Clothing Effects on Limb Tourniquet Application

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ABSTRACT

Background: Sometimes tourniquets are applied over clothing. This study explored clothing effects on pressures and application process. **Methods:** Generation 7 Combat Application Tourniquets (C-A-T7), Generation 3 SOF® Tactical Tourniquets–Wide (SOFTTW), Tactical Ratcheting Medical Tourniquets (Tac RMT), and Stretch Wrap And Tuck Tourniquets (SWATT) were used with different clothing conditions (Bare, Scrubs, Uniform, Tights) mid-thigh and on models (ballistic gel and yoga mats). **Results:** Clothing affected pressure responses to controlled force applications (weight hangs, n=5 thighs and models, nonlinear curve fitting, $p < .05$). On models, clothing affected secured pressures by altering surface interactions (medians: Gel Bare C-A-T7 247mmHg, SOFTTW 99mmHg, Tac RMT 101mmHg versus Gel Clothing C-A-T7 331mmHg, SOFTTW 170mmHg, Tac RMT 148mmHg; Mats Bare C-A-T7 246mmHg, SOFTTW 121mmHg, Tac RMT 99mmHg versus Mats Clothing C-A-T7 278mmHg, SOFTTW 145mmHg, Tac RMT 138mmHg). On thighs, clothing did not significantly influence secured pressures (n=15 kneeling appliers, n=15 standing appliers) or occlusion and completion pressures (n=15). Eleven of 15 appliers reported securing on clothing as most difficult. Fourteen of 15 reported complete applications on clothing as most difficult. **Conclusions:** Clothing will not necessarily affect tourniquet pressures. Surface to tourniquet interactions affect the ease of strap sliding, so concern should still exist as to whether applications over clothing are dislodged in a distal direction more easily than applications on skin.

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

Introduction

Limb tourniquet placement over clothing risks missing injuries[1] and is associated with looseness, risking ongoing bleeding and venous occlusion without arterial occlusion.[2] To avoid these problems, Tactical Combat Casualty Care (TCCC) guidelines recommend limb tourniquet application on skin unless providing Care Under Fire.[3]

Many clinical and staged pictures of tourniquets applied over clothing exist in research literature and tourniquet-training-associated videos.[4] The study purpose was to explore clothing effects on thigh tourniquet application. The hypotheses were clothing could affect the application process, pressure measurements, and tourniquet pressures.

Methods

The Drake University Institutional Review Board approved this prospective study, which took place October 2018 through April 2019.

The Generation 7 C-A-T (C-A-T7, Lot 121K177; C-A-T Resources, http://combattourniquet.com/), was purchased. One Generation 3 SOF® Tactical Tourniquet – Wide (SOFTTW; manufactured 3 April 2017, 11 January 2019, 14 January 2019; Tactical Medical® Solutions, www.tacmedsolutions.com) was purchased; two were donated. Tactical Ratcheting Medical Tourniquets (Tac RMT; 10 November 2015; m2® Inc., www.ratchetingbuckles.com) were donated. Stretch Wrap And Tuck Tourniquets (SWATT; Lot# J068287, manufactured 5 January 2018, H & H Medical Corp., www.swattourniquet.com) were donated.

Tourniquets

The 3.8cm-wide nonelastic tourniquets were the C-A-T7, SOFTTW, and Tac RMT. The C-A-T7 has a hook-and-loop strap, non-self-securing redirect buckle, and windlass tightening system.[5] The SOFTTW has a smooth strap, self-securing slider redirect buckle, and windlass tightening system.[5] The Tac RMT has a smooth strap, self-securing overlapping-rectangles redirect buckle, built-in holding loop above the redirect buckle, and self-securing ratcheting buckle on a toothed ladder tightening system.[5] The SWATT is a 10.4cm-wide by 150cm-long elastic tourniquet that is not self-securing.

Pressure Measurements

Pressures were measured using a neonatal blood pressure cuff (2.2cm × 6.5cm bladder, single tube) at 18mmHg above atmospheric pressure (baseline).[6] The bladder was on the medial thigh under the tourniquet (approximately 180° from the redirect buckle C-A-T7, SOFTTW, Tac RMT). The bladder was connected to a Vernier Gas Pressure Sensor, Vernier LabPro interface, and Logger Pro Software (Vernier Software and Technology, www.vernier.com). Pressures were recorded every second for hanging weights and completed application trials, and every tenth of a second for trials ending after the strap was secured. During experiments, appliers did not receive information regarding pressures.

Tourniquet Recipients

Tourniquets were applied mid-thigh. Inclusion criteria were age ≥ 18 years, systolic blood pressure < 140mmHg, and no

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known bleeding or clotting abnormalities, circulation problems, pain syndromes, peripheral neuropathies, connective tissue disorders, or conditions counter to the positioning required for thigh use.

Tourniquets were applied to two thigh models. One was a 57.5cm circumference, 20% synthetic ballistic gel cylinder (Gel, Clear Ballistics; clearballistics.com) suspended via a rod through the 2.54cm-diameter central stainless steel tubing.[5,7,8] The other was two 5mm-thick yoga mats (Mats, 61cm x 173cm, 1002569059, Home Depot, homedepot.com) rolled one around the other with a 48.0cm circumference and suspended via a 1.2cm-diameter metal rod through the center.

Tourniquet Appliers

Inclusion criteria were age ≥ 18 years, willingness to watch application videos,[9-11] practice applying tourniquets with technique feedback and real-time pressure data, and a dominant-hand weight pull > 9kg. Exclusion criteria were conditions counter to tourniquet application (hand, wrist, elbow, or shoulder injuries).

Applier Pulling Force

To determine single-arm downward pulling force, increasing weight increments of 4.54kg were attached to a C-A-T7 strap, which was placed over a smooth metal rod (1.2cm-diameter). Seated appliers pulled down on the free end of the strap with encouragement to engage their entire upper body strength and weight.

Three-Phases

This study used thighs and tourniquet applications with the following clothing conditions under the tourniquets: bare skin (Bare), scrubs (Scrubs), United States Military Army Combat Uniform (Uniform), and compression tights (Tights). For each condition involving clothing, the under-tourniquet-pressure was measured with the bladder at skin (Scrubs Skin, Uniform Skin, Tights Skin) or thigh model surface (Scrubs Skin, Uniform Skin) and at clothing surface (Scrubs Clothing, Uniform Clothing, Tights Clothing).

Phase 1 investigated clothing influence on pressure effects of controlled force application. A Tac RMT (0.1000kg) was draped over bare or clothed, thighs or thigh models. Strap ends were joined together (C-clamp, 0.0938kg) and had 4.54kg weights attached by carabiners (rope plus three carabiners, 0.23761kg) at 20 second intervals for total applied forces from 4 to 271N (0.95 to 61lbf). The inflated bladder was 180° from the downward hanging weights. Recipients (n=5) lay so the medial mid-thigh was upward.

Phase 2 investigated clothing influence on tourniquet application and secured pressure (ability to pull tight and secure strap, n=15 appliers on thighs). Only nonelastic tourniquets were involved. For thighs, recipients sat upright, thigh parallel to the floor, lower leg at a right angle to the thigh, and attempted to maintain a relaxed thigh. Applications were videoed. For thigh models, 22.70kg was attached for 20 seconds to the end of the model-encircling tourniquet strap.

