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Covey, Captain Dana C

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-The Evolution of Modern Combat Orthopaedic Care from Clinical Investigation to Battlefield Application: Three Decades of Research to Decrease Morbidity and Mortality

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Corresponding Author's Institution:	UC San Diego: University of California San Diego
Corresponding Author E-Mail:	dcovey@health.ucsd.edu
Order of Authors:	Dana Curtis Covey, MD, MSc
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The Evolution of Modern Combat Orthopaedic Care from Clinical Investigation to Battlefield Application: Three Decades of Research to Decrease Morbidity and Mortality

Recipient of the 2026 OREF Clinical Research Award

Principal Investigator: Captain Dana C. Covey, Medical Corps, United States Navy (Ret.)

Clinical Professor of Orthopaedic Surgery

University of California, San Diego

Principal Investigator Information:
Dana C. Covey, MD, MSc, FAAOS, FAOA
Clinical Professor of Orthopaedic Surgery
Department of Orthopaedic Surgery
University of California San Diego
9300 Campus Point Drive
La Jolla, CA 92037
Office: 619-543-2644
Cell: 858-342-3884
Fax: 619-543-2540
Email: dcovey@health.ucsd.edu
Affiliation: Department of Orthopaedic Surgery, University of California San Diego

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The Evolution of Modern Combat Orthopaedic Care from Clinical Investigation to Battlefield Application: Three Decades of Research to Decrease Morbidity and Mortality

Abstract

Over 52,000 U.S. service members were wounded in the wars in Iraq and Afghanistan over two decades of war. These years also witnessed a continued evolution in the treatment of polytraumatized patients, especially those injured in combat. Because most of those wounded-in-action sustain musculoskeletal injuries, providing skilled treatment as soon as possible after injury has saved the lives and improved the musculoskeletal function for numerous service members injured in these conflicts. Orthopaedic surgeons have been crucial members of forward surgical teams that have performed life and limb-saving care under challenging forward deployed conditions, sometimes under fire. In this setting, military orthopaedic surgery has continued to evolve, building in part upon experience gained in smaller conflicts where the United States was not a principal belligerent, but where war trauma familiarity was acquired that contributed to improvement of forward orthopaedic care in the recent wars in Iraq and Afghanistan. The presented body of work addresses multiple facets of orthopaedic combat care including the intermingling of surgeon and team preparation, logistics, clinical studies, and the concept of far forward surgical treatment, to increase survival and improve outcomes of those sustaining acute battlefield musculoskeletal trauma.

Introduction

Successful treatment of severely injured patients in the combat environment is one of the most difficult challenges faced by orthopaedic surgeons.[1] Providing skilled treatment immediately after injury has saved the lives and improved musculoskeletal function for many patients wounded in recent wars. Orthopaedic surgeons have been crucial members of forward surgical teams that have performed life and limb-saving care.[2]

Conducting clinical studies during ongoing combat operations is challenging in a myriad of ways. In the author's experience, not the least of these is a fog of war combined with limited resources, the undulating nature of battlefield kinetics where case volume varies from mass casualties to individual patient, and where wounds vary from catastrophic to non-life or limb threatening.[3,4] However, work over the last three decades by orthopaedic surgeons addressing multiple interconnected themes related to combat surgery have helped to mitigate injury, improve treatment, decrease mortality, and enhance outcomes in survivors.

Providing expeditious and optimal frontline orthopaedic surgery requires not only a skilled orthopaedic team, but also a complex support system that must be able to span continents and oceans.[5] The presented body of work addresses multiple facets of combat orthopaedic care including the intermingling of surgeon and team preparation, logistics, clinical studies, and the concept of far forward patient treatment, to improve the outcomes of acute battlefield musculoskeletal injuries.

Recent Battlefield Statistics

Approximately 52,143 U.S. service members have been wounded in the wars in Iraq and Afghanistan over two decades of cnflict.[6] Although case-fatality rates in the recent wars in Afghanistan and Iraq are the lowest in U.S. military history,[7] it remains that most personnel who are wounded-in-action sustain musculoskeletal injuries, many of which are mutilating.[8] The historically high survival seen among wounded service members is due to multiple factors that include enhanced training, on-time logistics, safer combat vehicles, improved body armor, tactical medical and surgical advances, early blood transfusions, prompt tourniquet placement, and rapid medical evacuation. These measures, most of which are orthopaedically related, contributed to improved treatment of life-and-limb threatening musculoskeletal injuries, and were associated

with a 44% reduction in mortality.[7] With improved protection afforded the thorax and abdomen by modern body armor, we found that orthopaedic surgeons were often faced with treating catastrophic battlefield extremity injuries that were infrequently seen in survivors of past conflicts.[2]

