

Lower Extremity Combat Sustained Peripheral Nerve Injury in US Military Personnel

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Background: Since the civil war, combat sustained peripheral nerve injuries (CSPNI) have been documented during wartime. Warfare has evolved and current combat involves a greater severity of blast injuries secondary to increased use of improvised explosive devices. The purpose of this study was to describe CSPNI and report outcomes after evaluation and treatment. We hypothesize that a shorter time to evaluation will improve outcomes.

Methods: A database including all active duty service members who sustained a CSPNI and were treated by the PNC between 2004 and 2009 was used. Service member demographic information, injury mechanism, CSPNI description, and Medical Research Council (MRC) final motor and sensory outcomes were queried from this database.

Results: One hundred and four military service members sustained 144 PNIs. The average age was 26.7 years, and nearly all were men (98.1%). There was no correlation between Sunderland classification and age, specific PNI, injury type, or time to evaluation. Higher Sunderland classifications were found to be correlated with worse final motor ($r = 0.51, P < 0.001$) and final sensory ($r = 0.41, P < 0.001$) scores. Final motor and sensory scores were not associated with specific nerve injury, mechanism of injury, initial EMG, or surgical procedure. Shorter time to initial assessment was associated with improved final motor and sensory scores, but was not found to be statistically significant.

Conclusions: As the complexity of CSPNIs progress as combat weaponry evolves, a firm understanding of treatment factors is important. Our study demonstrates in recent conflict that military service members' initial injury severity is a key factor in expected outcome. (*Plast Reconstr Surg Glob Open* 2021;9:e3447; doi: 10.1097/GOX.0000000000003447; Published online 15 March 2021.)

INTRODUCTION

With the advent of current combat armaments and advancements in military medical trauma and critical care in wartime, survival rates of severe battle wounded military personnel have significantly increased. A component of combat-sustained injuries is peripheral nerve injuries (CSPNI), which have been documented since the Civil War. Treatment of CSPNI has evolved since the time of the World Wars, leading to improvements in accurate

diagnosis and patient outcomes.¹ However, in contemporary warfare, there has been a shift toward the use of explosive devices, such as Improvised Explosive Devices (IEDs), resulting in increased injury severity and complexity. Additionally, these wounds are often more contaminated due to the mechanism of injury.²

In recent conflicts, the use of IEDs has increased immensely, peaking in 2010.³ Recent data have shown that blast injuries account for up to 78% of casualties sustained in current conflicts in Iraq and Afghanistan.^{2,4,5} Of these cases, 54% affected the extremities with an equal distribution between the upper and lower limbs.^{6,7} Specifically in the lower extremity, the common peroneal and tibial nerves were most at risk.⁸

The conflicts in Afghanistan and Iraq have shown the lowest US case-fatality rates in history. This is largely attributed to improvements in protective equipment, administration of battlefield medical care, and the medical evacuation (MEDEVAC) process. Modern battlefield medical care has increased the utilization of tourniquets, blood transfusions,

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and rapid pre-hospital transport. Due to these advancements, a greater number of warfighters are surviving with more complicated injuries (including PNIs) than ever before.^{2,4} Body armor has contributed to increased patient survival with more complex peripheral nerve injuries because it is designed to protect the vital internal organs, leaving the extremities vulnerable to injury.⁹⁻¹¹

Despite a growing amount of recent literature regarding CSPNIs, there is still a relative lack of information on the treatment and outcomes of CSPNIs. The goal of this study is to report the outcomes of lower extremity CSPNIs encountered in a military multidisciplinary peripheral nerve clinic. We hypothesize that decreased time to evaluation and treatment will lead to improved outcomes.

METHODS

The Peripheral Nerve Consortium (PNC) is a multidisciplinary cohort of orthopedic surgery, plastic surgery, neurosurgery, neurology, physical medicine and rehabilitation, and pain management providers who collaborate to evaluate, diagnose, and treat complex peripheral nerve injuries for the United States military service members, allied service members, and veterans. The PNC prospectively collects and maintains a secure, anonymized database with demographic information, injury patterns, initial stabilization procedures, and peripheral nerve injury characteristics.

All patients were wounded-in-action in either Operation Iraq Freedom (OIF) or Operation Enduring Freedom (OEF) and survived through follow-up. All patients in the database were included because they all had complete peripheral nerve injury data. Cases of combat-sustained, lower extremity PNI were identified from the database, which was retrospectively reviewed between 2004 and 2009. Demographic information, injury year and conflict, time to initial evaluation, mechanism of injury (ie, IED, rocket-propelled grenade, gunshot wound), type of injury (ie, penetrating, blunt, or stretch), stabilization procedures (ie, fasciotomy, amputation), and nerve injury (ie, complete or incomplete) were recorded. The determination of complete versus incomplete injuries was determined from documentation of initial injury stabilization and electrodiagnostic. Nerve injuries were included if the nerve deficits involved motor and sensory function. If multiple nerves (>2) were injured proximally to their terminal branches, the injuries were categorized into lumbar plexus with sacral plexus injuries included in this group.

