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Comparison Of Non-Clinical Tourniquet Research for Appliance Superiority & Tolerance (CONTRAST): A systematic review and meta-analysis of commercial and improvised tourniquet devices for arterial occlusion, application speed, and tolerance

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All authors meet the ICMJE and CRediT authorship criteria.

Abstract

Background: Tourniquets are effective tools to manage life-threatening extremity hemorrhage. Commercial devices are recommended over improvised techniques; however, mass casualty incidents and austere environments may prevent access to commercial devices. The aim of this review is to systematically search and meta-analyze commercial and improvised tourniquets for the outcomes of: arterial occlusion, application speed, and patient tolerance.

Methods: We searched MEDLINE, Embase, CINAHL, Cochrane Library, SPORTDiscus, and ProQuest Dissertations & Theses Global using controlled terms; without date limits. Manikin, animal, and operative studies were excluded. Tourniquet devices were pooled by design and compared. Data regarding provider training and experience, recipient anthropometrics, application site, ease of application, speed, tolerance, and device efficacy were examined.

Results: 5,169 studies were screened. The 36 included studies were prospective trials on healthy volunteers and published between 2000 and 2021. There were 8,205 unique tourniquet applications to 1,921 subjects using 23 unique commercial and improvised devices. Median

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sample size was 20 participants (IQR 26), ranging from 1 to 773 participants; and 102 (IQR = 152) applications ranging from 20 individual applications to 1,546 unique applications. The most commonly assessed outcomes were: rates of arterial occlusion (*n* = 30), pain (*n* = 18), speed of application (*n* = 13), and amount of mechanical advantage (e.g., Windlass turns) required (*n* = 13). Male participants outnumbered females 1,414 to 169, mean age ranged from 21 to 45 years of age. Devices were pooled into five categories according to mechanical advantage mechanism: elastic, friction, mechanical, pneumatic, and windlass. Initial hemostasis was achieved in 95% of upper extremity placements (CI = 0.89–0.98, *p* = 0.02), and 88% of mid-thigh applications (CI = 0.78–0.94, *p* <0.01). In both groups, pneumatic and mechanical tourniquet devices had the highest rates of success, with friction and elastic devices having the lowest rates of success. Meta-analysis showed that mechanical and pneumatic advantage systems had superior rates of hemostasis, ease of use, and pain tolerance scores. Due to study heterogeneity, we could not determine which devices were the fastest to apply. The overall risk of bias assessment for included studies found the certainty of studies ranged from moderate to critical.

Conclusion: In pre-clinical studies, mechanical and pneumatic advantage systems appear to be the superior tourniquet design. Due to the low certainty of evidence and non-randomizable nature of traumatic injury, pre-clinical tourniquet devices will likely continue to be tested on well volunteers. Adoption of a minimum data set, agreed upon definitions for testable metrics, and a standardized experimental design, could improve the comparability and quality of future tourniquet device studies.

Level of evidence: Systematic review, level IV.

Keywords: tourniquet, extremity, limb, injury, trauma

Background

Decades of controversy discouraged tourniquet use (Husum et al., 2004; Navein et al., 2003), which had been a hemorrhage control tool for hundreds of years (Forrest, 1982). Two decades of recent evidence; however, show tourniquets to be a safe and effective early intervention for extremity hemorrhage for injured adults in the military (Beekley et al., 2008; Lakstein et al., 2003), civilian care (Kauvar et al., 2018), and for children (Kragh et al., 2012). The controversy surrounding tourniquets has shifted from whether they are safe and effective, to which tourniquet design is superior, and what role improvised devices should play in patient care (Cornelissen et al., 2020; Stewart, et al., 2015). The Committee on Tactical Emergency Casualty Care (Callaway et al., 2011), American College of Surgeons (Hartford Consensus Group; Jacobs et al., 2015), and American College of Emergency Physicians (Bulger et al., 2014) all suggest commercial devices be used before improvised devices. Their recommendations are acknowledged to be based on weak evidence and grant that there may be limited role for improvised devices if commercial devices are unavailable. Others have argued that there will likely always be a need for improvised devices (Stewart et al. 2015), with recent reviews of improvised devices highlighting the need to examine differing designs (Cornelissen et al., 2020). There are dozens of commercially available generations and designs of tourniquet available (Martinson et al., 2020), and a potentially endless number of improvised designs. This abundance of tourniquet designs and the inherent difficulty in randomization of trauma patients to specific hemostasis devices necessitates pre-clinical trials to compare efficacy. Prior work and their cumulative endpoints have not been comprehensively compared.

Because of the challenges inherent in testing tourniquet designs in a clinical setting there will remain the need to examine devices in pre-clinical settings. This review gathered pre-clinical data from 2002-2021 to compare device designs and determine what data points are routinely reported and whether there is superiority to any specific design. The purpose of this review is to systematically search the literature and meta-analyze commercial and improvised device effectiveness for three outcomes of interest: rates of arterial occlusion, application speed, and patient tolerance.

Methods

This is a systematic review and meta-analysis of pre-clinical studies that examined extremity tourniquets. The review was registered (Picard & Douma, 2018) and reported according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (Page et al., 2021).

Literature search

We developed search strategies in conjunction with a library science information specialist (CP, MJD, JK) for the following databases: Ovid MEDLINE, Ovid Embase, CINAHL, Cochrane Library, SPORTDiscus, and ProQuest Dissertations & Theses Global. Search terms used in all databases included a combination of keywords and controlled vocabulary terms, with no date or language limits applied. The librarian (JK) strategically selected keywords based on the highest frequency that the keywords appeared in articles found in PubMed, which included "tourniquets hemorrhage" and "tourniquets arterial." To recover as many results in which tourniquets were used in non-surgical contexts, a modified version of a military medicine filter (Campbell, 2015) was included in the search strategy where possible. We searched for eligible studies published in the English language from database inception through July 2, 2020. An expanded grey literature search including targeted website searching, internet database searching, and grey literature database searching, was performed following previously published methods (Douma et al., 2020). The search was re-run on June 7, 2021 to identify any new and potentially eligible research (Supplement 1). We also hand-searched bibliographies from previously published systematic reviews of tourniquets and hemorrhage control for eligible studies.

Review question

The review question was framed using the PICOST framework (Schardt et al., 2007).

Population: Healthy adult volunteers.

Intervention: Any tourniquet devices applicable for use by trained or untrained first aid providers including manufactured or improvised (not purpose-built or marketed as a hemorrhage control device) medical device tourniquets were assessed (intervention and comparison).

Comparison: Any comparison or tourniquet device.

Outcomes: Rates of arterial occlusion (determined by palpation, ultrasound, doppler, or plethysmography), time to hemostasis (how long after application it was measured), speed of application, and patient tolerance (defined using any validated pain scale). Secondary outcomes were ease of tourniquet use, method for determining hemostasis, training received, patient anthropometric data, and any other standard data reported.

Study design: Conference abstracts and trial protocols were excluded. All languages were included provided a peer-reviewed English translation was available. Inclusion criteria were pre-clinical studies that assessed any commercial or improvised tourniquet devices.

***Time*:** No date restrictions were applied.

Article screening and data extraction

Three reviewers (CP, DOD, MJD) independently and in duplicate, screened titles and abstracts, and subsequent full-text articles using Covidence (Melbourne, Australia). Any discrepancies between reviewers were resolved by consensus or independent arbitration.

Inclusion criteria

Because of the foreseeable need to continue with pre-clinical testing of tourniquet designs (due to the inherent challenges of comparing tourniquets on injured patients), the inclusion criteria for study design were set as pre-clinical studies that assessed any commercial or improvised tourniquet devices. Clinical cohort studies, case reports, case series, animal and manikin studies, and intra-operative applications of tourniquets were excluded. Studies of patients less than 18 years of age were excluded. Only English language studies were included.

Outcomes

Primary outcomes assessed included rates of arterial occlusion (determined by palpation, ultrasound, doppler, or plethysmography), time to hemostasis (how long after application it was measured), speed of application, and patient tolerance (defined using any pain scale). Secondary outcomes were ease of tourniquet use, method for determining hemostasis, training received, any patient anthropometric data collected, and any other standard data reported.

Data extraction

The same three reviewers (CP, DOD, MJD) independently and in duplicate, extracted data into a pre-piloted database (Excel; Microsoft Corporation, Redmond, WA). Extracted data included: study setting, study design, tourniquet devices assessed, sample size, participant demographics, anthropometrics, participant vital signs, the method for and location used to determine cessation of peripheral pulses, the technique for applying a tourniquet, skill/training level of tourniquet applier, extremity examined, successful occlusion rates, methods for determining arterial occlusion, tourniquet occlusion pressures, tourniquet application speed, time to arterial occlusion, perceived ease of tourniquet use, tourniquet breakage rate, and distress/pain caused by tourniquet application.

Data analysis and risk of bias assessment

Data analysis

Due to the wide variability in sample sizes, descriptive statistics were reported both as mean (M) and standard deviations (SD); and as median (Mdn) and interquartile ranges (IQR) for the study sample population size and characteristics of all studies. Due to the contextual heterogeneity of data, device-specific data were meta-analyzed only between: guided and unguided applications: guided applications had real-time ultrasound (visual or doppler) feedback during application; with only efficacy and pain level compared. Analysis was restricted to devices with a minimum: of 40 applications that had final arterial occlusion confirmed with some form of ultrasound (either colour flow, or audio doppler). Continuous outcomes were reported as mean differences (MD) with 95% confidence intervals (CIs).

We combined groups such as female and male, right and left for arm and leg measurements following formulations from the Cochrane Handbook (Higgins et al., 2019), and converted mean median IQR and Range to mean Median (McGrath et al., 2020) (Supplement 2). Data were transformed for the following variables: i) body mass index (BMI), which was reported in some papers instead of weight and height; ii) blood pressure (BP), BP was not always reported as systolic (SBP) and diastolic (DBP), some papers it is reported as mean arterial pressure (MAP) only; iii) numeric pain score (NPS) were not consistently recorded, for these we generated a vector, averaged the scores and converted scores to an 11-point (0–10) scale. Transformation formulas for BMI (Forbes et al., 2011; Papanicolaou, 2009), MAP (Gavish et al., 2008), and NPS are available in the supplemental materials (Supplement 2).

