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Evaluation of a Prototype Body-Borne Weapon Mount System during Live Fire

by Courtney A Haynes, Andrew J Tweedell, Daniel M Baechle, and Frank Morelli

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Courtney A Haynes and Andrew J Tweedell
Human Research and Engineering Directorate, DEVCOM Army Research Laboratory

Daniel M Baechle
Weapons Materials Research Directorate, DEVCOM Army Research Laboratory

Frank Morelli
CCDC Data & Analysis Center

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ORCID ID(s): Courtney A Haynes, 0000-0001-8820-6297; Daniel M Baechle, 0000-0002-8875-8582

14. ABSTRACT

The “Third Arm” (3ARM) body-borne weapon mount system was developed to mitigate upper extremity fatigue, aid in weapon stabilization, and improve marksmanship during live-fire engagements. Fourteen military servicemen completed three live-fire shooting scenarios (“paced”, “prone”, and “lateral”) with and without the 3ARM while measures of muscle activity, weapon movement, and shot timing, accuracy, and precision were collected. The paced target engagement scenario compared 3ARM to the Control condition during sustained live fire when engagement time is held constant. The prone scenario determined whether 3ARM would affect the user’s ability to transition between standing and prone firing positions to engage a target. The lateral target engagement scenario evaluated whether 3ARM affects target engagement times when slewing the weapon across the body. Paced trials revealed some mitigation of fatigue and preservation of muscular endurance with 3ARM as well as improved vertical control of the weapon. Shot timing was unaffected during the lateral trials; the prone trials revealed some loss of mobility with the 3ARM as evidenced by longer postural transition times. Small improvements in shot precision and accuracy were observed with the 3ARM for some shot scenarios. Generally, users felt that the 3ARM effectively alleviated some of the weight of the weapon and reduced fatigue development in the arms. Critiques revealed that 3ARM can impose back pain, possibly due to the asymmetry of its current design. Additionally, participants encouraged design improvements to better accommodate different firing postures and maneuverability. Recommendations are provided for both design improvements and possible alternative use cases for 3ARM.

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1. Introduction

Weapons are vital to a Soldier's operational effectiveness and survivability. Depending on their specific Military Occupational Specialty (MOS), Soldiers may be fielded with a variety of different weapon systems. While the standard M4 carbine weighs approximately 8 lb, some squad automatic weapons and sniper systems can exceed 20 lb. The addition of scopes, optics, and rail-mounted accessories only increases weapon weight. While simply carrying these weapon systems poses a significant physical burden, performing an unsupported marksmanship task further challenges the Soldier to bear the full weight of the weapon in their extended arms and maintain a tightly controlled aim point to hit their target. Weapon weight and the sustained static nature of this task can quickly result in upper extremity fatigue and loss of aim stability, both of which can negatively affect shooting performance. A prototype weapon mount called "Third Arm" (3ARM) was developed with the intention of reducing the physical demands of marksmanship (Green et al. 2019). Specifically, 3ARM was designed to mitigate fatigue development associated with firing military weapon systems while also providing improved weapon stability and shooting performance. This study utilized a series of shooting scenarios coupled with biomechanical and marksmanship analysis techniques to evaluate different aspects of the 3ARM system.

The fatigue experienced during sustained physical exertion, such as that during prolonged target engagement with a weapon, may be referred to as localized muscle fatigue. Localized muscle fatigue can be described as a temporary loss of voluntary force production capacity during exertion (Chaffin 1973). There are several ways, both direct and indirect, to observe and quantify fatigue development. Among the direct methods are techniques that monitor changes in force production over time or track the duration for which a specific level of force can be maintained (Chaffin 1973; Milner-Brown et al. 1986; Nussbaum et al. 2001; Beck et al. 2015). In the former case, fatigue may be quantified as a percent decline in force over time, and in the latter, fatigue may be quantified as a time-to-fatigue, or an endurance time. Indirect methods of quantifying fatigue often involve the use of surface electromyography (EMG), in which electrodes attached to the skin overlying the muscles enable the measurement of the electrical signals associated with muscle contraction. Although EMG signals are not proportional to muscle force, analyses of the signal content (e.g., amplitude, frequency, power) can provide insight regarding fatigue development in the muscle. EMG amplitude is a measure of the signal magnitude and is typically calculated as the root mean square (RMS) value of the signal. Amplitude does not correlate to absolute muscle force, but it can provide a relative measure of the intensity of contraction. Median frequency (MF) is the frequency at which the power of the EMG signal is divided into halves of equal amplitude (Cifrek et al. 2009; Phinyomark et al. 2012). More comprehensibly, it describes an important central motor frequency driving muscle contraction. As fatigue develops during submaximal contractions, muscles attempt to maintain force output by reducing contraction frequency but recruiting more motor units to produce the necessary force (Bigland-Ritchie 1986; Enoka et al. 1989). Thus, during fatigue, MF decreases while the amplitude of the signal increases (Hakkinen and Komi 1983; Merletti et al. 1984; Krogh-Lund and Jørgensen 1991; Allison and Fujiwara 2002; Phinyomark et al. 2012). For this research effort, both direct and indirect biomechanical analysis techniques were leveraged to objectively quantify differences in fatigue development during shooting with and without the 3ARM system.

In addition to reducing fatigue, another intention of the 3ARM system was to improve weapon aim stability. Stability is a complex phenomenon that can be evaluated using a variety of methods which should be carefully selected based on the application. Stability is not always achieved through perfect stationarity. Often, in motor control tasks, stability is defined not as a static point but as a controlled orbital fluctuation about a specific point or physical state (Dingwell and Kang 2007; Riva et al. 2013). For a marksmanship task, the goal is to exert motor control of the weapon to maintain a steady aim point relative to a desired target position. However, the weight and size of the weapon as well as the extended posture of the limbs required for weapon control also result in postural sway and jitter that are detrimental to task performance (Morrison and Newell 2000; Pellegrini et al. 2004; Lakie 2010). Thus, weapon control (and ultimately marksmanship performance) is affected by the resulting sum of constructive, intentional motor control and destructive postural perturbations.