Phase 3 investigated clothing influence on the complete tourniquet application process and pressures (n=15 appliers). Secured pressures, occlusion pressures, completion pressures, and the number of windlass 180° turns (nearest 45°), ladder teeth (clicks), or circumferential wraps (nearest 90°) at occlusion and completion were recorded. Occlusion was defined as loss of audible Doppler pulse from the dorsal pedal artery (Ultrasonic Doppler Flow Detector Model 811 with 9.5MHz adult flat probe; Parks Medical Electronics, www.parksmed.com). Occlusion was hands off for the Tac RMT but held for the others. Completion was defined as occluded with hands off with the windlass rod secured at a rotation beyond the occlusion position (C-A-T7 and SOFTTW), one click past occlusion (Tac RMT), or the end of the SWATT secured under a previous wrap. For applications that were not completed, the final pressure; number of turns, clicks, or wraps; and the reason for incompletion were recorded (applier inability, recipient discomfort, or other). For secured, occlusion, and completion data points, a 5 second pause occurred before moving onward. Tourniquets were removed 5 seconds after completion. The recipients sat as in Phase 2. Because we realized appliers had knelt in Phase 2, appliers stood in Phase 3. Applications were videoed.

Tourniquet Applications

Nonelastic tourniquet application technique consisted of a tourniquet-holding location above the redirect buckle and a strap-pulling direction downward, tangential to the limb at the redirect buckle.[8] Appliers pulled with their dominant hand. Nonelastic tourniquets were not replaced unless a problem occurred. A new SWATT was used by each applier. Each SWATT application consisted of a minimally stretched 450° wrap followed by fully stretched wraps through occlusion and completion.

Statistical Analysis

For thigh applications, the order of tourniquet and clothing condition were randomized to avoid a potential order effect. Double data entry with crosscheck was used for written data and organizing pressure data from LoggerPro into Microsoft® Office Excel 2003 (Microsoft Corp., www.microsoft.com). Because the bladder was not directly visible under clothing and could be other than under the center of SWATT wraps, pressure data was validated before analysis: points were removed for video-detectable evidence of bladder location problems or physiologically incorrect values. Graphing and statistical analyses were performed with GraphPad Prism, version 7.04 for Windows (GraphPad Software Inc., www.graphpad.com) and with IBM SPSS Statistics for Windows, version 26 (IBM Corp., www.ibm.com). Nonlinear curve fitting (least squares and extra sum-of-squares F test), paired t test, one-way repeated measures analysis of variance analysis (ANOVA), two-way ANOVA, and two-way repeated measures ANOVA were used for pressure data. Values in text are medians, minimums to maximums. χ^2 test and Fisher's exact test were used for contingency data. Statistical significance was set at $p \leq .05$.

Results

Recipients and Appliers

For recipient and applier information, see Table 1.

Phase 1: Hanging Weights

Controlled-force-application triplicates had little pressure variance (coefficient of variation: thighs 1.38%, 0.03 to 8.51%, thigh models 1.26%, 0.03 to 6.57%). This was a low noise system suitable for answering the physics question: Can clothing cause a pressure response difference?

TABLE 1 *Recipients and Appliers*

Phase	Recipient Median (Minimum–Maximum)	Applier Median (Minimum–Maximum)
Phase 1: Hanging Weights	*n* = 5	NA
Sex	1 male, 4 females	NA
Age (yr)	22 (20–59)	NA
Thigh circumference (cm)	52.0 (46.0–65.5)	NA
Phase 2: Secured Strap	*n* = 11	*n* = 15
Sex	4 males, 7 females*	5 males, 10 females
Age (yr)	21 (19–62)	21 (19–62)
Thigh circumference (cm)	48.5 (42.8–65.5)	NA
Single arm pull (kg)	NA	27 (18–36)
Height (cm)	168 (160–191)	169 (157–191)
Phase 3: Completed Application	*n* = 13	*n* = 15
Sex	3 males, 10 females**	3 males, 12 females
Age (yr)	21 (19–59)	21 (19–59)
Thigh circumference (cm)	52.0 (42.5–61.5)	NA
Single arm pull (kg)	NA	27 (18–36)
Height (cm)	168 (157–193)	168 (157–191)
Systolic Pressure (mmHg)	112 (92–136)	NA

All Phase 1 recipients were also Phase 2 and 3 recipients. Thirteen Phase 2 appliers were also Phase 3 appliers.
*Two males and two females were recipients twice in Phase 2.
**One male and one female were recipients twice in Phase 3.

On thigh models, Bare weight hangs had lower pressure responses per weight than did hangs involving Scrubs or Uniform, but this was not the case for thigh weight hangs (Figure 1A). One phase decay equations fit the thigh and thigh model pressure responses better than straight line equations (Figure 1B). The pressure response for each individual's thigh and each thigh model had different curves rather than a shared curve for all conditions (Figure 1C and 1D). The condition creating the greatest response difference was compression tights (two individuals had compression tights [2XU, www.2xu.com]). For any condition, the thighs of different individuals and the two thigh models had different curves rather than a shared curve (Figure 1B). The response curve differences between different individuals' thighs were greater than the differences among conditions for a single individual. One-way repeated measures ANOVA comparing thigh pressures at 27.24kg resulted in $p = .3866$ for conditions with highly overlapping 95% confidence intervals: Bare 301–419mmHg, Scrubs Skin 300–437mmHg, Scrubs Clothing 289–440mmHg, Uniform Skin 281–425mmHg, Uniform Clothing 291–412mmHg. Therefore, the clothing-related statistically significantly different curves for the pressure responses (simple physics) did not result in statistically different thigh pressure values within the pressure range of clinical interest (tights data excluded).

Phase 2: Secured Strap

Values indicating bladder location problems resulted in removal of two thigh C-A-T7 data sets (both from Applier 6 Uniform Skin triplicate) and four thigh SOFTTW data sets (two from Applier 6 Scrubs Skin triplicate and two from Applier 6 Uniform Skin triplicate).

Our initial plan included sliding Sharpie markers (3.80cm circumference) under the secured strap to determine if a specific number could indicate appropriate secured pressure before tightening system use. This idea failed: with no apparent relationship to secured pressure, Sharpies could be slid under the strap until they occupied the entire stretch between the redirect buckle and the stabilization plate or corresponding structure.

Eleven appliers indicated securing on clothing as most difficult with eight specifying Uniform as most difficult. One indicated Bare as most difficult; one indicated no differences in difficulty, and two did not rate difficulty.

Thigh-secured triplicate variances were C-A-T7 8.97%, 1.42 to 24.95%; SOFTTW 7.79%, 2.02 to 22.17%; Tac RMT 10.46%, 0.24 to 38.74%. Model-secured triplicate variances were C-A-T7 0.67%, 0.10 to 2.42%; SOFTTW 1.01%, 0.31 to 4.09%; Tac RMT 1.63%, 0.54 to 4.70%.