Electrodiagnostic findings of electromyography (EMG) and nerve conduction studies (NCS) were scored on a scale from 0 to 2. These correlated with complete injury, incomplete injury, and normal electrodiagnostic studies as 0, 1, and 2, respectively; unfortunately, these were not recorded for all patients. The time to initial evaluation as well as the final follow-up with the PNC was recorded. At this point, the peripheral nerve injury was scored according to the Sunderland classification by a consensus from the PNC (Sunderland). At the final follow-up, motor strength and sensory function were reported as a consensus from the multidisciplinary PNC.

Motor testing was conducted in accordance with the British Medical Research Council (MRC) Score of muscle strength.¹² Sensory testing was conducted per the modified British Medical Research Council Score of sensory recovery.¹³ This score reports sensory nerve function as S0: absence of sensibility, S1: recovery of deep cutaneous pain, S1+ recovery of superficial pain, S2: recovery of some degree of superficial cutaneous pain, S3: return of pain and tactile sensibility, static 2 point discrimination (s2PD) >15 mm, S3+: s2PD 7–15 mm, S4: s2PD < 7 mm. For the ease of recording (Birch: outcomes), we graded all S3+ and greater as 2, S1–S3 as 1, and absence of sensation as 0. A recovery was deemed functional when $M \geq 3$ and $S \geq 3$.¹⁴

In our calculations, we used the raw number of PNIs identified instead of the total number of patients, as a single patient could have multiple PNIs. Injury characteristics were totaled, and percentages were reported. Nerves were categorized as complete or incomplete based on the description from the initial analysis by the PNC. Time to initial evaluation and follow-up were recorded as the average number of days with the SD. To compare multiple non-parametric independent groups of continuous variables, the Kruskal–Wallis test was utilized.^{9,15,16} Spearman's coefficient was used to evaluate correlations between motor and sensory outcomes with Sunderland score. Spearman correlation was also used to evaluate the association between motor/sensory evaluations with days to initial evaluation as well as to correlate days to initial evaluation with final sensory outcomes. In addition, odds ratios were calculated for chi-squared tests on any 2 binary variables.

This was a database study, and all available data were used. A post hoc analysis was used to show we had achieved sufficient power with the given sample size of 144 nerves.¹⁰ For any given bivariate correlation, sufficient power of 94% was achieved to find at least a small to medium effect size ($|\rho| = 0.2$). For the resulting Kruskal–Wallis tests, the study achieved appropriate power for only a medium to large effect size ($f = 0.3$).

RESULTS

Over the study period, 104 military service members sustained 144 PNIs. The average age was 26.7 years, and nearly all were men (98.1%). Patients were evaluated by the PNC at an average of 5 months after injury and were followed for an average of 19 months. Most of the lower extremity PNIs were penetrating injuries (75.7%) sustained by an IED (56.6%), and the most common nerve injured was the peroneal nerve (Table 1).

There was no correlation between Sunderland classification and specific PNI, injury type, or time to evaluation. Higher Sunderland classifications were found to be correlated with worse final motor ($r = 0.51$, $P < 0.001$) and final sensory ($r = 0.41$, $P < 0.001$) scores (Table 2 and 3). The age of the patient was not correlated with Sunderland classification of injury (Table 3).

Final motor and sensory scores were not associated with specific nerve injury, mechanism of injury (Table 4). Worse initial EMG studies were associated with worse final motor nerve function ($P = 0.024$). Shorter time to initial

Table 1. Demographics of Military Peripheral Nerve Injuries (PNI)