Inertial measurement units (IMUs) affixed to a body (e.g., limb segment or a weapon) provide a means of quantifying the motion of that body as a time-series of acceleration or gyroscopic movement. Similar time-series have been generated from the study of complex, dynamic physical systems, and researchers have developed entropy analysis measures to describe the irregularity of these time-series signals (Grassberger and Procaccia 1983; Pincus 1991; Richman and Moorman 2000; Ramdani et al. 2009). Sample entropy (SampEn) is one such measure that computes a statistic describing the conditional probability that a signal which repeats itself within a tolerance r for m samples will continue to repeat itself for $m+1$ samples (Ramdani et al. 2009). Greater values of SampEn indicate greater irregularity or unpredictability in the signal. Leveraging SampEn analysis, IMU acceleration data was used to quantify weapon control during live-fire shooting scenarios.

In addition to biomechanical assessments of fatigue and weapon control, more conventional measures of shooting performance were evaluated. The shooting scenarios used in this study were designed to simulate possible real-world engagements and evaluate whether the 3ARM design affects target engagement time or point-of-impact metrics. Previously published work has documented a number of marksmanship metrics that quantify target acquisition and engagement time, accuracy, and shot precision (Head et al. 2017; Morelli et al. 2017; Brown et al. 2018). Hit percentage, which calculates the ratio of hits on target to the number of shots taken, provides an overall measure of the effectiveness of target engagement. The accuracy of each shot or a group of shots may be determined by calculating the distance between the shot or the shot group center from the designated target center. Precision, defining the proximity of the shots to each other, can be calculated as the mean distance between a group of shots and their shot group center point. Time metrics may be defined based on the requirements of a specific shooting scenario, but target engagement times have been defined as the time elapsed between movement initiation and target acquisition, the time elapsed between shots, or the total time required for target engagement (Morelli et al. 2017; Brown et al. 2018). Timing and shot performance metrics have shown to be an effective means of discriminating between various experimental conditions including fatigue (Head et al. 2017), recoil dynamics (Morelli et al. 2017), and shooting postures (Brown et al. 2018).

The goals of this research were to quantify the effects of the 3ARM system on fatigue development, weapon aim stability, and marksmanship performance. Using biomechanical and marksmanship analysis techniques, this report describes procedures that evaluated the shooter-3ARM system performance in several live-fire scenarios, including paced, sustained target engagement, prone-to-standing target engagement, and lateral (side-to-side) target engagement. Each engagement scenario was completed with and without the 3ARM, and it was hypothesized that the 3ARM would result in less fatigue development, improved weapon aim control, and improved marksmanship performance compared with the Control condition.

2. Methods

2.1 Participants

Fourteen male participants were recruited from an active duty or military reserve population (180.8 ± 6.4 cm, 99.6 ± 16.9 kg, 35.0 ± 7.5 years) including two military academy cadets and recruits from a variety of MOSs including 11B, 13J, 15B, 19K, 25U, 42A, 49A, 51Z, 72D, 88M, and 94R. All participants confirmed that they had received military marksmanship training, had normal or corrected-to-normal vision, and were free from current or chronic joint pain. Participants were excluded if they had doctor-imposed restrictions to load carriage or if they were currently taking medication affecting judgment, decision-making, or reaction time. All procedures performed in this study were reviewed and approved by the Institutional Review Board of the US Army Combat Capabilities Development Command Army Research Laboratory. Command approval was received from appropriate unit personnel prior to recruiting military volunteers. Following a briefing on instrumentation and study procedures, all participants provided written informed consent prior to participation.

2.2 Test Equipment

The 3ARM system is a carbon-fiber, articulated mechanical arm that is designed to suspend the weapon in front of the user to help support its weight and stabilize weapon aim (Green et al. 2019). The mechanical arm is mounted to a carbon fiber insert that conforms and is secured to the posterior ballistic plate inside a body armor vest (Fig. 1). The "Q arm"—so named because it has the appearance of a question mark—provides the point of attachment to the weapon. A clamp is mounted to the top Picatinny rail ("pic rail") of the weapon, and a mating receiver for this attachment is affixed to the end of the Q arm. A pin connector is used to secure the weapon to or detach the weapon from the Q arm. The 3ARM has a mass of 1.6 kg (~3.5 lb) in this testing configuration.

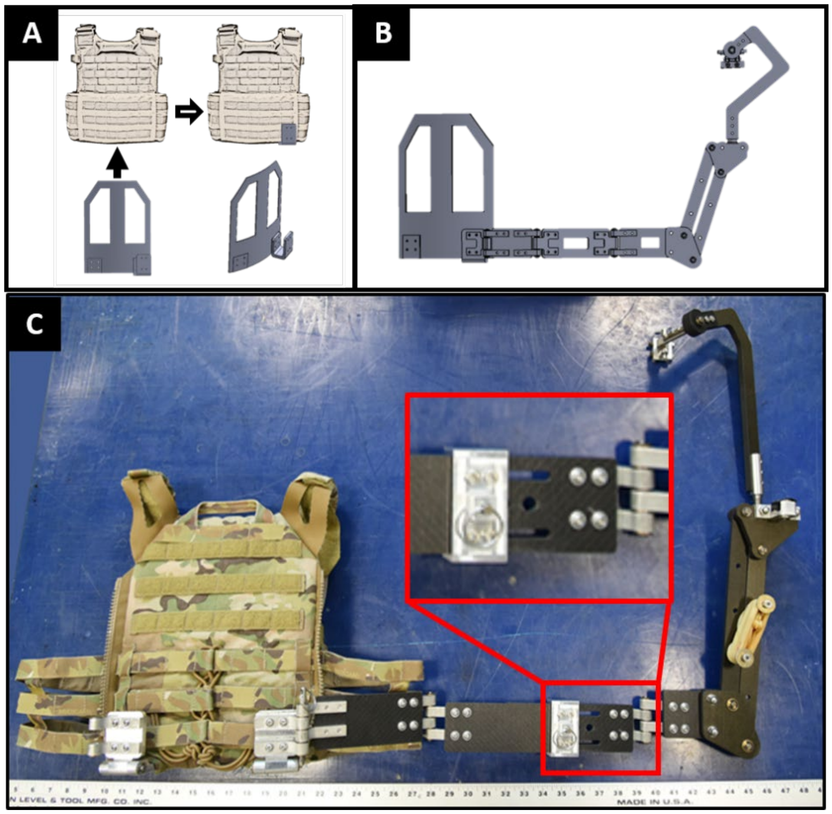


Fig. 1 Computer-aided design (CAD) drawing and actual prototype image. A) CAD drawing of carbon-fiber insert that conforms to the ballistic plate fitted with a rear hinge allowing for articulation away from the body. B) CAD drawing of full 3ARM prototype with "Q arm" attachment for connection to the weapon pic rail. C) Prototype 3ARM used in current evaluation. A sliding mechanical design (enlarged) secured by pins allows for adjustment of the length of the middle carbon-fiber link. An elastic element seen on the distal link of the 3ARM helps to support the load of the weapon and suspend it in front of the user.

