniquet because the time for applying that tourniquet has started (so make sure you let the Director know if you are not ready). You will have a maximum of 5 minutes to complete each tourniquet application. Once the application time starts, there is no restart, so proceed to fix any problems you encounter and continue with each tourniquet application until you complete the application or the Director says "Stop."
14) When you have completed the tourniquet application, take your hands off the tourniquet while saying "Done."
15) If the Director says "Stop," stop your application efforts, and take your hands off the tourniquet.
16) Do not talk to the Recipient.
17) Once you have said "Done," you are done interacting with that tourniquet during that application.
18) After you have said "Done," the Releaser will release and remove the tourniquet from the Recipient's leg and will place the next tourniquet for your use.
19) The Releaser will also address any audible Doppler pulse issues and any Recipient leg position issues between releasing and removing one tourniquet and allowing the next tourniquet application.
20) Ready yourself for the next tourniquet application (kneel on the mat with your hands on your thighs).

Tourniquet applications are not a race and are not a competition. Simply do your best to be quickly correct with each of your tourniquet applications.

## Applier Trainer Instructions

1) Meet the Applier in the Olin lobby.
2) Bring the Applier to outside the research training room (back of the anatomy lab, room adjacent to the tourniquets application room).
3) Ask the Applier the COVID-19 symptoms questions.
4) Enter the research training room.
5) Have the Applier wash his/her hands in the research training room.
6) Help the Applier with the informed consent form and sign as the witness to the Applier's consent.
7) Present the Applier with the Applier Instructions and make sure the Applier takes his/her time reading all the Applier Instructions. Let the Applier know that he/she can reread any of the Applier Instructions at any time.
8) Help the Applier as needed with watching the general tourniquet use video. Make sure the Applier knows he/she can use pause and can re-watch any portions of the video. Also make sure the applier knows he/she can take notes on the blank sheet of paper that is the back of the questions sheet.
9) When the Applier has finished watching the general tourniquet training video, close the video player and have the Applier answer the post-video questions that are present on the other side of the sheet of paper available for note taking.
10) Help the Applier as needed with watching the eight individual tourniquet application videos **in the assigned order**. Have the Applier place a check mark after each watched video on the small piece of paper with the order list. Make sure the Applier knows he/she can use pause and can rewatch any portion of any of the videos so long as he/she stays in sequence order (in other words, once the Applier has moved to the next video, the Applier can't go back).
11) When the Applier has finished watching all eight individual tourniquet application videos, take the Applier to the tourniquets application room. Also take the notes/questions/answers sheet and the order of videos to watch small piece of paper to the tourniquets application room.
12) Clean the Applier training station in the research training room.