Patients	104
Average age (y)	26.72 (7.54)
Gender (% men)	102 (98.1)
Months to initial evaluation	5 (8.96)
Average follow-up (mo)	14 (17.97)
PNI	
Mean number of PNI per patient	1.4 (0.53)
Mechanism of injury	
Improvised explosive device	82 (56.6)
Gunshot wound	27 (18.8)
Rocket propelled grenade	21 (14.6)
Motor vehicle collision	8 (5.6)
Other	6 (4.2)
Type of injury	
Penetrating	109 (75.7)
Blast	29 (20.1)
Stretch	6 (4.2)
Specific PNI (% of complete injury per nerve)	Total number (% of all PNI)
Peroneal	56 (38.6)
Complete	10
Incomplete	46
Tibial	48 (33.1)
Complete	2
Incomplete	46
Femoral	8 (5.5)
Complete	0
Incomplete	8
Sciatic	23 (15.9)
Complete	3
Incomplete	20
Lumbar plexus	10 (6.9)
Complete	0
Incomplete	10
Associated injuries	
Multiple nerve injuries	97 (66.9)
Associated fractures	95 (65.5)
Traumatic brain injury	60 (41.4)
Compartment syndrome	57 (39.3)
Vascular injury	42 (30.3)
Amputation	33 (22.8)

assessment trended toward improved final motor and sensory scores but was not found to be statistically significant ($\rho = 0.11$, $P = 0.218$; $\rho = 0.14$, $P = 0.112$, respectively).

There was also a trend but no statistical significance between blast injuries (RPG and IED) and a necessity of grafting (75%) required instead of direct nerve repair when compared to other mechanisms of injury (33%, $P = 0.086$). IED as a mechanism was significantly associated ($P = 0.036$) with amputation as treatment compared with nerve repair or grafting when compared with all other mechanisms (RPG, MVC, GSW, Other). A complete

Table 3. Sunderland Correlation with Final Motor, Final Sensory, and Age

	Motor	Sensory	Age
Sunderland	-0.510	-0.406	0.027
<i>P</i>	<0.001	<0.001	0.786

Spearman's rho correlation calculated for motor, sensory and age.

description of the surgical procedure by the mechanism of injury is outlined in Table 5. No differences in final sensory or motor scores were seen based on surgical procedure ($P = 0.1651$ and $P = 0.4605$, respectively) (Table 6).

DISCUSSION

In contemporary warfare, there is an increased survival of casualties with severe injuries, which historically were unsurvivable. Advancements in tactical medical care, protective equipment such as body armor, and more efficient evacuation strategies have improved patient survival.^{17–20} As a result, service members may have CSPNI that are more severe than in previous wars. The purpose of our study was to evaluate outcomes in lower extremity CSPNI. We hypothesized that shorter time to evaluation would result in improved outcomes. This study demonstrated 3 key findings: (1) the peroneal and tibial nerves were most commonly affected by wartime injuries; (2) higher-grade injuries by Sunderland classification were associated with worse motor and sensory outcomes; (3) no statistical association was found between time to evaluation or age of patient to final nerve outcomes for both motor and sensory function.

In modern combat, there has been an increased reliance on blast mechanisms to injury service members (IED, GSW, and RPG). We did not find a correlation between the mechanism of injury and final motor or sensory outcome for CSPNI (motor $P = 0.678$, sensory $P = 0.091$). There was a near-significant difference for final sensory with GSW mechanism, resulting in the worst outcomes. Additionally, we did find evidence that blast injuries caused more extensive injury than other mechanisms of injury on nerves. This is supported by the high rate of nerve grafting required in these cases (75%). Specifically, for IED there was a significantly higher rate of amputations than nerve grafting and repair combined compared with other mechanisms of injury. However each of these mechanisms constitutes a high-energy injury, and it is

Table 2. Sunderland Classification by Nerve Injured, Injury Type, and Days to Initial Evaluation, with the Highest Frequency per Nerve

Sunderland	1	2	3	4	5	Average
Peroneal	1 (2.4)	14 (33.3)	10 (23.8)	15 (35.7)	2 (4.8)	3.07
Tibial	3 (8.3)	13 (36.1)	5 (13.9)	11 (30.6)	4 (11.1)	3.00
Femoral	1 (2.0)	3 (6.0)	—	1 (2.0)	—	2.20
LP	—	—	3 (5.0)	1 (16.7)	2 (33.3)	3.83
Sciatic	1 (6.7)	6 (40)	3 (20)	3 (20)	2 (13.3)	2.93
Blunt	1 (4.2)	9 (37.5)	4 (16.7)	8 (33.3)	2 (8.3)	3.04
Penetrating	3 (4.1)	26 (35.6)	17 (23.3)	20 (27.4)	7 (9.6)	3.03
Stretch	1 (16.7)	1 (16.7)	—	3 (5.0)	1 (16.7)	3.33
Mean days (SD)	157.83 (312.52)	103.11 (141.12)	366.48 (493.66)	110.39 (224.71)	89.40 (80.39)	150.06 (268.8)
Median days (IQR)	39 (220)	44.5 (98)	117 (616)	50 (87)	90.5 (177)	55.5 (125)

LP: Lumbar plexus.

