A Comprehensive Pre-Fielding Framework for Combat Tourniquets: Model Development and Laboratory Evaluation

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Abstract

Background

Extremity hemorrhage remains a leading cause of preventable death in combat trauma, and tourniquets are central to Tactical Combat Casualty Care. Manual windlass tourniquets are effective but remain dependent on correct placement, adequate tightening, reassessment, and user skill. Emerging automatic tourniquet technologies may reduce operator dependence but require structured preclinical evaluation before operational use. This study aimed to develop and apply a requirements-driven biomedical engineering framework within the Israel Defense Forces Medical Corps to guide preclinical evaluation of emerging automatic combat tourniquet technologies.

Methods

The proposed framework linked operational requirements to engineering tests and staged release decisions. It integrated operational requirements, benchmarking against Combat Application Tourniquet (CAT) reference standards, architecture screening, simulator testing, surface pressure mapping, iterative refinement, and proposed manufacturing and release-readiness criteria.

Results

Ten reference CATs generated 280.4 ± 29.5 mmHg after four complete windlass turns and required 2.30 ± 0.48 180-degree turns to reach 200 mmHg (mean ± standard deviation). CAT calibration supported a standardized mid-thigh simulator application location. Prototype efficacy and production-lot acceptance are not established by the reported results.

Conclusions

Pre-fielding evaluation of automatic combat tourniquets should not rely on pressure generation alone. A staged requirements-driven framework that integrates operational requirements, reference benchmarking, simulator pressure testing, surface pressure mapping, usability considerations, and manufacturing readiness may support safer and more disciplined progression from prototype development to clinical validation and role-specific operational evaluation.

Keywords: Military Medicine; Casualty; Combat Application Tourniquets; Bleeding; Pre-hospital

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INTRODUCTION

Extremity hemorrhage remains one of the leading causes of preventable death on the battlefield [1,2]. Rapid hemorrhage control using extremity tourniquets has therefore become a central component of Tactical Combat Casualty Care doctrine and modern military prehospital medicine [1,3]. The Combat Application Tourniquet (CAT; C-A-T Resources, Rock Hill, SC, USA) is currently considered a standard individual tourniquet within many military organizations, including the Israel Defense Forces Medical Corps (IDF-MC). Combat evidence supports early tourniquet use, particularly when applied before shock develops [3-5].

At the same time, the operational success of a manual windlass tourniquet is not guaranteed. Effective CAT use requires correct placement, adequate strap pre-tightening, sufficient windlass torque, secure locking, and reassessment. Recent military medicine work continues to show substantial variability in CAT application performance [6]. IDF-published studies add relevant evidence: introduction of advanced tourniquets increased IDF tourniquet use rates from 5.5% to 22.8%, but user-dependent technique remained important [7]. A slack-reducing modification improved applied pressure and hemorrhage-control rate, supporting the broader point that design features can mitigate common application errors [8]. Other IDF studies have reported persistent nonmedical-user failure rates and gaps between confidence and competence despite training [9,10].

These observations highlight the need for a structured pre-fielding evaluation process for emerging tourniquet technologies. A combat tourniquet is not merely a compression device; it is an integrated biomedical engineering system that must achieve occlusion, maintain pressure, distribute load efficiently, tolerate harsh field conditions, support one-handed use, provide clear user feedback, remain manufacturable, and fit a defined operational role. Evaluation should therefore extend beyond whether a prototype can generate pressure under ideal conditions.

With the outbreak of the "Swords of Iron" War, the IDF-MC, in collaboration with the Directorate of Defense Research and Development (DDR&D) innovation program, initiated an R&D effort aimed at evaluating automatic tourniquet technologies. The program sought to improve hemorrhage-control performance by reducing application time, shortening time to arterial occlusion, and minimizing dependence on operator skill. Because the CAT was the currently fielded standard tourniquet in the IDF-MC, available CAT devices were used as an operational reference benchmark to anchor the evaluation framework in an existing and clinically familiar capability.

