Accepted Manuscript

From Pull to Pressure: Effects of Tourniquet Buckles and Straps

Michael J. Valliere, MD, Piper L. Wall, DVM, PhD, Charisse M. Buising, PhD

PII: S1072-7515(18)30434-4

DOI: 10.1016/j.jamcollsurg.2018.06.005

Reference: ACS 9176

To appear in: *Journal of the American College of Surgeons*

Received Date: 5 June 2018

Accepted Date: 5 June 2018

From Pull to Pressure: Effects of Tourniquet Buckles and Straps

Michael J Valliere, MD[a], Piper L Wall, DVM, PhD[a], Charisse M Buising, PhD[b]

[a]Surgical Education Department, Iowa Methodist Medical Center, UnityPoint Health, Des Moines, IA
[b]Biochemistry, Cell and Molecular Biology, Drake University, Des Moines, IA

Disclosure Information: Nothing to disclose.
Presented at the Iowa Committee on Trauma Resident Research Competition, Iowa City, IA, November 2017; the Region VII Advances in Trauma 40[th] Annual Meeting, Kansas City, MO, December 2017; and the 41[st] Annual Residents Trauma Papers Competition during the American College of Surgeons Committee on Trauma Annual Meeting, San Antonio, TX, March 2018 (1[st] Place, Basic Laboratory Science).

Correspondence:
Piper Wall, DVM, PhD
1415 Woodland, Suite 218
Surgical Education Department
Iowa Methodist Medical Center, UnityPoint Health
Des Moines, IA 50309
(515) 708-6695 cell phone
piperwall@q.com

Brief Title: Tourniquet Buckles and Straps

ABSTRACT

Background: Limb tourniquet pressures >100mmHg prior to tightening system use eases achieving arterial occlusion, minimizes tightening system problems, and probably minimizes discomfort. This study examined effects of buckle and strap features on converting pulling force to strap pressure.

Study Design: Twenty-two buckle and strap combinations were evaluated using a thigh-diameter, ballistic gel cylinder and three thighs. Weights of 14.11, 27.60, and 41.11kg provided pulling force. The contribution of buckle movement was evaluated: all buckles on gel and 12 on thighs allowed limited vertical movement, 12 on gel and 4 on thighs held static.

Results: Force conversion patterns per combination were similar on gel and thighs, including greatest force conversion with some buckle movement allowed. Smooth, round re-direct buckles without engagement of a strap securing mechanism had the best conversions of pulling force to tourniquet pressure; two such achieved arterially occlusive pressures, neither commercially available. Among hook-and-loop secured tourniquets and threaded for self-securing tourniquets, the Generation 7 Combat Application Tourniquet (C-A-T7) and the Tactical Ratcheting Medical Tourniquet (Tac RMT) had the best conversions of pull to pressure (thigh applications/each weight, mean ± SD: C-A-T7 91±11, 164±30, 228±34mmHg; Tac RMT 82±13, 150±16, 222±17mmHg). Other RMTs with the same buckle but different strap fabrics performed less well. Even lower pressures occurred with the Tactical Mechanical Tourniquet, the Special Operations Forces® Tactical Tourniquet, the Parabelt, and the SAM XT Extremity Tourniquet (165±11, 178±13, 131±14, and 106±14mmHg all at 41.11kg, respectively).

Conclusion: Buckle design and strap fabric affect the conversion of pulling force to tourniquet strap pressure. Low-friction, smooth, round re-directs allow the best conversion.

Abbreviations used in the text:

2013 RMT = Mass Casualty Ratcheting Medical Tourniquet version produced until February 2013
ANOVA = analysis of variance
Black RMT = 2015 Black Ratcheting Medical Tourniquet (Paramedic)
CAM = 3.8cm wide cam strap
C-A-T = Combat Application Tourniquet
C-A-T biner = Generation 6 Combat Application Tourniquet modified by replacing the re-direct buckle with a standard oval climbing carabiner as the strap re-direct
C-A-T7 = Generation 7 Combat Application Tourniquet
MAT = Mechanical Advantage Tourniquet
N = Newton
Ped RMT = 2016 Pediatric Ratcheting Medical Tourniquet (<120lbs/55kg)
SAM = SAM XT Extremity Tourniquet
SAM no prong = SAM XT Extremity Tourniquet modified such that the prongs could not deploy
Red RMT = 2016 Red Ratcheting Medical Tourniquet (>120lbs/55kg)
RMT = Ratcheting Medical Tourniquet
SOFTTW RND = latest generation as of 2017 Special Operations Forces® Tactical Tourniquet Wide
SOFTTW SQR = prior generation as of 2017 Special Operations Forces® Tactical Tourniquet Wide
Tac RMT = 2015 Tactical Ratcheting Medical Tourniquet
TMT = Tactical Mechanical Tourniquet
Un = unthreaded
Wide RMT = 2015 Wide Ratcheting Medical Tourniquet (2 Inch)

Introduction

Effective current limb tourniquets stop blood loss via the circumferential application of sufficient inward pressure applied over a sufficient surface area to stop arterial flow. Most commercial limb tourniquet designs involve a nonelastic strap, some type of buckle allowing a 180° strap direction change (strap re-direct), a strap securing mechanism, and a mechanical advantage tourniquet tightening mechanism. Achieving inward pressures greater than 100mmHg (ideally greater than 150mmHg) prior to engagement of the mechanical advantage tourniquet tightening mechanism is desirable from the standpoint of ease of achieving arterial occlusion (1,2), minimizing tightening system problems (1-4), and probably minimizing recipient discomfort. "Get it tight to get it right" is an apt directive with tighter being better concerning strap tightness prior to engagement of the mechanical advantage tourniquet tightening system.

Many of the buckles allowing the 180° strap re-direct also secure the strap against backsliding via friction. These types of buckles are "friction buckles." A common alternate method of securing the strap against backsliding is the use of hook-and-loop fabric. This method of strap securing can be combined with the use of a friction buckle, such as is the case in the double routed Generation 6 Combat Application Tourniquets (C-A-T, C-A-T Resources), or can be used with a buckle that merely allows strap direction change but does not secure the strap against backsliding, such as is the case in the single routed Generation 6 C-A-T or the Generation 7 C-A-T.

Any design feature that creates resistance to strap tightening during the pull to strap tightness prior to mechanical advantage system engagement has the potential to adversely affect the applier's ability to pull the strap tight. Additionally, any design or application method that provides a mechanical advantage during strap pulling should improve the applier's ability to achieve strap tightness. The purpose of this study, therefore, was to examine the effects of different design features and application methods on achieving strap tightness prior to any mechanical advantage system engagement. The hypotheses were that low-friction buckles would be advantageous and that allowing the buckle to move as the limb is compressed would also be advantageous for achieving maximum strap tightness for any applied pulling force.

Methods

The Drake University Institutional Review Board approved the human thigh aspects of this prospective study. The study occurred throughout the summer and fall of 2017.

The following tourniquets were donated by their respective companies for this or prior studies: the modified Generation 6 C-A-T (C-A-T biner), the modified SAM XT Extremity Tourniquet (SAM no prong, SAM Medical), all of the Ratcheting Medical Tourniquets (RMTs, m2® Inc.), and the Parabelt (RevMedX). The other tourniquets were purchased: the Generation 7 C-A-T (C-A-T7), the SAM XT Extremity Tourniquet (SAM), the Tactical Mechanical Tourniquet (TMT, Combat Medical), the 2017 generation Special Operations Forces® Tactical Tourniquet Wide (SOFTTW RND, Tactical Medical® Solutions), and the prior generation SOF® Tactical Tourniquet Wide (SOFTTW SQR). The cam strap was also purchased (CAM, New River Gear). The buckle and strap features are shown in Table 1 and in Figure 1.