Dichotomous outcomes were reported as risk ratios (RR) and absolute risk reduction (ARR), with 95% confidence intervals. Random effects models were used, taking into account both within and between-study variability. We used the inverse variance method for continuous outcomes and the Mantel-Haenszel method for dichotomous outcomes. A p-value<0.05 was considered statistically significant. All meta-analyses were performed using Review Manager 5.3 (The Nordic Cochrane Centre, Copenhagen, Denmark, 2014). Heterogeneity was assessed by visual inspection of the forest plot, by using Chi^2 (with $p < 0.10$) to identify statistical significance, and the I2 statistic (I2 > 60%) to identify heterogeneity.

Risk of bias assessment

The risk of bias was assessed independently and in duplicate, for included studies by two reviewers (CP & DOD) with consensus arbitrated by a third reviewer (MJD). The risk of bias was assessed using the Cochrane Risk Of Bias In Non-Randomized Studies of Interventions (ROBINS-I) tool (Sterne et al., 2016).

Results

Studies identified

The final search identified a total of 9,236 results. 36 articles met full inclusion criteria; with one article excluded because it did not disclose the design of the tourniquet used (Ali et al., 2021) (Figure 1). Inter-rater agreement was fair to moderate between reviewer agreement (CP/MJD, κ=0.51; DOD/MJD, κ=0.37).

Characteristics of studies

All studies were prospective trials on healthy volunteers published between 2,000 and 2021. There were 8,205 unique tourniquet applications on 1,921 subjects. The mean sample size of included studies was 55.60 (SD = 130.39, Mdn = 20, IQR = 26) participants; with a mean of 210.91 applications (SD = 304.03, Mdn = 102, IQR = 152). Study sample sizes ranged from 1 participant (Kragh et al., 2019) to 773 participants (Weppner et al., 2013), and total tourniquet applications ranging from 20 individual applications (Peponis et al., 2016) to 1,546 individual applications (Weppner et al., 2013) (Table 1).

Participant data

Fourteen studies reported full demographic details including age, sex, limb circumference, and baseline vital signs (Table 1). Men outnumbered women 1,414 to 169, and the mean age of participants ranged from 21 to 45 years of age. 17 studies reported on height, weight, or BMI, 17 reported on limb circumference, and 17 reported full or partial baseline vital signs (Table 2).

Device data

There were 23 unique tourniquets evaluated. For the purposes of meta-analysis, devices were grouped by their mechanical advantage mechanism (elastic, friction, mechanical, pneumatic, or windlass) (Table 3). Although there may be changes in designs across generations, for the purpose of pooling data, all generations of any given commercial device were aggregated. Similarly, for improvised devices (blood pressure cuff, improvised windlass, surgical tubing, etc.), data were pooled irrespective of materials or brand used.

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Figure 1

Literature Screening and Inclusion Diagram

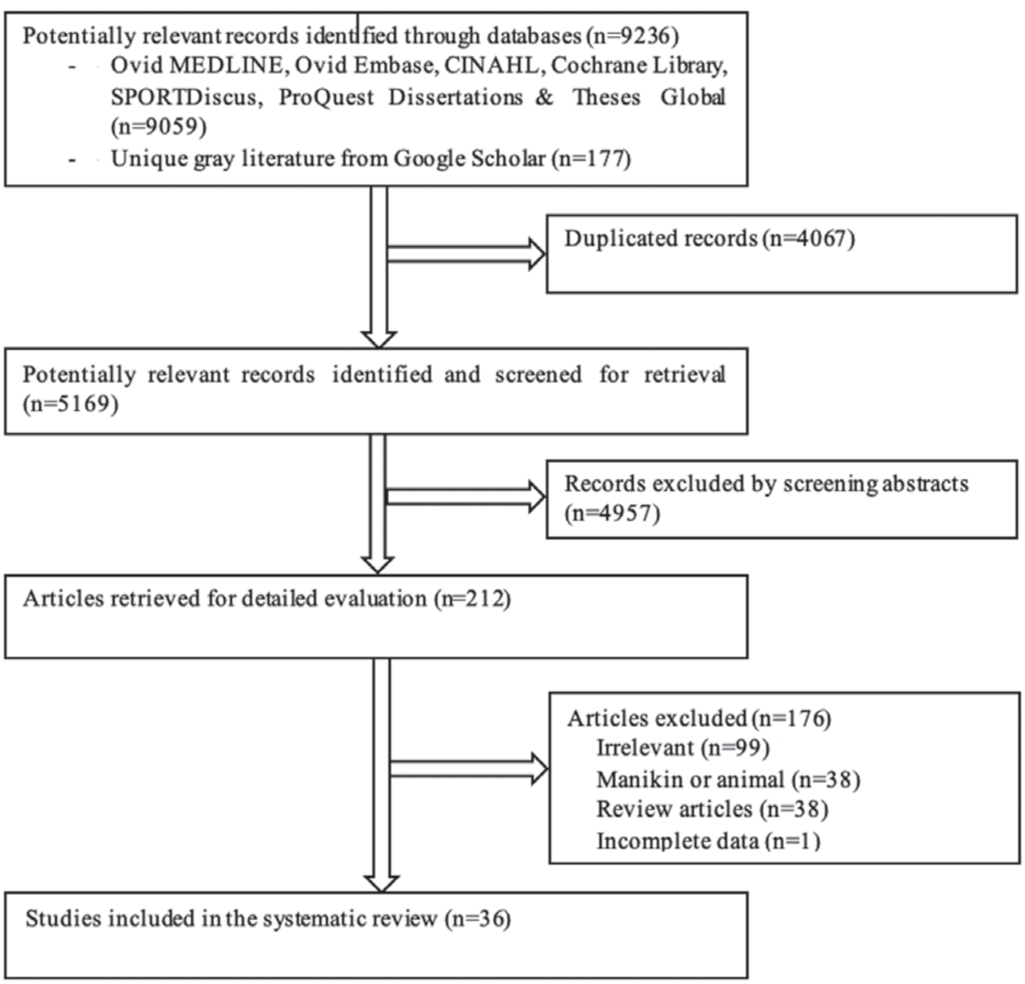


Table 1

Characteristics of Data Included in Studies

Author, year	Sample (*n*)	Applications (*n*)	Occlusion	Time of hemostasis	Application speed	Patient tolerance	Ease of use	Hemostasis assessment	Provider training	Anthropometrics	Other standardized reporting data
Alterie et al., 2018	41	708	Y	--	-	Y	-	D	Y	Y	Advantage
Beaven et al., 2017	12	24	Y	Y	Y	Y	-	U	Y	-	Advantage
Beaven et al., 2018	24	48	Y	-	Y	Y	-	U	Y	-	-
Beaven et al., 2021	12	24	Y	Y	Y	Y	-	D	Y	-	Breakage
Calkins et al., 2000	15	157	Y	Y	Y	-	-	P, D	Y	-	-
Childers et al., 2011	166	256	Y	Y	-	-	-	D	Y	-	Advantage, breakage
Guo et al., 2011	20	200	Y	-	Y	Y	Y	D	Y	Y	-
Heldenberg et al., 2015	23	828	Y	-	-	Y	Y	D, P	Y	-	-
Higgs et al., 2016	40	40	Y	Y	Y	-	-	P	Y	-	-
Jaffer et al., 2012	58	116	Y	Y	Y	Y	-	S, U	Y	Y	-
King et al., 2006	10	100	Y	-	Y	Y	Y	D, P	Y	-	-
Kragh et al., 2019	1	100	-	-	-	-	-	-	Y	-	Breakage
Martinez et al., 2018	50	102	Y	-	Y	-	-	U	Y	-	-
Peponis et al., 2016	20	20	Y	-	-	-	-	P, S, U	Y	-	Advantage
Sanak, 2017	24	24	Y	-	-	-	-	U	Y	-	-
Savage et al., 2013	22	65	Y	-	Y	Y	Y	D, P	Y	-	Advantage
Schreckengaust et al., 2014	89	-	Y	Y	Y	-	-	D	Y	-	-
Slaven et al., 2015	12	24	Y	Y	-	Y	-	D	Y	-	Advantage, breakage, skin pressure
Swan et al., 2009	10	120	Y	-	-	Y	Y	D	-	-	-
Taylor et al., 2011	24	72	Y	-	-	-	-	D	Y	-	-
Unlu et al., 2015	52	306	Y	-	Y	-	-	U	Y	Y	Advantage
Unlu et al., 2017	145	188	Y	-	-	-	-	U	Y	-	Advantage
Vuillemin et al., 2018	72	72	Y	-	Y	-	-	U	Y	-	-
Wall, Buising, Grulke, et al., 2017	15	60	Y	Y	-	Y	-	D, S	Y	Y	Advantage, skin pressure
Wall, Buising, Nelms, et al., 2017	15	293	Y	Y	-	Y	-	D	Y	Y	Advantage, skin pressure
Wall et al., 2013	17	187	Y	Y	-	Y	Y	D	Y	Y,	Advantage, skin pressure
Wall et al., 2014	16	192	Y	Y	-	-	-	S, U	Y	Y	Advantage, skin pressure
Wall et al., 2015	16	151	Y	Y	-	Y	-	D	Y	Y	Advantage, skin pressure
Wall et al., 2016	16	96	Y	Y	-	Y	-	D	Y	-	Breakage, skin pressure
Wall et al., 2019	22	400	Y	-	-	Y	-	S	Y	-	Breakage, skin pressure
Wall et al., 2020	28	225	Y	-	-	Y	-	S	Y	-	Breakage, skin pressure
Wall, Welander, Sahr, et al., 2012	15	90	Y	Y	-	Y	Y	D	Y	Y	-
Wall, Welander, Singh, et al., 2012	15	30	Y	Y	Y	Y	Y	D	Y	Y	-
Walters et al., 2005	18	174	Y	-	-	Y	-	D	-	Y	-
Wenke et al., 2005	26	22	Y	Y	-	-	-	D, S	-	Y	-
Weppner et al., 2013	773	1546	Y	-	-	-	-	D	Y	Y	Advantage, breakage

Abbreviations – D- Doppler (audible), N- No, P- Palpation, Ultrasound (visual), S- Plethysmography (SpO2), Y- Yes