Evolving Battlefield Orthopaedic Care

Lessons Learned from Recent Conflicts

History has repeatedly shown that advances in patient care often occur during wartime.[9] Studying recent conflicts, the Persian Gulf War of 1991, which lasted only six weeks with relatively few casualties – although many were expected -- exposed potential weaknesses in contemporary combat casualty care. From a surgical standpoint, we felt that field hospitals needed to be smaller, more agile, and able to adapt to rapidly changing battlefield conditions to achieve early golden hour access for wounded service members.[10] However, positioning of damage control surgical capabilities far forward to enable expeditious patient access to this capability was a relatively new concept. Within this framework, important orthopaedic recommendations were incorporated by war planners to improve surgical team mobility, and orthopaedic care of combat wounds.[11] Orthopaedic leaders of all three services established important surgical equipment standardization (e.g., external fixators) across different services and varied wartime operational platforms.

Between the end of the Persian Gulf War and the onset of major combat operations in Afghanistan and Iraq in 2002 and 2003, respectively, military orthopaedic surgery continued to evolve, based in part on experience gained in smaller conflicts where the United States was not a principal belligerent, but involved for humanitarian reasons.[12,13] These contingencies included Somalia, the Balkans War, Haiti, and the Tamil War in Sri Lanka where orthopaedic injuries were

common, and we assimilated lessons about optimal forward of war wounds.[14,15,16] Reports from this author and others emanating from these Military Operations Other than War (MOOTW) combined with other studies, helped guide U.S. military medicine to make contemporary changes in the strategies and systems of forward battlefield musculoskeletal care.[17,18,19]

Injury Protection Efforts

Improved Battlefield Vehicular Design. During the 1990s Balkans Civil War, the association of lumbar burst fractures with lower extremity injuries seen in United Nations peacekeepers who were vehicle occupants wounded by antitank mines was recognized, a finding not mentioned in previous literature (Fig. 1). We reported that a sitting occupant may experience an axial spinal load that is transmitted by the vehicle as it accelerates upward from a blast causing anterior and posterior compressive failure of the vertebral body.[20] The severity of these injuries was related to the vehicle type, explosive charge, occupant location with respect to the blast, occupant posture, and the seat cushioning. In a subsequent study, Commandeur et al.[21] also found similar musculoskeletal injuries from under-vehicle explosions. This injury pattern has been termed a modern "deck-slap" injury, in reference to an analogous mechanism first reported during World War II in Navy personnel injured by sea-mine detonations.[22] Ramaswamy et al.[23] extended our initial findings and demonstrated that a relatively simple combat vehicle modification from a flat bottom to a V-hull can have a significant positive effect on reducing fatality and orthopaedic injury rates from under-vehicle explosions. This new vehicle design was introduced in Iraq and Afghanistan and is still in use.

Improved Body Armor. To reduce the severity of perineal and junctional blast trauma, a two-tiered system of personal pelvic and junctional protection called the "Pelvic Protection System" (PPS) was fielded in Afghanistan in 2011.[24] Over a 12-month period, we found that in a

cohort of 36 service members who sustained at least one traumatic above-knee amputation in Afghanistan, with or without perineal injuries, patients who wore the PPS had significantly fewer ($p = 0.012$) junctional/perineal injuries[25]. The protection was best for those service members who wore both tiers of pelvic protection (Fig. 2; $p = 0.007$). Our clinical findings suggested that the use of a tiered PPS can significantly reduce the risk of having severe perineal and lower extremity junctional injury in service members who sustain traumatic above knee amputations from explosive blasts.

Improved Training for Forward Treatment of Battlefield Trauma. Better preparation of surgical teams has led to greater unit cohesion and the confidence to optimally treat combat casualties. In support of this, practical training for deploying surgical personnel endeavored to simulate real field conditions.[26] To help achieve this goal, we conducted a prospective study of 51 military patients who elected to undergo ambulatory surgery in a modified field surgical hospital with an environment and equipment that orthopaedic surgeons would have in a battlefield setting. Orthopaedic surgical team training proved valuable, and at an average two-year follow- there were no patient anesthetic, bleeding, infectious or other significant perioperative complications. State-of-the art surgical cadaver and simulation training was also established at a tertiary military medical center to educate deployment-bound surgeons on important principles of battlefield orthopaedic surgery.[27]

To complement this Department of Defense training, the author and orthopaedic colleagues conceived, developed, and presented multiple military orthopaedic symposia at annual meetings of the American Academy of Orthopaedic Surgeons, along with a new, and separate, Extremity War Injuries Symposium, which began in 2006, and is still ongoing. These symposia presented best practices for state-of-the-art care for patients sustaining combat trauma and helped prepare

military orthopaedic surgeons for the injuries they would encounter in either Afghanistan or Iraq. Some of these symposia were published and are included among the references cited in this manuscript.