Table 4. Final Motor and Sensory by Specific Nerve Injury, Mechanism of Injury, and Initial EMG

Final motor	0	1	2	3	4	5	Average final motor	Final sensory	0	1	2	Average Final Sensory
Peroneal	10 (20)	6 (12)	12 (24)	5 (10)	14 (28)	3 (6)	2.32	Peroneal	4 (8)	41 (82)	5 (10)	1.02
Tibial	4 (9.1)	9 (20.5)	10 (22.7)	6 (13.6)	13 (29.5)	2 (4.5)	2.48		2 (4.5)	37 (84.1)	5 (11.4)	1.07
F	1 (16.7)	2 (33.3)	1 (16.7)	1 (16.7)	1 (16.7)	—	1.83		—	6 (100)	—	1.00
LP/LS	2 (25)	1 (12.5)	—	—	5 (62.5)	—	2.63		1 (11.1)	8 (88.9)	—	0.89
Sciatic	4 (21.1)	2 (10.5)	4 (21.1)	2 (10.5)	6 (31.6)	1 (5.3)	2.37		3 (15)	17 (85)	—	0.85
Motor	0	1	2	3	4	5	Average final motor	Sensory	0	1	2	Average final sensory
GSW	7 (29.2)	1 (4.2)	3 (12.5)	5 (20.8)	7 (29.2)	1 (4.2)	2.29		4 (16.7)	19 (79.2)	1 (4.2)	0.88
IED	10 (13.7)	10 (13.7)	17 (23.3)	7 (9.6)	25 (34.2)	4 (5.5)	2.53		5 (6.7)	65 (86.7)	5 (6.7)	1.00
PRG	3 (14.3)	7 (33.3)	4 (19)	2 (9.5)	4 (19)	1 (4.8)	2.00		—	18 (85.7)	3 (14.3)	1.14
MVC	1 (25)	—	2 (50)	—	1 (25)	—	2.00	MVC	—	4 (80)	1 (20)	1.20
Other	—	2 (40)	1 (20)	—	2 (40)	—	2.40	Other	1 (25)	3 (75)	—	0.75
Motor	0	1	2	3	4	5	Average final motor	Sensory	0	1	2	Average final sensory
EMG								NCS				
0 (complete)	8 (23.5)	8 (23.5)	8 (23.5)	2 (5.9)	8 (23.5)	—	1.82	0	2 (5.9)	31 (91.2)	1 (2.9)	0.97
1 (abnormal)	3 (10.3)	3 (10.3)	8 (27.6)	2 (6.9)	8 (27.6)	5 (17.2)	2.83	1	1 (3.4)	26 (89.7)	2 (6.9)	1.03
2 (normal)	—	—	—	2 (66.7)	1 (33.3)	—	3.33	2	—	3 (100)	—	1.00

Kruskal Wallis *P* (MOI/Motor): 0.678; Kruskal Wallis *P* (MOI/Sensory): 0.091; Kruskal Wallis *P* (EMG/Motor): 0.024 (difference is from 0 versus 1, *P* = 0.039 from pairwise comparisons with Bonferroni correction)Kruskal Wallis *P* (NCS/Sensory): 0.707

Table 5. Surgical Procedures

	GSW	IED	MVC	RPG	Other	Total
Amputation	5	21	0	3	0	29
Graft	3	6	0	0	0	9
Repair	5	1	1	1	0	8
Neurolysis	2	2	0	0	1	5
New fasciotomy	5	28	2	6	2	43
No surgery	7	22	5	10	3	47
Total	27	80	8	6	20	141

Monte Carlo estimation for the Fisher exact test for all forms of treatment (*P* = 0.0401); Monte Carlo estimation between nerve repair and nerve graft (*P* = 0.056). GSW, gunshot wound; IED, improvised explosive device; MVC, motor vehicle crash; RPG, rocket propelled grenade.

not surprising that we found few significant differences between the mechanism of injury and final motor function and final sensory function.

The common peroneal nerve was found to be the most common injured nerve in our study, comprising 38.6% of CSPNI, followed by the tibial nerve in 33% of cases. These nerves were injured likely most often due to their anatomic location being most distal in the lower extremities. Improvised explosive devices are most commonly used by burying them underground; therefore, their destructive

force would most likely affect the most distal part of the lower extremity first. The slightly higher prevalence of peroneal nerve injury we believe to be due to the superficial course of the peroneal nerve, as it courses around the fibular head laterally, and that the nerve is relatively affixed at this location. Explosive forces are known to produce a shock wave that can cause a significant amount of energy passing through soft tissues,²¹ and therefore there is a lot of potential for a stretch on the nerve, with focal areas of restricted movement.