This article describes a requirements-driven biomedical engineering framework developed by the IDF-MC to guide preclinical evaluation of emerging combat tourniquet technologies. It reports the framework, qualitative architecture screening, and CAT reference measurements. It does not establish final-prototype efficacy, clinical effectiveness, or production-lot acceptance.

METHODS

Ethics Statement

Self-application of developmental tourniquets by team members was conducted under approval of the Israel Defense Forces Medical Corps Human Use Committee (Helsinki approval No. 2399-2023), which covered evaluation of tourniquets under development. The quantitative results presented in this report were obtained from bench and simulator testing; no participant-level usability or physiological outcomes are reported.

Study design

A bench-based engineering evaluation was conducted to develop and apply a structured pre-fielding framework for emerging automatic combat tourniquet technologies (Figure 1). The framework was developed after the outbreak of the Swords of Iron War. Functional and mechanical testing was conducted by five engineers during 2024-2025. NOVEL testing was conducted at the Technion mechanical engineering laboratory; pressure testing was conducted at the IDF-MC biomedical engineering laboratory, and mechanical testing of CATs was conducted at the IDF Trials and Quality Assurance Unit. Engineering personnel were already qualified for comparable device testing and

received project-specific instruction. Screening began with five preliminary samples submitted by private companies participating in the DDR&D innovation program. Selected prototype devices underwent multiple iterations, with 5-10 samples tested per iteration. Usability considerations arose from engineering experience and informal handling of devices by team members, including self-application to assess operation and comfort; this was not a formal usability study, and no participant-level usability outcomes are reported.

