Performance-based Differences in Prefrontal Cortex Activation

Assessing Dynamic Marksmanship Performance Using Functional Near-Infrared Spectroscopy

Owen F. Salmon, MS[1]; Thomas X. Statz[2]; Cierra B. Ugale, MS[3]; Matthew D. Segovia, MS[4]; Joshua R. Thompson, BS[5]; Hunter D. Dobbs, BS[6]; Rachel M. Rauth, BS[7]; Cory M. Smith, PhD[8]*

ABSTRACT

Introduction: Marksmanship is a fundamental skill for all servicemembers. However, the underlying neurophysiological differences in performance among marksmen remain unclear. Incorporating neurophysiological tracking such as functional near-infrared spectroscopy (fNIRS) may identify performance-based differences in prefrontal cortex (PFC) activation during dynamic marksmanship scenarios. This study examined cognitive load within the PFC during a simulated dynamic marksmanship scenario in non-proficient and proficient marksmen. **Methods:** Twenty-four participants (12 men, 12 women) wore an fNIRS device over their forehead during a simulated stationary pistol marksmanship task (to determine proficiency status) and a dynamic shoot/no-shoot course of fire (COF) (to assess cognitive load). Relative concentrations of oxyhemoglobin (HbO_2), deoxygenated hemoglobin (deoxygenated Hb), and total hemoglobin (total Hb) were tracked to quantify PFC activation differences in twelve proficient (≥80% hit percentage) and twelve non-proficient (<80% hit percentage) marksmen. **Results:** No difference in completion time was observed between groups during the dynamic COF (p=.34). However, non-proficient marksmen showed 26.3% higher HbO_2 (p=.02) and 42.1% higher total Hb (p<.01) in the PFC compared to proficient marksmen. **Conclusion:** Tracking PFC hemodynamic activity identified proficiency-based differences in cognitive load during a dynamic COF. Applying fNIRS during marksmanship-related tasks may be useful in developing stress resilience and mission readiness for servicemembers.

Keywords: *marksmanship; functional near-infrared spectroscopy; cerebral hemodynamics; motor skills; psychomotor performance; task performance and analysis; military*

Introduction

Marksmanship is a critical sensorimotor skill required for all active duty servicemembers regardless of their military occupational specialty. Under dynamic marksmanship environments, optimizing marksmanship performance requires complex cognitive processes that are heavily influenced by the prefrontal cortex (PFC).[1,2] The PFC plays a crucial role in executive function, adaptive behavior, and higher-order cognitive processes essential for proficient performance in dynamic marksmanship scenarios.

The combined physical and psychological stress associated with real-world operations has been shown to result in perceptual distortions, tunnel vision, reduced fine motor skills, and loss of situational awareness.[3–7] We hypothesize that the impaired marksmanship performance may be caused by excessive strain on cognitive resources, leading to heightened PFC activation as the servicemember is overwhelmed by competing cognitive inputs, ultimately resulting in poor performance.[8,9] For example, Johnson and colleagues reported that 72% of the performance variability in proficient marksmen was accounted for by the activation over the frontal lobe, while only 37% of performance variability was accounted for in non-proficient marksman during a lethal force judgment exercise.[10] Thus, quantifying the degree of cognitive load during operational tasks, such as marksmanship and lethal force decision-making, remains critical, highlighting the need for knowledge products that can rapidly improve the operational performance of non-proficient servicemembers.

Despite its importance, proficiency in marksmanship during qualification courses generally consists of static assessments, where individuals have the foreknowledge of the drills, targets, and distances they will be firing upon before being evaluated.[11] While this standardized approach is useful for categorizing general proficiency levels in weapon handling, its translation to real-world dynamic lethal force scenarios may be limited.[12–14] To better quantify mission readiness in terms of marksmanship ability, it is essential to look beyond performance outcome metrics, such as hit percentage, and look into the cognitive load associated with marksmanship tasks.[15–17]

Functional near-infrared spectroscopy (fNIRS) is a portable, non-invasive neuroimaging technique that quantifies relative changes in oxygenated hemoglobin (HbO_2) and deoxygenated hemoglobin (Hb) to infer neural activation in brain regions associated with cognitive and motor tasks.[18–20] Recently, fNIRS has been applied to the prefrontal cortex (PFC) to identify differences in hemodynamic activity during cognitive and dexterity tasks based on proficiency levels.[21–24] It is effective for tracking PFC activity, such as executive function, inhibitory

*Correspondence to owen_salmon1@baylor.edu
[1]**Owen F. Salmon**, [2]**Thomas X. Statz**, [3]**Cierra B. Ugale**, [4]**Matthew D. Segovia**, [5]**Joshua R. Thompson**, [6]**Hunter D. Dobbs**, [7]**Rachel M. Rauth**, and [8]**Dr. Cory M. Smith** are affiliated with Robbins College of Health and Human Sciences, Human & Environmental Physiology Laboratory, Department of Health, Human Performance and Recreation, Baylor University, Waco, TX.

control, working memory, and cognitive flexibility, which are essential components during lethal force scenarios.[25,26] Due to its portability and ability to handle motion artifacts, fNIRS has advantages as an operational marker of cognitive load during dynamic lethal force marksmanship compared to other physiological-based wearable sensors such as heart rate,[27,28] skin conductance,[29] and electroencephalography.[30] Thus, this study examined the cognitive load of the PFC using fNIRS during a simulated dynamic marksmanship scenario in non-proficient and proficient marksmen.