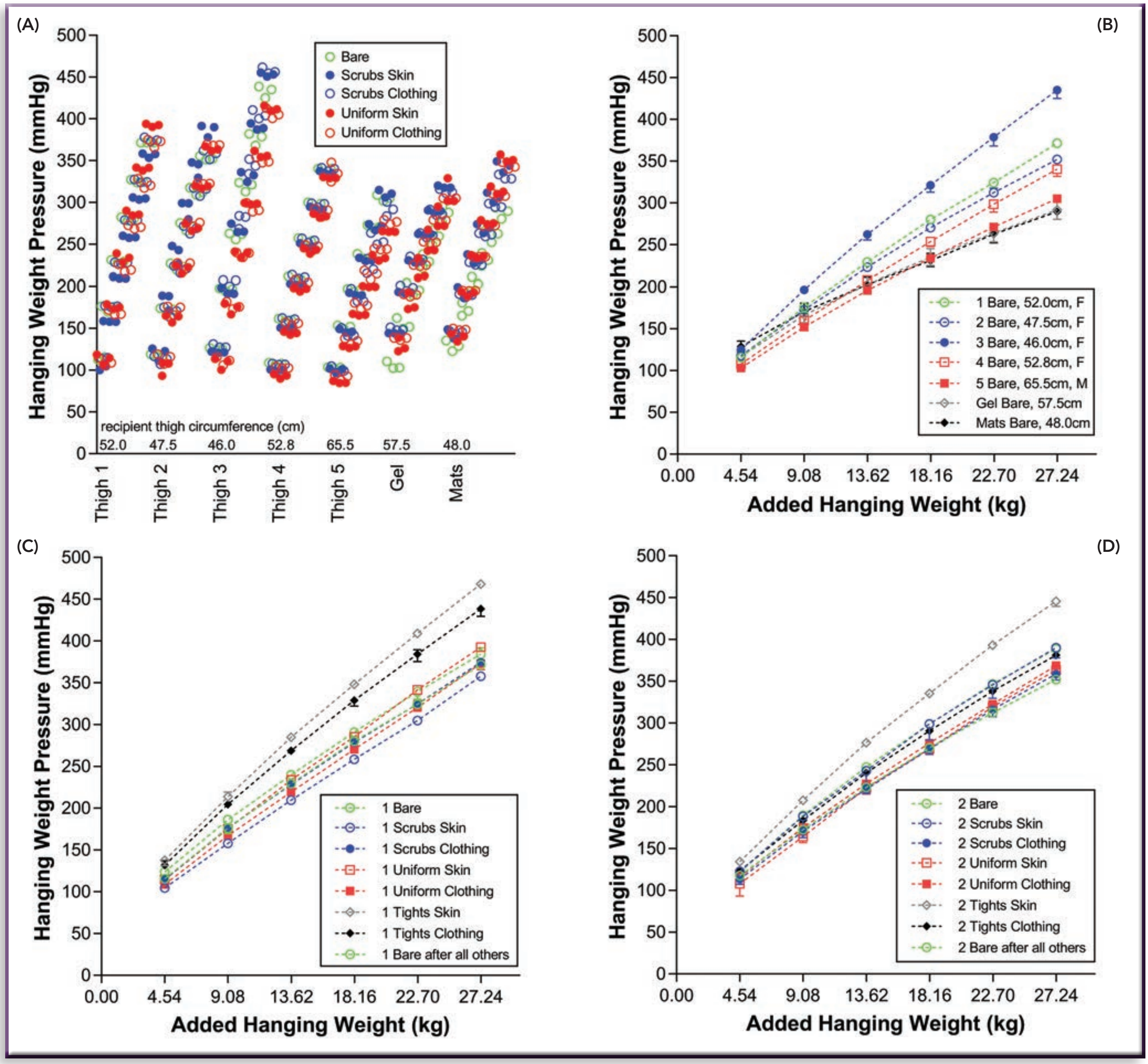
On thighs, appliers did not consistently achieve higher or lower secured pressures with any condition (Figure 2A–2C). With 197 of 223 secured pressures > 150mmHg, C-A-T7 secured pressures were generally highest followed by Tac RMT (60 of 225) then SOFTTW (20 of 221). Applier strength was not directly related to secured pressures (Figure 2A–2C).

On thigh models, Bare applications had lower secured pressures than clothing (Figure 2D). With clothing, the location of the bladder did not make a clinically interesting difference in secured pressures. With clothing, secured pressures on thigh models exceeded most matched pressures on thighs (compare Figure 2D to Figure 2A–2C).

To determine the reason for lower Bare pressures on thigh models, we placed clothing under the tourniquet for only half the model circumference (top, back, bottom, or front half). We concluded lower Bare pressures related to thigh model surface tackiness, which was more apparent with the Gel than Mats. Strap contact with tacky surfaces inhibited strap sliding around the models and into redirect buckles, resulting in lower secured pressures. Neither clothing nor recipients' thighs had surface tackiness.

Also on thigh models, we altered the Tac RMT holding location from the built-in loop adjacent to the redirect to the far end of the ladder. This resulted in higher secured pressures (Mats Bare: 157 versus 99mmHg, Mats Uniform Clothing:

FIGURE 1 *Phase 1: Hanging weight pressures.*



On each panel, the y-axis has the same scale and shows pressure exerted for controlled force applications. Panels show individual triplicate values as separate symbols or as medians with bars indicating the minimum and maximum values. **(A)** Strap pressures with different clothing conditions on thighs and models. The added hanging weights resulted in cumulative weights of 4.54, 9.08, 13.62, 18.16, 22.70, and 27.24kg. **(B)** Strap pressures for Bare on each thigh and model. Rather than linear equations, the best fits for the indicated curves are one phase decay equations (preferred curve fit for all conditions: Bare, Scrubs Skin, Scrubs Clothing, Uniform Skin, Uniform Clothing; $p < .05$, except for one Uniform Clothing $p = .095$). Rather than a shared one phase decay, the best fit was different curves for each thigh and model and every condition ($p < .0001$, except two models Bare $p = .1294$ for shared equation). **(C)** Strap pressures for Thigh 1 for all conditions. Rather than a shared equation, each clothing condition had a different one phase decay curve ($p < .0001$). **(D)** Strap pressures for Thigh 2 for all conditions. Rather than a shared equation, each clothing condition had a different one phase decay curve ($p < .0001$). The same was true for the remaining three thighs and both models ($p < .0001$).

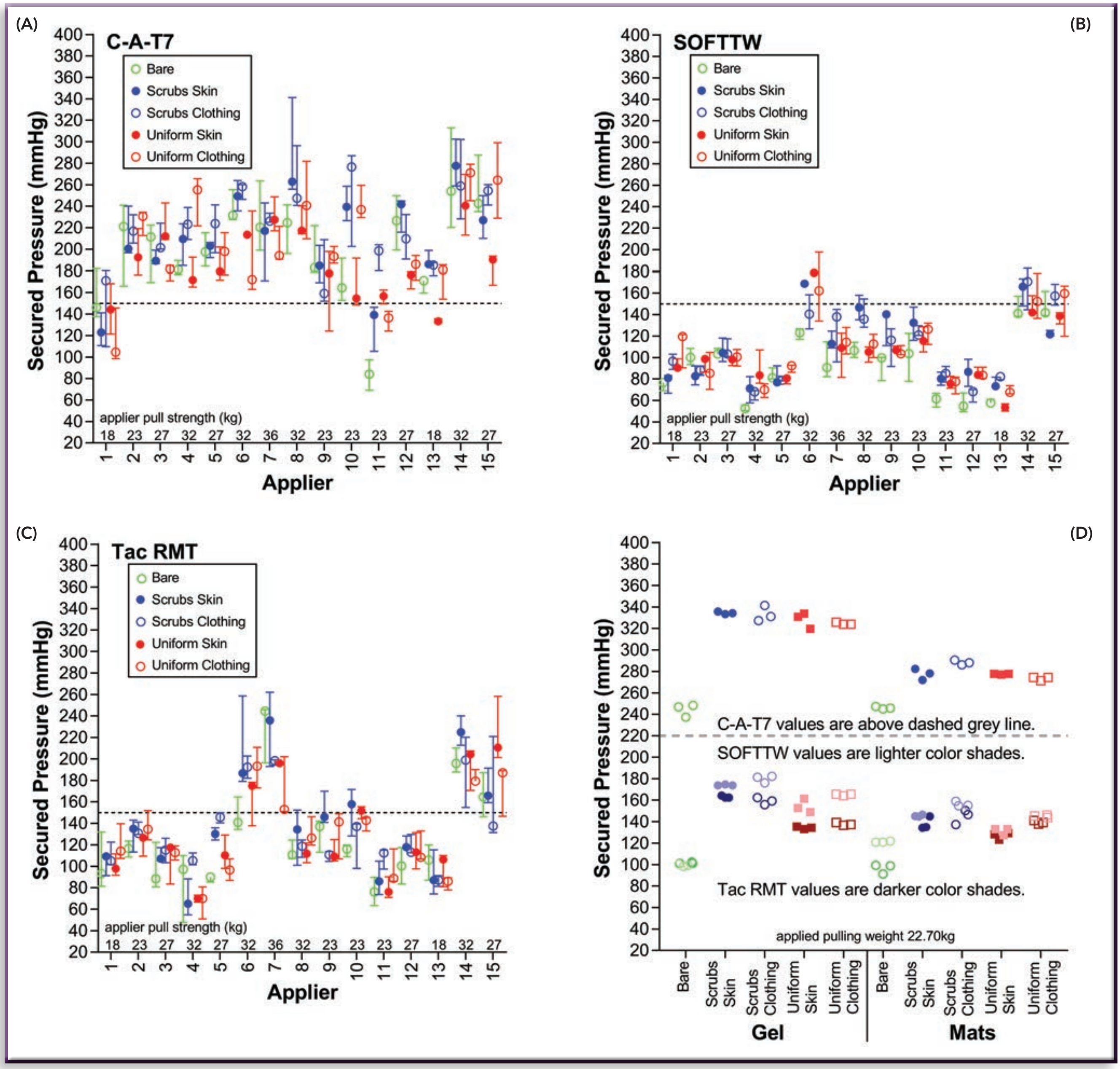
184 versus 139mmHg), consistent with the physics advantage of a moving versus stationary pulley.