The 3ARM is reconfigurable such that it can support both right- and left-handed shooting postures, and the system has some adjustability to achieve a good fit for each user. First, the body armor vest (CRYE Precision Jumpable Plate Carrier, CRYE Precision LLC, Brooklyn, New York) itself has adjustable shoulder and cummerbund straps that allow the user to adjust the height of the body armor plates and snug the vest securely to the torso. This ensures that the body armor plates contour appropriately against the torso and aid in distributing the additional weight of the 3ARM system comfortably. Second, the middle carbon-fiber link of the 3ARM has a sliding mechanism that allows the user to adjust the length of that segment (Fig. 1). When a weapon is mounted to the Q arm, the weight is supported by engaging the elastic element on the distal four-bar linkage of the 3ARM. The effect of adjusting the length of the middle carbon fiber segment is to ensure that the 3ARM fits close to the body to minimize its profile, and to provide the proper geometry so that the weapon weight is supported by the elastic element. The Q arm is also available in two sizes (standard and large) that can be used to provide proper suspension of the weapon and engagement of the elastic element. The standard size was appropriate for most users, but the larger Q arm provided better fit for users who were taller or who had longer arms and/or larger torsos. Finally, the height of the Q arm can be adjusted and secured using a pair of hex nuts on the threaded pintle mount that attaches the Q arm to the top plate of the four-bar linkage. Adjusting the height of the Q arm ensures that the user can shoulder and sight the weapon properly while it is held approximately level with the ground.

The weapon used for this evaluation was the long-barrel (16 inch) Sig Sauer MCX semi-automatic rifle system (SIG SAUER, Inc., Newington, New Hampshire; Fig. 2a). This weapon fires 5.56 × 45-mm rounds and was used with an EOTech 4x optic (EOTEch Inc., Ann Arbor, Michigan; Figs. 2b and 2c). The rail clamp of 3ARM was mounted immediately in front of the optic, just above the weapon's ejector port. This allowed the weapon to be mounted to 3ARM near its center of mass while still accommodating the necessary optic.

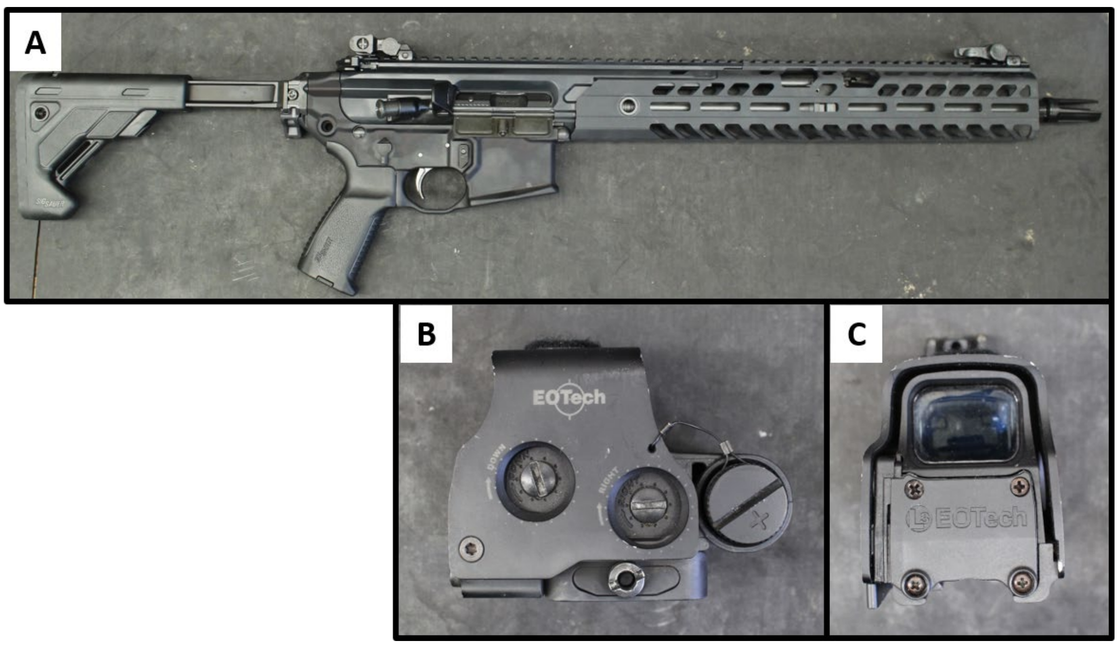


Fig. 2 A) Sig Sauer MCX rifle used in this evaluation. B) Side-view of EOTech scope used with Sig Sauer MCX. C) Posterior view of EOTech sight used in this evaluation.

All targets used in this evaluation were e-silhouettes (Fig. 3a). Depending on the shot scenario being completed, either stationary or pop-up e-silhouettes were used to present targets to the participants. All targets were instrumented with an acoustic scoring system (TDCue, AAI Corp., Cockeysville, Maryland; Fig. 3b) that provides an x-y location pair corresponding to shot placement as the round passes through the target. This enables hit/miss determination as well as shot error distance calculations.

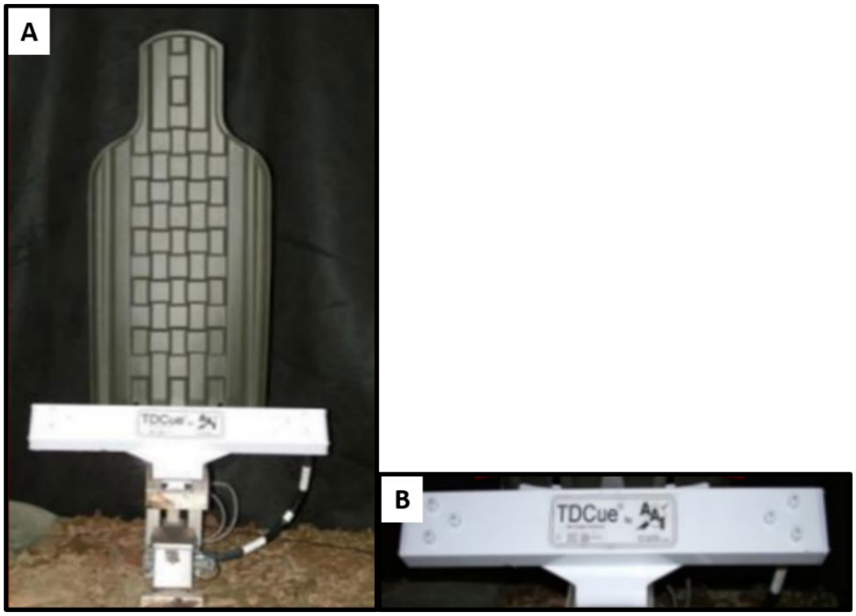


Fig. 3 A) E-silhouette with acoustic target mount. B) Acoustic target scoring mount.