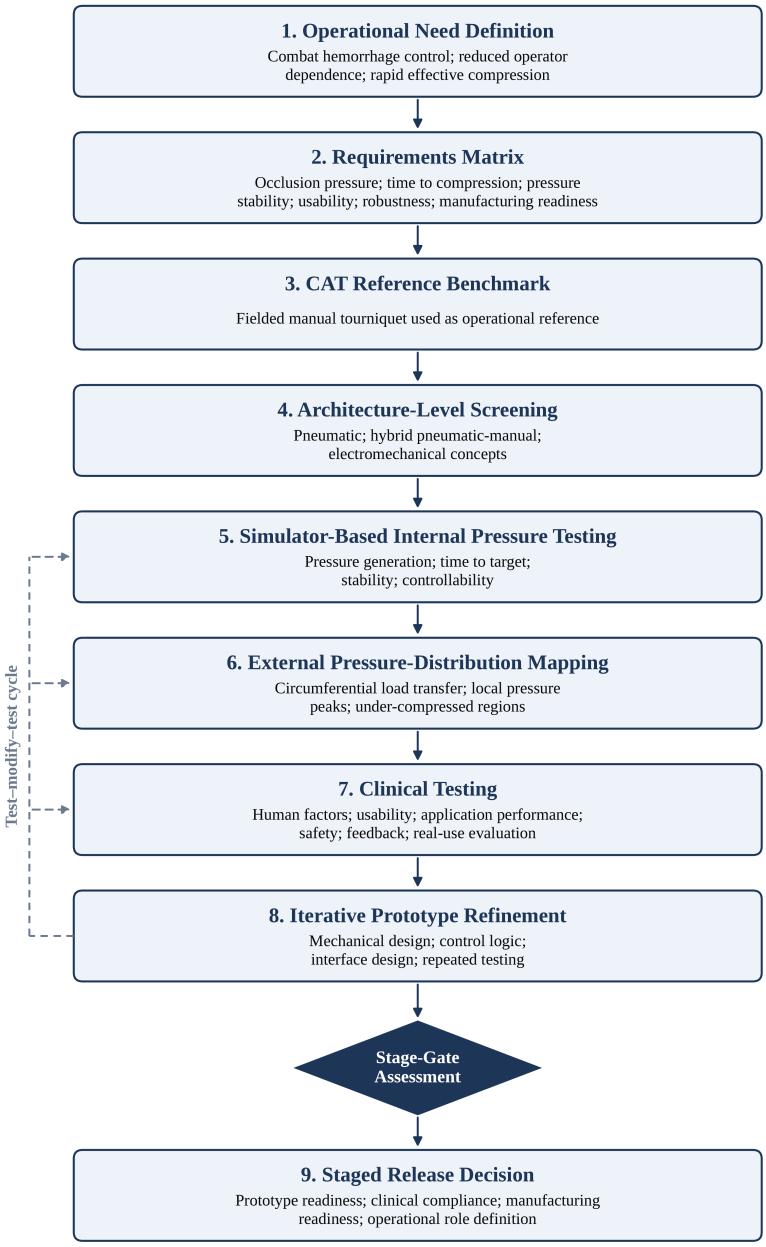


Figure 1. Requirements-driven pre-fielding evaluation framework for automatic combat tourniquets.

Definition of operational and engineering requirements

Requirements were defined before prototype evaluation through an internal IDF-MC process involving military biomedical engineers and physicians with prior combat medical experience. This process was informed by IDF-MC doctrine, operational needs, and lessons learned before and during the Swords of Iron War. Requirements addressed occlusion pressure, time to effective compression, pressure stability, circumferential load distribution, limb-size compatibility, operator dependence, one-handed usability, user feedback, mechanical robustness, environmental suitability, and manufacturing consistency. They defined the domains assessed at successive stages of the framework (Table 1).

Requirement domain	Specification	Target or decision criterion	Rationale
Occlusion pressure	Device should generate sufficient pressure for effective hemorrhage control	Engineering target during HapMed simulator testing: approximately 200-250 mmHg	Supports effective occlusion without relying solely on user technique
Application and occlusion time	Device should be rapidly applied and reach effective compression after activation	Time to target pressure assessed during simulator testing	Speed is critical in self-aid, buddy aid, and mass-casualty scenarios
Pressure stability	Device should maintain pressure and avoid clinically meaningful drift	Stable pressure over 5 hours; alert or correction if pressure falls > 30 mmHg	Maintains occlusion during evacuation and reassessment intervals
Circumferential pressure distribution	Compression should be distributed efficiently around the limb interface	Avoid excessive local pressure peaks (pinching) and under-compressed regions	Pressure distribution affects both effectiveness and tissue damage risk
Limb compatibility	Device should fit the expected operational limb-size range	Functional across anthropometric reference range of 5th-95th percentiles	Supports broad military and home-front use
Operator dependence	Device should reduce reliance on perfect manual technique	Simplified application sequence; reduced need for precise windlass manipulation	Addresses known user-dependent failure modes
One-handed use	Device should support self-application where feasible	Required for self-aid and constrained operational environments	Relevant to wounded soldiers and limited caregiver availability
Mechanical robustness	Device should tolerate foreseeable high-load and repeated-use conditions	No loss of functional compression under expected stress testing	Combat use includes rough handling and non-ideal application
Environmental suitability	Device should tolerate field conditions, storage, contamination, and transport	Continued function during environmental exposure: 0°C-45°C, and long-term storage: (-10°C)-50°C	Military storage and field use may exceed civilian conditions
Manufacturing consistency	Prototype performance should be reproducible across batch-produced units	Batch-level quality-control acceptance before release	Prototype success does not guarantee production readiness

Table 1. Operational and engineering requirements for tourniquet evaluation.

Reference benchmarking with the CAT

Ten Gen7 CAT devices from IDF inventory provided the reference benchmark. For each device, the number of 180-degree windlass turns required to reach an applied pressure of 200 mmHg and the applied pressure after four complete windlass turns were recorded. Ten new devices were used for subsequent destructive component testing (all components were evaluated for each device). Band and buckle tensile testing used a Zwick Z010 universal testing machine (ZwickRoell, Ulm, Germany) at 300 mm/min, following ASTM D5035. Windlass three-point bending used an Instron 5966 universal testing system (Instron, Norwood, MA, USA) at 1.2 mm/min, following ASTM D790. Failure was defined as complete component breakage followed by a drop in measured load to zero; breaking load denotes the maximum load before failure.