Table 2

Participant Characteristics and Anthropometrics

First author, year	Age	Male (%)	Wt. (Kg)	Ht. (cm)	BMI	Leg circ (cm)	Arm circ (cm)	HR (/min)	SBP (mmHg)	DBP (mmHg)	MAP (mmHg)
Alterie et al., 2018	31.4 (6.9)	28 (68.3)	-	-	-	-	-	-	-	-	-
Beaven et al., 2017	31.5 (5.2)	10 (83.3)	-	-	-	-	-	-	-	-	-
Beaven et al., 2018	39.2 (18)	20 (83.3)	-	-	-	-	-	-	-	-	-
Beaven et al., 2021	29.6 (5.4)	12 (100.0)	-	-	-	-	-	-	-	-	-
Calkins et al., 2000	-	-	-	-	-	-	-	-	-	-	-
Childers et al., 2011	21 (3.1)	166 (100.0)	79 (9.8)	176 (9)	26 (4.2)	61 (5.3)	-	69 (12.7)	124 (13.6)	68 (10)	48 (8.7)
Guo et al., 2011	22.5 (3.6)	12 (60.0)	61.5 (10.4)	170.2 (3.6)	21.2 (3.3)	47.5 (6.8)	25.1 (3.3)	77.8 (10.4)	123.6 (16.4)	69 (9.8)	47.7 (9.2)
Heldenberg et al., 2015	21 (2.9)	23 (100.0)	-	-	-	-	-	-	-	-	-
Higgs et al., 2016	34 (12.2)	32 (80.0)	-	-	-	-	-	-	-	-	-
Jaffer et al., 2012	22.5 (2.3)	35 (60.3)	74 (11.4)	175.7 (11.1)	24 (2.6)	44.5 (4.6)	-	75.2 (6.7)	119.4 (3)	76 (5.9)	43.7 (4.2)
King et al., 2006	-	-	-	-	-	-	-	-	-	-	-
Kragh et al., 2019	-	-	-	-	-	-	-	-	-	-	-
Martinez et al., 2018	25.9 (3.1)	-	-	-	-	-	-	-	-	-	-
Peponis et al., 2016	33.9 (9.7)	11 (55.0)	-	-	26.4 (0)	-	-	-	-	-	-
Sanak, 2017	-	-	-	-	-	-	-	-	-	-	-
Savage et al., 2013	-	-	-	-	-	-	-	-	-	-	-
Schreckengaust et al., 2014	-	-	-	-	-	-	-	-	-	-	-
Slaven et al., 2015	33.2 (13.8)	7 (58.3)	-	-	-	52.9 (7.5)	-	-	114.7 (13)	-	-
Swan et al., 2009	36.5 (6)	-	69.8 (5.4)	173 (4)	23.3 (1.7)	-	-	-	123 (6)	72 (4)	43.7 (3.6)

continued…

First author, year	Age	Male (%)	Wt. (Kg)	Ht. (cm)	BMI	Leg circ (cm)	Arm circ (cm)	HR (/min)	SBP (mmHg)	DBP (mmHg)	MAP (mmHg)
Taylor et al., 2011	36 (0)	-	-	-	-	-	-	-	-	-	-
Unlu et al., 2015	24.5 (3.8)	-	-	-	23.5 (2.3)	49.6 (5)	39 (11.3)	-	-	-	92.7 (0)
Unlu et al., 2017	32 (7)	145 (100.0)	-	-	25 (1.8)	56.8 (4)	-	-	-	-	88.7 (0)
Vuillemin et al., 2018	27.1 (4.7)	71 (98.6)	-	-	23.8 (0)	54.4 (0)	-	-	-	-	-
Wall, Buising, Grulke, et al., 2017	29.6 (15.2)	7 (46.7)	-	-	-	51.2 (5)	27.6 (4.1)	-	102.4 (10.5)	63.7 (8.4)	39.7 (7.1)
Wall, Buising, Nelms, et al., 2017	29.5 (14.9)	8 (53.3)	-	-	-	-	-	-	111.3 (11.7)	66.5 (8.4)	42.9 (7.4)
Wall et al., 2013	26.8 (12.3)	6 (35.3)	75.4 (18.2)	169.3 (12.7)	26.2 (4.1)	48 (6.7)	28.5 (5.8)	-	116.6 (0)	60 (0)	-
Wall et al., 2014	29.1 (13)	7 (43.8)	72 (18.2)	172.6 (12.5)	24.2 (3.8)	52 (7.5)	29.9 (5)	-	107.5 (13)	71.9 (13)	44.5 (10.4)
Wall et al., 2015	29.4 (13.5)	8 (50.0)	76.1 (14.8)	172 (12.5)	25.7 (3.1)	37.9 (3.5)	24.9 (3.4)	-	108.3 (13.5)	-	-
Wall et al., 2016	45 (31)	8 (50.0)	-	-	-	53.3 (3.8)	29.9 (5.6)	-	119 (0)	70.5 (0)	-
Wall et al., 2019	-	6 (30.0)	-	-	-	47.1 (0)	-	-	-	-	-
Wall et al., 2020	31.1 (17.4)	3 (23.1)	-	172.5 (12.5)	-	52 (6.5)	-	-	113 (15.2)	-	-
Wall, Welander, Sahr, et al., 2012	22.9 (6.6)	8 (53.3)	71.4 (16.6)	174.1 (10.3)	23.3 (3.4)	51.1 (3)	29.2 (4.4)	74.5 (12.5)	-	-	-
Wall, Welander, Singh, et al., 2012	21 (1)	8 (53.3)	75.9 (22.5)	175.6 (11.9)	24.4 (4.7)	49.1 (6.3)	29.1 (4.2)	78.5 (13.5)	128.5 (13.6)	81.3 (11.1)	49.9 (9.1)
Walters et al., 2005	35.3 (7.2)	16 (88.9)	83.4 (10.5)	177 (6.9)	26.6 (2.8)	59.5 (4.5)	34 (4.1)	65 (8.8)	122 (6.9)	75 (8.8)	46.7 (6.7)
Wenke et al., 2005	23 (1)	17 (65.4)	82.5 (2.8)	176 (2)	26.6 (0.9)	59.8 (1)	32.5 (0.6)	67 (3)	117 (3)	64 (3)	41 (2.4)
Weppner et al., 2013	21.7 (3)	773 (100.0)	88.4 (10.9)	177.6 (6.3)	28 (3)	60.7 (5)	-	67.8 (11.3)	119.8 (14.6)	77.3 (8.6)	45.6 (8.1)

Table 3

Device Characteristics by Mechanical Advantage Mechanism

Mechanism	Device name and manufacturer
Elastic	Stretch Wrap and Tuck Tourniquet[1] (SWAT-T™; H&H Medical Corp) “Ribbed Elastic Band” (Manufacture data not provided) Multipurpose Emergency “Israeli” Bandage (First Care Products, Jerusalem, Israel) Surgical Tubing[2] (Manufacture data not provided)
Friction	“Half Hitch” (Manufacture data not provided) Canvas Belt[3] (Manufacture data not provided) The One-Handed Tourniquet[1] (OHT; Hemodyne, Inc.)
Mechanical	“Ladderlock and Ratchet” (Manufacture data not provided) Ratcheting “Cargo Strap” (Manufacture data not provided) Self-Applied Tourniquet System[1] (SATS; Tactical Medical Solutions, LLC) Ratcheting Medical Tourniquet[1] (RMT; m2® inc.,) Last Resort Tourniquet (Hammerhead, LLC.)
Pneumatic	Pneumatic Tourniquet (Stryker® Single-Belly Pneumatic Tourniquet; Sustainability Solutions “Bladder Tourniquet” (Manufacture data not provided) Emergency Medical Tourniquet[1] (EMT; Delfi Medical Innovations, Inc) Sphygmomanometer (BP Cuff)[1] (Propper, Rankin Biomedical, Holly, MI; AllHeart, Louisiana, Missouri; Hokanson, Bellevue, Washington)
Windlass	Combat Application Tourniquet[1] (C-A-T®; North American Rescue Products Inc) “CT” Tourniquet (Manufacture data not provided) Improvised Russian Tourniquet[3] (wooden rod and cloth bandage) Special Operations Force Tactical Tourniquet[1] (SOFTT; Tactical Medical Solutions LLC) The Mechanical Advantage Tourniquet (Bio Cybernetics International) Windlass Tourniquet (Military Medical Equipment Research Institute; Tianjin, China) Tactical Mechanical Tourniquet1 (TMT; Alphapointe™)

[1] Different models and generations are pooled
[2] Different lengths and widths of tubing are pooled
[3] Different lengths of dowel and bandage are pooled

Table 4

Risk of Bias Assessment

Study	D1	D2	D3	D4	D5	D6	D7	Overall
Alterie et al., 2018	-	X	+	-	+	-	X	X
Beaven et al., 2017	X	X	+	X	+	+	+	X
Beaven et al., 2018	X	+	+	X	+	-	-	X
Beaven et al., 2021	X	-	+	X	+	+	+	X
Calkins et al., 2000	X	+	!	+	+	+	X	!
Childers et al., 2011	X	X	+	X	+	+	X	X
Guo et al., 2011	-	+	-	!	+	-	+	!
Heldenberg et al., 2015	X	X	-	+	+	+	X	X
Higgs et al., 2016	X	X	!	+	+	+	+	!
Jaffer et al., 2012	-	+	-	-	+	+	+	-
King et al., 2006	-	+	-	+	+	+	+	-
Kragh et al., 2019	!	X	-	+	+	-	-	X
Martinez et al., 2018	X	-	-	-	+	+	+	X
Peponis et al., 2016	!	X	+	-	+	+	-	!
Sanak, 2017	X	X	+	+	+	+	-	X
Savage et al., 2013	X	-	-	+	+	-	-	X
Schreckengaust et al., 2014	!	+	+	+	+	-	+	!
Slaven et al., 2015	X	X	+	-	+	-	-	X
Swan et al., 2009	X	?	-	+	+	+	X	X
Taylor et al., 2011	X	X	+	+	+	+	+	X
Ünlü et al., 2015	-	+	+	+	+	+	+	-
Ünlü et al., 2017	X	X	+	-	+	+	+	X
Vuillemin et al., 2018	X	+	-	+	+	+	+	X
Wall, Buising, Grulke, et al., 2017	-	X	+	-	+	+	+	X
Wall, Buising, Nelms, et al., 2017	-	X	+	-	+	-	-	X
Wall et al., 2013	-	X	+	-	+	-	+	X
Wall et al., 2014	-	X	+	!	+	+	+	!
Wall et al., 2015	-	X	+	-	+	+	+	X
Wall et al., 2016	X	X	+	-	+	+	+	X
Wall et al., 2019	X	+	+	-	+	+	-	X
Wall et al., 2020	X	+	+	-	+	+	+	X
Wall, Welander, Sahr, et al., 2012	-	+	+	+	+	-	-	-
Wall, Welander, Singh, et al., 2012	-	X	+	-	+	+	-	X
Walters et al., 2005	-	?	+	-	+	-	X	X
Wenke et al., 2005	X	?	+	+	+	+	X	X
Weppner et al., 2013	-	X	+	-	+	+	+	X

Domains:
D1: Bias due to confounding.
D2: Bias due to selection of participants.
D3: Bias in classification of interventions.
D4: Bias due to deviations from intended interventions.
D5: Bias due to missing data.
D6: Bias in measurement of outcomes.
D7: Bias in selection of the reported result.