2.3 Instrumentation and Procedures

Participants worked with range safety personnel to zero the weapon system using a target at 25 m. Once the weapon was zeroed, the participant donned the 3ARM system. Adjustments were then made to ensure that the weapon was properly supported during standing fire and also that the user was able to achieve a prone firing posture. Once the system was properly fitted, 3ARM was doffed to allow for anthropometric measurements and instrumentation.

To document the range of body sizes the system currently accommodates, upper body anthropometric measurements were recorded for all participants using previously published guidelines and body segment definitions (Gordon et al. 2012). Means (±SD) and ranges of body segment lengths are provided in Table 1.

Table 1 Mean (±SD) and range of body size and segment lengths for sample group (n = 14)

Measurement	Mean	Range
Height (cm)	180.8 (6.4)	170.0–188.5
Mass (kg)	99.6 (16.9)	72.8–132.1
Right upper arm (cm)	33.9 (1.9)	30.7–36.8
Right forearm (cm)	27.8 (2.1)	23.6–31.9
Right hand (cm)	19.4 (3.9)	10.2–22.6
Left upper arm (cm)	33.8 (2.3)	28.4–36.5
Left forearm (cm)	27.6 (2.0)	23.9–31.7
Left hand (cm)	19.4 (4.0)	10.1–22.6
Trunk height (cm)	42.4 (2.1)	40–47.5

Participants were instrumented with bipolar surface EMG sensors to measure muscular contractions during the live-fire trials as well as IMUs to track orientation and movement of body segments necessary for controlling weapon aim. EMG sensors were fixed bilaterally to the skin overlying muscles of the trunk and upper extremities including upper trapezius, anterior deltoid, biceps brachii, triceps brachii, brachioradialis, latissimus dorsi, and lumbar erector spinae. The skin over each muscle was prepped by shaving and lightly abrading the skin to remove hair and dead skin cells. Adhesive Ag/AgCl bipolar surface electrodes (2.0 cm, HEX Dual Electrodes, Noraxon USA, Inc., Scottsdale, Arizona) were placed over each muscle, and a wireless transmitter (Noraxon DTS, Noraxon USA, Inc., Scottsdale, Arizona) was paired with each electrode and secured to the skin using medical-grade adhesive tape. IMUs (myoMotion, Noraxon USA, Inc., Scottsdale, Arizona) were secured using neoprene straps to the pelvis, head, upper arms, forearms, and hands. Another IMU was secured with medical tape to the seventh cervical vertebrae, and two additional IMUs were fixed to the weapon (one on the buttstock and one on the barrel) using tape and a custom-made pic rail sensor mount). A shot microphone, which was used to record the time stamps associated with each shot fired, was also integrated into the hardware setup via the Noraxon Analog Input System (Noraxaon USA, Inc., Scottsdale, Arizona). EMG, IMU, and shot timing data were recorded synchronously at 1500 Hz using Noraxon myoResearch software (3.8, Noraxon USA, Inc., Scottsdale, Arizona).

Participants completed three shooting scenarios with only the body armor vest (Control) and with the body armor vest fitted with the 3ARM. During each trial, participants fired 30 rounds as prescribed at targets located at a distance of 75 m. Each scenario was designed to evaluate different aspects of the 3ARM functionality.

2.3.1 Shot Scenario 1: Paced Target Engagement ("Paced") and Muscular Endurance Task

The paced target engagement scenario ("paced") was used to evaluate whether 3ARM can effectively mitigate fatigue development during sustained live fire compared to the Control condition when engagement time is held constant. As a measure of endurance, participants were asked to hold their weapon support arm fully extended and parallel to the ground with palm facing downward. A 3.6-kg (8-lb) kettlebell was placed in their hand and they were asked to hold the weight as long as possible without allowing their arm to change position. The time elapsed during this static hold served as a surrogate endurance measure for the weapon support arm. Once the participant's arm began to drop, the endurance task was concluded, and participants were required to rest for approximately 10 min prior to completing the live-fire trials.

The paced target engagement scenario consisted of the participant firing single rounds at a static center target at a range of 75 m. Using a stopwatch, a supervising range safety officer provided verbal cues to the participant to fire a total of 30 rounds at a rate of 1 round every 6 s (~180-s trial; Fig. 4). Participants were instructed to maintain target acquisition even between shots and were only relieved of the weapon once all shots had been fired. Immediately upon the conclusion of the live-fire trial, participants repeated the endurance task. Rest (~10 min) was required following the endurance trial, and the paced trial and muscular endurance task were completed once more for the remaining condition (Control or 3ARM).