Limb and Lifesaving Interventions

Pre-Field Hospital Casualty Care

Tourniquets. The goal of pre-hospital care is to begin life-saving treatment, and recent widespread use of modern tourniquets to treat combat extremity wounds has had a marked impact on survival (Fig.3). In a study of 232 injuries at a major combat theater hospital in Iraq, Kragh and coworkers[28] found a statistically significant improvement in survival rates with the use of extremity tourniquets. Tourniquet use in the absence of shock was strongly associated with survival (90% vs. 10%; $p < 0.001$). Prehospital tourniquets were applied in 194 of 232 patients of which 22 died (11% mortality), whereas nine of 38 patients who had emergency department application died (24% mortality; $p = 0.05$). Four patients (1.7%) sustained transient nerve palsy at the level of the tourniquet. No amputations resulted solely from tourniquet use.

In a prospective study carried out at a forward surgical team during the Iraq War, we documented that tourniquets applied for penetrating injuries with severe bleeding reduced transfusion requirements and helped maintain adequate blood pressure.[29] We found that hemorrhage from penetrating orthopaedic injuries was less ($p = 0.001$) as measured by transfusion requirements in patients presenting with effective tourniquets compared to those patients having no, or ineffective tourniquets. Furthermore, the group with effective tourniquets (compressed hemorrhage) presented with significantly higher mean systolic and diastolic blood pressures than the group with no tourniquets or ineffective ones (Fig. 4). Our study's only notable complication was a peroneal nerve palsy in one patient. Tourniquets were not the proximate cause of amputation

and did not determine the choice of an immediate amputation level. Our findings supported a study of U.S. combat casualty care data during the Iraq and Afghanistan Wars that suggested increased tourniquet use was a factor in the overall reduction in mortality.[7]

Junctional Injuries. However, tourniquet use is not feasible in cases of very proximal extremity wounds and orthopaedic junctional injuries. The latter wounds span the root of an extremity and the adjacent torso to include the shoulder and thoracic outlet, or the pelvis, lower part of the abdomen, and proximal part of the thigh (Fig. 5).[30] Junctional areas are traversed by major neurovascular structures where proximal and distal hemorrhage control is often necessary in the torso and extremity. These life-threatening injuries are often due to explosive trauma that causes bleeding in the pelvic region proximal to the inguinal ligament, the perineum, or the gluteal region, or causes bleeding in the shoulder from the subclavian or axillary vessels. There has yet to be fielded a proven pre-hospital treatment for massive exsanguinating junctional injuries. Emergency surgery to obtain vascular control is paramount.

Eastridge et al.[31] studied died-of-wounds deaths (i.e., those occurring after reaching a medical treatment facility) from 287 potentially survivable battle injuries in Iraq and Afghanistan and showed that 21% of these deaths were due to junctional injuries. An analogous study of service members who were killed-in-action (i.e., died before reaching a medical treatment facility), 976 service members had potentially survivable wounds (Fig. 6).[32] Hemorrhage accounted for 91.0% of these battlefield deaths, with junctional injuries comprising 19.3% of the fatal hemorrhage cases.

Medical Evacuation. Increased survival rates of combat casualties have also been linked to progress made in the transport of wounded personnel from the point of injury to level 2 or level 3 surgical teams.[7] These levels are within a 5-tiered system where 1 is the lowest and 5 is the

highest level of care that can be provided. An impetus to decrease medical evacuation (medevac) times was spurred by a Department of Defense goal to achieve medevac transports within 60 minutes of injury, thus embracing the concept of the so-called golden hour of trauma.[33]

Treatment of Polytraumatized Battlefield Patients

Forward Field Hospital Casualty Care

Damage Control Surgery. The past two decades have witnessed continued evolution in the treatment of polytraumatized patients, especially those injured in combat. The term "damage control" was coined by the U.S. Navy in reference to "the capacity of a ship to absorb damage and maintain mission integrity."[34] Using this naval terminology, Rotondo et al.[35] recommended a strategy called "damage control surgery" (DCS) for treating patients who sustained multivisceral injuries from penetrating abdominal trauma. This concept was advocated for patients *in extremis* and was performed in three phases: (1) rapid initial stabilization surgery; (2) a period in the intensive care unit for physiologic optimization; and (3) return to the operating room when the patient can withstand prolonged surgery for definitive treatment.