Architecture Screening

Emerging automatic tourniquet concepts were classified according to compression architecture. The three architectures underwent qualitative evaluation by a multidisciplinary panel of military medical and engineering experts. Concepts were screened according to expected pressure stability, mechanical complexity, controllability, modifiability, user-interface simplicity, one-handed application potential, environmental suitability, and compatibility with the predefined requirements. The architecture selected for continued refinement was chosen by expert judgment against these criteria.

Simulator-based applied pressure testing

Prototype systems were evaluated using simulator-based applied pressure testing via the HapMed™ Tourniquet Trainer (CHI Systems, PA, USA, Version 1.12). The HapMed is designed to simulate tourniquet application and provide objective pressure and occlusion-related feedback [11,12]. In the present evaluation, it was used as a repeatable pressure-assessment platform rather than as a training tool. Applied pressure as measured by the HapMed simulator was obtained to assess pressure generation, time to effective compression, response to user-initiated adjustments, and maintenance of pressure over time. The predefined engineering target during HapMed simulator testing was 200-250 mmHg applied pressure, based on previous studies [9-12] and on internal CAT reference evaluation. Testing was repeated after major design modifications to determine whether performance changes were reproducible and whether the modification introduced new engineering risks. Pressure behavior was interpreted together with usability observations and mechanical performance, rather than as an isolated endpoint.

Surface pressure-distribution mapping

Surface pressure measurements used a NOVEL capacitive sensor system (Novel Electronics Inc., PA, USA; sensor model Elastisens ES-25-50-10). Matrix-arranged sensors conformed to the curved simulator surface (sensor size: 10 × 20 mm^2; sensor area: 70 × 300 mm^2). Initial calibration followed the manufacturer's instructions using a dedicated calibration weight system. The sensor array was wrapped circumferentially around the HapMed, perpendicular to its long axis, approximately 20 cm from the display. The framework includes surface mapping to assess load distribution at the device-limb interface; the results reported here are limited to CAT reference measurements.

Reference Calibration

Reference calibration used unused Gen7 CATs applied over the NOVEL sensor on the HapMed simulator. The windlass was turned until the HapMed display indicated occlusion. Table 2 contains six distal, four mid-thigh and three proximal CAT applications. A separate mid-thigh application with a training device (trial 14) is displayed for transparency but excluded from CAT summaries and Figure 2. Mean surface contact pressure was calculated by averaging the loaded NOVEL sensors. The selected mid-thigh location was marked for subsequent testing.

Iterative engineering refinement

The framework incorporates iterative testing after design modifications to assess reproducibility and identify new engineering risks. Evaluation domains include pressure regulation, load transfer, circumferential pressure distribution, mechanical robustness, limb-device interface behavior, user-

interface predictability, and consistency between applications. These domains guide the test-and-modify process; they are not presented as a documented classification of observed failures or demonstrated improvements. Applied-pressure testing is considered alongside mechanical assessment, surface mapping, and usability considerations.

Manufacturing-readiness and operational release framework

Manufacturing readiness is a required pre-fielding domain in the framework. Destructive testing was performed during device evaluation, but this report does not establish completion or acceptance of a production-lot sampling exercise. The proposed lot-assessment approach referenced ISO 2859-1:1999, Special Inspection Level S-4, for a nominal batch of 1,000 units, with acceptance quality limits (AQLs) of 2.5% for lower-severity defects and 0.65% for critical defects. The proposed categories included cosmetic, ingress-protection and minor software defects, and failure to achieve target pressure as a critical defect. Classification requires assessment of each defect's functional consequences. This is a planning component, not a validated lot-release rule or evidence of ISO-compliant acceptance. Lot size, sample size and acceptance/rejection numbers must be specified before applying a release rule. Manufacturing assessment should include destructive testing, component inspection, interface consistency, surface finishing and environmental robustness.