Judgement
! Critical
X Serious
- Moderate
+ Low
? No information

Twelve studies placed tourniquets directly on skin, 11 placed tourniquets over clothing, and eight studies did not report this data. Researchers applied tourniquets in 13 studies, participants applied tourniquets in 20 of the studies, and in two studies tourniquets were applied by both. Of the studies where participants applied the tourniquets, four did not report on either participant training or experience level.

Tourniquet application data

Initial arterial occlusion measurement

Arterial occlusion was measured immediately after tourniquet placement in all 14 studies, except for one study which delayed initial assessment for 60 seconds (Wall et al., 2016). There were nine studies that monitored to ensure that hemostasis was maintained: these repeated measures were taken at 30 seconds (Childers et al., 2011), 60 seconds (Swan et al., 2009; Wall et al., 2013; Wall, Welander, Sahr, et al., 2012; Wall, Welander, Singh, et al., 2012), 90 seconds (Peponis et al., 2016), and 120 seconds (Wall, Buising, Nelms, et al., 2017; Wall et al., 2015, 2016). The most common method for assessing hemostasis was using doppler ultrasound (Table 2). The most common location to assess for mid-thigh applications was the dorsal pedal artery and the most common location to assess upper extremity placement was at the radial artery (Supplement 3). In 19 studies the application of the tourniquet was guided by ultrasound (the device was tightened until obliteration of pulses) (Supplement 3).

Initial hemostasis was achieved in 88% of mid-thigh applications (CI = 0.78–0.94, $p < 0.01$), and 95% of upper extremity placements (CI = 0.89–0.98, $p = 0.02$) although we were unable to pool results by tourniquet design in either group due to heterogeneity. For the mid-thigh applications there was significant within-group variability (I^2 = 85–99%) and between-group heterogeneity ($I^2 = 98\%$, $p < 0.01$) (Figure 2). For arm applications there was also significant within-group heterogeneity (I^2 = 0–96%); between-group heterogeneity was more moderate (I^2 = 33%), but failed to achieve statistical significance ($p = 0.06$) (Figure 3). In light of the heterogeneity no between-group pooling was attempted and we are unable to determine if there is any significant difference in the rates of arterial occlusion by device.

Speed and ease of application

Although speed of application was reported in 19 studies (Table 1), there are significant differences in how speed was determined. Start time definitions varied: from the beginning of a clinical scenario (to examine delays due to uniform design) (Higgs et al., 2016; Martinez et al., 2018), or beginning of the device application (Guo et al., 2011). End time definitions were defined as: when the provider was satisfied with device placement (Guo et al., 2011), or as devise the point when final corrections were made to improperly tensioned device placements (Unlu et al., 2017). Due to the considerable heterogeneity, there was no attempt made to pool the results.

Figure 2

Hemostasis Rates for Tourniquets Applied at Mid-Thigh

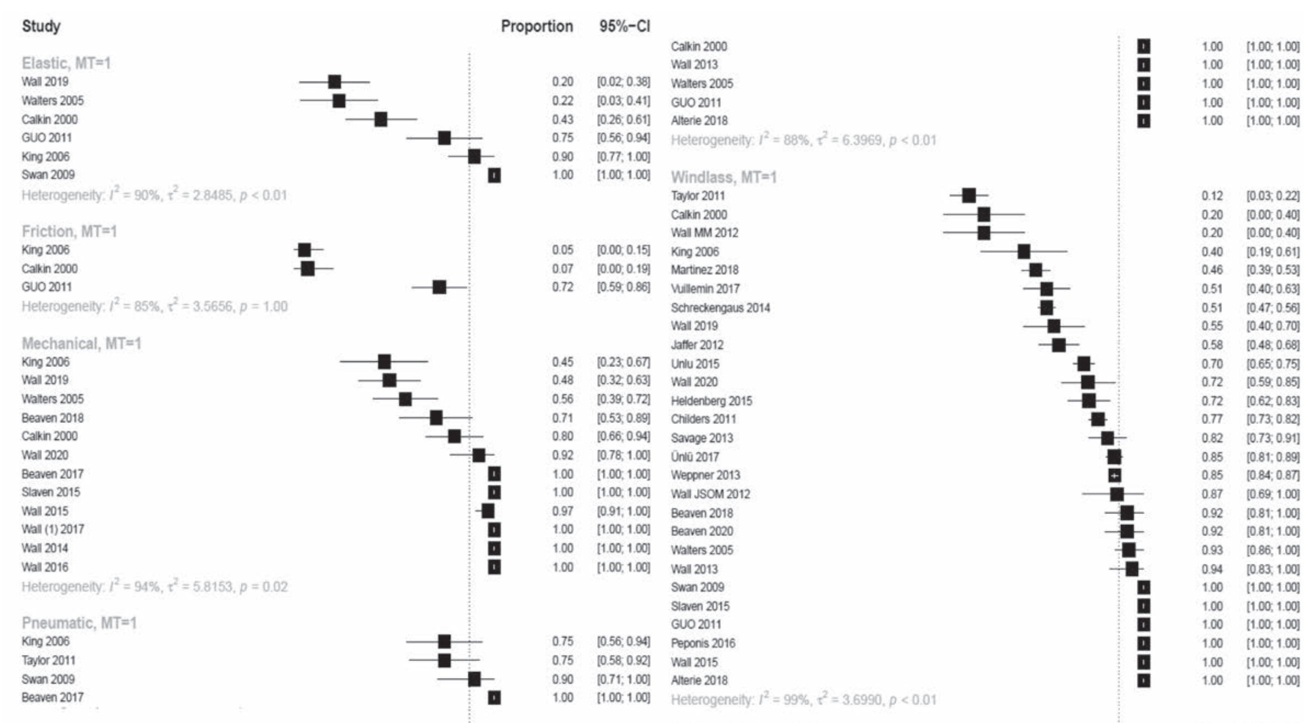
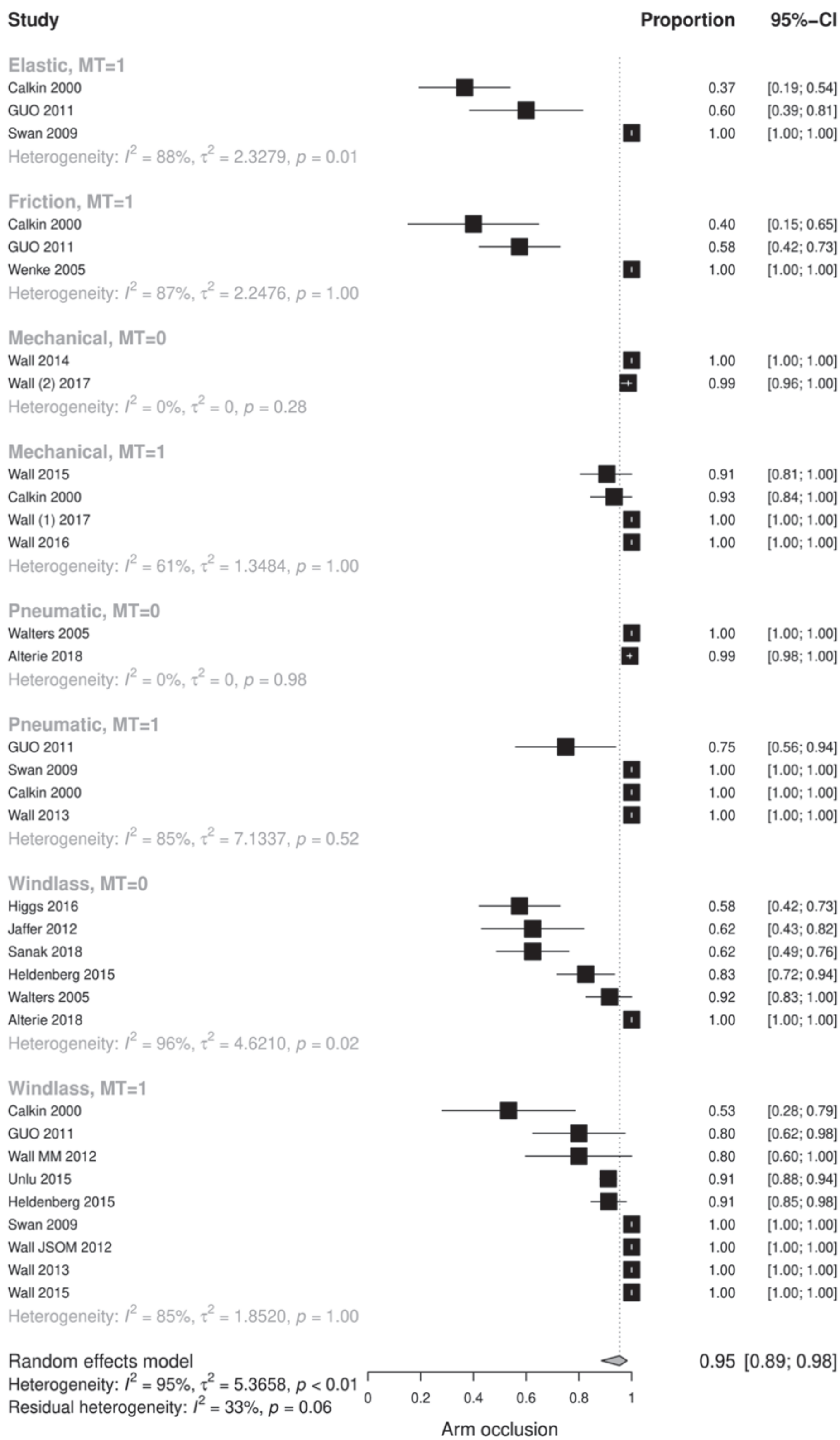


Figure 3

Hemostasis for Tourniquets Placed on the Arm



Note: "MT=0"-Non-mid-thigh application; "MT=1"-Mid-thigh application

Ease of application was examined in a minority ($n = 8$) of studies (Table 1). When studies are examined individually application difficulty ranged between 2.05 and 9.83 (on a 0–10 scale) (Figure 4); however, due to the significant heterogeneity in the studies (within group, $I^2 = 66–98\%$; between group, $I^2 = 99\%$, $p < 0.01$) we were unable to pool results by tourniquet design or comment on whether or not there is any device superiority (Figure 4).