Damage Control Orthopaedics. The concept of "damage control orthopaedics" (DCO) developed as an outgrowth of the principles of DCS because evidence suggested that the push for urgent definitive orthopaedic surgery led to increased complications in under-resuscitated patients.[36,37,38] Similar to DCS, the goal of DCO is to limit the physiologic insult to patients *in extremis* and provide rapid provisional skeletal stabilization -- usually with external fixation -- followed by physiologic optimization and definitive reconstruction after the patient is stabilized.[39] There is often a so-called "first hit" which is defined as the patient's initial traumatic injury.[40] In cases of civilian trauma, reducing the seriousness of the first hit has occurred through improvements in injury prevention. Improved outcomes of vehicular trauma have occurred with

the advent of crumple zones, airbags, seatbelt laws, child car seats, and maturation of civilian trauma systems. In contrast, the "second hit" represents an insult to the traumatized patient that occurs during treatment, and one that the orthopaedic surgeon can potentially modulate.

In cases of severe battlefield orthopaedic trauma, we felt the evidence suggested that improved prevention, or reduction of injury from the "first hit" can be achieved by better personal body armor, re-designed combat vehicles, enhanced training, rapid medical evacuation, and the close availability of a forward surgical team.[41,42] Reducing adverse effects from a "second hit" involves preventing multisystem organ failure and acute respiratory distress syndrome through prompt hemorrhage control, permissive hypotension, and urgent surgical treatment to include rapid provisional fracture stabilization to prevent the dangerous triad of coagulopathy, hypothermia and acidosis.[43] This is followed by rapid medical evacuation to a facility that can provide a higher level of intensive care for physiologic optimization prior to further orthopaedic surgery.[5] Such a musculoskeletal trauma care pathway can be characterized as "Battlefield DCO", which has become a current model for treatment of patients with severe combat trauma.

Hemorrhage Control. Active bleeding in combat wounded patients encountered by orthopaedic surgeons can be considered compressible or noncompressible.[40] For compressible extremity hemorrhage, a tourniquet is often used until removed for surgical hemostasis. For noncompressible hemorrhage, hemostatic dressings can be applied if feasible, and temporary vascular shunts can be used in some cases.[44] But in the instance of severe junctional trauma, we feel that proximal vascular control offers the best opportunity for success.[30] Forward systemic treatment of ongoing hemorrhage, metabolic derangements and dilutional coagulopathy may include fresh whole blood from a walking blood bank of pre-screened donors, blood component therapy, and permissive hypotensive resuscitation.[45,46,47] Adding tranexamic acid to blood

component-based resuscitation following combat injury results in improved measures of coagulopathy and survival, a benefit that is most prominent in patients requiring massive transfusion.[48]

Negative Pressure Wound Management. Negative pressure wound therapy (NPWT) has revolutionized the treatment of soft tissue wounds resulting from traumatic and nontraumatic causes. We reported that in combat wounds, this treatment augments wound granulation and healing, promotes wound contraction, controls wound secretions, decreases wound edema, reduces skin maceration, and improves pain management.[41,49] The use of the transportable negative pressure wound system during aeromedical evacuation had the potential to improve pain management, facilitate wound healing, and simplify in-flight wound care (Fig. 7). Due to aeromedical limitations and other concerns, NPWT was not routinely used in the management of soft-tissue wounds before casualties arrived in the United States early in the Iraq and Afghanistan wars. This changed when a commercially produced NPWT system successfully completed air worthiness testing by the military. In a prospective, observational study, Fang et al.[50] reported NPWT is feasible during intercontinental aeromedical evacuation of combat casualties without an increase in wound complications or a significant impact on air crew workload. The study authors recommended further research to evaluate the efficacy of NPWT in combat wounds compared with other wound care techniques.

Beyond the Combat Zone

Reconstruction and Rehabilitation Interventions. We found that away from the battlefield, the care of patients with orthopaedic war injuries has continued to advance.[51] New techniques for the fixation of open, comminuted, battlefield fractures having large zones of injury and soft-tissue loss are being developed. Recent progress in surgery for brachial plexus injuries has improved the

previously poor prognosis for those sustaining combat related brachial plexus wounds. The use of free-functioning muscle transfer and novel nerve transfers, as well as an improved understanding of nerve physiology, has improved the outcomes of reconstruction. Advances in restorative and regenerative medicine include the development of biomimetic prostheses, optimization of the human-prosthesis interface with neurocontrol devices, improved osseointegrated fixation, and lengthening of short residual limbs.[52,53] Lessons learned from the recent conflicts noted in this paper will be instrumental in shaping important aspects of current and future military orthopaedic practice in the optimal treatment of high-energy, complex musculoskeletal combat trauma.