Statistical analysis

Quantitative measurements are summarized as mean ± standard deviation (SD) where available. Each CAT reference-calibration observation represents an individual application; trial 14, performed with a QuickT training device, was excluded from CAT summaries. Location-specific sample variances were calculated using the VAR.S function in Microsoft Excel (version 2509) and compared descriptively with numerical summaries and graphical inspection. No inferential tests were performed. Mechanical results lacking recoverable raw measurements are reported without SD. Confidence intervals are not reported.

RESULTS

Operational and Engineering Requirements

The first framework output was an operational and engineering requirements matrix that served as the basis for screening, testing, refinement, quality-control assessment, and release-readiness decisions. The matrix emphasized that candidate technologies should be evaluated across multiple domains, including compression performance, pressure stability, load distribution, usability, robustness, field suitability, and production consistency (Table 1).

Reference benchmarking with the fielded manual tourniquet

Ten Gen7 CAT devices generated a mean applied pressure of 280.4 ± 29.5 mmHg after four complete windlass turns. The mean number of 180-degree windlass turns required to reach 200 mmHg was 2.30 ± 0.48, and time to target pressure was 14.3 ± 3.2 seconds. The mean tensile breaking load was 6,323 ± 75 N for the strap and 153 N for the buckle; the reported buckle deformation was 49.5 mm. In three-point bending testing, the windlass had a mean peak breaking load of 205 N, with a mean flexural deflection of 5.84 mm at that load.

Architecture-level screening of emerging automatic tourniquet concepts

Architecture-level screening showed that each automatic compression concept introduced distinct engineering trade-offs. Pneumatic systems offered rapid compression and broad surface contact but required careful assessment of sealing integrity, puncture tolerance, contamination, and pressure decay. Hybrid pneumatic-manual systems added redundancy but increased conversion complexity and user workload. Electromechanical circumferential-tightening systems were judged to offer the greatest potential for controlled actuation, pressure regulation, and iterative software-mechanical refinement, but introduced requirements related to power readiness, firmware behavior, load transfer, ingress protection, and long-term storage. Based on modifiability, controllability, and compatibility with the predefined

Test #	Location	Mean surface contact pressure, mmHg (kPa)	Applied pressure, HapMed (mmHg)
1	Distal	863 (115)	198
2	Distal	675 (90)	135
3	Distal	803 (107)	121
4	Distal	833 (111)	115
12	Distal	578 (77)	120
13	Distal	563 (75)	116
5	Mid-thigh	578 (77)	204
6	Mid-thigh	548 (73)	207
7	Mid-thigh	540 (72)	200
8	Mid-thigh	545 (72.7)	196
14	Mid-thigh	195 (26*)	0*
9	Proximal	398 (53)	205
10	Proximal	395 (52.7)	199
11	Proximal	443 (59)	210

Table 2. CAT Gen7 reference calibration across HapMed simulator application locations. Values are for individual CAT applications; surface contact pressure was measured with the NOVEL sensor and applied pressure with the HapMed display. *Trial 14 used a training device, and was excluded from CAT summaries and Figure 2 as NOVEL registered surface pressure but HapMed displayed zero.

requirements, the electromechanical architecture was selected for continued refinement.

Reference Calibration

CAT calibration compared three HapMed application locations (Table 2, Figure 2). Distal placement produced a mean applied pressure of 134.2 ± 32.1 mmHg, compared with 201.8 ± 4.8 mmHg at mid-thigh and 204.7 ± 5.5 mmHg proximally. Mid-thigh sample variances were 22.9 $mmHg^2$ for applied pressure and 5.1 kPa^2 for surface pressure, compared with 30.3 $mmHg^2$ and 12.6 kPa^2 proximally, and 1,029 $mmHg^2$ and 309 kPa^2 distally. Mean surface pressures were 73.7 ± 2.3 kPa at mid-thigh and 54.9 ± 3.6 kPa proximally. Both mid-thigh and proximal placements showed relatively low variability. Mid-thigh was selected and marked as the fixed engineering reference because its observed sample variances were numerically lowest. This descriptive choice does not establish statistical superiority or tissue safety.