Phase 3: Completed Application

Values indicating bladder location problems resulted in removal of one thigh C-A-T7 data set (from Applier 8 Scrubs Skin), four thigh SOFTTW data sets (one from Applier 8 Scrubs Skin, one from Applier 11 Uniform Skin, and two from Applier 9 Tights Skin), three thigh Tac RMT data sets (two from Applier 8 Scrubs Skin and one from Applier 11 Scrubs Skin), and 10 thigh SWATT data sets (two from Applier 5 Uniform Skin, one from Applier 8 Scrubs Skin, the entire triplicate from Applier 8 Uniform Skin, one from Applier 9 Bare, one from Applier 10 Scrubs Skin, one from Applier 10 Scrubs Clothing, and one from Applier 13 Uniform Skin). One thigh SWATT completion data point was removed for the completion wrap not placed over the bladder (from Applier 8 Scrubs Clothing).

Thirteen individuals applied in both Phase 2 and 3. The secured pressures achieved standing were higher than kneeling with the C-A-T7 and Tac RMT, but standing was not statistically different from kneeling with the SOFTTW (Figure 3A). C-A-T7 secured pressures were higher than Tac RMT, which were higher than SOFTTW.

FIGURE 2 *Phase 2: Secured strap pressures.*



On each panel, the y-axis has the same scale and shows pressure exerted with the strap secured over different clothing conditions on thighs (A–C) and models (D). In panels A–C, dotted lines at 150mmHg indicate the desired secured pressure threshold.[4,12-14] In panel D, the dashed line separates C-A-T7 pressures from SOFTTW and Tac RMT pressures. Panels show individual triplicate values as medians with bars indicating the minimum and maximum values or as separate symbols. In A–C, applier single arm pull strength is shown above the x-axis. **(A)** C-A-T7. **(B)** SOFTTW. **(C)** Tac RMT. **(D)** Secured pressures on models with C-A-T7, SOFTTW, and Tac RMT with an applied pulling weight of 22.70kg.

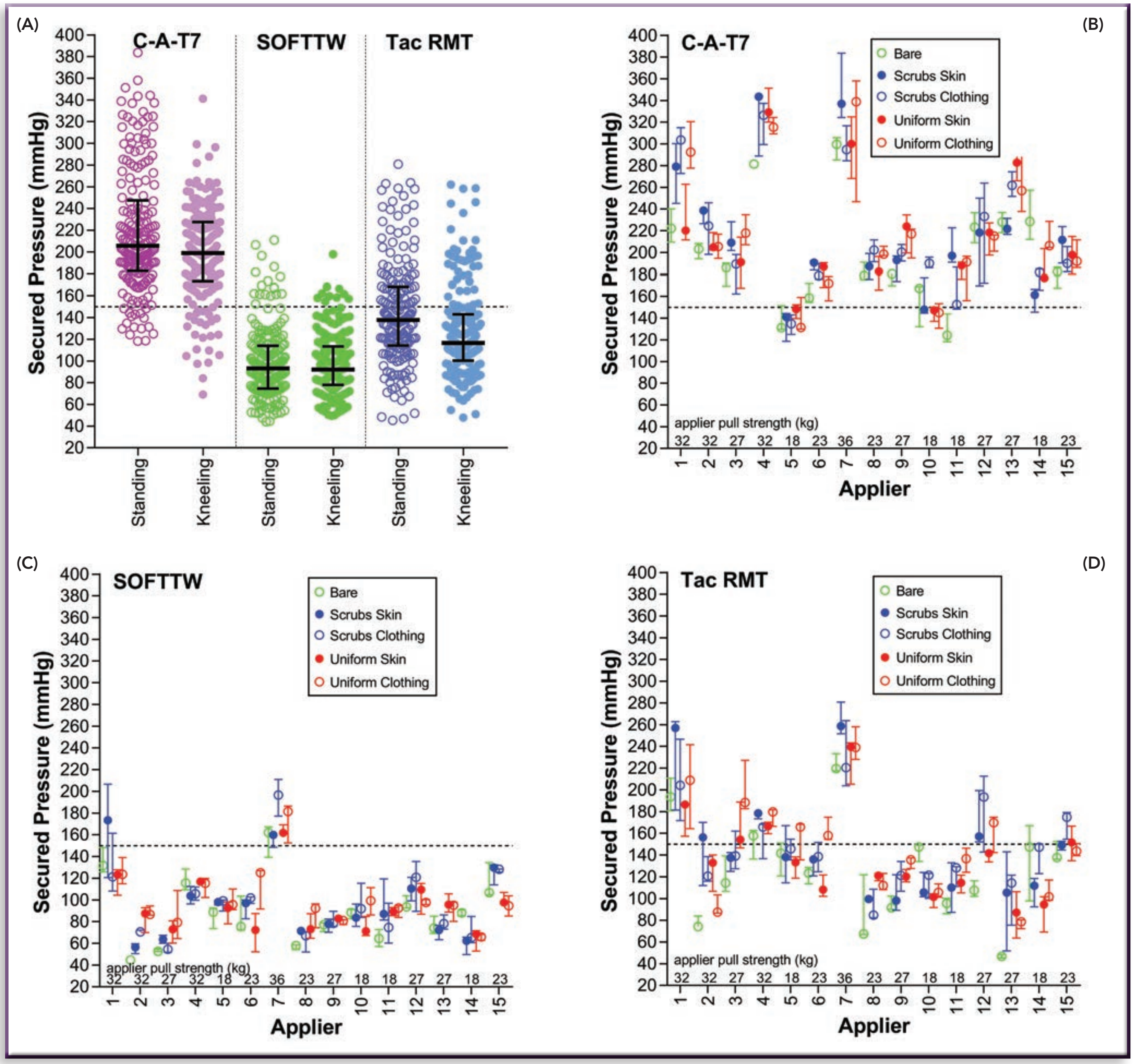
Fourteen appliers indicated completed applications on clothing as most difficult with 12 specifying Uniform as most difficult (five indicated the pocket increased difficulty). One indicated clothing as most difficult with the SWATT and SOFTTW, but Bare as more difficult with the Tac RMT and C-A-T7.

Eleven recipients indicated completed applications on clothing caused the least discomfort with six specifying Uniform and five Scrubs causing the least discomfort. One indicated Bare for least discomfort with the SWATT but Uniform for other tourniquets.

Triplicate variances on thighs were as follows: secured C-A-T7 6.72%, 0.68 to 20.95%; SOFTTW 9.09%, 0.37 to 26.69%; Tac RMT 9.25%, 1.66 to 45.86%; occlusion C-A-T7 8.00%, 0.10 to 28.43%; SOFTTW 7.01%, 0.84 to 23.80%; Tac RMT 5.16%, 0.15 to 29.19%; SWATT 7.20%, 0.58 to 23.11%; completion C-A-T7 8.00%, 0.67 to 30.49%; SOFTTW 7.17%, 2.21 to 22.29%; Tac RMT 5.18%, 0.84 to 18.20%; SWATT 7.83%, 1.77 to 27.09%.