Patient tolerance

21 studies assessed the pain levels associated with tourniquet application (Table 1). There range of reported pain varied from 0.75 to 6.60 (on a 0–10 scale) for individual studies (Figure 3). Pain scores varied dramatically between studies for similar tourniquet designs. There was significant study heterogeneity both within groups ($I^2 = 73–98\%$) and between groups ($I^2 = 98\%$) so further pooling was not attempted (Figure 5), as such we cannot make recommendations on the most tolerable design.

Training received

There was some level of training to apply tourniquets discussed in all but two included studies (Walters et al., 2005; Wenke et al., 2005). Training ranged from timed sessions with provider practice until comfort was achieved (Guo et al., 2011), to simply providing product instructions for use (Savage et al., 2013), and at worst some cases included remedial training (Martinez et al., 2018; Wall, Welander, Singh, et al., 2012). Baseline training may have influenced the training standards and providers ranged in skill from unskilled novices (Unlu et al., 2015) to experienced combat pre-hospital providers "medics" (Savage et al., 2013) or research staff. However, only one study attempted to correlate provider training, experience, and education level with the ability to correctly place tourniquets (Vuillemin et al., 2018).

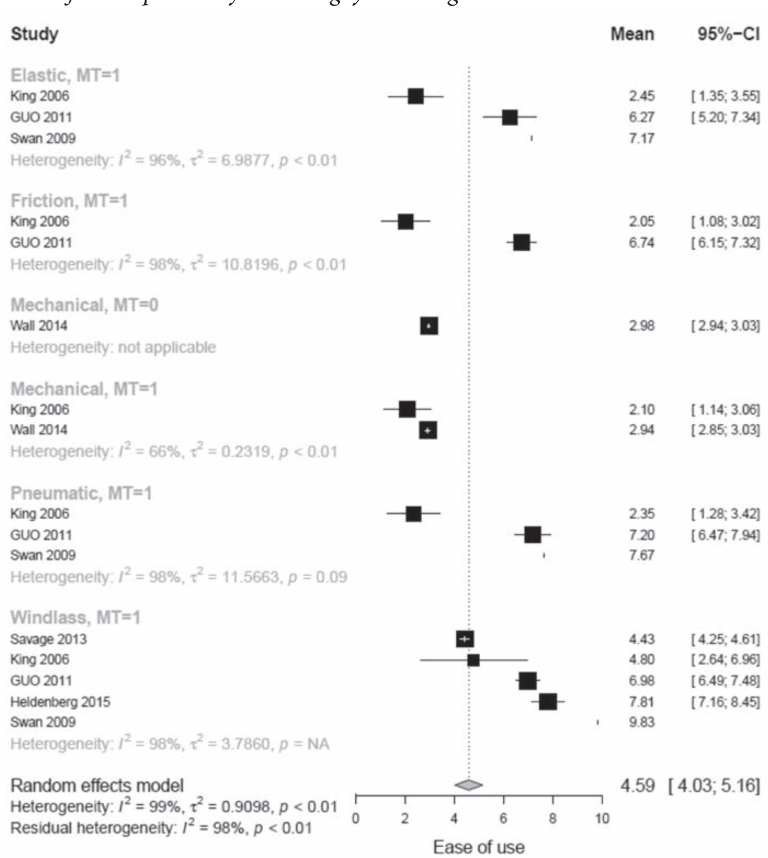
Other standardized data reported

Other standardized data that were collected included provider empathy scores (Vuillemin et al., 2018); items from a novel skill performance tools (Martinez et al., 2018); whether the device was applied directly to skin, normal uniform material, or heavier personal protective equipment (Supplement 3). The most commonly reported additional standardized data were the amount of mechanical advantage required, the frequency of device breakage, and the final pressure applied beneath the tourniquet devices (Table 2).

Advantage (Degree of mechanical advantage). Advantage was quantified as total degrees (or turns) of the windlass, number of wraps for elastic, tooth advances for mechanical devices, and inflation pressure for pneumatic devices (Supplement 3). There was significant variation in how authors defined the mechanism action with some devices such as windlass and elastic tourniquets needing significant movement (180 degree wraps or turns) between each increment, while others could be adjusted in

Figure 4

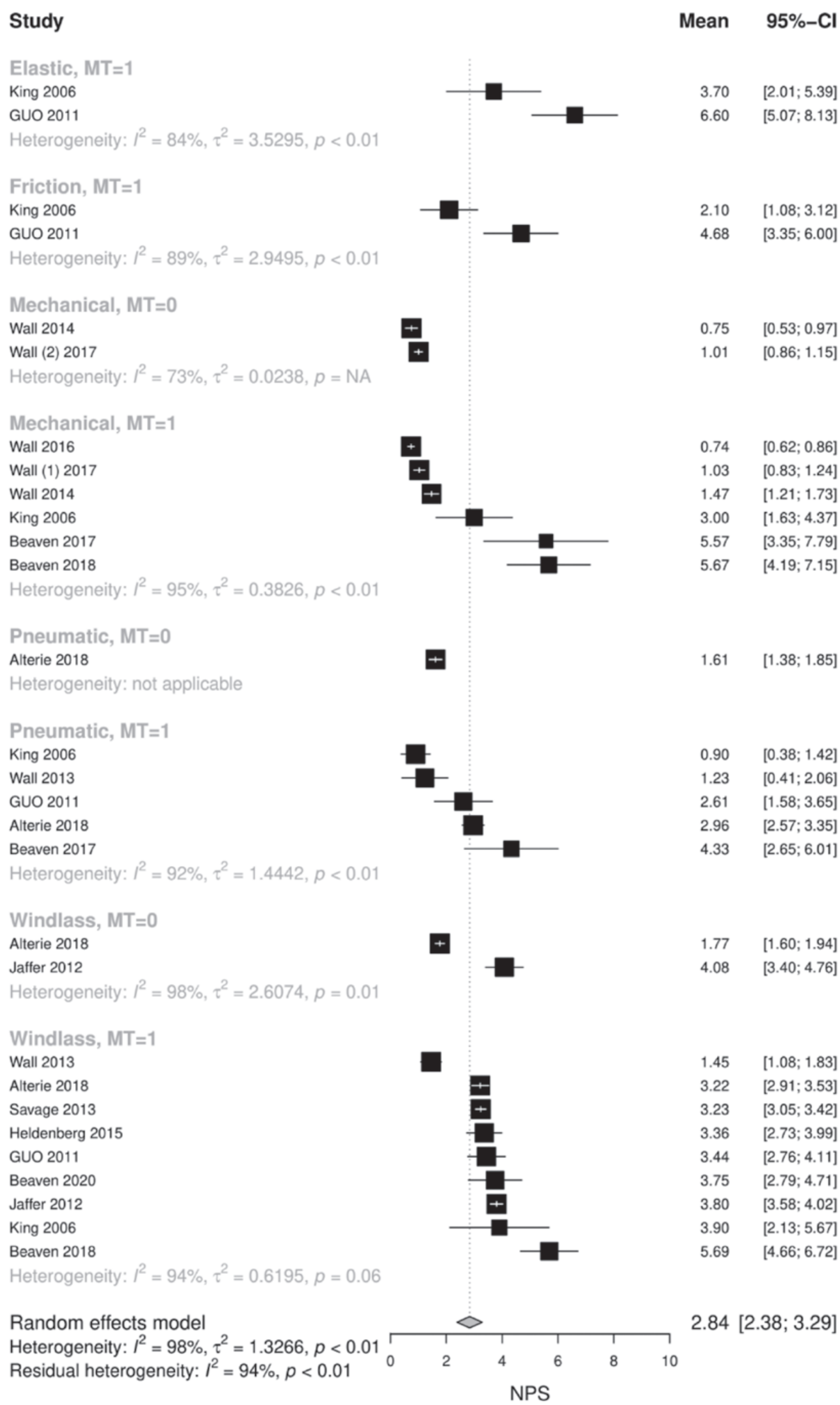
Ease of tourniquet use by tensioning system design



Note: "MT=0"-Non-mid-thigh application; "MT=1"-Mid-thigh application

Figure 5

Pain score according to tourniquet tensioning system



Note: “MT=0”-Non-mid-thigh application; “MT=1”-Mid-thigh application much smaller increments (ladder lock and pneumatic devices). Furthermore, the total amount of mechanism action may have been significantly affected by initial tensioning pressure.

Breakage or device failures. Failures were noted in 8 studies. Device failures included mechanical teeth skipping (Wall et al., 2015); windlass, strap or baseplate failure (Beaven et al., 2021) biological, radiological or nuclear (CBRN, or extensive device deformation (Slaven et al., 2015)50, 75, 100, 125, 150, 175 (CAT only. Failure rates were not compared because some devices were used extensively (Slaven et al., 2015) 50, 75, 100, 125, 150, 175 (CAT only, exposed to environmental degradation (Childers et al., 2011; Weppner et al., 2013)1st Battalion, 6th Marines reported a 10% (10/92, and while both of these conditions significantly increased the likelihood of failure, they were not consistently reported in the literature.

Skin surface pressure. Below tourniquet pressure was examined in 8 studies (Table 1). In all 8 studies pressure measurements were made using pneumatic cuffs (Supplement 3) placed under the device. Although the results were not pooled for meta-analysis included studies found that occlusion pressured were not adversely affected by initial tensioning pressure (Slaven et al., 2015) 50, 75, 100, 125, 150, 175 (CAT only, and that uniformly windlass tourniquets had the highest occlusion pressures. Sub-tourniquet tissue pressures have been linked to complication rates in the surgical literature (Mohler et al., 1999; Ochoa et al., 1972) and with the heterogeneity noted in the literature reviewed, this is likely a compelling area for further review in patients who receive emergency tourniquets.

Quality assessment

We evaluated the risk of bias in all 36 studies using the Cochrane Risk Of Bias In Non-Randomized Studies of Interventions (ROBINS-I) tool (Sterne et al., 2016). Overall, the certainty of the evidence was judged to be very low to moderate across all outcomes (Supplement 4) due to a lack of random sequence generation in randomized studies (selection bias), a lack of allocation concealment in non-cross over trials (selection bias), and the inability to blind participants and outcome assessors (performance and detection bias). Despite the large degree of homogeneity in the study populations, there were both skew and heterogeneity noted in the published studies suggesting that there may have been systematic bias towards an under reporting of pain (potentially due to attrition bias) and wide heterogeneity in the collection of ease-of-use outcomes (Supplement 5).