Simulator-based applied pressure testing and surface pressure-distribution mapping

Applied pressure testing and surface pressure-distribution mapping were included as a component of the evaluation framework. HapMed and NOVEL results reported here are limited to the CAT reference measurements presented in Table 2 and Figure 2. Quantitative spatial mapping results for the automatic prototypes are not presented.

Manufacturing readiness and release-readiness decisions

The framework separates simulator performance from operational release. Simulator testing is an early engineering milestone; progression requires additional assessment of reproducibility, manufacturing readiness, usability and field-use risk. The CAT remained the operational reference standard, while emerging automatic technologies were considered suitable for controlled evaluation or role-specific deployment only after additional validation steps.

DISCUSSION

The main contribution of this study is a staged preclinical framework for evaluating emerging automatic combat tourniquet technologies. Rather than treating performance as a single pressure endpoint, the framework evaluates whether a candidate device can generate, regulate, distribute, maintain, and reproduce compression while meeting

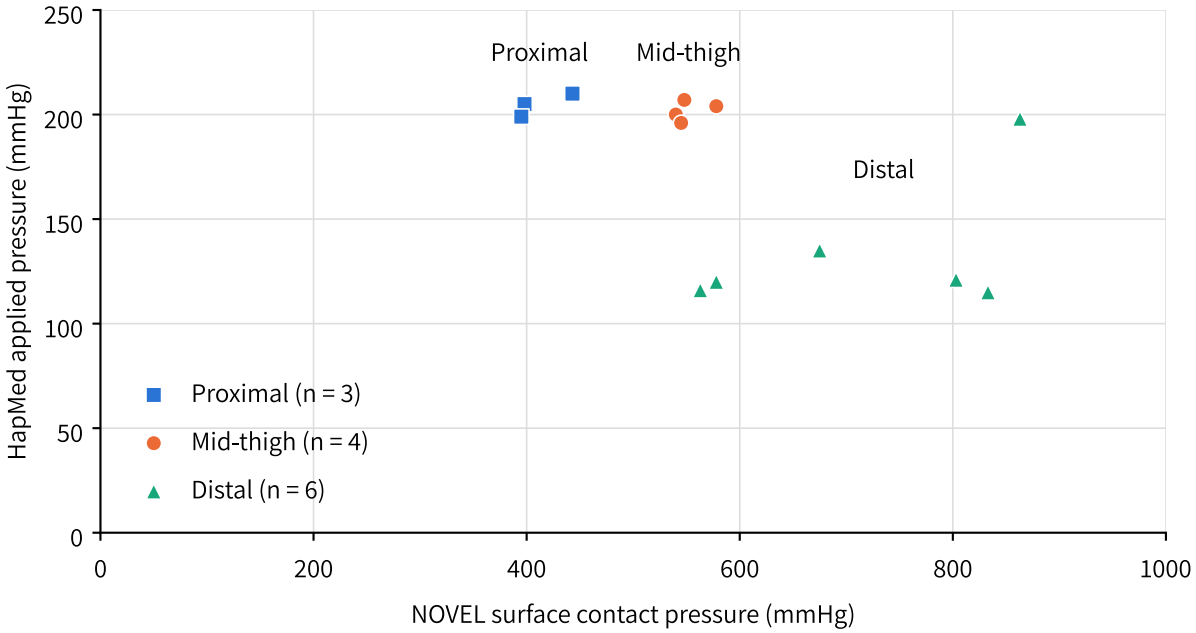


Figure 2. CAT Gen7 reference calibration across HapMed simulator application locations.

operational, usability, robustness, and manufacturing-readiness requirements.

Existing Frameworks

Previous tourniquet studies have employed focused evaluation approaches that informed the staged structure of the present framework. Wall et al. (2013) used a comparative device-evaluation approach, progressing from controlled application of different tourniquet designs to measurement of occlusion-related pressures [13]. Their findings provided insight into how design characteristics, including width, tightening mechanism, and device-limb interaction, influence occlusion efficiency. In contrast, Nachman et al. (2017) followed an iterative design-modification approach, translating a recognized CAT application failure mode (residual slack before windlass tightening) into a design modification intended to reduce slack, which was subsequently evaluated using pressure profile and hemorrhage-control outcomes [8]. This approach provides a useful model for iterative refinement, in which an observed failure mode is converted into a design intervention and retested against functional endpoints. Hingtgen et al. (2020) addressed a complementary aspect by focusing on objective pressure-measurement methodology, characterizing a cuff-based system for measuring surface-applied pressure [14].