A previously purchased tourniquet that was initially planned to be used in this study is the Mechanical Advantage Tourniquet (MAT, Pyng Medical). The MAT was not used in previous studies because of high recipient discomfort when use was attempted on bare skin (severe pinching during mechanical advantage use). For this study, the MAT was tested on the ballistic gel and found to be too gel damaging (shearing stress tears).

Hook-and-Loop Tourniquet Modifications

The Generation 6 C-A-T (C-A-T biner) was modified by using an oval climbing carabiner (REI) for the strap re-direct instead of any part of the built in buckle. The pre-production model SAM XT Extremity Tourniquet (SAM no prong) was modified by replacing the springs inside the buckle casing with metal sleeves so that the buckle's prongs could not deploy. For each tourniquet, these modifications resulted in smooth, round, low-friction strap re-directs of relatively large diameters with no buckle related strap securing mechanisms.

Double Ring Friction Buckle Tourniquets

The different RMT models had differences in strap widths and materials, buckle widths, re-direct surface characteristics, and re-direct diameters. The RMT model with the overlapping metal rings composed of the smaller diameter round stock and no rough coating is an older model (2013 RMT) that is no longer produced.

Several of the RMT models were also used with the strap only routed around the bottom of the two metal rings to create a re-direct with the same width, surface character, and diameter but without the friction of the normal routing of the overlapping metal rings. This 'unthreaded' (un) strap routing modification removes the buckle related strap securing mechanism of these tourniquets.

Sliding Bar Friction Buckle Tourniquets

As with several of the RMT models, the Parabelt and both versions of the SOFTTW were also used with the strap only routed around the bottom portion of each tourniquet's buckle. This 'unthreaded' (un) strap routing modification removes the buckle related strap securing mechanism of these tourniquets.

Spring-loaded Cam Buckle Strap

The cam strap was not modified and was not designed as a tourniquet. The cam strap was designed to secure paddle craft to vehicle roof racks.

Pressure Measurements

Pressures under each tourniquet were measured using a #1 neonatal blood pressure cuff (2.2cm × 6.5cm bladder, single tube). Each cuff bladder was inflated to 10-11mmHg above atmospheric pressure to avoid complete collapse of the bladder during tourniquet applications. Atmospheric pressure was used as baseline pressure. The bladder was placed under the strap of each tourniquet approximately 180° from the location of the tourniquet buckle strap re-direct.

Each inflated bladder was connected to a gas pressure sensor system (Vernier Gas Pressure Sensor, Vernier LabPro interface, and Logger Pro Software; Vernier Software and Technology). Pressure was continuously displayed graphically with numeric values displayed every second. Each tourniquet application's data was saved as complete, combined graphic and numeric data.

Strap Force Application

Pulling force was applied to each tourniquet strap by attaching increasing amounts of weight to the strap (Figures 2 and 3). Each of the three weight increments was approximately 13.63 kg or 30 pounds for total hanging weights of 14.11, 27.60, and 41.11 kg (31.05, 60.72, and 90.44 pounds). The applied pulling forces, therefore, were 138.12, 270.10, and 402.30 N.

In all of the protocols, the buckle re-direct started near the middle of the side of the gel (Figure 2A) or near the middle of the lateral side of the thigh (Figure 3A). This allowed the initial pulling force to be applied tangential to the gel or thigh circumference. Buckles with re-directs that allowed easy strap movement stayed in contact with the gel or thigh. Buckles with re-directs that precluded easy strap movement tended to rotate outward, away from the gel or thigh surface as strap pulling force was increased.

Buckle Re-Direct Movement

In all protocols, the hanging weights were predominantly supported by the buckle securing system and not by the gel or thigh. In the first ballistic gel protocol and first thigh protocol, some vertical movement of the tourniquet buckle was allowed by securing the buckle with a system of ropes and carabiners (Figures 2 and 3). The system used with the thighs had shorter and more vertical ropes and therefore allowed less vertical movement. In the second ballistic gel protocol and second thigh protocol, vertical movement of the tourniquet buckle was prevented by securing exclusively (or almost exclusively in the case of the C-A-T biner) with carabiners (Figure 4).

The differences in allowance of buckle re-direct movement were used to alter the mechanical advantage of the re-direct. If one thinks of the strap and re-direct as a pulley system, no movement of the re-direct is akin to a fixed pulley system, which is a 1:1 system with no mechanical advantage. A system in which the pulley (or buckle re-direct) moves could achieve up to a 2:1 mechanical advantage.

Protocol Runs

Each tourniquet listed in Table 1 was used on a 57.5cm circumference cylinder of 20% ballistic gel (Clear Ballistics). A subset of the tourniquets with securable strap setups was used on the thighs of the authors (tourniquet location thigh circumferences of 49.0, 48.0, and 55.0cm).

On the gel, each tourniquet was assessed three times with some vertical movement of the buckle (Figure 2), and a subset of tourniquets were assessed one time with prevention of vertical movement of the buckle (Figure 4). For each of the three protocol runs with some buckle vertical movement allowed, the order of use on the gel was randomized by drawing numbered slips of paper from a box. The first of the three protocol run orders was used for the single run subset with the prevention of buckle movement protocol. The tourniquets used in the gel subset with prevention of buckle vertical movement were the C-A-T biner, SAM no prong, Tac RMT, Red RMT, Black RMT, Ped RMT, 2013 RMT, Wide RMT, Parabelt, SOFTTW RND, SOFTTW SQR, and CAM.

On the thigh, the order of tourniquet use was assigned from least pressure development to greatest pressure development for each application session. This was done because leg discomfort became increasingly noticeable with the higher pressure applications. The tourniquets used on the thigh with some buckle vertical movement allowed were the C-A-T7, C-A-T biner, SAM, SAM no prong, TMT, Tac RMT, 2013 RMT, Wide RMT, Parabelt, SOFTTW RND, SOFTTW SQR, and CAM. The tourniquets used on thigh with prevention of buckle vertical movement were the C-A-T biner, Tac RMT, SOFTTW RND, and CAM.

During gel protocol runs, the tourniquet and pressure measuring system were placed and then each weight was applied at either 100 or 200 second intervals, depending on the previously determined rapidity with which the tourniquet ceased to have pressure increases (100 second intervals were only used for the C-A-T biner, SAM, and Parabelt un). Following removal of the weights and removal of the tourniquet, the gel was rested at least 30 minutes prior to assessment of the next tourniquet. This 30 minute time period was previously determined to be sufficient to allow the gel to resume its starting shape following tourniquet application (5).

During thigh protocol runs, the tourniquet and pressure measurement system were placed and then each weight was applied. Preliminary runs indicated that 40 seconds would be sufficient for each weight addition. The pressure responses observed in the early thigh protocol runs resulted in decreasing the time for each weight addition to 30 seconds. A variable amount of time was taken between runs. Based on the results from a previous study (6), a thigh rest interval was not necessary for good pressure data.