Discussion

Included studies

This review was mostly of low quality pre-clinical studies with wide variations in their samples, study designs, and data collection parameters. Although there have been data collection recommendations in place since the 2010 Quantico Tourniquet Summit (Tourniquet working group, 2010), these are not widely followed. Previous authors who have reviewed tourniquet use have called for data registries (Kauvar et al., 2018) to address discrepancies in data reporting. We would add that authors should consider using reporting guidelines (Reeves & Gaus, 2004) and formalization of data collection recommendations through consensus with civilian and military stakeholders to determine tourniquet specific reporting items are needed.

Participant data

There were significant differences in the degree of training received between groups who applied tourniquets. Within studies that compared providers with different skill levels, higher skilled providers ("medics") tended to have higher tourniquet application success than lower skilled providers (soldiers) (Heldenberg et al., 2015). Likewise, time from the last training session and having received additional training (Martinez eat al., 2018; Wall, Welander, Singh, et al., 2012) Wrap, and Tuck Tourniquet (SWAT-T also seemed to improve tourniquet application success. Baseline skill and training may have contributed significantly to overall placement success and limit the degree of internal comparability for included studies.

There is both an over-representation of men and an under-collecting of baseline anthropometric data in the included studies. As baseline blood pressure increases so too would the required tourniquet pressure needed to interrupt that flow. Additionally, previous research suggests that increasing muscle mass (Wall et al., 2016) 5.1cm-wide, and side-by-side-3.8cm-wide non-elastic strap-based tourniquets.MethodsRatcheting Medical Tourniquets (RMT and limb circumference (Shaw & Murray, 1982) may decrease tourniquet effectiveness. The lack of limb circumference and blood pressure data limits the degree to which these data can be compared internally. The over-representation of men in the sample may limit the degree of external generalizability to civilian settings.

Device data

There were differences not only in the generation of devices used, but also in the number of times that a device was used. Some studies reported that devices had never been used (Childers et al., 2011), other studies used devices that had been used extensively (over one hundred previous applications) (Wall et al., 2020) or times prior to the study and these device experience? differences may have affected performance. Previous research has shown that repeated use of windlass style tourniquets may result in internal band stretch and decreased efficiency (Polston et al., 2013), as well as increased device breakage rates. Some of the improvised devices may have been limited by having been of an inadequate size: Guo et al (2011) used latex tubing lengths that were significantly shorter (50cm versus 150cm) than what was used in other studies (King et al., 2006) and blood pressure cuff inflation targets (50mmHg) that are much lower than an expected systolic blood pressure in a healthy participant. Additionally, for those studies that did assess improvised tourniquets there may have been considerable difference in the quality of construction materials but not all studies specified the materials used.

Measuring arterial occlusion

Although there is some consensus that doppler assessment should be the standard method (TNCC updates 2010), there were differences in location, timing, and methods for determining cessation. Studies used various locations for assessing pulses

(Supplement 3), used more examinations with higher predictive levels (ex: palpation versus color or flow ultrasound) which could falsely skew the results. Additionally, delayed assessment could result in artificially high failure rates given that there is an anticipated and predictable loosening of the tourniquets either though device slippage and leak or through muscle relaxation (Wall et al., 2016).

Speed and ease of application

Although speed of placement is certainly a concern in clinical practice there was a high degree of inconsistency in how this was evaluated between studies. Differences in determining start (Wall et al., 2016) and stop times (Childers et al., 2016; Swan et al., Peponis et al., 2016; Wall et al., 2016), differences in tourniquet accessibility (Higgs et al., 2016; Martinez et al., 2018), or application technique (ex: one-handed) would all have significant impacts on the speed and ease of application.

Patient tolerance

While many studies discussed pain during tourniquet application, most discussed this as an unavoidable complication, and one that would be of less concern given the "life-or-limb" scenario typically present in injuries requiring tourniquet for hemorrhage control. Framing the discussion as life over limb (and suffering), however, fails to acknowledge that in pre-clinical research the severe pain (inability to tighten due to pain) was a failure criteria for many studies (Beaven et al., 2017, 2018, 2021; Swan et al., 2009; Wall et al., 2013; Wenke et al., 2005)we measured the effects of three common tourniquets on arterial pulses (Doppler signals. These pre-clinical failures are telling and suggest that there is likely a meaningful clinical consequence to not attending to discomfort. Indeed, in a study that compared guided versus unguided applications of windlass tourniquets the authors noted that applications guided by ultrasound had not only higher occlusion rates, but also significantly higher pain scores (Jaffer et al., 2012). The relationship between pain and occlusion rates may negatively affect success if severe pain may become a barrier for patients and providers. Indeed, this was the case in one of the trials which noted that participants with the highest empathy scores also tended to have the lowest initial success rates with tourniquet application (Vuillemin et al., 2018)and tourniquet application is one of the most critical lifesaving interventions on the battlefield. However, previous studies have shown high failure rates in tourniquet application. Our study aimed to assess the correlation between personality traits that may interfere with effective tourniquet application in a simulated extremity hemorrhage. Materials:Seventy-two French soldiers, previously trained to forward combat casualty care, were evaluated by self-administered questionnaires and submitted to the simulation in group of six. We focused on measuring the empathic personality of the subjects, their peer-to-peer relationships (altruism. The relationship between patient tolerance and tourniquet success is likely under-studied and pain should be included as a standardized data collection point in future research.

Practically speaking, when faced with life-threatening extremity hemorrhage, the best tourniquet is the one that is available to the rescuer. However, for decision-makers and individuals determining which device to obtain and train with, the choice of device can be a challenge. This review and meta-analysis challenges conventional wisdom. For over twenty years the windlass style devices, optimized for one-handed application and care-under-fire scenarios have emerged as the industry standard, despite evidence they may take longer to apply and have a higher failed application rate. For resource limited and space limited settings, the use of a multi-purpose device such as a manual blood pressure cuff may be the best device, as long as potential rescuers train how to use the device for this purpose. For two handed civilian application, elastic devices may be superior.

Limitations

As described above, our systematic review and meta-analysis was challenged by significant methodological and clinical heterogeneity among the included studies. Various tourniquet devices were used, devices were not applied or evaluated consistently, significant data transformation was required, all of which increased heterogeneity. Study quality varied and it is questionable whether evidence provided by healthy volunteer studies can be applied to life-threatening hemorrhage scenarios. Grouping of devices regardless of production model may have influenced results, likewise there may have been differences between individual devices within similar advantage categories that are not fully captured in our analysis.

Conclusion

We searched six databases to inform our meta-analysis of commercial and improvised hemorrhage control tourniquet device effectiveness for three outcomes of interest: arterial occlusion, application speed, and patient tolerance. Data from 23 unique devices, 8205 applications and 1921 subjects were analyzed. Four main device types were identified: windlass, mechanical, pneumatic, and friction. Pooled results studies favoured pneumatic and mechanical tourniquet devices for effectiveness of arterial occlusions. Due to methodological heterogeneity, we could not conclude with certainty which devices were reliably the fastest to apply. There was some signal from the included studies that simple mechanical devices were the easiest to apply and windlass were the most difficult. The most painful tourniquets were device utilizing elastic tensioning systems, the least painful tensioning systems were mechanical. We recommend the adoption of a minimum dataset, agreed upon definitions for testable metrics, and a standardized experimental design (with randomization) to improve the comparability and quality of future tourniquet device studies.

Implications for emergency nursing practice

1. Tourniquets are commonly used but the data comparing individual devices comes from pre-clinical studies and these are of generally poor quality and cannot easily be compared.
2. Practice guidelines that call for specific designs of tourniquet may not be based on patient-specific outcome measures or from between-device comparisons
3. Further research is needed to create a standardized method for assessing and reporting data elements in pre-clinical tourniquet device comparison studies.

About the authors

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Conflicts of Interest

None

Credit statement

Christopher Picard: Conceptualization, methodology, investigation, data curation, writing – original draft, writing – reviewing and editing, visualization, project administration.

Domhnall O'Dochartaigh: Investigation, writing – original draft, writing – reviewing and editing,

Jeffrey Bakal: Resources, writing – original draft, writing – Reviewing and editing, supervision.

Majid Nabipoor: Methodology, software, validation, formal analysis, writing – original draft, writing – reviewing and editing.

Janice Kung: Methodology, validation, Investigation, writing – original draft, writing – reviewing and editing.

Matthew Douma: Conceptualization, methodology, investigation, writing – original draft, writing- reviewing and editing, supervision.