Since these studies quantify fundamentally different aspects of the occlusion process, objective evaluation of tourniquet performance remains a challenge. Human volunteer studies typically use Doppler ultrasound as the reference standard for confirming cessation of distal arterial flow, providing a direct physiological endpoint but little information regarding the mechanical characteristics that produced occlusion. Consequently, these studies are well suited for validating effectiveness but are less informative for comparing engineering design features or identifying failure mechanisms [13,15]. In contrast, bench-top and simulator-based approaches, including the HapMed Tourniquet Trainer, quantify externally applied interface pressure under standardized conditions, allowing repeatable comparisons between tourniquet designs, application techniques, and user performance [8-12,16,17]. Although these methods improve experimental reproducibility, the reported pressure represents interface pressure on the simulator rather than direct pressure acting on the artery.

Pressure measurements depend on the measurement system and interface. Hingtgen et al. (2020) characterized a system for measuring limb tourniquet pressures [14]. Simulator and cuff-based

measurements should therefore be interpreted within their measurement conditions rather than treated as direct estimates of arterial wall pressure. Moreover, pressure thresholds reported in the literature vary according to the measurement system, limb model, and definition of successful application. Multiple HapMed-based investigations used displayed pressure values around 200 mmHg, together with simulated hemorrhage-control or application-time criteria, to define competent or effective application [9-11]. Other simulator studies have used thresholds near 180 mmHg [12], whereas human-limb studies have reported substantially broader and device-dependent pressures at arterial occlusion [13,15]. These differences indicate that no single external pressure value can be treated as a universal physiological threshold for emergency tourniquets.

The 200-250-mmHg HapMed interval was an internal engineering target. Published simulator criteria informed the approximately 200-mmHg lower boundary [9-12]. The IDF-MC team selected 250 mmHg pressure after internal professional discussion as a practical margin above that boundary, informed by preliminary CAT experience (minimum pressure performance of benchmark CAT applications at 4 turns) along with the intention to avoid unnecessary compression. Thus, the selected range should be interpreted as a comparative engineering acceptance criterion anchored to the performance of an established tourniquet, rather than as a direct estimate of pressure acting on the artery which would require Doppler or imaging-based validation methods.

IDF Comprehensive Framework

The present framework integrates previously separate evaluation domains into a staged pathway for automatic combat tourniquet development. This integration is particularly important for automatic systems, in which mechanical compression, software control, sensor feedback, power readiness, and user-interface behavior function as a coupled system. Evaluation must therefore address not only whether pressure is generated, but also how it is regulated, distributed, maintained, reproduced across applications, and translated into manufacturing-readiness and release-readiness decisions. Architecture-level screening showed that different automatic tourniquet concepts require different evaluation priorities. Pneumatic systems require assessment of pressure maintenance, sealing integrity, puncture tolerance, and contamination risk. Hybrid systems add redundancy but require evaluation of fallback mechanisms and user workload. Electromechanical systems provide greater potential for controlled actuation and iterative software-mechanical refinement, but introduce requirements related to power readiness, control algorithms, load transfer, environmental protection, long-term storage, and user-interface predictability.

The framework includes surface pressure-distribution mapping alongside applied-pressure testing to assess loading at the device-limb interface. In this report, NOVEL findings are limited to CAT reference measurements. No conclusions about spatial pressure distributions or mapping-based improvements in automatic prototypes can be drawn from the data presented. Manufacturing readiness is embedded as a required pre-fielding domain. Prototype success in simulator testing does not guarantee production readiness, particularly for military medical devices that may be stored for prolonged periods, exposed to harsh operational environments, and used under stress by operators with variable training. Candidate devices should therefore undergo assessment of production consistency, reliability, environmental robustness, storage suitability, and lot-to-lot variability before fielding.