Methods

Participants

Twenty-four healthy participants (12 men and 12 women) participated in the study (Table 1). All participants were self-reported novice marksmen (<5 hours of marksmanship practice per month) and demonstrated the fundamental knowledge and skillset to safely handle and discharge the inert pistol used throughout the study. Additionally, all participants had normal or corrected-to-normal vision and were free from any musculoskeletal injuries or neuromuscular disorders that would limit their pistol handling. Prior to enrolling in the study, all participants gave informed consent, filled out a health history questionnaire, and verified that they abstained from alcohol and caffeine consumption for 12 hours before the marksmanship testing. This study complied with the tenets of the Declaration of Helsinki and was approved by the Institutional Review Board (2004812).

The single-visit, within-subject design was used to assess the feasibility of fNIRS applied to the PFC to assess proficiency-based differences in cognitive load during a simulated close-quarters shoot/no-shoot marksmanship task (Figure 1). The laboratory visit began with sensor placement of the fNIRS equipment on the participant's forehead, followed by an introduction to the marksmanship simulator and the inert pistol used during the marksmanship tasks. During the familiarization period, each participant performed 5–10 practice shots on a projected target displayed at 3.04m, which allowed the participants to become comfortable with the recoil of the inert pistol and served to calibrate their shot dispersion pattern to the marksmanship simulator.

Following the practice shots, each participant transitioned to a stationary marksmanship task used to quantify marksmanship proficiency. The stationary marksmanship task was adapted from the U.S. Army Pistol Qualification Course Table IV.[31]

TABLE 1 *Participant Characteristics*

Characteristic	Group; mean (SD)*	
	Proficient marksmen; n=12	Non-proficient marksmen; n=12
Sex		
Male	8	4
Female	4	8
Age, y	27.3 (6.1)	23.3 (5.7)
Height, cm	163.4 (37.6)	171.2 (7.3)
Weight, kg	77.4 (25.4)	68.6 (11.0)
BMI, kg/m^2	26.3 (3.6)†	23.4 (3.0)
Resistance training, h/wk	4.3 (2.3)	3.2 (1.8)
Aerobic (cardio) training, h/wk	2.5 (1.7)	3.3 (2.4)
Marksmanship		
Stationary hit percentage	86.7 (7.8)†	42.5 (18.7)
Dynamic time to completion, s	141.9 (31.0)	163.8 (71.6)

*Unless otherwise specified.
†Significantly greater at $p<.05$.

It required participants to fire single shots upon 10 stationary human-silhouette (E-1) targets, presented individually or in doublets across nine engagement scenarios. Each target was projected at simulated distances ranging from 7–31 meters, with an exposure time of five seconds per scenario and a two-second shot delay between scenarios (Appendix A). Overall marksmanship performance was assessed by quantifying the number of hits on target. If a participant hit eight or more targets (≥80% hit percentage), they were allocated into a "proficient" marksmen group, which is a hit percentage rate between sharpshooter and expert level marksmen status.[31] Alternatively, if a participant hit less than eight targets (<80% hit percentage) they were allocated into a "non-proficient" marksmen group (Figure 1). Participants did not receive specific feedback regarding their overall performance and were blinded to their group allocation.

Following the stationary marksmanship task, each participant transitioned to a dynamic close-quarters shoot/no-shoot task that projected friendly and non-friendly human-silhouette targets in randomized order (Figure 1). The dynamic nature of the course simulated the participant moving through an office environment, while randomized friendly and non-friendly targets were projected onto the screen, either as stationary targets or targets that moved vertically or horizontally behind barriers. Each non-friendly target was randomized to be knocked down with 1–3 shots on target, and each non-friendly target had to

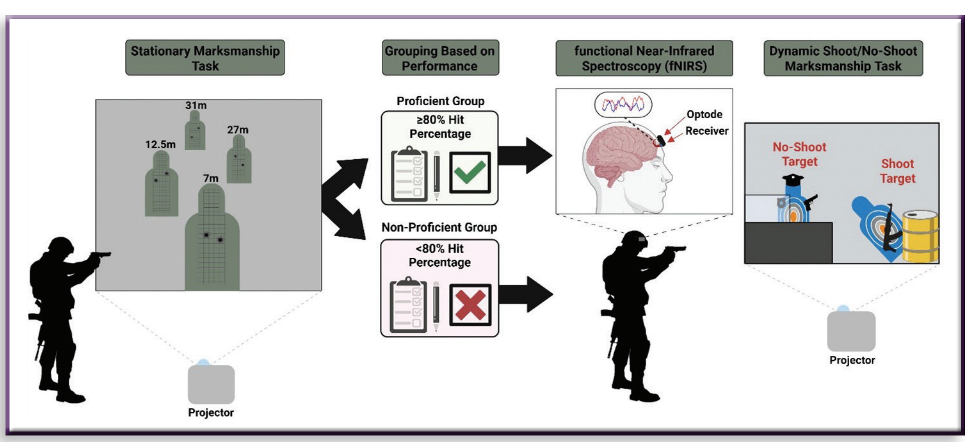


FIGURE 1 *Overview of study protocol (Created in BioRender. Smith, C. (2025) https://BioRender.com/b0o86vt).*

be knocked down to allow the participant to continue through the course. After completing both marksmanship tasks, the inert pistol was holstered, the fNIRS sensors were removed, and the study visit was completed.