During gel protocol runs, the horizontal gel cylinder was suspended by a rod placed through the stainless steel tube that traversed the center of the gel cylinder (Figure 2). During thigh protocol runs, the recipient sat with a relaxed and horizontal thigh and a 90° knee flexion with the foot flat on a support surface (Figure 3).

Convenience Sample Pulling Force

To help determine what pulling force range would be used, the single arm downward pulling force that each author could apply was investigated. Weight increments of 4.55kg (10 pounds) were used. The strap used in the pull was that of the C-A-T biner. The strap re-direct so that strap downward pull would lift the weights was a fixed smooth metal bar with a diameter of 4.60mm.

Statistical Analysis

Numeric pressure data were organized in Microsoft® Office Excel 2003 (Microsoft Corp). For each re-direct buckle and strap setup, pressures at the end of each weight hang interval were analyzed using one-way repeated measures analysis of variance (ANOVA) with the Tukey's multiple comparison test or one-way ANOVA with the Tukey's multiple comparison test. For comparisons between pulling force effects with tourniquets on the gel versus on thighs and with some vertical buckle movement allowed versus vertical buckle movement prevented, paired t-tests were used. Graphing and statistical analyses were performed with GraphPad Prism version 5.02 for Windows (GraphPad Software Inc.). Statistical significance was set at $p \leq .05$. Medians are shown with minimums and maximums.

Results

Convenience Sample Pulling Force

The two female authors, each of whom had some arm injury issues at the time of testing, were each able to apply 177.9N of pulling force (40 pounds force). The male author, who is younger and had no arm injuries at the time of testing, was able to apply 355.9N of pulling force (80 pounds force).

Examples of the pressure development with the applied strap forces can be seen in Figure 5. Thigh pressure development rapidly reached a maximum with the application of each weight set and then slightly decreased over the time to final pressure measurement before the next weight set addition. As compared to thigh pressure development, gel pressure development tended to have a rounded shoulder with the addition of each weight set. After each rounded shoulder, the smoothness of pressure development on the gel varied by tourniquet. Round, smooth re-direct setups, especially with smooth straps instead of hook-and-loop, tended to have smooth and rapid pressure developments to plateaus for each weight set. Re-directs that weren't round or weren't smooth often had one or more small, abrupt, distinct pressure increases during the period between weight set additions (Figure 5B and D). These small, distinct pressure increases were caused by small but visible, distinct movements of the strap through the re-direct.

The tourniquet pressures achieved with each applied strap force are shown in the panels of Figure 6. With some vertical movement of the re-direct buckle allowed (Figure 6A-C) and with the strap run through the buckle as it would be applied, only a few commercially available tourniquets achieved pressures greater than 100mmHg with the lowest applied pulling force. All of the tourniquet applications achieved pressures greater than 100mmHg with 27.60 kg of hanging weight (270 N pulling force).

As compared to the prevention of vertical buckle movement, allowing some vertical movement of the re-direct buckle resulted in greater tourniquet pressures for the same applied strap forces (compare Figure 6A-C to Figure 6D-F, $p < .0001$ for vertical buckle movement allowance versus prevention in gel applications and $p = .0155$ for vertical buckle movement allowance versus prevention in thigh applications). Among tourniquet applications with some vertical movement of the buckle allowed, applications on the gel tended to have slightly higher pressures than did tourniquet applications on thighs (Figure 6A-C, $p = .0005$), but the setup used in those gel applications also allowed more vertical movement of the buckle than did the setup used in those thigh applications (Figure 1A-D to Figure 3A-D). Among tourniquet applications with prevention of vertical movement of the buckle, a statistically significant difference in attained pressures was not present for gel versus thigh applications (Figure 6D-F, $p = .2223$).

For a given setup, the amount of strap travel through each buckle visually corresponded to the conversion of pulling force to pressure. This can be seen by comparing the strap travel in Figure 2 (C-A-T biner) to the strap travel in Figure 3 (SOFTTW RND). Comparing Figure 2 to Figure 4 allows a visual appreciation of the difference in buckle vertical movement between the setup allowing some buckle vertical movement (Figure 2) versus the setup preventing buckle vertical movement (Figure 4).

Smooth, round re-directs without engagement of a strap securing mechanism were associated with the best conversions of pulling force to tourniquet pressure: C-A-T biner, 2013 RMT unthreaded, and SAM no prong (Figure 6). Despite roughness, the round re-direct of the Tac RMT unthreaded provided a very similar conversion of pulling force to tourniquet pressure as did the SOFTTW RND unthreaded (Figure 6).

Re-direct diameter did not appear to have an important effect on converting pulling force to tourniquet pressure. Despite sharing the same diameter and roughness, the re-directs of the other RMTs in both their unthreaded and threaded configurations did not provide the same conversion of pulling force to tourniquet pressure as did the Tac RMT unthreaded and Tac RMT, respectively (Figure 6). This indicates an influence of strap material and possibly strap width versus re-direct width (Table 1) on pulling force conversion to tourniquet pressure.

The inclusion of strap self-securing mechanisms in the buckle impaired the conversion of pulling force to tourniquet pressure. The impairment was least with the paired, overlapping metal rings of the 2013 RMT and Tac RMT and the spring-loaded cam buckle of the CAM (Figure 6).

Most of the pressures were lower than would be required to achieve and maintain arterial occlusion. The visually apparent venous congestion that resulted during the few longer time interval weight application sets while establishing thigh weight timing should reinforce the importance of having limb tourniquets achieve and maintain arterial occlusion (Figure 7).

In all of the protocol runs, tourniquet applications that achieved higher pressures created visibly obvious asymmetric gel and thigh indentation: indentation was greater at the bottom of the gel and thigh than at the top (Figure 2, 3, and 7). This is quite different from the symmetric indentation pattern that the authors typically observe with gel or thigh tourniquet applications that do not involve attachment of the tourniquet buckle to a fixed location separate from the gel or thigh.

Tourniquet Buckle Robustness

Two C-A-T7s were used in this study because the buckle of the first C-A-T7 deformed with increased outward bowing during the 11th use of the first C-A-T7 (five uses during development of the gel protocol that allowed some vertical buckle movement, three uses during the gel protocol that allowed some vertical buckle movement, one use during development of the thigh protocol that allowed some vertical buckle movement, and two uses during the thigh protocol that allowed some vertical buckle movement). The buckle of the second C-A-T7 bowed outward during the 1st use (thigh protocol that allowed some vertical buckle movement). Both C-A-T7s were unused prior to this study.

The SAM, TMT, Red RMT, Black RMT, Ped RMT, SOFTTW RND, and the CAM were also unused prior to this study. The rest of the tourniquets had been applied a variable number of times prior to this study. No tourniquets other than the two C-A-T7s developed any buckle deformation during this study.

Discussion

The key finding of this study is that low-friction, smooth, round re-directs allowed the best transduction of pulling force to tourniquet strap pressure. A secondary finding is that allowing the buckle to move in the direction of pull as the limb compresses improves the transduction of pulling force to tourniquet strap pressure (this is not the same as letting the whole tourniquet slide around the limb, which is not helpful).