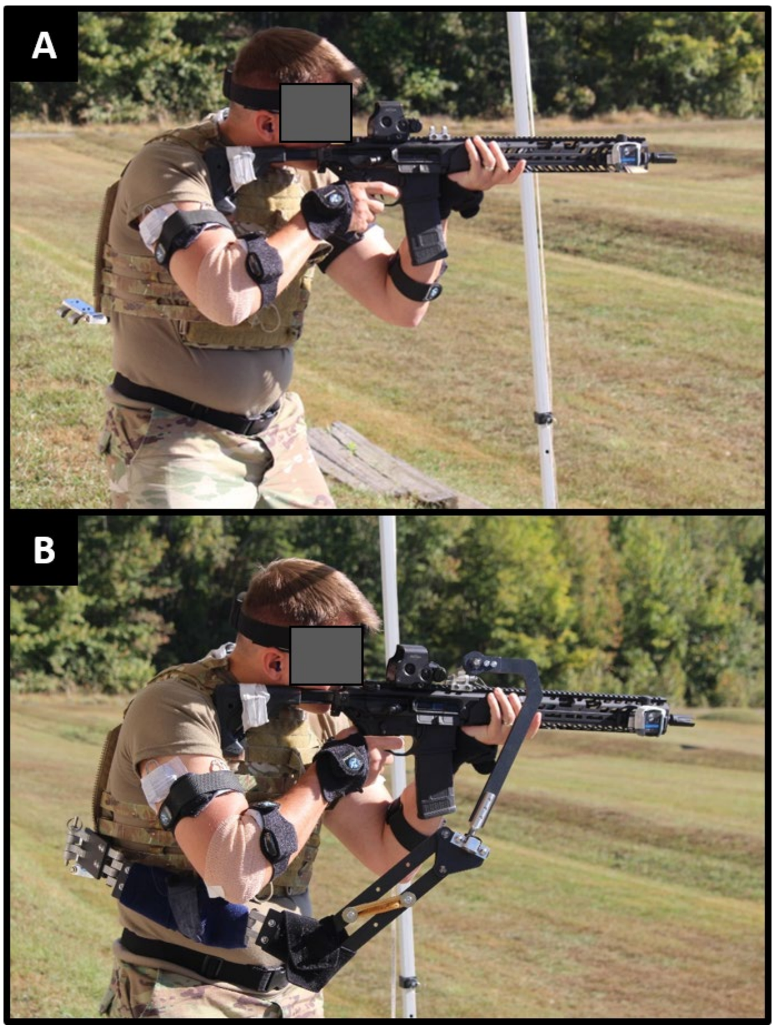


Fig. 4 An instrumented participant completing the paced firing scenario for both the Control (A) and 3ARM (B) conditions

To ensure that any fatigue being measured during the paced trials or endurance tasks was due to the shot scenario and not a result of the preceding test procedures, the paced shot scenario was always completed first. After a significant rest period (~10 min), participants completed the remaining two shot scenarios. The sequence in which they completed the prone or lateral target engagement scenarios was balanced among participants as was the sequence in which they performed the Control and 3ARM trials within each scenario.

2.3.2 Shot Scenario 2: Standing-to-Prone (“Prone”) Target Engagement

The standing-to-prone (“prone”) target engagement scenario was developed to determine whether 3ARM would affect the user’s ability to drop to a prone firing position and engage a target. In order to achieve the prone shooting posture with 3ARM, the user must guide the mechanical arm out away from their body with the elbow, and the user’s natural arm must be tucked between their body and the mechanical 3ARM. Participants were asked to practice this maneuver prior to completing the prone firing trials. At the start of the trial, participants were given a full 30-round magazine and instructed to drop to the prone firing position as quickly as possible to discharge a group of five self-paced shots on a center target located at 75 m (Fig. 5). Participants then rose to a standing position and discharged another self-paced five-round shot group. Participants continued firing five-round groups alternately from prone and standing postures until all 30 rounds had been discharged (three groups from prone, three groups from standing). For all shots, participants were instructed to put equal emphasis on speed and accuracy. As with the paced trials, the prone scenario was completed for both the Control and 3ARM conditions.

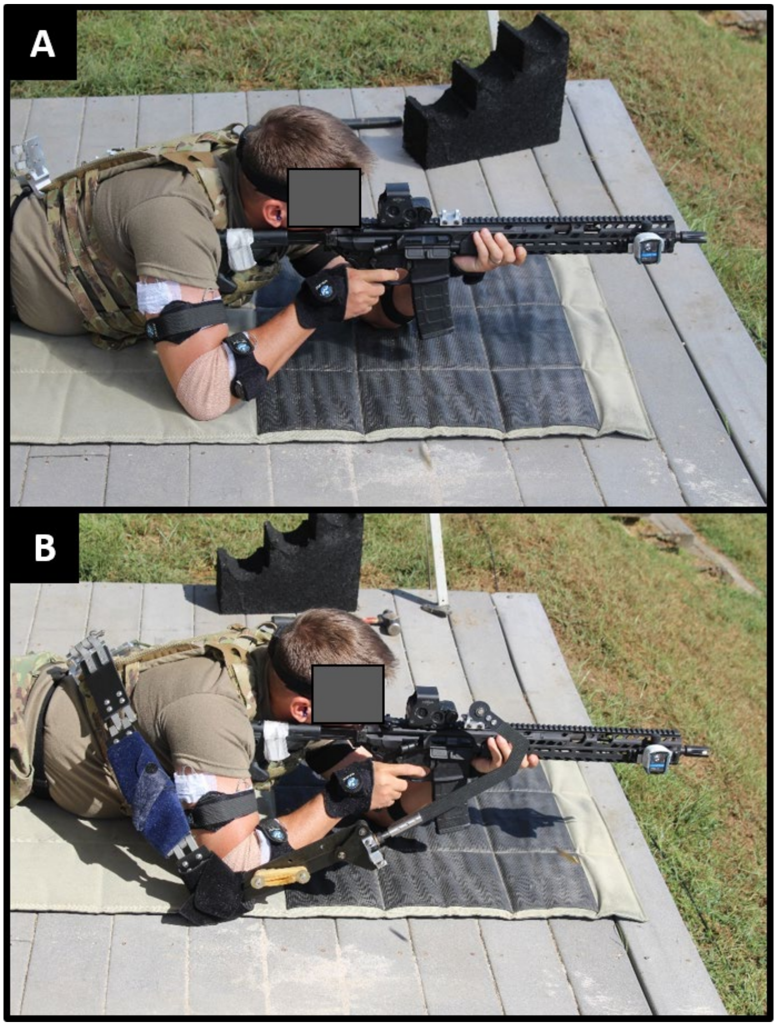


Fig. 5 An instrumented participant completing the prone firing scenario for both the Control (A) and 3ARM (B) conditions. Note that for the 3ARM condition, the user's natural arm is between their body and the mechanical arm.

2.3.3 Shot Scenario 3: Lateral Target Engagement ("Lateral")

The lateral target engagement scenario ("lateral") was designed to evaluate whether 3ARM affects target engagement times when slewing the weapon across the body. During this scenario, pop-up targets were presented to the left and right of the shooter at a range of 75 m and approximately 40 m removed from the center target (slew angle of ~30°; Fig. 6). Participants were instructed to have the weapon oriented downrange toward a center target in a low-ready position. As each pop-up target was presented, participants were asked to engage each target with a single round as quickly and accurately as possible. Target presentations were controlled by a custom computer program. Participants were required to practice the task prior to the data collection trials to become accustomed to target presentation time and location of the pop-up targets. During data collection trials, the program presented

15 left targets and 15 right targets during each engagement scenario, but the sequence of their presentation and the timing between successive targets was randomized (~3–15 s). The total duration for these trials was approximately 5–6 min. As with the other shot scenarios, participants completed the lateral shot scenario for both the Control and 3ARM conditions.