This study found that higher-grade injuries by Sunderland Classification correlated with worse final outcomes in motor and sensory scores. These more significant injuries have a greater amount of the factors that normally aid in nerve regeneration disrupted such as endo- and perineurium. Supporting this was the significant association between initial EMG studies and final motor strength (*P* = 0.024) with worse initial EMG study portending worse final motor strength. Combined, these show that final nerve outcome is intimately dependent on the initial nerve injury.

This study did not find any correlation with age and final nerve outcome in this study when looking at motor and sensory nerves. Younger patients have better recovery after nerve injuries.²²⁻²⁴ He et al has shown that there

Table 6. Type of Nerve Surgery by Outcome

Motor	0	1	2	3	4	5	Average Final Motor	Sensory	0	1	2	Average Final Sensory
Amputation	5 (17.9)	5 (17.9)	5 (17.9)	4 (14.3)	7 (25)	2 (7.1)	2.32	Amputation	4 (13.8)	24 (82.8)	1 (3.4)	0.9
Graft	4 (44.4)	1 (11.1)	1 (11.1)	1 (11.1)	1 (11.1)	1 (11.1)	1.67	Graft	1 (11.1)	8 (88.9)	—	0.89
Repair	2 (28.6)	1 (14.3)	2 (28.6)	1 (14.3)	1 (14.3)	—	1.71	Repair	—	6 (85.7)	1 (14.3)	1.14
Neurolysis	—	—	2 (50)	—	2 (50)	—	3.00	Neurolysis	1 (25)	3 (75)	—	0.75
New fasciotomy	4 (11.1)	3 (8.3)	12 (33.3)	4 (11.1)	11 (30.6)	2 (5.6)	2.58	New fasciotomy	3 (8.6)	30 (85.7)	2 (5.7)	0.97
No surgery	5 (11.9)	10 (23.8)	5 (11.9)	4 (9.5)	17 (40.5)	1 (2.4)	2.50	No surgery	—	37 (86)	6 (14)	1.14
Total	20 (15.9)	20 (15.9)	27 (21.4)	14 (11.1)	39 (31)	6 (4.8)	2.40	Total	9 (7.1)	108 (85)	10 (7.9)	1.01

Motor: Monte Carlo estimation for all forms of treatment (*P* = 0.4605); Monte Carlo estimation between nerve repair and nerve graft (*P* = 0.9605). Sensory: Monte Carlo estimation all forms of treatment (*P* = 0.1651); Monte Carlo estimation between nerve repair and nerve graft (*P* = 0.6987).

was a significant difference in nerve regeneration with poorer outcomes in patients over 50 years compared with younger.²² Most active duty personnel in combat roles are men <30 years old and were the focus of this study. Our study had only 1 patient over the age of 50 years. The minimal variability in age makes finding an age-dependent difference in nerve recovery difficult.

Earlier evaluation and treatment may play a role in outcomes for these patients. Although we did not find a significant association between time to evaluation and the final outcome, there was a trend for an association in sensory nerve final outcome ($P = 0.112$). Time to proper evaluation is a challenge in the battlefield setting for several reasons to include distracting injuries, inconsistent handoff between levels of care, and in the severely injured prolonged periods of sedation. Other studies^{2,8} have supported earlier evaluation and treatment of PNIs leading to better outcomes. Methods that can be implemented in the future to prevent delayed diagnosis and treatment include standardized neurologic examinations that are to be performed at specific levels of care and increased teaching to forward-deployed units so that they actively try and identify nerve injuries. Ultimately, outcomes from nerve repair are similar when performed in a delayed fashion compared with acute repair after injury²⁵ with ideal repair within a few weeks to months of injury.²⁶

This investigation had 3 main limitations. First, this study is a retrospective review of data collected early in the life of the US Military PNC resulting in incomplete records such as operative reports. Second, we had inconsistent treatment and diagnostic evaluation performed on patients to include electrodiagnostic studies. Third, it includes irregular follow up, which is partially attributed to the nature of military service as members move duty stations and leave service. The future direction of the PNC is for stricter data input, standardized evaluation of peripheral nerve injury, and diagnostic tool usage, as well as, the inclusion of new functional outcome information such as return to duty and ability to perform military physical fitness testing.

The severity and complexity of CSPNIs will continue to progress as the nature of combat weaponry evolves. This makes this analysis important in the current assessment and treatment of these combat-related injuries, especially with the recent increased use of improvised explosive devices. We conclude that the proper treatment of CSPNI requires early identification and intervention to prevent worse outcomes.

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