Data Collection. Improved capture of musculoskeletal data during the recent wars can help guide future treatment decisions. With the goal of expanding upon smaller studies, some of which are referenced herein, the Military Extremity Trauma Amputation/Limb Salvage (METALS) study was undertaken as a retrospective cohort study of U.S. service members who sustained a major limb injury while serving in Afghanistan or Iraq between 2003 and 2007.[54] It found that major lower-limb trauma sustained by service members results in substantial long-term disability, but at an average of three years post-injury, those treated with amputation appeared to have better functional outcomes than those treated with limb salvage. As a follow-on to the METALS study, the Major Extremity Trauma Research Consortium (METRC) was funded in 2009 by the U.S. Department of Defense.[55] This project was designed to help build infrastructure and evaluate whether a large enough number of patients treated at civilian trauma centers could populate studies that address current priorities for combat casualty care.

Follow-on Treatment. Challenges do not end with the acute care phase of battlefield orthopaedic trauma. Many patients require rehabilitation and post-acute services including mental health care to optimize recovery and reintegration back into military service and everyday life.[56]

Furthermore, questions and challenges regarding limb salvage versus amputation still exist.[57] For many service members secondary adverse health effects (e.g., osteoarthritis, cardiovascular disease, obesity, chronic pain, and depression) can develop in the years following injury that can have significant implications over the course of their remaining lives in a predominantly young patient population.[58]

Conclusion

The U.S. military medical system has made many critical and highly effective changes in the way battlefield resuscitative and orthopaedic surgical care is provided to service members over the last three decades. The relatively recent emphasis on leaner, faster-moving military units added to the imperative to push field surgical teams farther forward, closer to battle -- so they too, were made leaner and more mobile -- a fundamental departure from previous wars.[17] Areas for future improvement include better methods to control of junctional hemorrhage in the field to prevent exsanguination, optimizing damage control resuscitation and damage control orthopaedics, developing better methods to combat infection, and improved techniques for reconstruction of severe battlefield injuries. Taken in total, our contributions over several decades that have encompassed myriad aspects of battlefield musculoskeletal care during multiple conflicts have contributed to improved treatment of combat orthopaedic injuries and have contributed to an historically low case fatality rate for the wars in Iraq and Afghanistan.

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Figure Legends

Fig. 1. Under vehicle explosive detonations causing "deck slap" lower extremity injuries and lumbar burst fracture**.** (A) Photograph of severe open right hindfoot ''deck slap" injury from an explosion below the patient's armored vehicle. (B) Radiographs showed comminuted calcaneal, talar, and cuboid fractures. Bluman EM, Ficke J, Covey DC. War wounds of the foot and ankle: Causes, characteristics, and initial management. *Foot Ankle Clin N Am.* 2010; 15:1-21. (C) Lateral radiograph of L2 burst fracture from an under-vehicle blast. Covey DC, Lurate RB, Hatton CT. Field hospital treatment of blast wounds of the musculoskeletal system during the Yugoslav civil war. *J Orthop Trauma* 2000; 14:278-86.

Fig. 2. A pelvic protection system (PPS) can decrease junctional and perineal injuries ($p = 0.012$) in service members sustaining above knee amputations from explosive blasts. (Adapted from: Covey DC. Decreasing lower extremity junctional and perineal injury from explosive blast with a pelvic protection system. *Injury*. 2023; 54(7):110784.)

Fig. 3. U.S. service member with bilateral field tourniquets (Combat Application Tourniquets^{R}) placed on the battlefield for severe lower extremity trauma sustained from detonation of an Improvised Explosive Device (IED).