Maximizing tourniquet strap pressure prior to mechanical advantage system engagement is highly desirable (1-4). Therefore, the implications of the key finding are that designers and purchasers of limb tourniquets should consider the frictional characteristics of tourniquet re-direct buckles and straps. Some characteristics are obviously suboptimal. For tourniquets with straps that are secured against backsliding by hook-and-loop material, examples of suboptimal design choices are using re-direct buckles with rough surfaces or edges (C-A-T7), using triglides (TMT), or adding prongs that deploy too easily (SAM). For designers and purchasers who aren't fond of hook-and-loop, there are re-direct buckle designs that can secure non-hook-and-loop straps against backsliding. The trick is to find designs that are physically robust and prevent backsliding without markedly impairing the conversion of strap pull to tourniquet pressure. Re-direct friction buckle designs involving sliders (Parabelt and SOFTTW) may be acceptable for very strong appliers, but those same appliers would be able to reach higher pressures during the initial strap pull with different design choices. Overlapping metal ring re-direct friction buckles (RMTs) appear to have variation in impairment of pull conversion to pressure with subtle strap material differences: among the current RMT designs (2015 and 2016 dates), the strap width and strap material used in the Tactical RMT clearly converted pulling force to circumferential pressure better than did the strap widths and strap materials used in the Red, Black, and Pediatric RMT (Table 1 and Figure 6). Spring-loaded cam buckle designs may have some advantages, but the weight and size of the cam buckle used in this study would both be larger than desirable for a limb tourniquet.

The implication of the finding concerning application technique is that tourniquet holding techniques that completely prevent any movement of the re-direct buckle as the limb is compressed are not advantageous as compared to holding techniques that allow some movement of the re-direct buckle as the limb is compressed. However, movement of the re-direct buckle in the direction of force application as a result of limb compression is quite different from allowing the entire tourniquet to slide around the limb.

The three pulling forces were chosen based on the pulling forces applied by the authors, the prong deployment force for the SAM, and the weights available. Comparisons of the strap pressures achieved in this study with the thigh strap pressures achieved in prior studies support the relevance of the chosen pulling forces: 1) Single appliers pulled 2013 RMTs to pressures of 35 to 206mmHg (median 89mmHg), indicating correctly vectored pulling forces from less than 138 N (30 pounds force) up to 270 N (60 pounds force)(7). 2) Appliers who were sometimes assisted pulled single routed Generation 6 C-A-Ts to target pressures of 50 to 200mmHg, indicating correctly vectored pulling forces from less than 138 N up to 270 N (1). 3) Appliers who were sometimes assisted pulled a 2013 Tactical RMT and a current generation Tactical RMT to target pressures of 25 to 150mmHg, indicating correctly vectored pulling forces from less than 138 N to perhaps 204 N (1). 4) With a goal of achieving pressures greater than 100mmHg, single appliers pulled a current generation Tactical RMT to 88 to 196mmHg (median 125mmHg) and a current generation Wide RMT to 63 to 174mmHg (median 128mmHg), indicating correctly vectored pulling forces from less than 138 N up to 402 N (90 pounds force) (8). 5) With a goal of achieving pressures greater than 100mmHg, appliers who had assistance available pulled a current generation Tactical RMT to 100 to 186mmHg (median 126mmHg), indicating correctly vectored pulling forces from slightly less than 138 N up to 270 N (9). 6) With a goal of achieving 120mmHg, appliers who were often assisted pulled current generation Tactical RMTs to 102 to 140mmHg (median 121mmHg), indicating correctly vectored pulling forces slightly more than 138 N (6). The majority of the appliers in these studies were undergraduate students. It seems likely that military personnel might tend to apply greater pulling forces.

An obvious limitation of this study is that the majority of the data came from applications on a ballistic gel cylinder, and the pressure traces showed some differences in the shape of pressure development between the gel cylinder and actual thighs. Additionally, not every setup that was used on the gel was used on the thighs. However, among setups used on the gel and the thighs, the pressures developed for each pulling force were similar for gel applications and thigh applications (Figures 5 and 6).

A use limitation of this study is that it only explored re-direct buckle design influences on conversion of pulling force to circumferential pressure. Tourniquet designers and purchasers must also consider how well designs prevent strap backsliding; how well designs will function in challenging environments; the weight, size, and ease of use of different designs; and the physical robustness of different designs.

A consideration regarding the findings from this study is that the pulling forces in this study were applied in a vector that started tangential to the gel or thigh surface at the location of the buckle re-direct. Tangential to the limb surface at the strap re-direct would be the correct vector for force application. In our observation, many tourniquet appliers fail to use the ideal vector for force application (many appliers pull the strap outward, away from the limb). The use of suboptimal strap pulling technique makes the choice of a good re-direct buckle design even more important for achieving desirable strap pressures prior to engaging the windlass, ratcheting buckle, or any other mechanical advantage tightening system.

Conclusions

Tourniquet buckle and strap systems need to secure the strap against backsliding and need to withstand the likely forces that will be applied to them. Within these constraints, tourniquet strap re-direct buckles should minimally impair the conversion of pulling force to circumferential pressure. This force conversion is best accomplished with low-friction or directional-friction buckle designs.

Acknowledgement

We thank James Howe for his work preventing the prongs of the SAM no prong from deploying, for his help with the ballistic gel mold, and for the provision of some equipment. We thank Joe Buising for his help getting buckle and setup pictures.

References

1. Slaven SE, Wall PL, Rinker JH, et al. Initial tourniquet pressure does not affect tourniquet arterial occlusion pressure. J Spec Oper Med 2015;15:39–49.
2. Polston RW, Clumpner BR, Kragh JF Jr, et al. No slackers in tourniquet use to stop bleeding. J Spec Oper Med 2013;13:12–19.
3. Kragh JF Jr, O'Neill ML, Walters TJ, et al. The military emergency tourniquet program's lessons learned with devices and designs. Mil Med 2011;176:1144–1152.
4. Kragh JF Jr. Burrows S, Wasner C, et al. Analysis of recovered tourniquets from casualties of Operation Enduring Freedom and Operation New Dawn. Mil Med 2013;178:806-810.
5. Rometti MRP, Wall PL, Buising CM, et al. Significant pressure loss occurs under tourniquets within minutes of application. J Spec Oper Med 2016;16:15-26.
6. Wall P, Buising C, Nelms D, et al. Paired tourniquet distance effects. J Spec Oper Med 2017;17:37-44.
7. Wall PL, Coughlin O, Rometti M, et al. Tourniquet pressures: strap width and tensioning system widths. J Spec Oper Med 2014;14:19–29.
8. Wall PL, Weasel J, Rometti M, et al. Pressures under 3.8cm, 5.1cm, and side-by-side 3.8cm-wide tourniquets. J Spec Oper Med 2016;16:28-35.
9. Wall P, Buising C, Grulke L, et al. Effectiveness of pulse oximetry versus Doppler for tourniquet monitoring. J Spec Oper Med 2017;17:36-44.