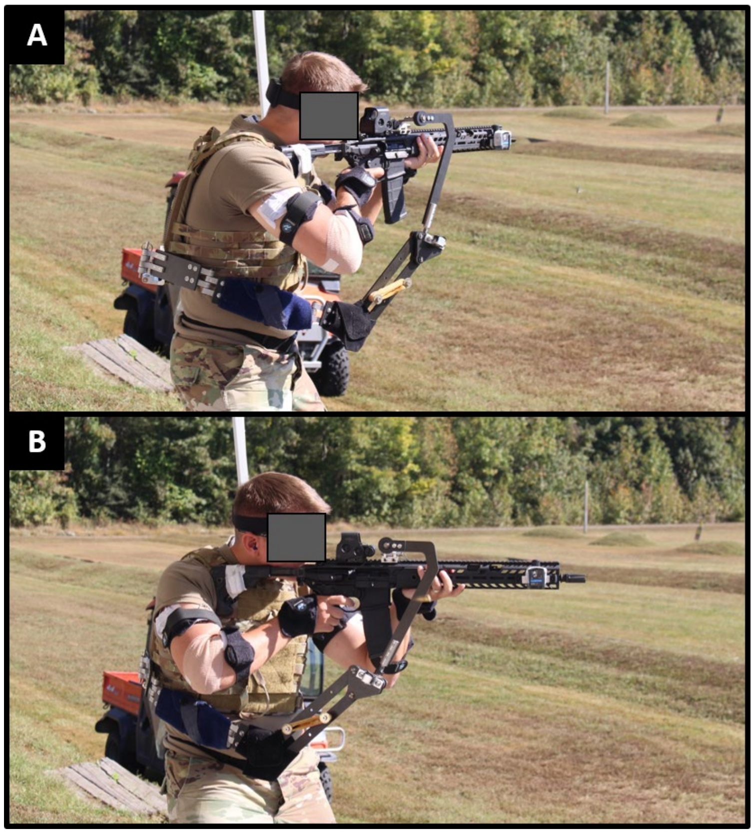


Fig. 6 An instrumented participant completing the lateral firing scenario for the 3ARM condition. A) The participant slews left of center to engage a left pop-up target. B) The participant slews right of center to engage a right pop-up target.

2.3.4 Condition and After-Action Questionnaires

Following each condition (Control or 3ARM) within each shot scenario, participants were asked to complete a Condition Questionnaire (CQ) rating the quality of their experience in completing the most recent live-fire trial. The CQ included a seven-point Likert scale ranging from Strongly Disagree to Strongly Agree and prompted the participants to rate different elements of marksmanship performance. For the paced live-fire trials, participants rated their experience in terms of fatigue and discomfort, ability to maintain weapon aim point, comfort in holding the weapon, control of the weapon, and confidence in shot placement. For the prone and lateral live-fire trials, participants rated their experience in terms of fatigue and discomfort, ability to acquire the target, comfort in holding the weapon, freedom of movement during target engagement, control of weapon orientation, satisfaction with speed of target engagement, and confidence in shot placement. Participants were also asked to document any areas of the body in which they experienced pain or discomfort during the trial, and they were asked to rate the severity of the pain/discomfort.

At the conclusion of all live-fire trials, participants completed an After-Action Questionnaire (AAQ) to compare the 3ARM with the Control condition. The AAQ allowed participants to express a preference for either the Control or 3ARM condition in terms of the various marksmanship elements rated in the CQ. The AAQ also included short answer questions prompting feedback on possible improvements to the 3ARM system, alternative use-case scenarios for the 3ARM, and ideas to improve the fit and comfort of 3ARM. The CQ and AAQ are provided in Appendixes A and B.

2.4 Data Analysis

Shot performance was analyzed for all live-fire trials, but other dependent measures were specific to each shot scenario. Additional data analysis included measures of muscle fatigue development, timing, and measures of weapon control.

2.4.1 Shot Performance

Participants were instructed to aim for the target's center of mass, and data was provided by the target system in the form of x-y coordinates corresponding to shot location relative to the target's center of mass (0,0). Negative y coordinates indicate locations below the center of mass, and negative x coordinates indicate locations to the left of the center of mass. Based on these x-y coordinates, shot performance for each condition and each shot scenario was quantified using three different metrics: hit percentage, distance of the center of the shot group (DCSG), and mean radius. Hit percentage is an indication of effectiveness and is calculated as the number of shots on target divided by the total number of shots for that trial (Head et al. 2017; Morelli et al. 2017; Brown et al. 2018; Eq. 1).

$$Hit\ Percentage = \frac{n_{on\ target}}{n_{total}} \tag{1}$$

All shots taken by a particular participant for a given scenario are referred to as a shot group. The center of the shot group is the mean x and y coordinates ($\bar{X}$,$\bar{Y}$) for each shot within the group. The DCSG from the target center is a measure of accuracy quantifying the proximity of the average shot of the group to the center of mass of the target (Head et al. 2017; Morelli et al. 2017). The DCSG was calculated using the standard distance equation (Eq. 2). Lower DCSG corresponds to a more accurate shot group.

$$DCSG = \sqrt{(\bar{X})^2 + (\bar{Y})^2} \tag{2}$$

The final measure of shot performance is mean radius. Mean radius indicates how closely the shot group is clustered together providing a measure of precision. Mean radius is calculated as the mean of the distances between each individual shot and the coordinates of the DCSG (Morelli et al. 2017; Eq. 3). A lower value of mean radius indicates better shot precision.

$$Mean\ Radius = \frac{\sum\sqrt{(X-\bar{X})^2+(Y-\bar{Y})^2}}{n} \tag{3}$$

Paired samples or repeated measures statistical analyses were performed on the subsequent data. Prior to these analyses, Shapiro–Wilk tests were performed to determine normality then parametric and non-parametric tests for significances were chosen for analysis.