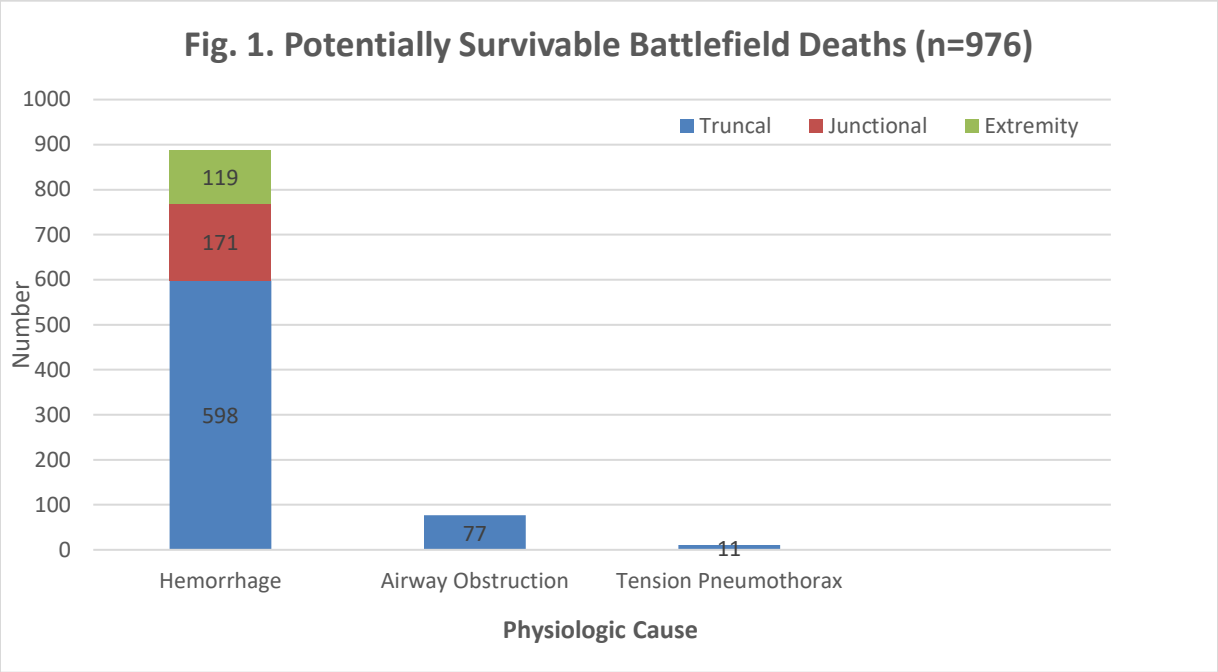
Fig. 4. Effective placement of field tourniquets can maintain blood pressure in cases of nonjunctional extremity vascular injury. SBP – Systolic Blood Pressure. DBP – Diastolic Blood Pressure. GCS – Glasgow Coma Scale. Adapted from: Covey DC, Gentchos CE. Field

tourniquets in an austere military environment: A prospective case series. *Injury*. 2022; 53:3240-3247.

Fig. 5. (A). Blast injury of the left proximal thigh caused by an Improvised Explosive Device (IED) in Afghanistan. (Adapted from Covey DC, Schwartz AK. Orthopaedic junctional injuries. *J Bone Joint Surg*. 2019; 101(19):1783-1792.). (B). Blast injury of the right axillary region caused by a rocket propelled grenade in Iraq.