Hemodynamic Monitoring of the Prefrontal Cortex

To quantify changes in hemodynamics within the PFC, a continuous wave fNIRS probe (PortaLite MkII. Artinis Medical System, Elst, Utrecht, The Netherlands) was placed 2cm above the right eyebrow for each participant and adhered to the skin using hypoallergenic double-sided tape. To further secure the sensor to the participant's head and protect the sensor from contamination by ambient light exposure, the sensor was wrapped with a black disposable foam elastic bandage around the participant's head (3M Corporation, St. Paul, MN, USA). The fNIRS sensor consisted of three light-emitting diodes and two detectors, placed at inter-optode distances of 2.9, 3.5, and 4.1cm for the three long channels and 0.70, 0.80, and 0.74cm for the three short channels. The control unit was synced to a laboratory desktop (HP Envy Desktop. HP Inc., Palo Alto, CA) via a Bluetooth dongle and placed in a belt bag secured to the participant's hip. All fNIRS-derived hemodynamic concentrations (HbO_2, deoxygenated Hb, and total Hb) were collected at a sampling frequency of 25Hz and telemetrically sent to the desktop and visualized using Oxysoft software (version 3.4, Artinis Medical Systems B.V., Elst, Utrecht, The Netherlands).

Stationary and Dynamic Shoot/No-Shoot Marksmanship Tasks

The screening protocol and the shoot/no-shoot course of fire (COF) were performed using an inert recoil-enabled Glock 17 pistol (Laser Ammo Ltd., Great Neck, NY), equipped with a custom drop-in barrel. The barrel was customized to have an infrared SureStrike vibration-activated laser integrated into the end of the barrel. To simulate recoil, pressurized green gas (Elite Force Airsoft, Fort Smith, AR) was loaded into the hollow magazine chamber before being inserted into the magazine housing. The screening protocol was a custom design course built into the "M-Range" software add-on using the Smokeless Range 2.0 Judgmental and Marksmanship Shooting Simulator (Laser Ammo Ltd., Great Neck, NY). Similarly, the shoot/no-shoot COF was also performed using the Smokeless Range simulator; however, a pre-designed course in the Tactical Targets software (standardized Course #6) was used.

During both the screening and shoot/no-shoot COF, each participant stood approximately 3.05m from a white wall with a projected display area corresponding to 1.83x2.74m (ViewSonic Home theater PA503S DLP Projector. ViewSonic Inc., Brea, CA, USA). To assess target hits and misses and display the total number of shots fired, a short-throw camera (Laser Ammo Ltd., Great Neck, NY) was mounted behind the projector and calibrated to detect the appropriate display area. Prior to completing the stationary marksmanship task and the shoot/no-shoot COF, the marksmanship simulator was calibrated to adjust for light fluctuations and screen parameters.

Hemodynamic Processing

Throughout the entire visit, the relative concentration values of HbO_2, deoxygenated Hb, and total Hb were calculated using the modified Beer-Lambert law equation using Oxysoft (version 3.4, Artinis Medical Systems B.V., Elst, The Netherlands) with the differential pathlength factor calculated based on a standardized age-based equation.[32] The fNIRS data obtained during the dynamic shoot/no-shoot task was segmented out from the total visit based on the time duration of the task. The data was then filtered for Mayer waves, respiration, and heart pulsation through the examination of the power density spectrum and by applying a low pass filter at 0.14Hz.

After filtering the data, the hemodynamic signals (HbO_2, deoxygenated Hb, and total Hb) from each of the three long channels (2.9, 3.5, and 4.1mm) were averaged together to represent one regional relative concentration value of HbO_2, deoxygenated Hb, and total Hb of the PFC. To quantify the time course of changes during the dynamic shoot/no-shoot task, the relative concentration values were bin-averaged into quartiles based on the total duration of the dynamic shoot/no-shoot marksmanship task (Table 1). The segmentation, filtering, and analysis of the fNIRS-derived hemodynamic response during the dynamic shoot/no-shoot task were performed offline using custom-built LabView programs (LabView Professional 2022, NI, Austin, TX).

Statistical Methods

For participant characteristics, marksmanship screening score, and total time of COF, an independent *t* test was performed to compare groups. For fNIRS parameters, a linear mixed effects model (LMM) with fixed effects for the marksmanship group (proficient marksmen and non-proficient marksmen) and time (Q_1, Q_2, Q_3, and Q_4) with random effects for intercept and participant were performed. Accounting for participant differences across all groups as a composite allowed for the examination of group differences across the time course of the shoot/no-shoot task.

For all LMMs, post hoc analyses using Fisher's Least Significant Difference (LSD) were used on all pairwise comparisons. The effect sizes for independent *t* tests were calculated using Cohen's *d* with allocated benchmarks consisting of small (d=.2), medium (d=.5), and large (d=.8).[33] All analyses were conducted using SPSS (version 29, IBM SPSS Inc., Chicago, IL), and an alpha level $p \leq .05$ was considered statistically significant for all comparisons.

Results

There were no significant differences between age, height, weight, resistance training, aerobic training, and time to complete the dynamic marksmanship task between marksmanship groups (d=.28–.68; p=.08–.24). There was a significant difference in body mass index (BMI) between groups, indicating the proficient marksmanship group had a higher BMI than the non-proficient marksmanship group (d=.90; p=.04) (Table 1). For the stationary marksmanship task, the average hit percentage for the proficient marksmanship group (86.7%) was significantly greater than the non-proficient marksmanship group (42.5%) (d=3.09; p<.001).

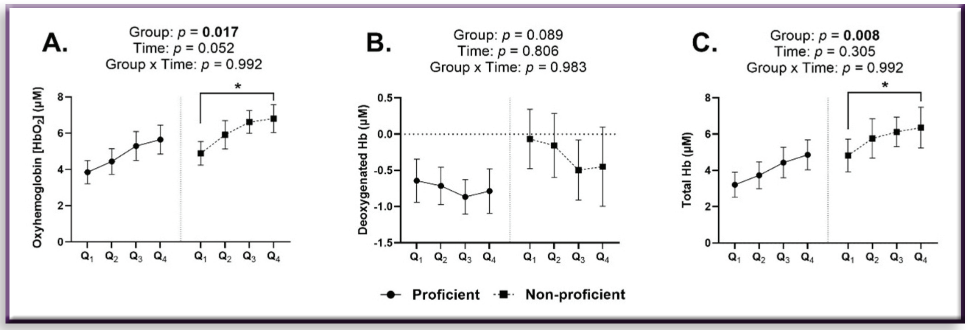
There was no significant group-by-time interaction, nor main effect for time for HbO_2 (Table 2). However, a significant difference in group indicated that the non-proficient marksmen had a 26.3% greater HbO_2 response on average than the proficient marksmen throughout the dynamic marksmanship COF (Figure 2A). For deoxygenated Hb, there was no significant group-by-time interaction nor main effects for time or group (Table 2). For total Hb, there was no significant group-by-time interaction nor main effect for time (Table 2; Figure 2B).