2.4.2 Paced Shot Scenario and Muscular Endurance Task–Dependent Measures

Paced trials afforded the most opportunity for objective comparisons between the Control and 3ARM conditions because shot number and engagement time were held constant. Endurance hold time was quantified prior to live-fire trials (Pre) and also immediately following the completion of paced Control and 3ARM trials. At the initiation of each hold trial, a digital marker was inserted into the data file. In post-processing, the orientation of the upper support arm was visually inspected, and researchers identified the instant at which the arm began to deviate from its static hold position. The elapsed time between this identified point of movement and the initial data marker was calculated as the endurance time for that trial. Endurance time provided a surrogate measure for fatigue development in the arm over the course of the trial.

Fatigue development was also quantified during this muscular endurance task and during live-fire trials using measures of muscle MF and contraction amplitude (Amp). MF is the frequency at which the power of an EMG signal is divided into halves of equal amplitude (Cifrek et al. 2009; Phinyomark et al. 2012). More directly, it describes an important central motor frequency driving muscle contraction. Amp measures refer to the magnitude of the EMG signal, typically calculated as an RMS value of the signal. Monitoring changes in both MF and Amp over time is a useful approach to objectively quantify fatigue development. As a muscle fatigues during submaximal static contractions, the MF decreases as the muscle attempts to maintain force by producing less frequent but stronger tonic contractions. Thus, appropriately, EMG Amp increases as a muscle experiences fatigue (Bigland-Ritchie et al. 1986; Allison et al. 2002; Walker et al. 2012).

All EMG signals were demeaned and filtered using a fourth-order, zero-lag bandpass filter between 10 and 450 Hz. MF measures were determined at each half-second during the endurance hold using a moving window of 1500 frames (1 s) and a step size of 750 frames (0.5 s). During the live-fire trials, MF was calculated using identical window and step size parameters but was quantified only during the 5-s periods of static weapon aiming preceding each shot. The time including weapon recoil and postural recovery following a shot was not included in the EMG analyses. Similarly, EMG Amp measures were calculated at the same time points using the same moving window parameters and were calculated as the RMS of the signal. The slopes of MF and Amp measures over the course of the muscle endurance task and over the duration of the live-fire trials were used to compare fatigue development between the Control and 3ARM conditions.

For the paced live-fire trials, IMU data was also analyzed to compare the stability of weapon aim between firing conditions. The barrel-mounted IMU produced course/pitch/roll orientations describing vertical motion (pitch) and the left-right motion (course) of the weapon during weapon aiming. Figure 7 shows the course and pitch trace recorded for a single participant during a live-fire trial. SampEn was used to quantify the randomness of the movement along these two axes during weapon aiming, with greater SampEn implying more randomness and less control of weapon movement. IMU data was downsampled to its true 100-Hz resolution, and SampEn was calculated for each period of static aiming prior to each shot. The data sample size N for each calculation was 450 frames (4.5 s), and data was made stationary prior to the SampEn calculation. Preliminary analysis was used to select the SampEn parameters of $m = 2$ and $r = 0.15\sigma$. SampEn was calculated for both the course and pitch orientations for each static aim period during the paced live-fire trials. The SampEn slope was used to compare weapon control between conditions.

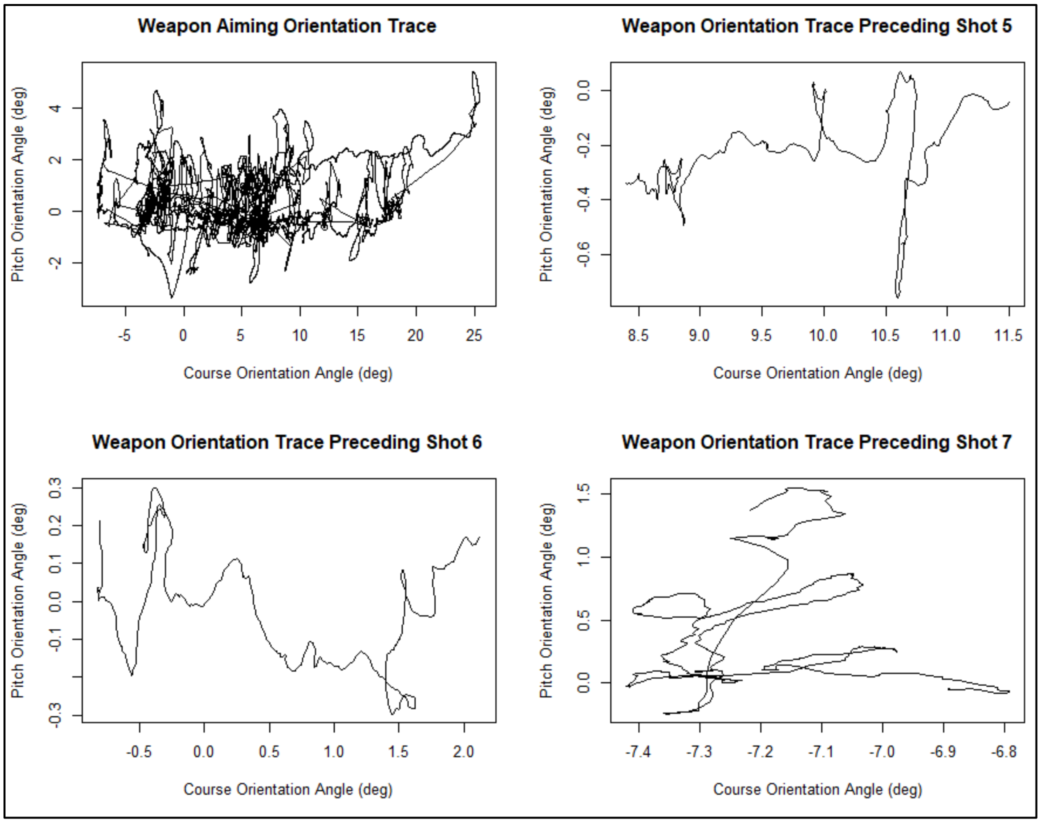


Fig. 7 Course and pitch orientation trace for a single participant completing a paced live-fire trial. Clockwise from top left: 1) course and pitch trace over the duration of the entire trial, 2) course and pitch trace for period of static aiming between shots 4 and 5, 3) course and pitch trace for period of static aiming between shots 5 and 6, and 4) course and pitch trace for period of static aiming between shots 6 and 7.