The Gen7 CAT served as the operational reference benchmark throughout the framework. As the current fielded standard, it provided a practical baseline for pressure generation, application characteristics, and mechanical robustness. CAT testing provided reference measurements for pressure generation, time to HapMed-indicated occlusion and component breaking load. These measurements defined comparison endpoints for subsequent prototype evaluation; the data reported here do not establish comparative performance of the final automatic prototype. Anchoring both HapMed-measured applied pressure and NOVEL surface-pressure measurements to CAT performance under standardized simulator conditions created a practical engineering reference endpoint. This approach does not replace physiological validation, but it provides a repeatable method for

comparing how candidate devices generate, regulate, and distribute compression before progression to human occlusion testing. The combined use of applied-pressure and surface-pressure endpoints also supports cross-verification within predefined engineering guardrails while preserving the distinction between simulator-based performance and clinical effectiveness.

Limitations. Several limitations should be acknowledged. First, the reported quantitative results concern bench and simulator testing, not clinical effectiveness. Simulators cannot reproduce active hemorrhage, tissue variability, pain, combat stress or evacuation conditions. The engineering pressure target therefore requires physiological validation, such as Doppler-confirmed arterial occlusion, before clinical interpretation. Second, the framework described herein is not evidence of final-product validation; as such, prototype pressure trajectories, spatial maps, iteration-specific outcomes and production-lot acceptance results are outside this report. Third, the reference benchmark used 10 devices of one CAT model and one simulator model, limiting generalizability. Fourth, some mechanical test settings and raw measurements were not recoverable, limiting reproducibility and uncertainty estimation. Fifth, NOVEL measurements may be affected by pad pinching or uneven device-sensor contact. Finally, informal team handling conducted internally does not constitute independent usability validation.

The study also highlights the limitation of defining success as universal replacement of the CAT. Manual tourniquets are inexpensive, lightweight, robust, logistically simple, and already embedded in training and supply systems. Automatic or electromechanical systems may reduce operator dependence and improve consistency of pressure control, but they also introduce life-cycle requirements related to power readiness, storage, maintenance, training, environmental robustness, and manufacturing consistency. Accordingly, the most defensible near-term role for emerging automatic tourniquet technologies may be selective deployment in settings where reduced operator dependence is particularly valuable or caregiver availability is limited, such as medical teams, casualty collection points, evacuation platforms, and mass-casualty kits.

CONCLUSIONS

Pressure generation alone is insufficient for determining the readiness of emerging automatic combat tourniquets. Candidate devices should be evaluated as integrated biomedical engineering systems that must generate and maintain effective compression, distribute load appropriately, remain mechanically robust, support predictable use, demonstrate manufacturing consistency, and fit a defined operational role. The proposed requirements-driven framework provides a structured preclinical pathway from operational need to prototype readiness. By combining CAT benchmarking, simulator-based pressure testing, surface pressure-distribution mapping, iterative refinement, and manufacturing-readiness assessment, this approach may support disciplined progression toward usability testing, clinical validation, and role-specific operational evaluation.

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Conflict of interest: none to declare

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Authors' contributions: YW and AH: conceptualization and framework development, methodology, investigation, data curation, formal analysis, and writing the original draft. LR and MS: methodology and data interpretation. DBH: engineering team leadership, methodology, supervision of framework development, data interpretation, and manuscript review and editing. MM and YZ: investigation, data curation, and formal analysis. SO: methodology, supervision of the research and development process, and manuscript review and editing. TE: leadership of protocol and experimental design, investigation, data curation, formal analysis, and data interpretation. IK: supervision, project administration, and critical review and editing.

Data availability: The data reported in this study were generated as part of a product development and evaluation process. Raw data beyond the findings presented in the manuscript are not publicly available. Requests for raw measurement data obtained from the commercially available Combat Application Tourniquet (CAT) will be considered by the corresponding author.

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