TABLE 2 *Interaction and Main Effect Results Based on the Mixed Effects Model Performed on fNIRS-derived Hemodynamic Responses During the Dynamic Shoot/No-Shoot Marksmanship Task*

	fNIRS-derived Hemodynamic Responses of the Prefrontal Cortex					
	HbO_2, μM		Deoxygenated Hb, μM		Total Hb, μM	
Effect	***F***	***P* value**	***F***	***P* value**	***F***	***P* value**
Group	$F_{1,87.47}$=5.88	0.017	$F_{1,88}$=2.97	0.089	$F_{1,88}$=7.38	0.008
Time	$F_{3,87.01}$=2.67	0.052	$F_{3,88}$=0.33	0.806	$F_{3,88}$=1.23	0.305
Group x time	$F_{3,87.01}$=0.34	0.992	$F_{3,88}$=0.05	0.983	$F_{3,88}$=.03	0.992

fNIRS = functional near-infrared spectroscopy.

FIGURE 2 *Functional near-infrared spectroscopy (fNIRS)-derived relative concentration values (mean ± SD) for oxyhemoglobin (HbO_2)* **[A.]**, *deoxyhemoglobin (deoxygenated Hb)* **[B.]**, *and total hemoglobin (total Hb)* **[C.]** *captured from the prefrontal cortex (PFC) and averaged across five time points (Q_1, Q_2, Q_3, and Q_4).*



-●- represents the proficient marksmanship group, and ■ represents the non-proficient marksmanship group.
*Significant main effect for group in which non-proficient > proficient (p<.05).

There was, however, a significant difference in group which indicated that on average, the non-proficient marksmen had a 42.1% greater total Hb response than the proficient marksmen throughout the dynamic marksmanship COF (Figure 2C).

Discussion

This study investigated the feasibility of using fNIRS to assess cognitive load differences between proficient and non-proficient marksmen during a dynamic shoot/no-shoot pistol marksmanship task. The results indicated that non-proficient marksmen exhibited significantly higher levels of PFC activation (as indicated by a 26.3% greater HbO_2 and 42.1% greater total Hb relative to proficient marksmen), while deoxygenated Hb remained unchanged (Figure 2A–C). Despite no significant differences in completion time during the shoot/no-shoot pistol marksmanship task (p=.34), the increased PFC activation in the non-proficient group suggests a greater oxygenated blood flow requirement to support neural activity in the PFC, which may be indicative of heightened cognitive effort.[34,35]

These findings align with those of Ortiz and colleagues who reported elevated total Hb in the PFC of non-proficient drone pilots, linking greater PFC activation to increased cognitive demands relative to proficient pilots.[36] Additionally, Ortiz et al. also found that as proficiency increased, there was an inverse relationship between PFC total Hb and self-confidence in the task supporting the neural efficiency hypothesis, where more proficient individuals optimize cognitive resources more efficiently.[34] Similarly, comparative fNIRS studies across various domains including medical simulations,[37–41] aviation,[42,43] and laboratory-based cognitive tasks[22,44] consistently show that novices and low performers routinely exhibit greater PFC activation due to increased cognitive load and reduced task automation in both males and females.[22,23,43] Zohdi and colleagues (2023) found that individuals classified as low performers during a verbal fluency task had greater PFC activation (i.e., elevated HbO_2) than moderate and good performers.[22] Likewise, Leff et al. and Nemani et al. reported greater HbO_2 responses in the PFC of novice medical students during fine motor skill tasks (knot tying and pattern cutting)[38,39] than expert practitioners. Additionally, Mark et al. demonstrated that individuals who underwent neuroadaptive flight training exhibited reduced cognitive workload (i.e., reduced HbO_2) during a dynamic flight task relative to novice individuals.[43] Collectively, these findings reinforce the notion that greater PFC activation in less proficient individuals reflects an increased reliance on cognitive resources, which may contribute to reduced neural flexibility and constrained task performance in high-stakes environments or occupational settings.[22,36,38,39,43] In marksmanship, where rapid threat discrimination and precision are critical, reduced PFC activation in more proficient marksmen may indicate a greater ability to streamline cognitive processes, thereby mitigating performance decrements.