# APPENDIX B.
# APPLICATION SCORING CRITERIA TO USE WITH VIDEOS

1. Strap pull mechanics
   a. Angle of strap pulls at redirect
   b. Applier pulling effort: strong/weak
   c. Pull force capture with hook-and-loop systems: good/poor
   d. Number of effortful pulls
   e. Body weight engagement versus just arms use
   f. Strap visual tightness: tight/not very tight
2. Redirect buckle location at start and finish of strap pull (lateral, medial, anterior, posterior) and accompanying pull direction
3. Tourniquet location relative to injury
   a. Proximal/distal
   b. Estimated distance proximal (<1 inch, 2–3 inches, >5 inches)
4. Holding location used to prevent slippage during strap pulling
   a. None
   b. Rod-securing bracket or triangle
   c. Rod
   d. Holding loop (Tac RMT)
   e. Ratcheting buckle
   f. Hand pressing on tourniquet "above" redirect
   g. Base of X8T dial
   h. Redirect buckle
5. Tightening system use to Doppler signal loss and at hands off
   a. Rod turns/ratchet clicks (0 rod turns defined as first time rod parallel to strap and each 180° rotation thereafter defined as one rod turn)
   b. Direction of rotation (rod or dial clockwise/counterclockwise or ratcheting buckle away from/toward applier)
6. How the rod of the SOFTTW5 was secured: bracket only, triangle only, both bracket and triangle (For this study, the instructional video for the SOFTTW5 allowed appliers to finish the application with the windlass rod only in the bracket, only in the triangle, or in both the bracket and the triangle. This was done specifically for examining the influence of securing the rod in the triangle versus in an open bracket between the two generations of SOFTTW. Correct medical use requires rod securing in the triangle.)
7. Why an application did not achieve arterial occlusion (elimination of audible Doppler signal) or did not have arterial occlusion when completed
   a. Understanding problems with the strap/redirect system: threading, clip, correct strap pull location
   b. Understanding problems with the tightening system
   c. Stopped advancing the tightening system prematurely when could have continued
   d. Applier too weak to advance tightening system sufficiently
   e. Ran out of tightening system (ladder teeth)
   f. Didn't secure windlass rod
   g. Didn't try to secure windlass rod
   h. Applier physically unable to secure windlass rod
   i. Tourniquet broke
   j. Hook-and-loop failure during tightening system use
   k. Strap backsliding during tightening system use
   l. List other
8. Application problems with or without arterial occlusion at Done
   a. Redirect problems
      i. Problem finding/recognizing clip
      ii. Problem using clip
      iii. Tried to unthread clip
      iv. Unthreaded clip
      v. Problem rethreading clip
      vi. Problem rethreading non-clip redirect
      vii. Problem figuring out where to pull
   b. Redid pull or did more pulling after using tightening system
   c. Tourniquet slipping around limb during strap pulling
   d. Spent time trying to decide what to do with what many appliers seemed to view as "excess" strap at the end of strap pulling
   e. Held strap while using the tightening system
   f. Significant hook-and-loop interaction during strap pulling
   g. Hook-and-loop difficulty other than interference with strap pulling
   h. Incorrect securing of limb encircling hook-and-loop strap:
      i. Did not secure all available hook-and-loop circumferentially
      ii. Had <2/3 side-to-side overlap of engaged hook-and-loop
   i. Hook-and-loop failure during tightening system use
   j. Strap backsliding during tightening system use
   k. Clip problem during tightening system use
   l. Lost hold of windlass rod
   m. Chose to redo windlass rod twisting
   n. Ratchet tooth skips
   o. Difficulty achieving locking pawl advancement
   p. Struggled with securing windlass rod
   q. Incorrect securing of windlass rod
      i. CAT7: incorrect or lack of bracket use, neither hook-and-loop strap used, only limb encircling strap placed over rod, only time strap placed over rod, time strap placed over rod followed with an attempt to place limb encircling strap over time strap, limb encircling strap placed in bracket before rod
      ii. SOFTTW3: rod not in triangle
      iii. TMT: rod balancing on open side of securing bracket, rod just under first part of securing bracket but not clipped in, rod balancing on wrong side of securing bracket
   r. List other

# APPENDIX C. DEFINITIONS OF MAJOR GROUPINGS USED AS X-AXIS LABELS IN FIGURE 2

*Orientation ("Bad" if either bad)* = placed with the (primary) redirect buckle lateral and oriented for downward optimal strap pulling.

**Strap/Redirect System:**

*Threading/clip* = threading the strap through a non-clip redirect buckle or using the clip of a clip redirect buckle.

*Minor understanding ("Bad" if any bad)* = speed of recognition of clip if present; recognition of correct strap-pulling location; time spent considering what to do with length of strap pulled through self-securing redirect buckle; holding of length of strap pulled through self-securing redirect buckle while using tightening system; minor hook-and-loop issue other than: failure to completely open, pull interference, or incorrect circumferential wrapping.

*Major understanding ("Bad" if any bad)* = tried to or unthreaded clip redirect buckle; concept problem rethreading redirect buckle; major hook-and-loop issue other than: failure to completely open, pull interference, or incorrect circumferential wrapping.

*Opened hook & loop* = opened all hook-and-loops ("Good") so entire hook-and-loop strap could pass through the redirect buckle and no hook-and-loop strap would be trapped against the leg.

*Pull technique ("Bad" if any true)* = angle of strap pull through redirect buckle >45° relative to strap entering redirect buckle; held rod during strap pulling; held redirect buckle during strap pulling.

*Pull hook & loop* = interference of hook-and-loop on strap-encircling limb with strap pulling through the redirect buckle ("Bad").

*Strap tightness* = tightening-system physical indication at occlusive completion that strap not optimally tight ("Bad"): CAT7, SOFTTW3, SOFTTW5, and TMT >2 rod turns; OMT >6 tooth advances; X8T >10 advance clicks; Tac RMT >7 tooth advances; RST >6 tooth advances.

*Strap security ("Bad" if any bad)* = hook-and-loop overlap length around limb circumference and side-to-side overlap or other issue affecting strap security.

**Tightening System:**

*Understanding* = applier understanding of how to use tightening system.

*Mechanical ("Bad" if any true)* = lost hold of rod, redid rod turning; skips or advance failures of ratcheting buckle; or any other tightening-system issue other than understanding how system works and other than securing the tightening system at completion.

**Occlusiveness:**

*Never occluded* = loss of the audible Doppler pulse never occurred ("Bad").

*Occluded at Done* = no audible Doppler pulse at "Done" ("Good").

**Tightening System:**

*Securing struggle* = physical difficulty securing the tightening system ("Bad").

*Tightening security* = incorrect securing of tightening system according to training videos ("Bad").

*Tourniquet security* = "Bad" if problem with strap security or tightening security.

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