As in Phase 2, appliers did not consistently achieve higher or lower secured pressures with any condition (Figure 3B–3D). With 200 of 224 secured pressures > 150mmHg, C-A-T7 secured pressures were generally highest followed by Tac RMT (77 of 222) then SOFTTW (16 of 223). Applier strength was not directly related to secured pressures (Figure 3B–3D).

FIGURE 3 *Phase 3: Secured strap pressures.*

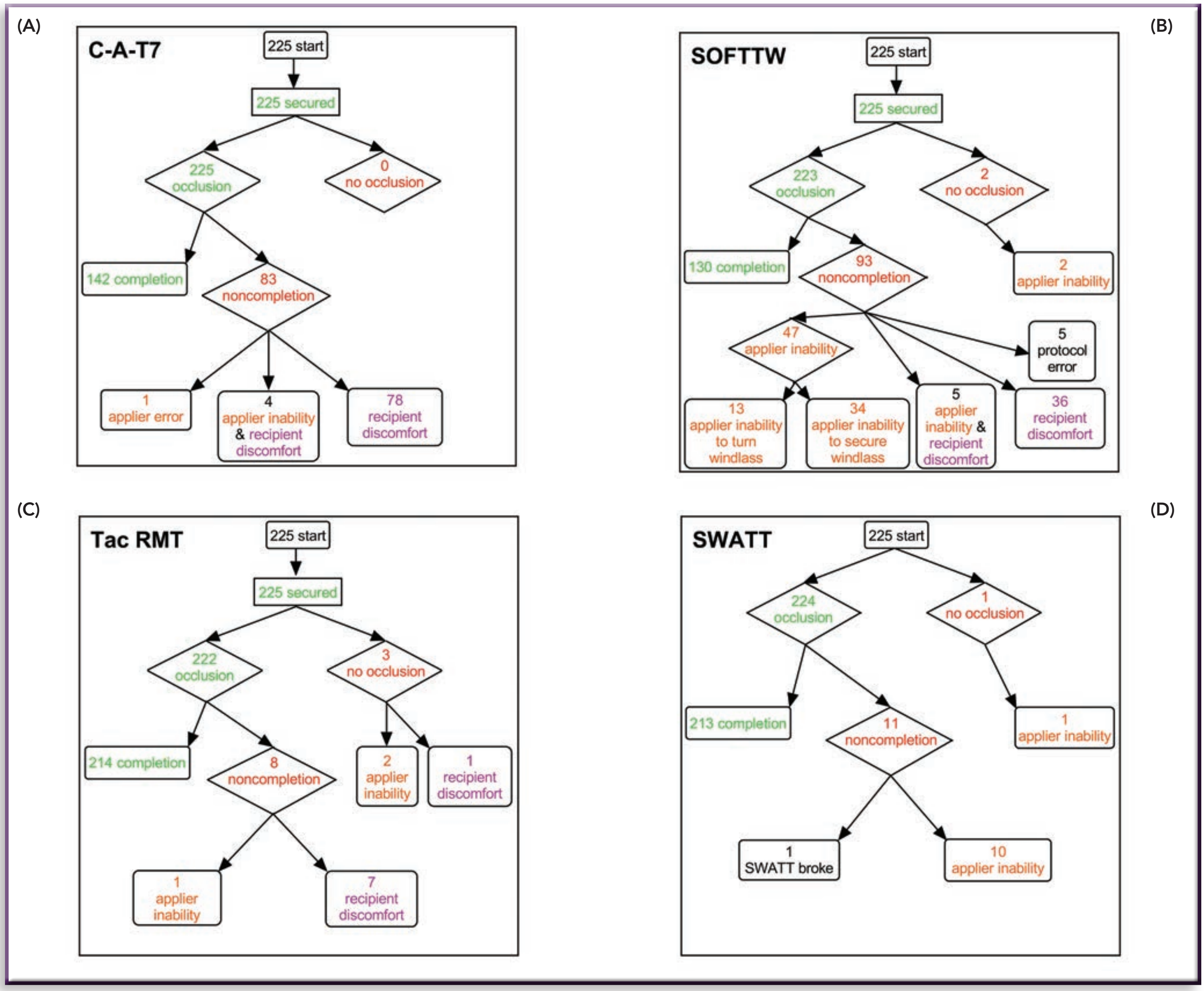


On each panel, the y-axis has the same scale and shows pressure exerted with the strap secured over different clothing conditions on thighs. Dotted lines at 150mmHg indicate the desired secured pressure threshold.[4,12-14] Panel A shows individual triplicate values with group medians and interquartile ranges, while panels B–D show individual triplicate values as medians with bars indicating the minimum and maximum values. In B–D, applier single arm pull strength is shown above the x-axis. **(A)** Secured pressures achieved when standing (Phase 3) versus kneeling (Phase 2) (n = 13 appliers, paired t test with Bonferroni correction: C-A-T7 $p = .0014$, SOFTTW $p = .7372$, Tac RMT $p < .0001$). **(B)** Phase 3 C-A-T7. **(C)** Phase 3 SOFTTW. **(D)** Phase 3 Tac RMT.

All applications with nonelastic tourniquets reached secured (Figure 4A–4C); most reached occlusion; reaching completion varied among tourniquets (Figure 4A–4D). Completion was least frequent with windlass tourniquets: recipient discomfort was the primary reason for C-A-T7 noncompletions. Recipient discomfort and applier inability to secure the windlass rod were the primary reasons for SOFTTW noncompletion, followed by applier inability to turn the windlass rod to a securable location. Applier technique issues caused noncompletions: hook-and-loop error resulted in one C-A-T7 noncompletion, technique problems lead to ten SWATT noncompletions.

Clothing and bladder conditions were not associated with higher or lower occlusion or completion pressures. C-A-T7 occlusion pressures were the highest (Figure 5A). Figures 5B–5D show C-A-T7 pressure changes from occlusion to completion are higher than SOFTTW ($p < .0001$). C-A-T7 had four pressure losses (median 6.3mmHg, 1.9 to 29.1mmHg) and one occlusion loss within 5 seconds of completion. SOFTTW had 26 pressure losses (median 22.4mmHg, 1.4 to 65.7mmHg) and 24 occlusion losses. Tac RMT had consistent pressure increases (one pressure loss of 5.6mmHg) and no occlusion losses. SWATT had 46 pressure losses (median 18.2mmHg, 1.4 to 59.7mmHg) and eight occlusion losses (one tuck failed