This feasibility study quantified hemodynamic differences in individuals stratified by performance during a marksmanship task and used the outcomes as a physiological indication of cognitive load. Despite the prominence of HbO_2 being reported in cognitive workload studies, the optimal fNIRS-derived marker to represent neural activity between HbO_2, deoxygenated Hb, or total Hb remains unclear, according to Luke and colleagues (preprint).[45] However, HbO_2 has been suggested to be more sensitive to task-related changes than deoxygenated Hb and shows greater test-retest reliability.[45] Moreover, total Hb, which represents the sum of HbO_2 and deoxygenated Hb, is less susceptible to extracerebral contamination and serves as a useful proxy measure of cerebral blood flow.[45,46] Given that this is one of the first studies to apply fNIRS to quantify cognitive load during a marksmanship task, we propose that HbO_2 and total Hb are the most sensitive indicators of increased cognitive load during dynamic pistol marksmanship, with differences in cortical activity based on proficiency levels aligning with the neural efficiency hypothesis (i.e., reduced PFC activity in more skilled marksmen).[34]

Beyond fNIRS-based applications, previous investigations into brain activity during rifle and pistol marksmanship tasks have used electroencephalography (EEG) to assess neural activity based on proficiency level (for a comprehensive review, refer to Martins and colleagues).[47] Decreased cortical activity has been linked to higher accuracy in stationary pistol marksmanship tasks,[48,49] and higher PFC coherence has been observed in proficient rifle shooters.[30] Additionally, global increases in theta, beta, and gamma power within the temporal and parietal regions during the shooting preparation stage (i.e., 6s before the shot) have been observed in proficient marksmen compared to less proficient marksmen and have been associated with improved attentional focus in skilled marksmen.[50,51] While different brain regions were highlighted in these studies, our fNIRS findings within the PFC align with these results, suggesting that proficient marksmen manage the demands of dynamic shooting tasks more efficiently than non-proficient marksmen (Figure 2). In the context of neuroimaging techniques, EEG is inherently more susceptible to motion artifacts within the head and upper body, which limits its applications to field applications that require dynamic movements or tactical engagements.[34] In contrast, fNIRS allows for natural movement, typically is smaller in size, and can be deployed in more real-world environments.[24] Thus, integrating fNIRS for military applications may be a robust and applicable neuroimaging technique for monitoring warfighter performance in training.

While this study provides novel insights into proficiency-based differences in PFC activation during dynamic marksmanship tasks, several limitations should be acknowledged. First, the sample consisted of civilians who would be considered novice marksmen, which may limit the generalizability of these findings to experienced shooters such as Special Operations Forces. While our findings align with the neural efficiency hypothesis, future research should include a broader range of expertise levels to determine whether similar trends exist in elite marksmen and servicemembers operating under high-stress conditions.

Second, although the study was designed to stratify participants based on marksmanship performance, it did not specifically account for potential sex-related differences in PFC activation, and as a result, the man-to-woman ratio differed between groups (proficient: 8 men / 4 women, non-proficient: 4 men / 8 women). Prior literature suggests that sex-based differences in PFC activation may exist during cognitive and motor tasks, potentially influencing the fNIRS-derived hemodynamic outcomes.[52–54] However, our statistical approach accounted for inter-individual variability by including the intercept as random factors, and sex differences were not anticipated to systematically impact marksmanship performance in this context. Future studies should consider balancing sex distribution across proficiency levels to clarify its influence on PFC activity during marksmanship.

Last, this study observed distinct patterns of PFC activation, as reflected in fNIRS-derived hemodynamic variables, between individuals stratified by proficiency level; however, causality cannot be definitively established. While greater cognitive load in non-proficient marksmen may indicate inefficient neural processing, it remains unclear whether skilled marksmen naturally exhibit lower cognitive load due to experience-driven efficiency. To determine any potential causality, future research should employ interventional studies that systematically increase or decrease PFC activation while measuring marksmanship outcomes. If cognitive training (e.g., neurostimulation, working memory enhancement) leads to improved accuracy, faster reaction times and better decision-making, it would suggest a direct causal link between PFC function and marksmanship ability.

Moving forward, fNIRS has the potential to be a field-ready physiological tool for real-time biofeedback, enabling the identification of performance-based differences in individuals during tasks specific to the military. In the context of the current findings, fNIRS could be integrated into marksmanship training tasks where individuals who are low performers (despite standard training) may benefit from incorporating cognitive load management techniques (such as autonomic regulation, time pressure management, and selective attention training, to promote more efficient PFC regulation).[10,55] For example, tactical breathing has been shown to improve tactical performance when used as a relaxation technique; however, the hemodynamic responses of the PFC have not been investigated.[56,57] Understanding the psychophysiological responses leading to poor tactical performance can be used to develop individualized training programs that target the deficit limiting performance. Future interventions could modulate PFC activity (such as cognitive training or neuromodulation) to assess their direct impact on marksmanship performance. Clarifying whether enhancing PFC efficiency translates to operational improvements would provide valuable insight for training strategies.

Conclusion

Understanding group differences in PFC activation during marksmanship tasks can provide critical insight into the neural and neurovascular mechanisms underlying superior performance in military personnel. This study supports the use of fNIRS-based technology as a tool for identifying cognitive load differences in marksmen with differing proficiency levels. Incorporating fNIRS as a physiological biofeedback tool can be useful for developing more comprehensive marksmanship training regimens that improve marksmanship skills and enhance cognitive resilience, leaving servicemembers better prepared for real-world operations.

Author Contributions

OFS and CMS conceived the study concept. OFS, CBU, MDS, HDD, JRT, RMR, and CMS recruited participants. OFS, TXS, HDD, JRT, MDS, CBU, and RMR coordinated and collected the data, and OFS and CMS analyzed the data. OFS, TXS, and CMS wrote the first draft. All authors read and approved the final manuscript.

Disclosures

The authors have indicated they have no financial relationships relevant to this article to disclose.

Funding

The authors have indicated they have no financial relationships relevant to this article to disclose.