Table 1. Tourniquet Buckle and Strap Features

Tourniquet (abbreviation, manufacturing date or lot number)	Buckle and redirect specification	Strap specification	Strap securing mechanism
Generation 7 Combat Application Tourniquet (C-A-T7, Lot 120B207)	4.048cm wide strap slot; re-direct rough, not round, 3.02mm thick	3.861cm wide x 3.02mm thick (uncompressed), hook-and-loop	Strap hook-and-loop
Generation 6 Combat Application Tourniquet with oval carabiner used for strap re-direct (C-A-T biner, Oct 08 2010)	8.334cm wide strap slot; re-direct smooth, round, 11.06mm diameter	3.930cm wide x 3.02mm thick (uncompressed), hook-and-loop	Strap hook-and-loop
SAM XT Extremity Tourniquet (SAM)	3.590cm wide strap slot; re-direct smooth till prongs engage, round till prongs engage,17.52mm diameter	3.874cm wide x 3.40mm thick (uncompressed), hook-and-loop	Strap hook-and-loop and buckle prongs
Modified SAM XT Extremity Tourniquet with nondeployable prongs (SAM no prong, pre-production)	3.548cm wide strap slot; re-direct smooth, round, 17.52mm diameter	3.840cm wide x 3.40mm thick (uncompressed), hook-and-loop	Strap hook-and-loop
Tactical Mechanical Tourniquet (TMT, Lot 040517)	Triglide; 5.140cm wide strap slot; re-direct slightly rough, rectangular, 5.80mm thick	5.146cm wide x 2.38mm thick (uncompressed), hook-and-loop	Strap hook-and-loop and triglide buckle
Tactical Ratcheting Medical Tourniquet (Tac RMT, Nov 10 2015)	Overlapping metal rings; 4.220cm and 3.696cm wide strap slots; re-direct rough, round,4.00mm diameter	3.708cm wide x 1.19mm thick mil spec webbing	Paired, overlapping, rough metal rings
Tac RMT with strap only routed around the bottom of the two metal rings (Tac RMT un, Nov 10 2015)	Bottom metal ring; 3.696cm wide strap slot; re-direct rough, round, 4.00mm diameter	3.708cm wide x 1.19mm thick mil spec webbing	None
Red RMT (Red RMT, Apr 15 2016)	Overlapping metal rings; 4.222cm and 3.730cm wide strap slots; re-direct rough, round,4.00mm diameter	3.879cm wide x 1.11mm thick webbing	Paired, overlapping, rough metal rings
Red RMT with strap only routed around the bottom of the two metal rings (Red RMT un,	Bottom metal ring; 3.730cm wide strap slot; re-direct rough, round, 4.00mm	3.879cm wide x 1.11mm thick webbing	None

April 15 2016)	diameter		
Black RMT (Black RMT, Nov 10 2015)	Overlapping metal rings; 4.220cm and 3.721cm wide strap slots; re-direct rough, round,4.00mm diameter	3.806cm wide x 1.10mm thick webbing	Paired, overlapping, rough metal rings
Pediatric RMT (Ped RMT, April 15 2016)	Overlapping metal rings; 4.228cm and 3.721cm wide strap slots; re-direct rough, round,3.98mm diameter	3.702cm wide x 1.10mm thick webbing	Paired, overlapping, rough metal rings
2013 version of Red RMT (2013 RMT)	Overlapping metal rings; 4.028cm and 3.725cm wide strap slots; re-direct smooth, round,2.90mm diameter	3.642cm wide x 1.20mm thick webbing	Paired, overlapping, smooth metal rings
2013 RMT with strap only routed around the bottom of the two metal rings (2013 RMT un)	Bottom metal ring; 3.725cm wide strap slot; re-direct smooth, round, 3.06mm diameter	3.642cm wide x 1.20mm thick webbing	None
Wide RMT (Wide RMT, Nov 10 2015)	Overlapping metal rings; 5.346cm and 5.012cm wide strap slots; re-direct rough, round,3.94mm diameter	5.088cm wide x 1.12mm thick webbing	Paired, overlapping, rough metal rings
Wide RMT with strap only routed around the bottom of the two metal rings (Wide RMT un, Nov 10 2015)	Bottom metal ring; 5.012mm wide strap slot; re-direct rough, round, 3.92mm diameter	5.088cm wide x 1.12mm thick webbing	None
Parabelt (Parabelt, Lot PT1116-21-04)	Sliding bar; 4.592cm wide strap slot; re-direct smooth, not round, 6.66mm thick; bottom of re-direct ridge; bottom of buckle smooth rectangle with notch	4.452cm wide x 2.22mm thick webbing	Sliding bar with ridge matched to notch on the bottom bar of the buckle
Parabelt with strap only routed around the bottom portion of the buckle (Parabelt un, Lot PT1116-21-04)	Bottom of buckle; 4.592cm wide strap slot; re-direct smooth rectangle with notch, 6.60mm thick	4.452cm wide x 2.22mm thick webbing	None
2017 generation Special Operations Forces® Tactical Tourniquet Wide with round buckle re-direct (SOFTTW RND, 04-03-2017)	Sliding bar; 4.103cm wide strap slot; re-direct smooth, round, 10.68mm diameter; bottom of re-direct upside down u-shape;	3.788cm wide x 1.14mm thick webbing	Sliding bar with upside down u-shape pulling onto round bottom bar of the buckle

	bottom of buckle smooth, round, 4.84mm diameter		
SOFTTW RND with strap only routed around the bottom portion of the buckle (SOFTTW RND un, 04-03-2017)	Bottom of buckle; 4.103cm wide strap slot; re-direct smooth, round, 4.84mm diameter	3.788cm wide x 1.14mm thick webbing	None
Prior generation SOFTTW with square buckle re-direct (SOFTTW SQR, 08-11-2014)	Sliding bar; 4.030cm wide strap slot; re-direct smooth, round, 7.82mm diameter; bottom of re-direct upside down u-shape; bottom of buckle smooth, rectangular, 3.08mm thick	3.715cm wide x 1.16mm thick webbing	Sliding bar with upside down u-shape pulling onto square bottom bar of the buckle
SOFTTW SQR with strap only routed around the bottom portion of the buckle (SOFTTW SQR un, 08-11-2014)	Bottom of buckle; 4.030cm wide strap slot; re-direct smooth, rectangular, 3.08mm thick	3.715cm wide x 1.16mm thick webbing	None
Cam strap with spring-loaded cam buckle (CAM)	Spring-loaded cam buckle; 3.756cm wide strap slot; re-direct rough, not round, 12.8mm thick	3.733cm wide x 1.5mm thick polypropylene webbing	Spring-loaded cam buckle with rough surface on each side

Figure legend

Figure 1. Buckles of tourniquets with hook-and-loop securing systems: Generation 7 Combat Application Tourniquet (C-A-T7), Generation 6 Combat Application Tourniquet with oval carabiner used for strap re-direct (C-A-T biner), SAM XT Extremity Tourniquet (SAM) with prongs deployed, modified SAM XT Extremity Tourniquet with nondeployable prongs (SAM no prong), and Tactical Mechanical Tourniquet (TMT). Buckles of tourniquets with overlapping metal ring securing systems: Tactical Ratcheting Medical Tourniquet (Tac RMT, same rough coated metal rings as the Red RMT, Black RMT, and Pediatric RMT - photos not shown), 2013 version of Red RMT (2013 RMT, smooth and smaller diameter metal rings than current RMTs), and Wide RMT (same rough coating and diameter metal rings as other current RMTs). Buckles of tourniquets with sliding bar securing systems: Parabelt, current version of Special Operations Forces® Tactical Tourniquet Wide with round buckle re-direct (SOFTTW RND), and prior version of SOFTTW with square buckle re-direct (SOFTTW SQR). Buckle of the cam strap with spring-loaded cam buckle securing system: spring-loaded cam buckle (CAM).