FIGURE 4 *Phase 3: Flow charts.*



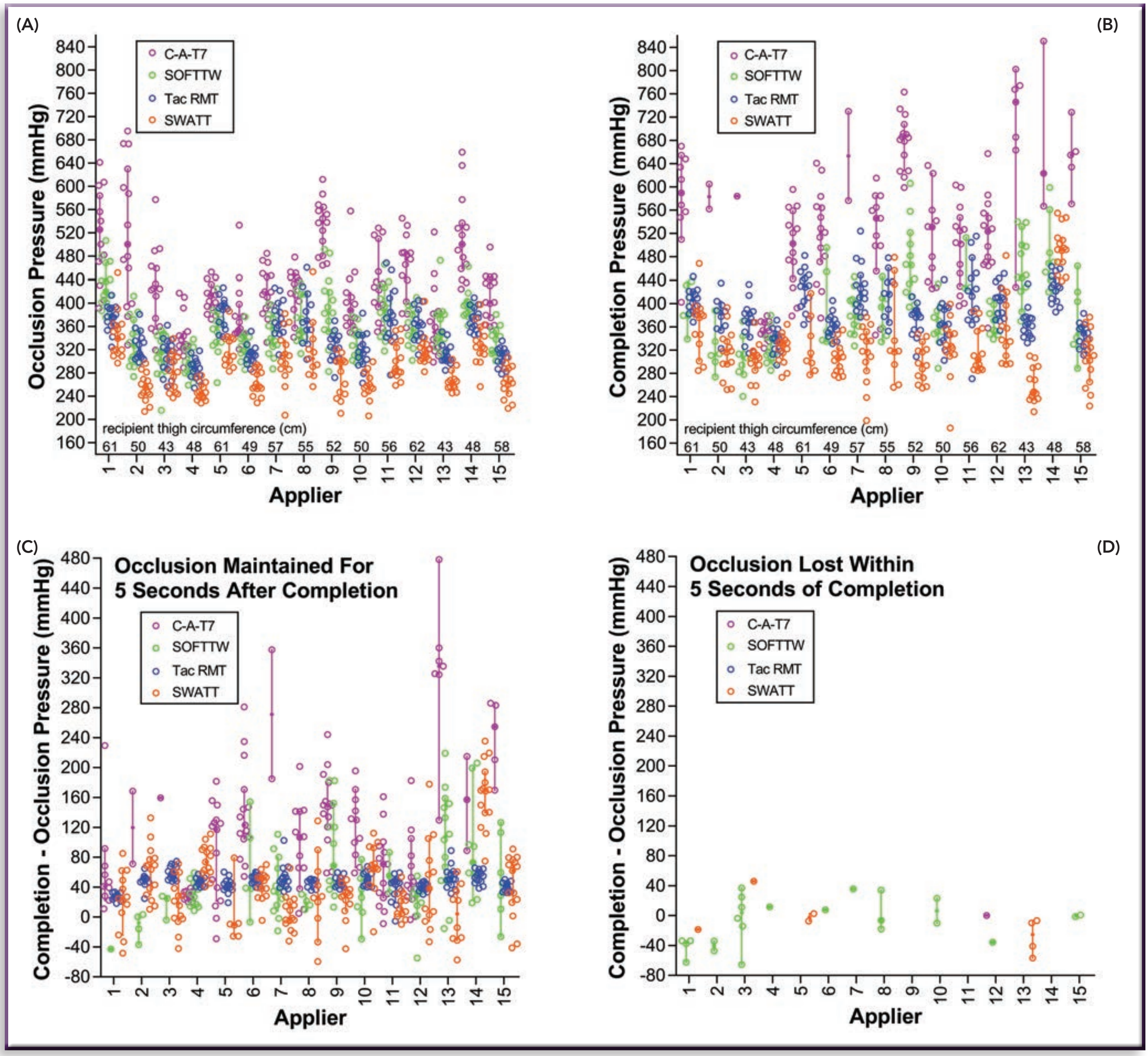
Each panel starts with 225 applications and shows the number of applications at each point along the path through the end of the trial. Fewer completions were achieved with the windlass tourniquets ($p < .0001$). The reasons for the windlass noncompletions were different; C-A-T-7 noncompletions were for recipient discomfort; SOFTTW noncompletions were split between recipient discomfort and applier inability ($p < .0001$). **(A)** C-A-T7. The 'applier error' was a failure to secure adequate hook-and-loop length; so the hook-and-loop connection pulled apart during turning of the windlass rod. The 'applier inability' was that they could not turn the windlass rod to a securable position. **(B)** SOFTTW. The inability in 'no occlusion' and 'applier inability & recipient discomfort' was that appliers could not turn the windlass rod to a securable position. The 'protocol error' was the directive to secure at the next location after occlusion and did not take into account the possibility of pulse return within 5 seconds after occlusion before moving to completion. This occurred in five SOFTTW applications, failing the definition of completion. **(C)** Tac RMT. The 'applier inability' in 'no occlusion' and 'noncompletion' was inability to advance the ratcheting buckle. **(D)** SWATT. One application did not reach occlusion for applier inability to maintain appropriate stretch during wraps. The same applier failed to reach completion in six additional applications, relating to inability to maintain appropriate stretch and problems with preplanning for the completing tuck (recipient thigh circumference 61cm). A different applier had two noncompletions: one involved problems with preplanning for the completing tuck and the other involved lost grip on the SWATT (recipient thigh circumference 62cm). The third applier with a noncompletion involved problems with preplanning for the competing tuck and resulting lost grip on the SWATT (recipient thigh circumference 61cm). The fourth applier with a noncompletion lost grip on the SWATT during the tucking process, resulting in a loss of stretch and loss of occlusion. The eleventh noncompletion resulted from SWATT breakage due to a sharp fingernail causing tearing while struggling for the completing tuck.

from poor technique). SWATT application videos showed appliers frequently not maintaining stretch going from occlusion to completion.

Most C-A-T7 occlusions took < 1 turn resulting in completions at 1 turn (Figure 5E–5F). SOFTTW required more windlass rod turns. Only three of 36 SOFTTW recipient discomfort noncompletions involved ≥ 3 turns. All 36 applier inability to reach completion would have had ≥ 3 turns (occlusions 2.75 turns or greater): 23 appliers could not rotate the rod to a securable location while 13 reached the rod-securable location but could not secure (Figure 4B). With the Tac RMT, the three noncompletions for applier inability (Figure 4C) involved 11, 12, and 13 clicks. The 18 clicks for Tac RMT completion followed a secured pressure of 51.7mmHg. Despite the SWATT instructional video,[11] most appliers did not do more than one wrap following occlusion (Figure 5E to 5F, applier 14 versus other appliers).

Three recipients had compression tights (two 2XU, one Adidas, adidas.com). Clothing versus Bare had a difference in completion versus noncompletion for only the Tac RMT and recipient discomfort ($p < .0001$).

FIGURE 5 *Phase 3: Occlusion and completion data.*



(continues)

All applications with tights reached occlusion. Seven C-A-T7 did not reach completion for recipient discomfort. Six SOFTTW did not reach completion: four for recipient discomfort, one for discomfort and applier inability to turn the windlass rod, and one for applier inability to secure the rod. All Tac RMT and all SWATT reached completion. As with scrubs and uniform, tights were not associated with consistently higher or lower secured, occlusion, or completion pressures than Bare (Figure 6A–6B). Pressures increased from occlusion to completion except with two SWATT applications (Figure 6C). No occlusion losses occurred within 5 seconds of completion. Turns, clicks, and wraps data was similar to Bare (Figure 6D).

With the observed standard deviations in secured pressures and occlusion pressures, the clothing state of the limb would have needed to make more than a 25mmHg difference in pressures to have a high probability of being detected with the number of subjects in this study (Table 2).