References

1. **Kerick SE.** *Neurocognitive adaptations associated with marksmanship training*. Dissertation. University of Maryland, College Park; 2001. Accessed September 9, 2024. https://www.proquest.com/docview/250713016/abstract/6D42D53FF0AF4492PQ/1
2. **Hatfield B, Haufler A, Contreras-Vidal J.** Brain processes and neurofeedback for performance enhancement of precision motor

behavior. In: Schmorrow DD, Estabrooke IV, Grootjen M, eds. *Foundations of Augmented Cognition. Neuroergonomics and Operational Neuroscience*. 5638. Springer; 2009:810-817. doi:10.1007/978-3-642-02812-0_91

3. **O'Donovan MP, Hancock CL, Bode VG, Hasselquist L.** A comparison of Expert and Novice marksmanship performance and postural mechanics using inertial measurement units (IMUs) during dynamic live-fire shooting. *Appl Ergon*. 2024;114:104131. doi:10.1016/j.apergo.2023.104131
4. **Anderson GS, Di Nota PM, Metz GAS, Andersen JP.** The impact of acute stress physiology on skilled motor performance: implications for policing. *Front Psychol*. 2019;10:2501. doi:10.3389/fpsyg.2019.02501
5. **Andersen JP, Di Nota PM, Beston B, et al.** Reducing lethal force errors by modulating police physiology. *J Occup Environ Med*. 2018;60(10):867. doi:10.1097/JOM.0000000000001401
6. **Nibbeling N, Oudejans RRD, Ubink EM, Daanen HAM.** The effects of anxiety and exercise-induced fatigue on shooting accuracy and cognitive performance in infantry soldiers. *Ergonomics*. 2014;57(9):1366–1379. doi:10.1080/00140139.2014.924572
7. **Choi HH, van Merriënboer JJG, Paas F.** Effects of the physical environment on cognitive load and learning: towards a new model of cognitive load. *Educational Psychology Review*. 2014; 26(2):225–244. doi:10.1007/s10648-014-9262-6
8. **Proctor S, Heaton K, Lieberman H, et al.** *Military cognitive performance and readiness assessment initiative: Final Report*. Defense Technical Information Center; 2017. Accessed August 28, 2024. https://apps.dtic.mil/sti/citations/trecms/AD1053085
9. **Johnson RR, Stone BT, Miranda CM, et al.** Identifying psychophysiological indices of expert vs. novice performance in deadly force judgment and decision making. *Front Hum Neurosci*. 2014; 8:512. doi:10.3389/fnhum.2014.00512
10. **Biggs AT, Hamilton JA, Thompson AG, et al.** Not according to plan: cognitive failures in marksmanship due to effects of expertise, unknown environments, and the likelihood of shooting unintended targets. *Appl Ergon*. 2023;112:104058. doi:10.1016/j.apergo.2023.104058
11. **Biggs A, Huffman G, Hamilton J, et al.** Small arms combat modeling: a superior way to evaluate marksmanship data. *J Def Anal Logist*. 2023;7(1):69–87. doi:10.1108/JDAL-11-2022-0012
12. **Morrison GB, Vila BJ.** Police handgun qualification: practical measure or aimless activity? *Polic Int J Police Strateg Manag*. 1998;21(3):510–533. doi:10.1108/13639519810228804
13. **Cooper D, Fuller J, Wiggins MW, Wills JA, Main LC, Doyle T.** Negative consequences of pressure on marksmanship may be offset by early training exposure to contextually relevant threat training: a systematic review and meta-analysis *Hum Factors*. 2024;66(1):294–311. doi:10.1177/00187208211065907
14. **Brown S, Villa J, Hancock C, Hasselquist L.** Stance and transition movement effects on marksmanship performance of expert shooters during a simulated multiple target engagement task. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*. 2018;62(1):1444-1448. doi:10.1177/1541931218621328
15. **Rao HM, Smalt CJ, Rodriguez A, et al.** Predicting cognitive load and operational performance in a simulated marksmanship task. *Front Hum Neurosci*. 2020;14:222. doi:10.3389/fnhum.2020.00222
16. **Chung GKWK, O'Neil HF, Delacruz GC, Bewley WL.** The Role of anxiety on novices' rifle marksmanship performance. *Educ Assess*. 2005;10(3):257–275. doi:10.1207/s15326977ea1003_6
17. **Smith CD, Cooper AD, Merullo DJ, et al.** Sleep restriction and cognitive load affect performance on a simulated marksmanship task. *J Sleep Res*. 2019;28(3):e12637. doi:10.1111/jsr.12637
18. **Bonilauri A, Sangiuliano Intra F, Baselli G, Baglio F.** Assessment of fNIRS signal processing pipelines: towards clinical applications. *Appl Sci*. 2021;12(1):316. doi:10.3390/app12010316
19. **Herold F, Wiegel P, Scholkmann F, Müller NG.** Applications of functional near-infrared spectroscopy (fNIRS) neuroimaging in exercise–cognition science: a systematic, methodology-focused review. *J Clin Med*. 2018;7(12):466. doi:10.3390/jcm7120466