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Supplement 1

Database Search Strategies

Database	Search
MEDLINE Ovid MEDLINE(R) ALL 1946 to June 6, 2021	1. Tourniquets/ 2. tourniquet*.ti,ab,kf. 3. Rhys*.ti,ab,kf. or cuff*.ti. 4. Hemostatic Techniques/is [Instrumentation] 5. Lofquist.ti,ab,kf. 6. Esmarch*.ti,ab,kf. 7. or/1-6 [Tourniquet] 8. exp HEMORRHAGE/pc, th [Prevention & Control, Therapy] 9. h?emorrhag*.ti,ab,kf. 10. ((blood* or bleed* or artery or arterial) adj2 (loss* or lose* or losing or flow* or stop* or occlud* or occlusion* or control*)).ti,ab,kf. 11. (hemoglobin adj2 (loss* or lose* or losing or flow* or stop* or occlud* or occlusion* or control*)).ti,ab,kf. 12. Shock, Hemorrhagic/th [Therapy] 13. military.nw. or Journal of Special Operations Medicine.jn. 14. exp Military Personnel/ 15. combat.ti,ab,kf. 16. (soldier* or sailor* or air men or air man or airmen or airman or armed forces or air force or military or naval or (navy not bean*) or coast guard* or submariner* or infantry* or marine corps or marines or army or special forces or warfight* or improvised explosive device* or warefare or land mine* or machine gun* or artillery or schrapnel or battlefield* or grenades or (grenade not (Spain or Carribbean)) or regimental or battalion*).ti,ab,kf. 17. exp Naval Medicine/ 18. exp Military Medicine/ 19. or/8-18 [Hemorrhage control] 20. 7 and 19 21. animals/ 22. humans/ 23. 21 not (21 and 22) 24. (rat or rats or mouse or mice or rodent* or porcine or swine).mp. 25. 23 or 24 [Animal studies] 26. 20 not 25 [Tourniquet Hemorrhage control Not Animal Studies] 27. remove duplicates from 26
Embase Ovid Embase 1974 to 2021 June 6	1. exp tourniquet/ 2. tourniquet*.ti,ab,kw. 3. Rhys*.ti,ab,kw. or cuff*.ti. 4. hemostatic technique/ 5. Lofquist.ti,ab,kw. 6. Esmarch*.ti,ab,kw. 7. or/1-6 [Tourniquet] 8. exp bleeding/pc, th [Prevention, Therapy] 9. h?emorrhag*.ti,ab,kw. 10. ((blood* or bleed* or artery or arterial) adj2 (loss* or lose* or losing or flow* or stop* or occlud* or occlusion* or control*)).ti,ab,kw. 11. (hemoglobin adj2 (loss* or lose* or losing or flow* or stop* or occlud* or occlusion* or control*)).ti,ab,kw. 12. hemorrhagic shock/th [Therapy] 13. military.jx. or Journal of Special Operations Medicine.jn. 14. exp soldier/ 15. combat.ti,ab,kw. 16. (soldier* or sailor* or air men or air man or airmen or airman or armed forces or air force or military or naval or (navy not bean*) or coast guard* or submariner* or infantry* or marine corps or marines or army or special forces or warfight* or improvised explosive device* or warefare or land mine* or machine gun* or artillery or schrapnel or battlefield* or grenades or (grenade not (Spain or Carribbean)) or regimental or battalion*).ti,ab,kw. 17. exp military research/ 18. exp military medicine/ 19. or/8-18 [Hemorrhage control] 20. 7 and 19 21. animal/ 22. human/ 23. 21 not (21 and 22) 24. (rat or rats or mouse or mice or rodent* or porcine or swine).mp. 25. 23 or 24 [Animal studies] 26. 20 not 25 [Tourniquet Hemorrhage control Not Animal Studies] 27. remove duplicates from 26

continued…

CINAHL	S1	(MH "Tourniquets")
	S2	TI tourniquet* OR AB tourniquet*
	S3	TI Rhys* OR AB Rhys* OR TI cuff*
	S4	(MH "Hemostatic Techniques+/MT/UT")
	S5	TI Lofquist OR AB Lofquist
	S6	TI Esmarch* OR AB Esmarch*
	S7	S1 OR S2 OR S3 OR S4 OR S5 OR S6
	S8	(MH "Hemorrhage+/PC/TH")
	S9	TI (h#emorrhage or h#emorrhages or h#emorrhagic or h#emorrhaging) OR AB (h#emorrhage or h#emorrhages or h#emorrhagic or h#emorrhaging)
	S10	TI (((blood* or bleed* or artery or arterial) N2 (loss* or lose* or losing or flow* or stop* or occlud* or occlusion* or control*))) OR AB (((blood* or bleed* or artery or arterial) N2 (loss* or lose* or losing or flow* or stop* or occlud* or occlusion* or control*)))
	S11	TI ((hemoglobin N2 (loss* or lose* or losing or flow* or stop* or occlud* or occlusion* or control*))) OR AB ((hemoglobin N2 (loss* or lose* or losing or flow* or stop* or occlud* or occlusion* or control*)))
	S12	(MH "Shock, Hemorrhagic/TH")
	S13	SO military
	S14	(MH "Military Personnel+")
	S15	TI combat OR AB combat
	S16	TI ((soldier* or sailor* or air men or air man or airmen or airman or armed forces or air force or military or naval or (navy not bean*) or coast guard* or submariner* or infantry* or marine corps or marines or army or special forces or warfight* or improvised explosive device* or warefare or land mine* or machine gun* or artillery or schrapnel or battlefield* or grenades or (grenade not (Spain or Carribbean)) or regimental or battalion*)) OR AB ((soldier* or sailor* or air men or air man or airmen or airman or armed forces or air force or military or naval or (navy not bean*) or coast guard* or submariner* or infantry* or marine corps or marines or army or special forces or warfight* or improvised explosive device* or warefare or land mine* or machine gun* or artillery or schrapnel or battlefield* or grenades or (grenade not (Spain or Carribbean)) or regimental or battalion*))
	S17	(MH "Military Medicine")
	S18	S8 OR S9 OR S10 OR S11 OR S12 OR S13 OR S14 OR S15 OR S16 OR S17
	S19	(MH "Animals+")
	S20	(MH "Human")
	S21	S19 AND S20
	S22	S19 not S21
	S23	TI (rat or rats or mouse or mice or rodent* or porcine or swine) OR AB (rat or rats or mouse or mice or rodent* or porcine or swine)
	S24	S22 OR S23
	S25	S7 AND S18
	S26	S25 NOT S24
SPORTDiscus	S1	TI tourniquet* OR AB tourniquet*
	S2	TI Rhys* OR AB Rhys* OR TI cuff*
	S3	TI Esmarch* OR AB Esmarch*
	S4	S1 OR S2 OR S3
	S5	DE "HEMORRHAGE"
	S6	TI (h#emorrhage or h#emorrhages or h#emorrhagic or h#emorrhaging) OR AB (h#emorrhage or h#emorrhages or h#emorrhagic or h#emorrhaging)
	S7	TI (((blood* or bleed* or artery or arterial) N2 (loss* or lose* or losing or flow* or stop* or occlud* or occlusion* or control*))) OR AB (((blood* or bleed* or artery or arterial) N2 (loss* or lose* or losing or flow* or stop* or occlud* or occlusion* or control*)))
	S8	TI ((hemoglobin N2 (loss* or lose* or losing or flow* or stop* or occlud* or occlusion* or control*))) OR AB ((hemoglobin N2 (loss* or lose* or losing or flow* or stop* or occlud* or occlusion* or control*)))
	S9	SO military
	S10	TI combat OR AB combat
	S11	TI ((soldier* or sailor* or air men or air man or airmen or airman or armed forces or air force or military or naval or (navy not bean*) or coast guard* or submariner* or infantry* or marine corps or marines or army or special forces or warfight* or improvised explosive device* or warefare or land mine* or machine gun* or artillery or schrapnel or battlefield* or grenades or (grenade not (Spain or Carribbean)) or regimental or battalion*)) OR AB ((soldier* or sailor* or air men or air man or airmen or airman or armed forces or air force or military or naval or (navy not bean*) or coast guard* or submariner* or infantry* or marine corps or marines or army or special forces or warfight* or improvised explosive device* or warefare or land mine* or machine gun* or artillery or schrapnel or battlefield* or grenades or (grenade not (Spain or Carribbean)) or regimental or battalion*))
	S12	S5 OR S6 OR S7 OR S8 OR S9 OR S10 OR S11
	S13	S4 AND S12

continued…

Cochrane Library	#1	MeSH descriptor: [Tourniquets] explode all trees
	#2	tourniquet*:ti,ab,kw
	#3	Rhys*:ti,ab,kw
Via Wiley	#4	cuff*:ti
	#5	[mh "Hemostatic Techniques"/is]
	#6	Lofquist:ti,ab,kw
	#7	Esmarch*:ti,ab,kw
	#8	#1 or #2 or #3 or #4 or #5 or #6 or #7
	#9	[mh hemorrhage/pc,th]
	#10	h*emorrhag*:ti,ab,kw
	#11	((blood* or bleed* or artery or arterial) near/2 (loss* or lose* or losing or flow* or stop* or occlud* or occlusion* or control*)):ti,ab,kw
	#12	(hemoglobin near/2 (loss* or lose* or losing or flow* or stop* or occlud* or occlusion* or control*)):ti,ab,kw
	#13	[mh "Shock, Hemorrhagic"/th]
	#14	MeSH descriptor: [Military Personnel] explode all trees
	#15	combat:ti,ab,kw
	#16	(soldier* or sailor* or air men or air man or airmen or airman or armed forces or air force or military or naval or (navy not bean*) or coast guard* or submariner* or infantry* or marine corps or marines or army or special forces or warfight* or improvised explosive device* or warefare or land mine* or machine gun* or artillery or schrapnel or battlefield* or grenades or (grenade not (Spain or Carribbean)) or regimental or battalion*):ti,ab,kw
	#17	MeSH descriptor: [Naval Medicine] explode all trees
	#18	MeSH descriptor: [Military Medicine] explode all trees
	#19	#9 or #10 or #11 or #12 or #13 or #14 or #15 or #16 or #17 or #18
	#20	#8 and #19
	#21	MeSH descriptor: [Animals] explode all trees
	#22	MeSH descriptor: [Humans] explode all trees
	#23	#21 not (#21 and #22)
	#24	rat or rats or mouse or mice or rodent* or porcine or swine
	#25	#23 or #24
	#26	#20 not #25
ProQuest Dissertations & Theses Global	S1	ti(tourniquet*) OR ab(tourniquet*)
	S2	ti(Rhys*) OR ab(Rhys*) OR ti(cuff*)
	S3	ti(Esmarch*) OR ab(Esmarch*)
	S4	1 or 2 or 3
	S5	ti(h?emorrhag*) OR ab(h?emorrhag*)
	S6	ti(((blood* or bleed* or artery or arterial) near/2 (loss* or lose* or losing or flow* or stop* or occlud* or occlusion* or control*))) OR ab(((blood* or bleed* or artery or arterial) near/2 (loss* or lose* or losing or flow* or stop* or occlud* or occlusion* or control*)))
	S7	ti((hemoglobin near/2 (loss* or lose* or losing or flow* or stop* or occlud* or occlusion* or control*))) OR ab((hemoglobin near/2 (loss* or lose* or losing or flow* or stop* or occlud* or occlusion* or control*)))
	S8	ti(combat) OR ab(combat)
	S9	ti((soldier* or sailor* or air men or air man or airmen or airman or armed forces or air force or military or naval or (navy not bean*) or coast guard* or submariner* or infantry* or marine corps or marines or army or special forces or warfight* or improvised explosive device* or warefare or land mine* or machine gun* or artillery or schrapnel or battlefield* or grenades or (grenade not (Spain or Carribbean)) or regimental or battalion*)) OR ab((soldier* or sailor* or air men or air man or airmen or airman or armed forces or air force or military or naval or (navy not bean*) or coast guard* or submariner* or infantry* or marine corps or marines or army or special forces or warfight* or improvised explosive device* or warefare or land mine* or machine gun* or artillery or schrapnel or battlefield* or grenades or (grenade not (Spain or Carribbean)) or regimental or battalion*))
	S10	5 or 6 or 7 or 8 or 9
	S11	4 and 10