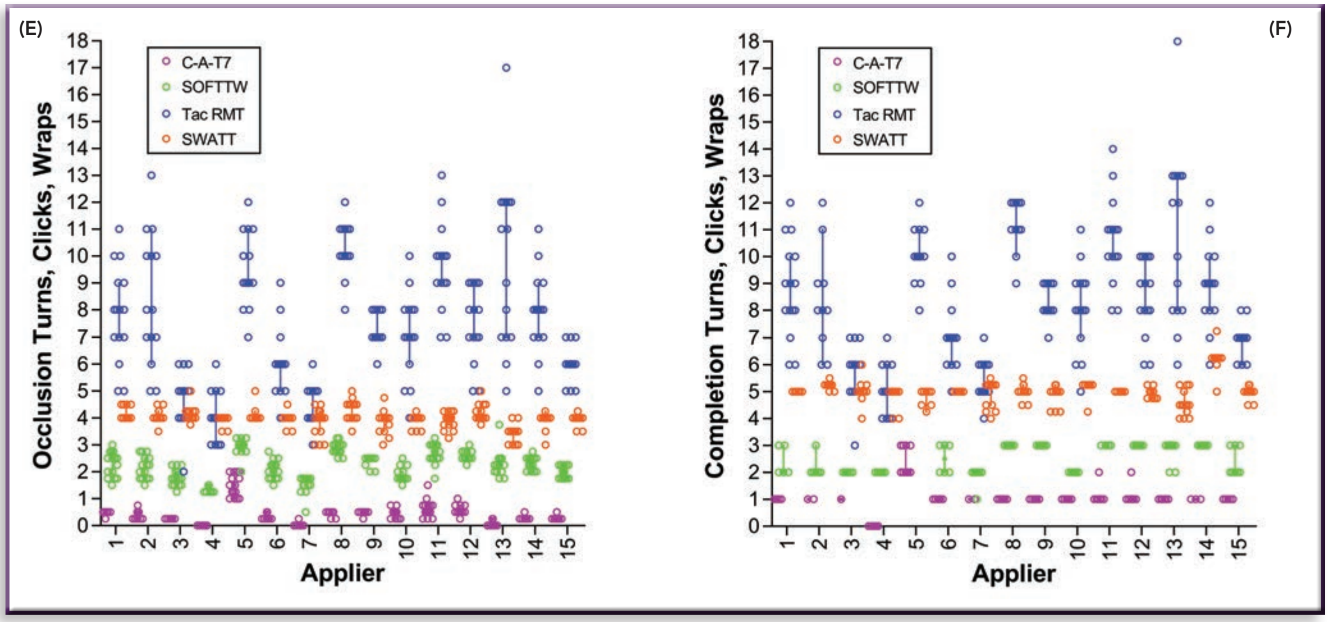
Issues

During Phase 3, two SOFTTWs broke: one by failure of the fabric holding the securing triangle (unknown number of uses, > 100) and one by failure of the rod-holding stitching (291st use). Three SWATTs broke: one during wrapping (5th use), one tore but application was successful (4th use), and one during struggling to tuck, related to sharp fingernails (4th use).

Discussion

Clothing might affect the application process and limb tourniquet pressures by fabric interaction with redirect buckles, alteration of compressibility, and clothing to tourniquet surface interaction. The directly clothing-related findings in the study were as follows: (1) A few appliers indicated the uniform pocket under redirect buckles as a hindrance, and most indicated applications over clothing as most difficult, but thigh-application pressure data did not show clothing pressure effects. (2) The bladder location (on top off or underneath

FIGURE 5 *Cont.*



On each panel, the x-axis is organized by applier. Panels A–F show individual triplicate values with lines indicating 95% confidence intervals. In A and B, recipient thigh circumference is shown above the x-axis. **(A)** Occlusion pressures are shown on the y-axis. Occlusion pressures were higher with the C-A-T7 than with the other two 3.8cm-wide nonelastic tourniquets ($p < .0001$). The number of pressure measurements shown are 224 C-A-T7 (1 data set removed for bladder location problems), 221 SOFTTW (2 data sets removed for bladder location problems and 2 applications did not reach occlusion), and 220 Tac RMT (3 data sets removed for bladder location problems, 1 of which did not reach occlusion, and 2 other applications did not reach occlusion). Occlusion pressures were lowest with the 10.4cm-wide SWATT ($p < .0001$). There are 215 SWATT pressure measurements shown (10 data sets removed for bladder location problems, 1 of which did not reach occlusion). **(B)** Completion pressures are shown on the y-axis. Completion pressures were highest with the C-A-T7 ($p < .0001$) and lowest with the SWATT ($p < .0001$). The number of completion pressures shown are 141 C-A-T7 (1 data set removed for bladder location problems), 129 SOFTTW (1 data set removed for bladder location problems), 212 Tac RMT (2 data sets removed for bladder location problems), and 204 SWATT (9 data sets removed for bladder location problems). **(C)** Completion minus occlusion pressures are shown on the y-axis. The pressure differences for applications that maintained occlusion for 5 seconds after completion are shown. **(D)** Completion minus occlusion pressures are shown on the y-axis. The pressure differences for applications that did not maintain occlusion for 5 seconds after completion are shown. In panels C and D, 26 SOFTTW applications had pressure decreases from occlusion to completion, and SOFTTW applications had the most occlusion losses within 5 seconds of completion, (24 SOFTTW occlusion losses, $p < .0001$). **(E)** Turns, clicks, or wraps to reach occlusion are shown on the y-axis. The C-A-T7 required fewer turns than the SOFTTW ($p < .0001$). There are 225 C-A-T7 turn measurements shown, 223 SOFTTW turn measurements shown (2 applications did not reach occlusion), 222 Tac RMT click measurements shown (3 applications did not reach occlusion), and 224 SWATT wrap measurements shown (1 application did not reach occlusion). **(F)** Turns, clicks, or wraps to reach completion are shown on the y-axis. The C-A-T7 required fewer turns than the SOFTTW ($p < .0001$). There are 142 C-A-T7 turn, 130 SOFTTW turn, 214 Tac RMT click, and 213 SWATT wrap measurements shown.

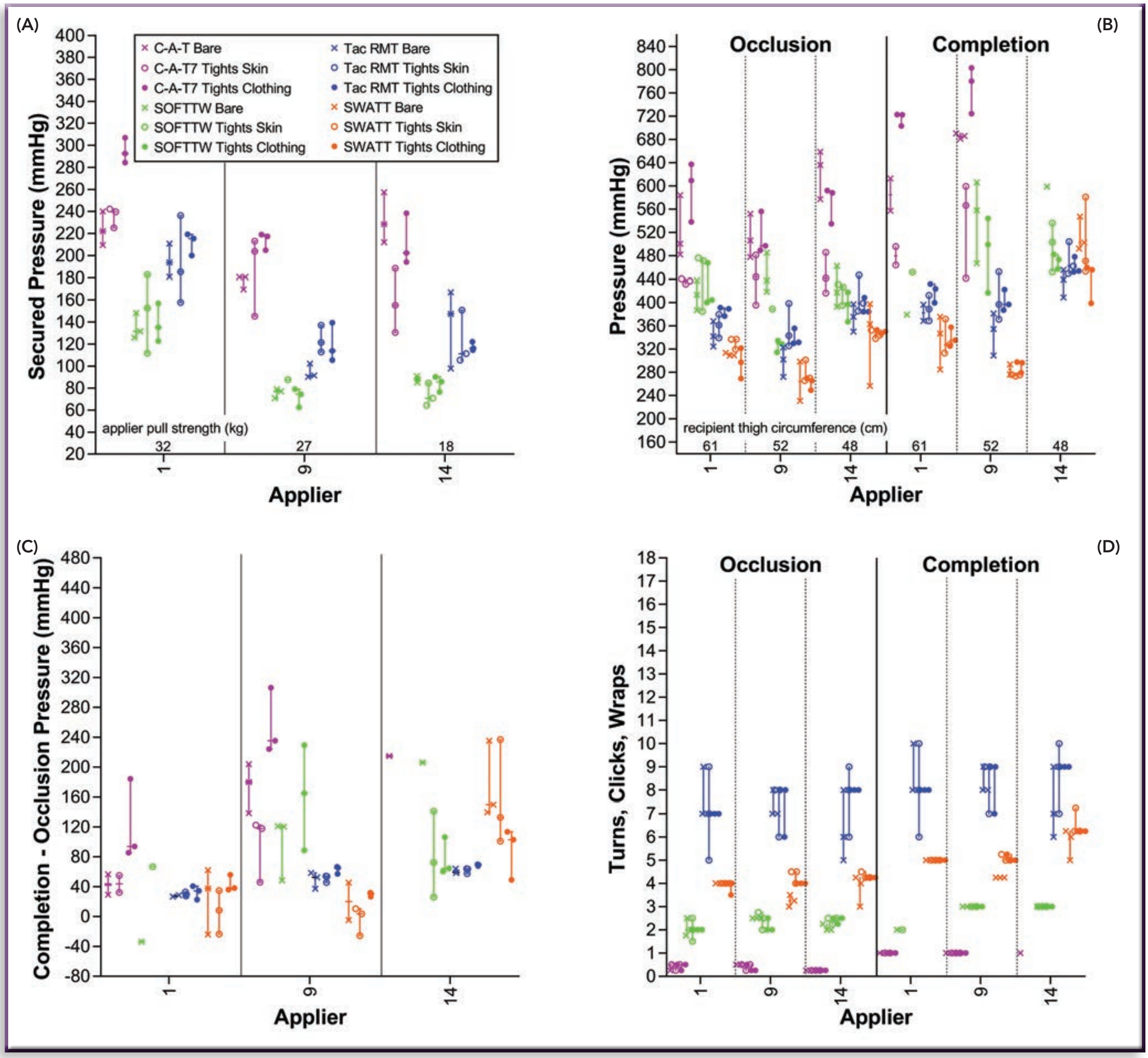
the clothing) did not result in clinically interesting pressure measurement differences. (3) Tights data with hanging weights show alteration of underlying compressibility changes pressure response to applied force. (4) Phase 2 thigh model data show surface interactions between tourniquets and what is beneath them affect secured pressures. Namely, interactions inhibiting strap movement to enter the redirect buckle interfere with secured pressure achievement. With the C-A-T7, SOFTTW, and Tac RMT, clean, dry scrubs and United States Military Army Combat Uniform pants appear to be as permissive to strap movement as clean, dry skin.