20. **Perrey S. Evaluating brain functioning with NIRS in sports:** Cerebral oxygenation and cortical activation are two sides of the same coin. *Front Neuroergonomics*. 2022;3:1022924. doi:10.3389/fnrgo.2022.1022924
21. **Meidenbauer KL, Choe KW, Cardenas-Iniguez C, Huppert TJ, Berman MG.** Load-dependent relationships between frontal fNIRS activity and performance: A data-driven PLS approach. *Neuro-Image*. 2021;230:117795. doi:10.1016/j.neuroimage.2021.117795
22. **Zohdi H, Amez-Droz V, Scholkmann F, Wolf U.** differences between good, moderate and poor performers of a verbal fluency task under blue light exposure: An SPA-fNIRS study. *Adv Exp Med Biol*. 2023;1438:69–74. doi:10.1007/978-3-031-42003-0_12
23. **Zohdi H, Scholkmann F, Wolf U.** Changes in cerebral oxygenation and systemic physiology during a verbal fluency task: differences between men and Women. *Adv Exp Med Biol*. 2022;1395:17–22. doi:10.1007/978-3-031-14190-4_3
24. **Bunce SC, Izzetoglu K, Ayaz H, et al.** Implementation of fNIRS for monitoring levels of expertise and mental workload. In: Schmorrow DD, Fidopiastis CM, eds. *Foundations of Augmented Cognition. Directing the Future of Adaptive Systems*. Springer; 2011:13–22. doi:10.1007/978-3-642-21852-1_2
25. **Friedman NP, Robbins TW.** The role of prefrontal cortex in cognitive control and executive function. *Neuropsychopharmacology*. 2022;47(1):72–89. doi:10.1038/s41386-021-01132-0
26. **Diamond A.** Executive functions. *Annu Rev Psychol*. 2013;64:135–168. doi:10.1146/annurev-psych-113011-143750
27. **Goris T, Brawner K.** *Examining the influence of heartbeat on expert marksman performance* [technical report] ARL-TN-0754. Aberdeen Proving Ground (MD): US Army Research Laboratory; April 2016. Accessed September 3, 2024. https://searchlib.cwu.edu/permalink/01ALLIANCE_CWU/1jketq5/alma99783744001866
28. **McDuff D, Gontarek S, Picard R.** Remote measurement of cognitive stress via heart rate variability. *Annu Int Conf IEEE Eng Med Biol Soc IEEE Eng Med Biol Soc Annu Int Conf*. 2014; 2014:2957–2960. doi:10.1109/EMBC.2014.6944243
29. **Tremayne P, Barry RJ.** Elite pistol shooters: physiological patterning of best vs. worst shots. *Int J Psychophysiol Off J Int Organ Psychophysiol*. 2001;41(1):19–29. doi:10.1016/s0167-8760(00)00175-6
30. **Gong A, Liu J, Jiang C, Fu Y.** Rifle shooting performance correlates with electroencephalogram beta rhythm network activity during aiming. *Comput Intell Neurosci*. 2018;2018:e4097561. doi:10.1155/2018/4097561
31. **Department of the Army.** Training and qualification – individual weapons (TC 3-20.40). Published online 2019. Accessed May 7, 2024. https://rdl.train.army.mil/catalog-ws/view/100.ATSC%2FD6C17734-DD08-40FD-A50B-094485756 46F-1564595433375/tc3_20x40wc1.pdf
32. **Scholkmann F, Wolf M.** General equation for the differential pathlength factor of the frontal human head depending on wavelength and age. *J Biomed Opt*. 2013;18(10):105004. doi:10.1117/1.JBO.18.10.105004
33. **Cohen J.** *Statistical power analysis for the behavioral sciences*. 2nd ed. Academic Press; 1988.
34. **Causse M, Chua Z, Peysakhovich V, Del Campo N, Matton N.** Mental workload and neural efficiency quantified in the prefrontal cortex using fNIRS. *Sci Rep*. 2017;7(1):5222. doi:10.1038/s41598-017-05378-x
35. **Stuss DT, Shallice T, Alexander MP, Picton TW.** A multidisciplinary approach to anterior attentional functions. *Ann N Y Acad Sci*. 1995;769:191–211. doi:10.1111/j.1749-6632.1995.tb38140.x
36. **Ortiz KR, Hunter JG, Thorpe AJ, et al.** Assessing the Relationship Between Learning Stages and Prefrontal Cortex Activation in a Psychomotor Task. *Proc Hum Factors Ergon Soc Annu Meet*. Published online August 28, 2024:10711813241260675. doi:10.1177/10711813241260675
37. **Keles HO, Cengiz C, Demiral I, Ozmen MM, Omurtag A.** High density optical neuroimaging predicts surgeons's subjective experience and skill levels. *PLoS One*. 2021;16(2):e0247117. doi:10.1371/journal.pone.0247117
38. **Nemani A, Yücel MA, Kruger U, et al.** Assessing bimanual motor skills with optical neuroimaging. *Sci Adv*. 2018;4(10):eaat3807. doi:10.1126/sciadv.aat3807
39. **Leff DR, Orihuela-Espina F, Atallah L, Darzi A, Yang GZ.** Functional near infrared spectroscopy in novice and expert surgeons—a manifold embedding approach. *Med Image Comput Comput-Assist*