Figure 2. Gel tourniquet and weights setup with some vertical buckle movement allowed. (A) Generation 6 Combat Application Tourniquet with oval carabiner used for strap re-direct (C-A-T biner) tourniquet setup placed around the center of the ballistic gel. The weight holding carabiner is attached to the tourniquet strap with a small C-clamp. Some vertical movement of the re-direct buckle will be allowed by rope stretch in response to increasing load. No weights are attached. (B) Same setup as Fig 2 panel A with the exception of three weight sets clipped on for a total of 41.11kg. The manila folder pieces protect the gel surface from possible shearing from the strings and the edges of the re-direct buckle. (C) Close up portion of Fig 2 panel A showing the buckle securing strings, C-A-T biner re-direct, and strap with no weight attached.

(D) Close up portion of Fig 2 panel B showing the buckle securing strings, C-A-T biner re-direct vertical movement (5.03cm), the amount of strap pulled through with 41.11kg attached to the strap (9.42cm), and the resulting asymmetric deformation of the gel.

Figure 3. Thigh tourniquet and weights setup with some vertical buckle movement allowed. (A) Current version of Special Operations Forces® Tactical Tourniquet Wide with round buckle re-direct (SOFTTW RND) tourniquet setup placed mid-thigh. The weight holding carabiner is attached to the tourniquet strap with a small C-clamp. Some vertical movement of the re-direct buckle will be allowed by rope stretch in response to increasing load. No weights are attached. (B) Same setup as Fig 3 panel A with the exception of three weight sets clipped on for a total of 41.11kg. (C) Close up portion of Fig 3 panel A showing the buckle securing strings, SOFTTW RND re-direct, and strap with no weight attached. (D) Close up portion of Fig 3 panel B showing the buckle securing strings, SOFTTW RND re-direct vertical movement (3.08cm), the amount of strap pulled through with 41.11kg attached to the strap (4.54cm), and the resulting asymmetric deformation of the thigh.

Figure 4. Gel tourniquet setup prevention of vertical buckle movement. (A) Close up of the re-direct and strap of the Generation 6 Combat Application Tourniquet with oval carabiner used for strap re-direct (C-A-T biner) with no weight attached. Very short, vertically oriented ropes secure the re-direct buckle against vertical movement. (B) Close up showing C-A-T biner re-direct vertical movement (1.52cm), the amount of strap pulled through with 41.11kg attached to the strap (8.77cm), and the resulting deformation of the gel.

Figure 5. Example gel and thigh pressure traces with different tourniquet setups. In all of the panels, gel pressure traces are shown with solid black lines for setups with some vertical buckle movement allowed and solid gray lines for setups with the prevention of vertical buckle

movement. Thigh pressure values are shown with stars for setups with some vertical buckle movement allowed and with crosses for setups with the prevention of vertical buckle movement. Thigh pressure values are connected with dashed lines. Thigh pressure symbols and lines are darker versions of blue, green, and red for setups with some vertical buckle movement allowed, and lighter versions of blue, green, and red for setups with the prevention of vertical buckle movement. Numbers for gel traces indicate the order of gel pressure trace acquisition with the tourniquet while numbers for thigh traces indicate the same thigh in each graph. (A) Generation 6 Combat Application Tourniquet with oval carabiner used for strap re-direct (C-A-T biner) pressure traces from both gel and both thigh protocols. (B) Strap with spring-loaded cam buckle (CAM) pressure traces from both gel and both thigh protocols. (C) Tactical Ratcheting Medical Tourniquet (Tac RMT) pressure traces from both gel and both thigh protocols. (D) Current version of Special Operations Forces® Tactical Tourniquet Wide with round buckle re-direct (SOFTTW RND) pressure traces from both gel and both thigh protocols.

Figure 6. Gel and thigh pressures with different pulling forces. In all of the panels, thigh pressure values are shown with stars. Among gel applications, hook-and-loop tourniquet pressure values are shown with solid circles; RMT pressure values are shown with triangles (solid when threaded, clear when unthreaded); slider buckle tourniquet pressure values are shown with diamonds (solid when threaded, clear when unthreaded); and spring-loaded cam buckle strap pressures are shown with asterisks. (A) Gel and thigh pressures with some buckle vertical movement allowed and with 14.11 kg of weight hanging from the strap (138.12 N pulling force). (B) Gel and thigh pressures with some buckle vertical movement allowed and with 27.60 kg of weight hanging from the strap (270.10 N pulling force). The vertical gray lines indicate groups of gel pressures with 270N of pulling force that are not statistically significantly different from

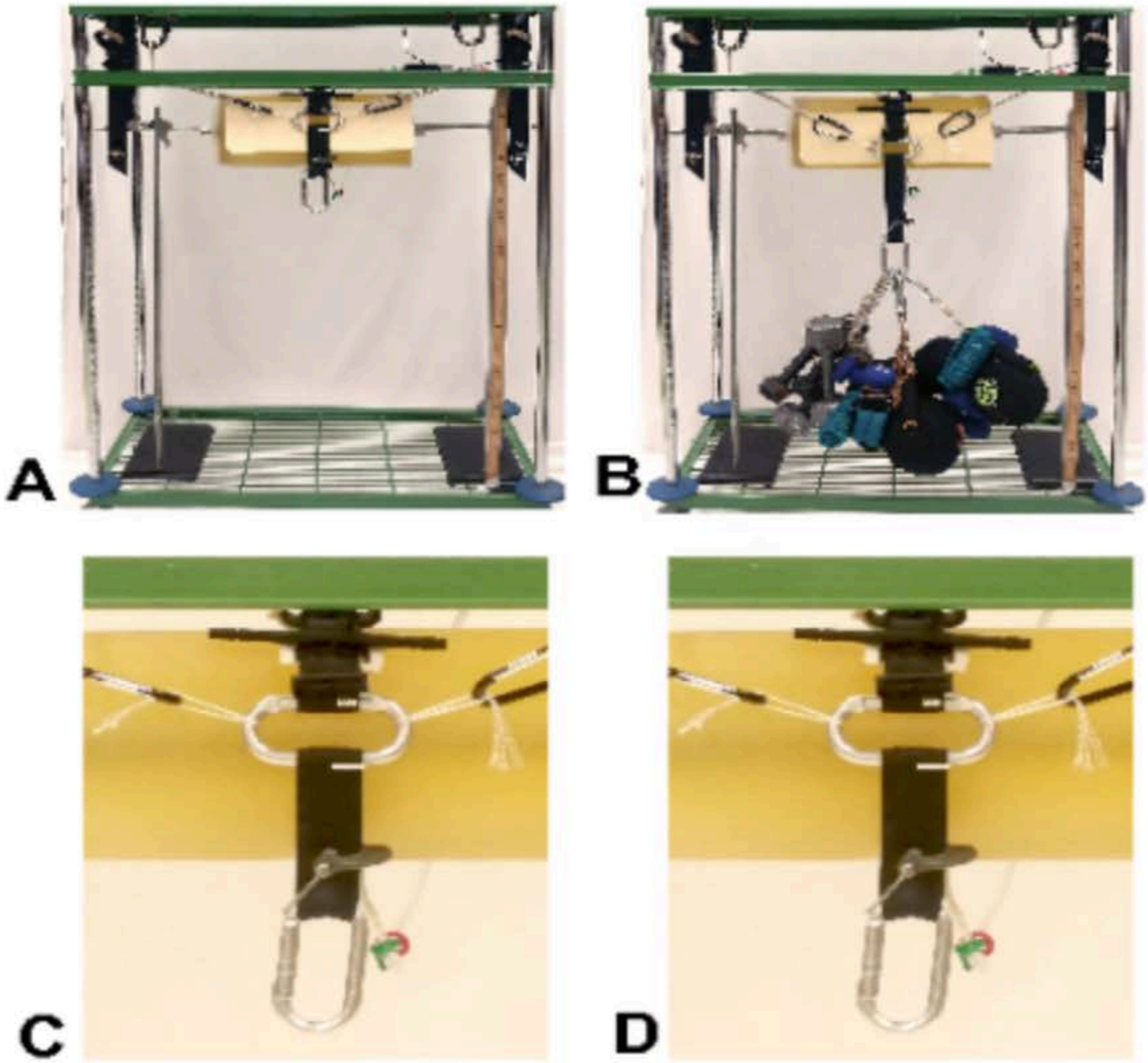
the highest pressure setup in each grouping. (C) Gel and thigh pressures with some buckle vertical movement allowed and with 41.11 kg of weight hanging from the strap (402.30 N pulling force). (D) Gel and thigh pressures with the prevention of buckle vertical movement and with 14.11 kg of weight hanging from the strap (138.12 N pulling force). (E) Gel and thigh pressures with the prevention of buckle vertical movement and with 27.60 kg of weight hanging from the strap (270.10 N pulling force). The vertical gray lines are those used in panel C. (F) Gel and thigh pressures with the prevention of buckle vertical movement and with 41.11 kg of weight hanging from the strap (402.30 N pulling force).