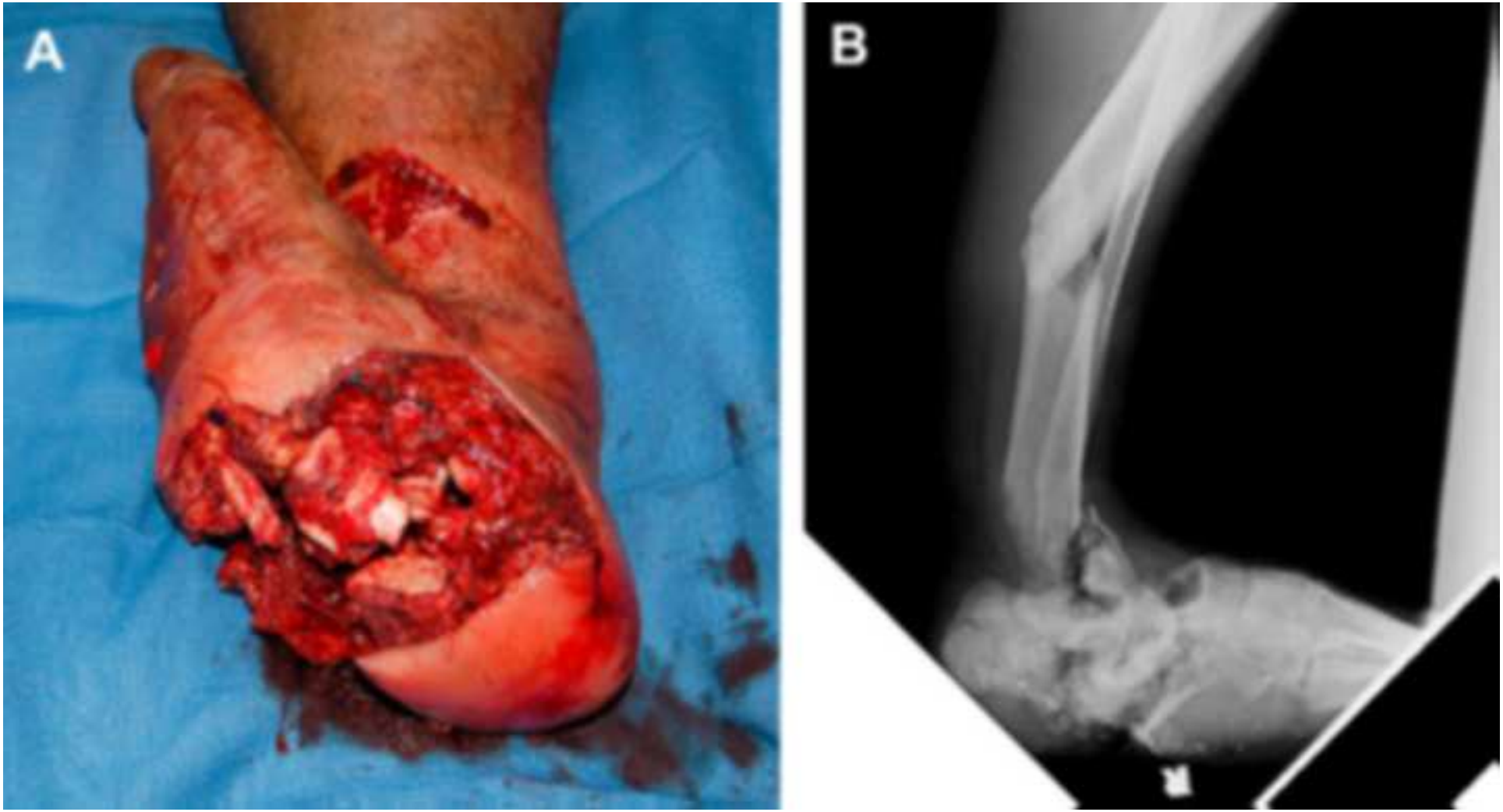
Fig. 6. Covey DC, Schwartz AK. Orthopaedic junctional injuries. *J Bone Joint Surg.* 2019; 101(19):1783-1792.

Fig. 7. U.S. service member with severe polytrauma from an Improvised Explosive Device (IED) in Afghanistan. The patient is shown with negative pressure wound therapy (NPWT) in place and is ready for aeromedical evacuation. (From Cannada LK, Vaidya R, Covey DC, et al: The traumatic amputee: surgical challenges and advances in prosthetics. *Instr Course Lect* 2013; 62:3-15.



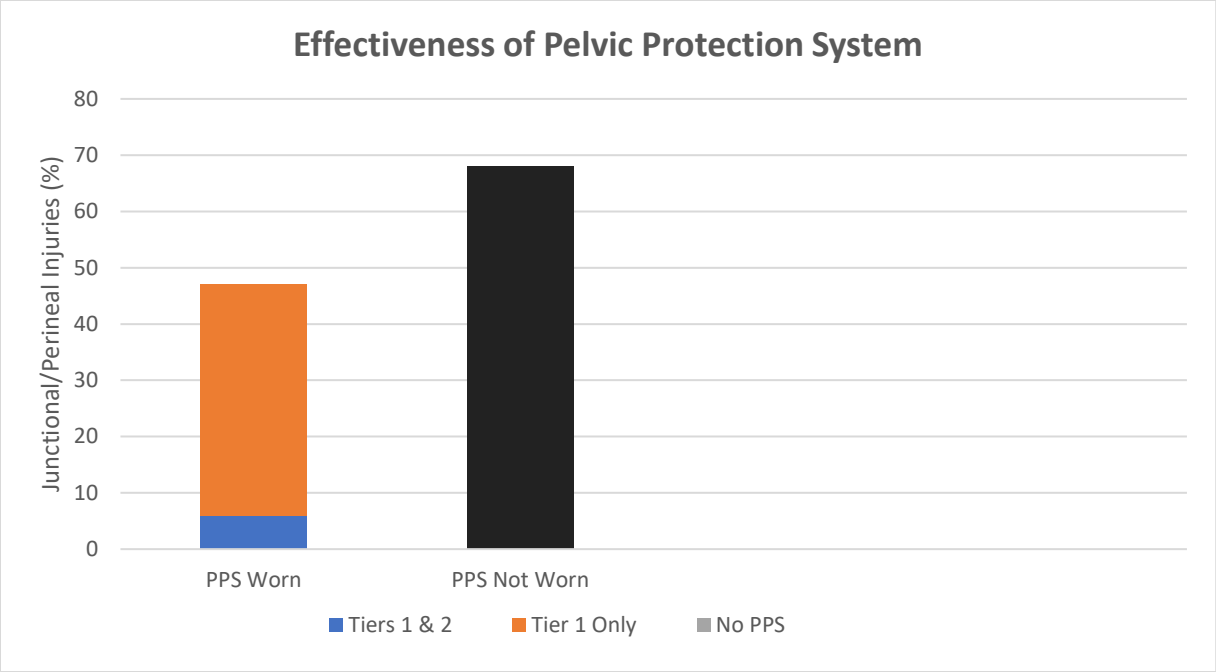
Adapted from Eastridge et al. J Trauma Acute Care Surg. 2012; 73(6) Suppl 5:S431-437.