Supplement 2

Statistical analysis notes

1- Body Mass Index (BMI) is reported in some papers instead of weight and height. We calculated BMI for reported weights and heights, BMI = weight (kg) / height^2 (m). Let X = weight and Y = height, $= \frac{X}{Y^2}$, and suppose $Y \sim N(\mu_Y, \sigma_Y^2)$, then $Y^2 \sim \sigma_Y^2 \chi^2\left(\frac{\mu_Y^2}{\sigma_Y^2}\right)$, then $\mu_{Y^2} = \mu_Y^2 + \sigma_Y^2$ and $\sigma_{Y^2}^2 = 2\sigma_Y^4 + 4\mu_Y^2\sigma_Y^2$, therefore an approximate variance by delta method is $var\left(\frac{X}{Y^2}\right) = \left(\frac{\mu_X}{\mu_{Y^2}}\right)^2\left(\frac{\sigma_X^2}{\mu_X^2} + \frac{\sigma_{Y^2}^2}{\mu_{Y^2}^2} - 2\frac{\sigma_X\sigma_{Y^2}\rho_{XY^2}}{\mu_X\mu_{Y^2}}\right)$ Approximation for var(X/Y) : http://www.stat.rice.edu/~dobelman/notes_papers/math/TaylorAppDeltaMethod.pdf.
approximation for X^2: http://personalpages.to.infn.it/~zaninett/pdf/statistical-distributions.pdf
We considered $\rho_{XY} = 0.32$.

2- Blood pressure is reported by SBP and DBP, however in some papers it is reported by MAP only, $MAP = \frac{1}{3} BBP + \frac{2}{3} SBP$. We used $\rho_{SBP,DBP} = 0.74$ to calculate related variance.
Correlation: https://pubmed.ncbi.nlm.nih.gov/18192832/

3- We combined groups like female and male, right or left arm or leg. For this combinations we used the following formulations from Cochrane hand book: "Cochrane Handbook for Systematic Reviews of Interventions"

	Group 1	Group 2	Combined groups
Size	N_1	N_2	N_1+N_2
Mean	M_1	M_2	$\frac{N_1M_1+N_2M_2}{N_1+N_2}$
SD	SD_1	SD_2	$\sqrt{\frac{(N_1-1)SD_1^2+(N_2-1)SD_2^2+\frac{N_1N_2}{N_1+N_2}(M_1^2+M_2^2-2M_1M_2)}{N_1+N_2-1}}$

4- Converting mean median IQR and Range to mean Median: Estimating the sample mean and standard deviation from commonly reported quantiles in meta-analysis, Statistical Methods in Medical Research, vol. 29, 9: pp. 2520-2537., First Published January 30, 2020.

5- In NPS for none-2, little-5, moderate-7, severe-10: we generated a vector of (0,0,1,1,1,1,1,2,2,2,2,2,2,3), then make average multiply by 10/3 to convert it to 0-10 scale. For SD again multiplied by 10/3. note that Var(aX)=a^{2}Var(X).

Supplement 3

Extended minimum data set

First author, year	Measure of advantage	Skin pressure measurement	Limb segment device was applied to	Clothing under tourniquet	Was application guided (Yes/No)	Pulse assessment location
Beaven et al., 2017	"Cuff pumps", Windlass turns	-	Upper Leg	None	Y	Popliteal
Beaven et al., 2018	-	-	Upper Leg	None	Y	Popliteal
Beaven et al., 2021	-	-	Upper Leg	Uniform and CBRN suit	Y	Popliteal
Calkins et al., 2000	-	-	Not specified	Not specified	N	Radial, dorsal pedal
Childers et al., 2011	Windlass turns	-	Upper Leg	Uniform	Y	Dorsal pedal
Guo et al., 2011	-	-	Upper arm*, upper leg*	-	N	Brachial, popliteal
Heldenberg et al., 2015	-	-	Upper arm, upper leg	-	N	Radial, Ulnar, dorsal pedal, posterior tibial
Higgs et al., 2016	-	-	Upper arm	Uniform	N	Radial
Jaffer, 2012 (Jaffer et al., 2012)	-	-	Upper arm, upper leg	Skin	Y	Femoral
King, 2006 (King et al., 2006)	-	-	Upper Leg	uniform, Winter clothes	N	Dorsal pedal, posterior tibial
Kragh, 2019(Kragh et al., 2019)	-	-	Upper leg	-	N	Not assessed
Martinez, 2018 (Martinez et al., 2018)	-	-	Upper leg*	-	N	Popliteal
Peponis, 2016 (Peponis et al., 2016)	Inflation pressure, windlass turns (180)	-	Upper leg	Uniform, CBRN suit	Y	Dorsalis pedis, posterior tibial
Sanak, 2018 (Sanak, 2017)	-	-	Upper arm	Uniform	N	Radial
Savage, 2013 (Savage et al., 2013)	-	-	Upper arm, upper leg	Uniform, winter clothes	N	Not specified
Schreckengaust, 2014 (Schreckengaust et al., 2014)	-	-	Upper leg	Uniform	N	Dorsal pedal
Slaven, 2015 (Slaven et al., 2015)	Windlass turns, length of mechanical device remaining	mmHg	Upper leg	Skin	Y	Dorsal pedal
Swan, 2009 (Swan et al., 2009)	Inflation pressure	-	Upper arm, lower arm, upper leg, lower leg	-	Y	Radial, posterior tibial

continued…

First author, year	Measure of advantage	Skin pressure measurement	Limb segment device was applied to	Clothing under tourniquet	Was application guided (Yes/No)	Pulse assessment location
Taylor, 2011 (Taylor et al., 2011)	-	-	Upper leg	-	Y	Popliteal
Unlu, 2015 (Unlu et al., 2015)	Windlass degrees	-	Upper arm, upper leg	-	N	Radial, ulnar, popliteal
Vuillemin, 2017 (Vuillemin et al., 2018)	-	-	Upper leg	Uniform	N	Popliteal
Wall, 2017a (Wall, Buising, Grulke, et al., 2017)	-	mmHg	Upper arm, upper leg,	-	Y	Radial, posterior tibial
Wall, 2017b (Wall, Buising, Nelms, et al., 2017)	Tooth advances	mmHg	Upper leg	Skin	Y	Dorsal pedal, posterior tibial
Wall, 2013(Wall et al., 2013)	Inflation pressure, number of turns, number of wraps	mmHg	Upper arm, upper leg	Skin	Y	Radial, posterior tibial
Wall, 2014 (Wall et al., 2014)	Windlass turns, ladder length	mmHg	Upper arm, upper leg	Skin	Y	Radial, posterior tibial, dorsal pedal
Wall, 2015 (Wall et al., 2015)	Windlass turns, ladder length, wraps	mmHg	Lower arm, lower leg	skin	Y	Not specified
Wall, 2016 (Wall et al., 2016)	Tooth advances	mmHg	Upper arm, upper leg	Skin	Y	Not specified
Wall, 2019 (Wall et al., 2019)	-	mmHg		Upper leg	-	Y
Wall, 2020 (Wall et al., 2020)	Windlass turns, Tooth advances, wraps	mmHg	Upper leg	Clothing, skin, uniform	Y	Pedal
Wall, 2012a (Wall, Welander, Sahr, et al., 2012)	Visual inspection	-	Upper arm, lower arm, upper leg, lower leg	Skin	N	Radial, posterior tibial
Wall, 2012b (Wall, Welander, Singh, et al., 2012)	Visual assessment	-	Upper arm, lower arm, upper leg, lower leg	Skin	Y	Radial, posterior tibial
Walters, 2005 (Walters et al., 2005)	-	-	Upper arm, upper leg	Skin	Y	Radial, popliteal
Wenke, 2005 (Wenke et al., 2005)	-	-	Upper arm, upper leg	Clothing	N	Radial, popliteal, dorsal pedal
Weppner, 2013 (Weppner et al., 2013)	Number of turns	-	Upper leg	-	Y	Dorsal pedal
Unlu, 2017 (Unlu et al., 2017)	Number of turns	-	Upper leg	Uniform	Y	Popliteal

Supplement 4

Sub group analysis of tourniquets by mechanical advantage mechanism

	n	Proportion [95% CI]	I^2	Subgroup difference p-value
Mid-thigh=1				
Elastic	6	0.64[0.29; 0.89]	90%	
Friction	3	0.18[0.02; 0.69]	85%	
Mechanical	12	0.95[0.76; 0.99]	94%	
Pneumatic	9	0.99[0.84; 0.99]	88%	
Windlass	27	0.83[0.68; 0.91]	99%	
Mid-thigh=1				
Elastic	3	0.72[0.24; 0.95]	88%	
Friction	3	0.73[0.25; 0.95]	87%	
Mechanical	4	0.98[0.87; 0.99]	61%	
Pneumatic	4	0.99[0.31; 1.00]	85%	
Windlass	9	0.93[0.80; 0.98]	85%	
Mid-thigh=0				
Mechanical	2	0.99[0.94; 0.99]	0%	
Pneumatic	2	0.99[0.96; 0.99]	0%	
Windlass	6	0.88[0.54; 0.98]	96%	
Mid-thigh=1				
Elastic	2	4.36[0.62; 8.11]	96%	
Friction	2	4.41[0; 9.00]	99%	
Mechanical	2	2.66[1.89; 3.44]	66%	
Pneumatic	2	4.79[0.04; 9.55]	98%	
Windlass	4	6.07[4.09; 8.05]	98%	
Mid-thigh=0				
Mechanical	1	2.99[2.94; 3.03]	-	
Mid-thigh=1				
Elastic	2	5.17[2.33; 8.01]	84%	
Friction	2	3.35[0.83; 5.87]	89%	
Mechanical	6	2.01[1.40; 2.61]	95%	
Pneumatic	5	2.29[1.16; 3.43]	92%	
Windlass	9	3.44[2.87; 4.00]	94%	
Mid-thigh=0				
Mechanical	2	0.89[0.64; 1.14]	73%	
Pneumatic	1	1.62[1.38; 1.85]	-	
Windlass	2	2.90[0.64; 5.16]	98%	

Abbreviations: "Mid-Thigh=0"-non-mid-thigh application; "Mid-Thigh=1"-Mid-thigh application

Supplement 5

Funnel plot of meta-analyzed studies