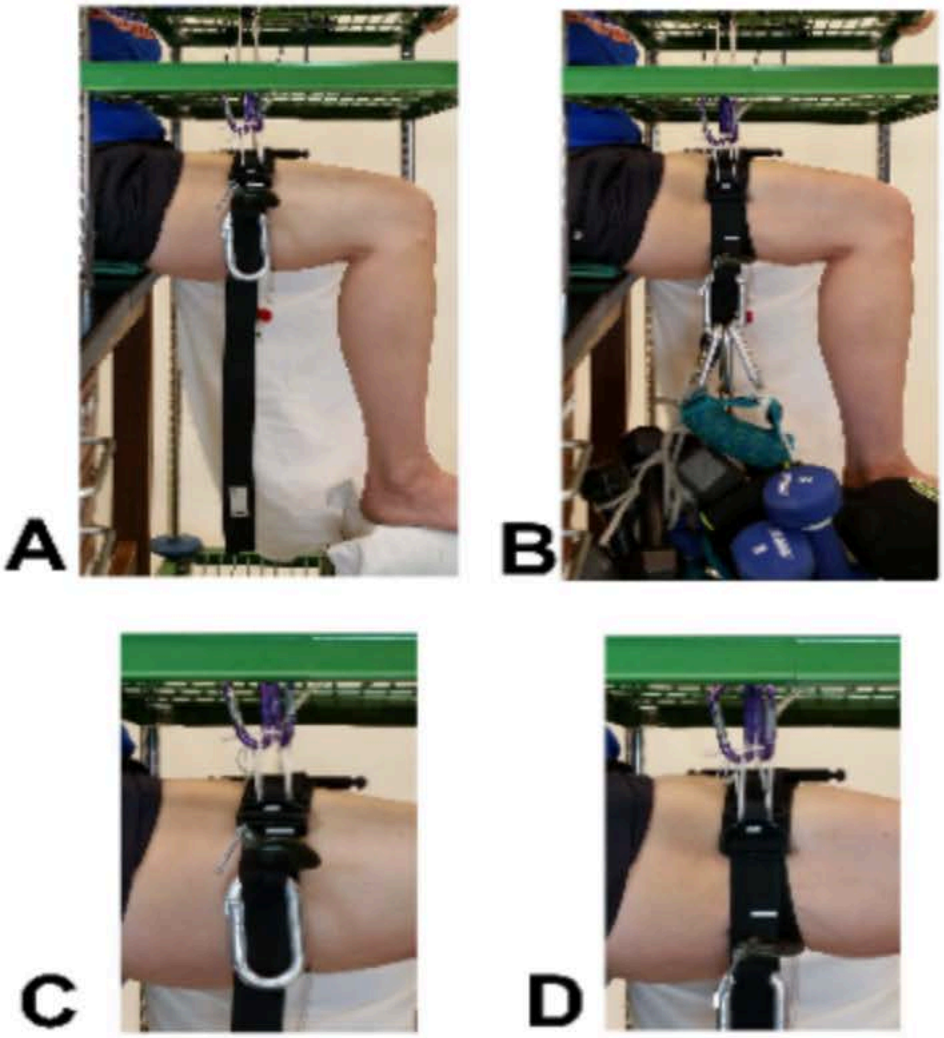
Figure 7. Venous congestion with sufficient pressure to occlude venous return but insufficient pressure to occlude arterial flow. (A) Thigh with strap with spring-loaded cam buckle (CAM) prior to applying weights to the strap. (B) Venous congestion of thigh with CAM with 41.11kg attached to the strap resulting in a strap pressure of 250mmHg, sufficient to occlude venous return but not arterial flow. Re-direct vertical movement 2.47cm with 7.28cm of strap pulled through the re-direct. (C) Pressure trace from CAM on thigh suggesting presence of ongoing pulsatile flow despite increases in pulling force and corresponding increases in applied pressure.

Précis:

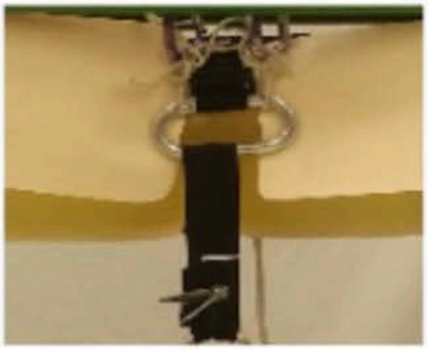
Buckle design and strap fabric affect the conversion of pulling force to tourniquet strap pressure. Buckles with low-friction, smooth, round strap redirects allow the best conversion of pulling force to tourniquet strap pressure.