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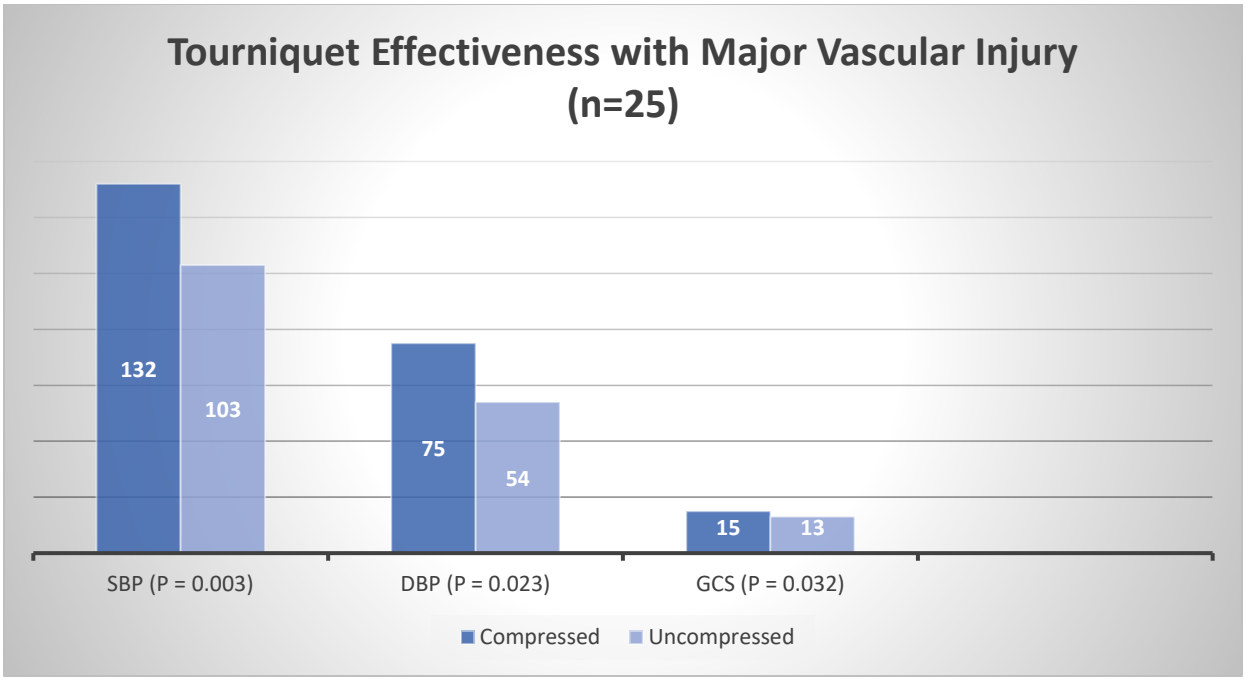




A pelvic protection system can decrease junctional and perineal injuries (n =36; p = 0.012) in service members sustaining above knee amputations from explosive blasts. Adapted from: Covey DC. Decreasing lower extremity junctional and perineal injury from explosive blast with a pelvic protection system. *Injury*. 2023 May 3:110784.

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Tourniquet Effectiveness with Major Vascular Injury (n=25)
132
103
75
54
15
13
SBP (P = 0.003)
DBP (P = 0.023)
GCS (P = 0.032)
Compressed
Uncompressed

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