Interv MICCAI Int Conf Med Image Comput Comput-Assist Interv. 2007;10(Pt 2):270–277. doi:10.1007/978-3-540-75759-7_33

40. **Leff DR, Elwell CE, Orihuela-Espina F, et al.** Changes in prefrontal cortical behaviour depend upon familiarity on a bimanual co-ordination task: an fNIRS study. *NeuroImage*. 2008;39(2):805–813. doi:10.1016/j.neuroimage.2007.09.032
41. **Walia P, Fu Y, Schwaitzberg SD, et al.** Portable neuroimaging differentiates novices from those with experience for the fundamentals of laparoscopic surgery (FLS) suturing with intracorporeal knot tying task. *Surg Endosc*. 2023;37(7):5576–5582. doi:10.1007/s00464-022-09727-4
42. **Causse M, Chua ZK, Rémy F.** Influences of age, mental workload, and flight experience on cognitive performance and prefrontal activity in private pilots: a fNIRS study. *Sci Rep*. 2019;9(1):7688. doi:10.1038/s41598-019-44082-w
43. **Mark JA, Kraft AE, Ziegler MD, Ayaz H.** Neuroadaptive training via fNIRS in flight simulators. *Front Neuroergonomics*. 2022;3:820523. doi:10.3389/fnrgo.2022.820523
44. **Saikia MJ.** K-means clustering machine learning approach reveals groups of homogeneous individuals with unique brain activation, task, and performance dynamics using fNIRS. *IEEE Trans Neural Syst Rehabil Eng*. 2023;31:2535-2544. doi:10.1109/TNSRE.2023.3278268
45. **Luke R, Shader MJ, Gramfort A, Larson E, Lee AK, McAlpine D.** Oxygenated hemoglobin signal provides greater predictive performance of experimental condition than de-oxygenated. *bioRxiv.* Preprint posted November 20, 2021. doi:10.1101/2021.11.19.469225
46. **Culver JP, Siegel AM, Franceschini MA, Mandeville JB, Boas DA.** Evidence that cerebral blood volume can provide brain activation maps with better spatial resolution than deoxygenated hemoglobin. *NeuroImage*. 2005;27(4):947–959. doi:10.1016/j.neuroimage.2005.05.052
47. **Martins LCX, Russo MT, Ribeiro P.** Neural correlates of shooting sports performance: a systematic review on neural efficiency hypothesis. *Rev Educ Física J Phys Educ*. 2022;91(4):350–374. doi:10.37310/ref.v91i4.2915
48. **Loze GM, Collins D, Holmes PS.** Pre-shot EEG alpha-power reactivity during expert air-pistol shooting: a comparison of best and worst shots. *J Sports Sci*. 2001;19(9):727–733. doi:10.1080/02640410152475856
49. **Kerick SE, Douglass LW, Hatfield BD.** Cerebral cortical adaptations associated with visuomotor practice. *Med Sci Sports Exerc*. 2004;36(1):118–129. doi:10.1249/01.MSS.0000106176.31784.D4
50. **Zhang J, Shi Y, Wang C, et al.** Preshooting electroencephalographic activity of professional shooters in a competitive state. *Comput Intell Neurosci*. 2021;2021:6639865. doi:10.1155/2021/6639865
51. **Haufler AJ, Spalding TW, Santa Maria DL, Hatfield BD.** Neuro-cognitive activity during a self-paced visuospatial task: comparative EEG profiles in marksmen and novice shooters. *Biol Psychol*. 2000;53(1):131–160. doi:10.1016/s0301-0511(00)00047-8
52. **Shirzadi S, Dadgostar M, Einalou Z, Erdoğan SB, Akin A.** Sex based differences in functional connectivity during a working memory task: an fNIRS study. *Front Psychol*. 2024;15:1207202. doi:10.3389/fpsyg.2024.1207202
53. **Yang H, Wang Y, Zhou Z, et al.** Sex differences in prefrontal hemodynamic response to mental arithmetic as assessed by near-infrared spectroscopy. *Gend Med*. 2009;6(4):565–574. doi:10.1016/j.genm.2009.11.003
54. **Zhao W, Hui M, Zhang X, Li L.** The relationship between motor coordination and imitation: an fNIRS study. *Brain Sci*. 2021;11(8):1052. doi:10.3390/brainsci11081052
55. **Stergiou M, Robles-Pérez JJ, Rey-Mota J, Tornero-Aguilera JF, Clemente-Suárez VJ.** Psychophysiological responses in soldiers during close combat: implications for occupational health and fitness in tactical populations. *Healthcare (Basel)*. 2023;12(1):82. doi:10.3390/healthcare12010082
56. **Tan L, Deady M, Mead O, et al.** Web-based mind-body tactical resilience training program for first responders: pre-post study assessing feasibility, acceptability, and usability. *JMIR Form Res*. 2023;7(1):e40145. doi:10.2196/40145
57. **Ibrahim F, Schumacher J, Schwandt L, Herzberg PY.** The first shot counts the most: tactical breathing as an intervention to increase marksmanship accuracy in student officers. *Mil Psychol*. 2024;36(6):689–700. doi:10.1080/08995605.2023.2258737

PMID: 40411779; *DOI:* 10.55460/4RIR-IM31

APPENDIX A

TABLE VI *Practice engagements 1 through 9, Standing, Baseline*

Engagement	Target type	Range, m	Exposure time, s
1	E-type	7 right	5
2	E-type	12.5	5
3	E-type	23	5
4	E-type	31	5
5	E-type	10	5
6	E-type	16.5	5
7	E-type	27	5
8	E-type	7 right	5
9	E-type	10	8
	E-type	12.5	

Note: There is a 2-second delay between all target engagements throughout this table. At the end of engagement 9, A 10-second delay is integrated for a magazine change.

The Special Operations Medical Association's Official Journal

JSOM

JOURNAL *of* SPECIAL OPERATIONS MEDICINE™

25 YEARS JOURNAL OF SPECIAL OPERATIONS MEDICINE 25 YEARS PUBLISHING EXCELLENCE

Summer 2025
Volume 25, Edition 2

THE JOURNAL FOR OPERATIONAL MEDICINE AND TACTICAL CASUALTY CARE

Inside this Issue:

- FEATURE ARTICLES: Maintaining, Storing, and Transporting Cold Whole Blood
- fNIRS-differentiated Marksmanship Performance
- Double-Trunk Mask for Efficient Oxygen Delivery
- A Review of JSOM Articles on Ultrasound Use by SOCM
- End-user Assessment of i-view
- Arctic or Extreme Cold Casualty Care Considerations
- IN BRIEF: Tool to Evaluate Tactical Combat Casualty Care in the Cold
- CASE REPORTS: Intraoral Neuroprosthesis for PTSD-Associated Nocturnal Behavior Disorder
- Undersea and Hyperbaric Medicine
- RHD and Valve Placement in an SOF Soldier
- ONGOING SERIES: Law Enforcement & Tactical Medicine, Prolonged Casualty Care, There I Was, Unconventional Medicine, Unconventional Resilience, Book Review, *and more!*

Dedicated to the Indomitable Spirit, Lessons Learned & Sacrifices of the SOF Medic

A Peer Reviewed Journal That Brings Together The Global Interests of Special Operations' First Responders