This study provides coefficient of variation and standard deviation information regarding audible Doppler detectable thigh occlusion pressure in individual adult tourniquet recipients. This study also provides coefficient of variation and standard deviation information regarding secured pressures achieved during applications without pressure data access by appliers who trained with real-time pressure data access and a strong emphasis on the importance of maximizing secured pressures.

Findings not related to clothing condition: (1) To consistently achieve desirable secured pressures, even trained appliers need real-time pressure data. (2) Sliding items under tourniquets is not reliable for indicating adequate secured pressure. (3) The Generation 3 SOFTTW redirect buckle prevents a secured pressure improvement from body weight engagement. In contrast, standing can help appliers reach higher secured pressures with the C-A-T7 and Tac RMT. (4) The mechanical advantage of a moving redirect impacts secured pressure. (5) Occlusion pressures differ for tourniquets of the same width. (6) Completion difficulties can be caused by design-related problems or applier technique.

Regarding redirect movement, allowing the redirect to act as a moving pulley system with movement inward and downward during tissue compression results in higher secured pressures.[5] This may explain the contrast between appliers generally achieving higher secured pressures with the Tac RMT than SOFTTW (Figure 3A) despite thigh models generally having higher secured pressures with the SOFTTW than Tac RMT (Figure 2D). In the models' system, attaching the Tac RMT holding loop to a vertically fixed location prevented redirect movement. With appliers using the holding loop, at least some inward redirect movement visually occurs as tissue compresses during strap pulling; some mechanical advantage from a

FIGURE 6 *Phase 3: Occlusion and completion data with tights.*



On each panel, the x-axis is organized by applier. Panels show individual triplicate values as medians with bars indicating the minimum and maximum values. All panels share the legend shown in panel A. Bare data is included for comparison with Tights Skin and Tights Clothing. **(A)** Secured pressures are shown on the y-axis. Applier single arm pull strength is shown above the x-axis. **(B)** Occlusion and completion pressures are shown on the y-axis. Recipient thigh circumference is shown above the x-axis. **(C)** Completion minus occlusion pressures are shown on the y-axis. **(D)** Turns, clicks, or wraps to reach occlusion and completion are shown on the y-axis.

moving redirect comes into play despite the proximity of the Tac RMT holding loop to the redirect buckle.

Regarding differences in occlusion pressure, among the 3.8cm-wide tourniquets, the C-A-T7 had the highest occlusion pressures by clinically significant amounts. This has implications for basing tourniquet certification on achieving a specified pressure expected to be thigh occlusive for 95% of adults. A different pressure value may be needed for each nonelastic 3.8cm-wide tourniquet.

Regarding design-related problems, successful Generation 3 SOFTTW applications were impeded by the redirect buckle: low secured pressures resulted in a need for multiple windlass rod turns. As turns increased, appliers became unable to continue turning and unable to secure the rod in the triangle. Unlike discomfort, which is unlikely to be relevant during clinical tourniquet use, applier inability will be relevant.

Regarding applier technique, successful SWATT applications are more technique sensitive throughout the application process than are nonelastic tourniquet applications. Small details matter and are easily overlooked. Despite watching a training video complete with commentary,[11] many appliers did the following: unrolled the SWATT “toward the thigh” rather than “away from the thigh”; failed to maintain stretch passing the roll under the thigh; and immediately planned the completion tuck at occlusion, regardless of the amount of SWATT

TABLE 2 *Power Analysis Variables and Resulting Sample Sizes Needed*

Standard Deviation (mmHg) for a Tourniquet Applier for Secured Pressure and for a Recipient Thigh for Occlusion Pressure*	Minimum Detectable Pressure Difference Created by Clothing State (mmHg)	Estimated Power Desired to Rule In or Out a Statistically Significant Difference with Two-Tailed $p = .05$	Estimated Number of Subjects Required
Secured Pressure			
32.8	10	0.80	193
		0.65	145
		0.50	121
	15	0.80	69
		0.65	52
		0.50	40
	20	0.80	37
		0.65	28
		0.50	21
	25	0.80	24
		0.65	18
		0.50	14
Occlusion Pressure			
28.1	10	0.80	170
		0.65	137
		0.50	104
	15	0.80	59
		0.65	45
		0.50	34
	20	0.80	32
		0.65	24
		0.50	18
	25	0.80	21
		0.65	16
		0.50	12

*Secured pressure standard deviations are an average for the C-A-T7, SOFTTW, and Tac RMT while occlusion pressure standard deviations are an average for the C-A-T7, SOFTTW, Tac RMT, and SWATT.

available for additional wraps. For example, applier 14 had one of the weakest pulls (18kg), applied to a 48cm thigh, and achieved occlusion at 3.9 and completion at 6.2 wraps (average). Appliers 3, 4, and 13 had greater pulls and applied to equal or smaller thighs. Occlusion and completion wrap averages were only 4.2, 3.9, 3.4 and 5.0, 4.9, 4.5, respectively. Many appliers had difficulty achieving a completion tuck, and some completion tucks were inadequate to remain in place with jostling. To summarize, anything not specifically pointed out may be missed (rolling direction), and things specifically pointed out are not always done (continuing wraps beyond occlusion).[11]

Some study limitations were clean and dry skin, clothing, and tourniquets; only 5 seconds for pulse return following completion; limited clothing types; and no subject transportation to explore clothing-related tourniquet displacement. A pressure measuring system limitation is progressively non-linear system performance at pressures > 550mmHg;[6] this means that many C-A-T7 occlusion and completion pressures were actually higher than measured. Some strengths were placements on human thighs; combination of controlled force applications (Phase 1 thighs and models and Phase 2 models) and human applier variability (Phase 2 and 3); investigation of possible effects on secured, occlusion, and completion pressures; and use of several different tourniquet designs.

Conclusions

To avoid missing proximal injuries, guidelines for emergency-use limb tourniquet applications in conditions other than Care Under Fire[3] should still recommend placement on bare skin rather than over clothing. However, applications over clothing with fabric pliability and coefficients of friction similar to scrubs and Army uniform pants are unlikely to result in or need pressures that are significantly different from applications on skin. Surface to tourniquet interactions affect the ease of strap sliding, so concern should still exist as to whether applications over clothing are dislodged in a distal direction more easily than applications on skin.

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Author Contributions

PW and CB developed the concept and contributed to all aspects of the project. EH and HS contributed to design; the acquisition, analysis, and interpretation of data; and the drafting and revising of the article. CHR contributed to design, the 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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