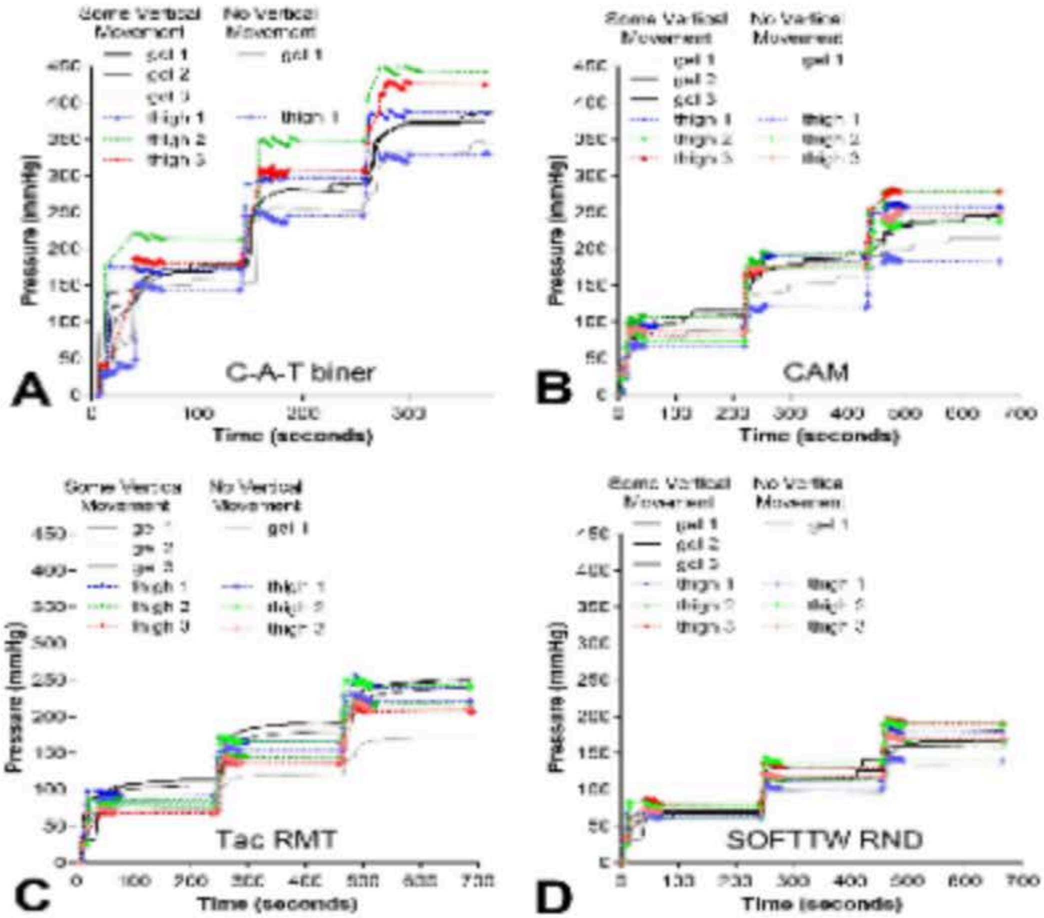

C-A-T7
C-A-T biner
SAM
SAM no prong
TMT
Tac RMT
2013 RMT
Wide RMT
Parabelt
SOFTTW RND
SOFTTW SQR
CAM


A
B
C
D

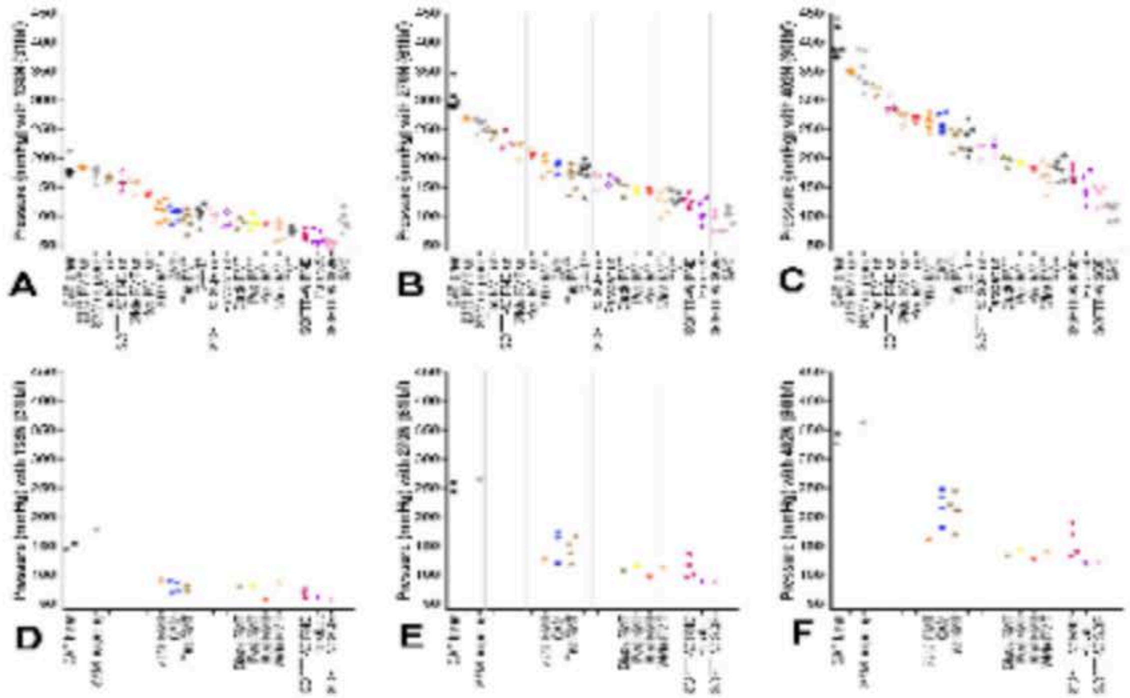


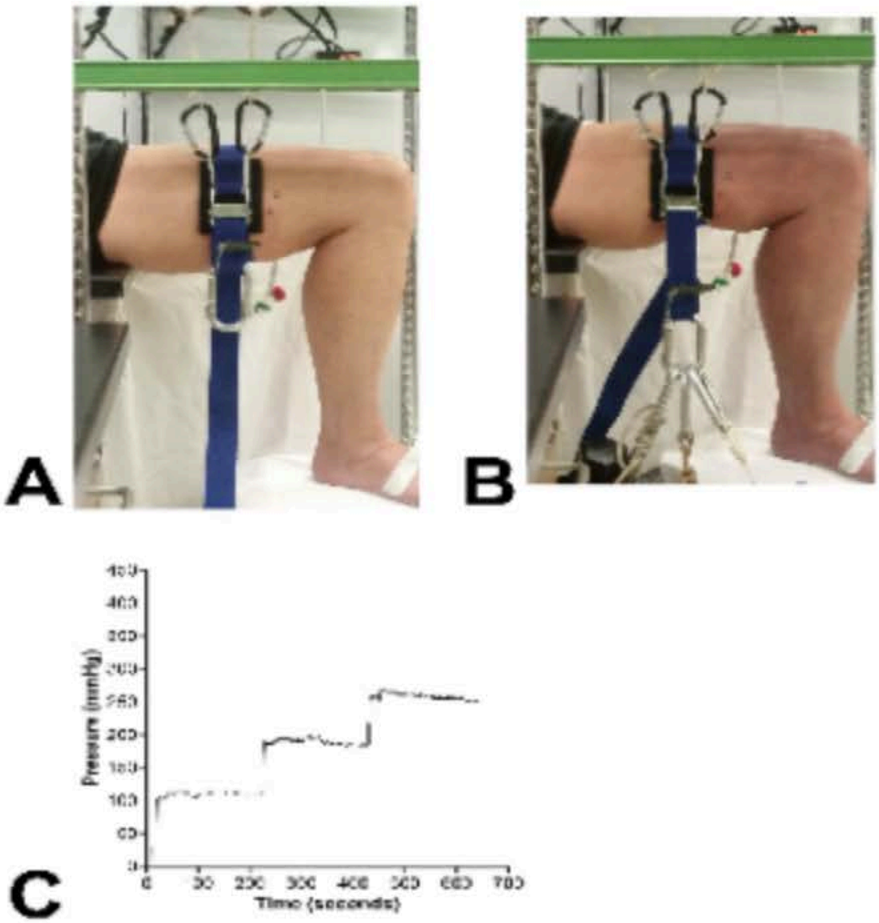
A

B




Some Vertical Movement
No Vertical Movement
gel 1
gel 2
gel 3
thigh 1
thigh 2
thigh 3
Pressure (mmHg)
Time (seconds)
C-A-T biner
CAM
Tac RMT
SOFTTW RND
A
B
C
D


A
B
C
D
E
F


A
B
C
Pressure (mmHg)
Time (seconds)