2.4.3 Prone Shot Scenario–Dependent Measures

The prone trials were used primarily to investigate the effect of 3ARM on transition time between shooting postures and target engagement time within firing postures. The time stamp for each shot was used to calculate the mean between-shot time for each prone shot group (three per trial) and each standing shot group (three per trial). The time elapsed between the final shot in a prone group and the first shot of a standing group was used as a measure of prone-to-standing (P2S) transition time. Similarly, the time elapsed between the final shot in a standing group and the first shot of a prone group was used as a measure of standing-to-prone (S2P) transition time. Since all participants fired their first group of five shots from a prone position and their final group of five shots from a standing position, there were three observations of P2S transition time and two observations of S2P transition time in each trial. Finally, the time between the first and last shot of the trial was calculated as a measure of total engagement time.

2.4.4 Lateral Shot Scenario–Dependent Measures

The lateral target shot scenario was used to evaluate response time to targets presented at a location offset from the user's position and requiring slewing of the weapon to engage the target. Movement initiation in response to target presentation was determined using the acceleration profiles recorded by IMUs mounted to the barrel and the weapon support hand. The shot microphone signal was used to determine the time that the shot was taken. The difference between the shot time and the movement initiation time was recorded as the lateral response time (Fig. 8). Response time was determined for each shot taken during the live-fire trials.

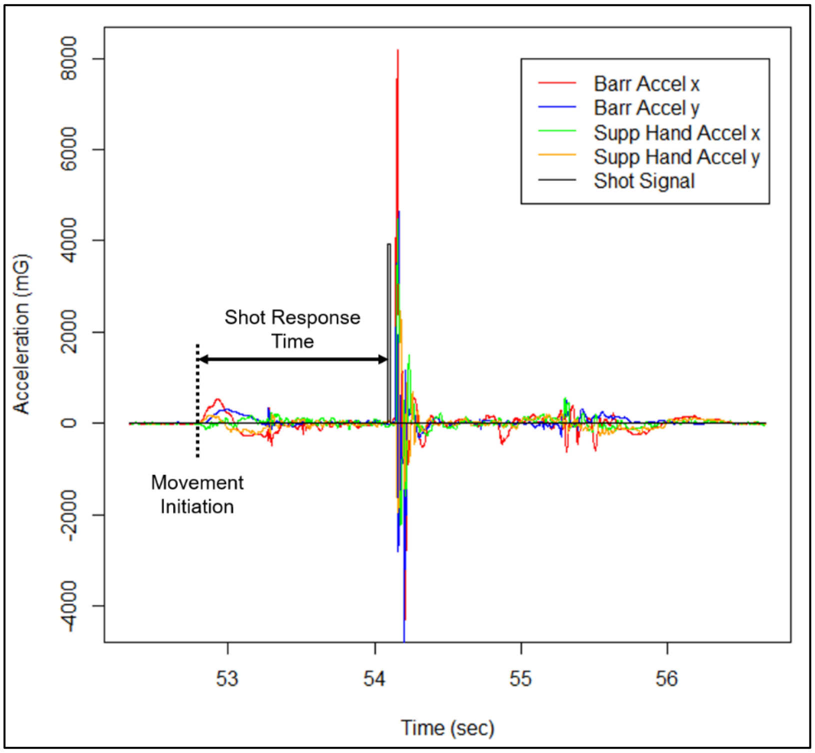


Fig. 8 A single shot response time recorded for one participant. The acceleration profiles for the barrel-mounted (Barr) and support hand (Supp Hand) IMUs were used to determine the instant of movement initiation in response to a target. The square-wave signal reported from the shot microphone was used to determine the time the shot was taken. The elapsed time between these two events is the lateral shot response time.

3. Results

Results are presented by shot scenario. Due to the outdoor testing, some data sessions were incomplete because of weather or unanticipated range closure (e.g., flyover). In at least one other case, a participant was contacted during his participation by a commanding officer and redirected to another duty location. This means that some data is missing either for a specific scenario (paced, prone, or lateral) or for a condition (Control or 3ARM) within a specific shot scenario. All usable data was retained and submitted for data analysis, and statistical tests that accommodate data sets with missing values were used. Due to the novelty of the application of EMG during a live-fire marksmanship task, there was a lack of data to calculate an appropriate effect size for EMG-derived variables. For this reason, we used an alpha value of 0.10 when evaluating statistical significance for EMG-derived measures, but a standard 0.05 alpha value was used for all other statistical analyses.

3.1 Paced Target Engagement Scenario and Muscular Endurance Task

Endurance hold time was quantified prior to live fire (Pre) and immediately following each of the Control and 3ARM paced live-fire trials. For the muscular endurance task measures, dependent measures were evaluated using a one-way repeated measures ANOVA with a fixed effect of condition (three levels: Pre, Control, 3ARM) and random subject effects. Analysis of endurance hold time revealed a significant main effect ($F_{2,26} = 36.70$, $p < 0.0001$) of condition. Tukey's post-hoc test further revealed significant differences between all pairs of conditions. Mean endurance time in the weapon support arm prior to live-fire was 56.3 ± 15.6 s, which was significantly greater ($p < 0.0001$ and $p = 0.0002$, respectively) than endurance time following either the Control or 3ARM trials. Endurance time following the 3ARM trial (37.5±15.9 s) was also significantly greater ($p = 0.0018$) than the endurance time following the Control trial (21.9 ± 10.0 s).

During the muscle endurance task, muscle MF and amplitude were analyzed for the muscles of the weapon support arm: upper trapezius (TRAP), anterior deltoid (DELT), biceps brachii (BIC), triceps brachii (TRI), brachioradialis (BRAC), latissiumus dorsi (LAT), and lumbar erector spinae (ES). Analysis of MF slope for each muscle indicated a significant main effect of condition ($F_{2,26} = 4.58$, $p = 0.19$) for the supporting LAT muscle. Post-hoc analyses clarified that during the Control condition, the MF slope for the supporting arm LAT muscle was significantly more negative than for either the Pre condition ($p = 0.0267$) or the 3ARM condition ($p = 0.055$; Fig. 9). Analysis of the Amp slope measures during the endurance hold task indicated a significant main effect of condition for the TRI muscle ($F_{2,26} = 7.45$, $p = 0.003$; Fig. 10). Post-hoc analyses determined that Amp slope during the Pre condition was significantly lower than for either the Control ($p = 0.051$) or 3ARM ($p = 0.002$) conditions. Amp slope measures for the endurance hold task did not reveal any significant differences between the 3ARM and Control conditions.

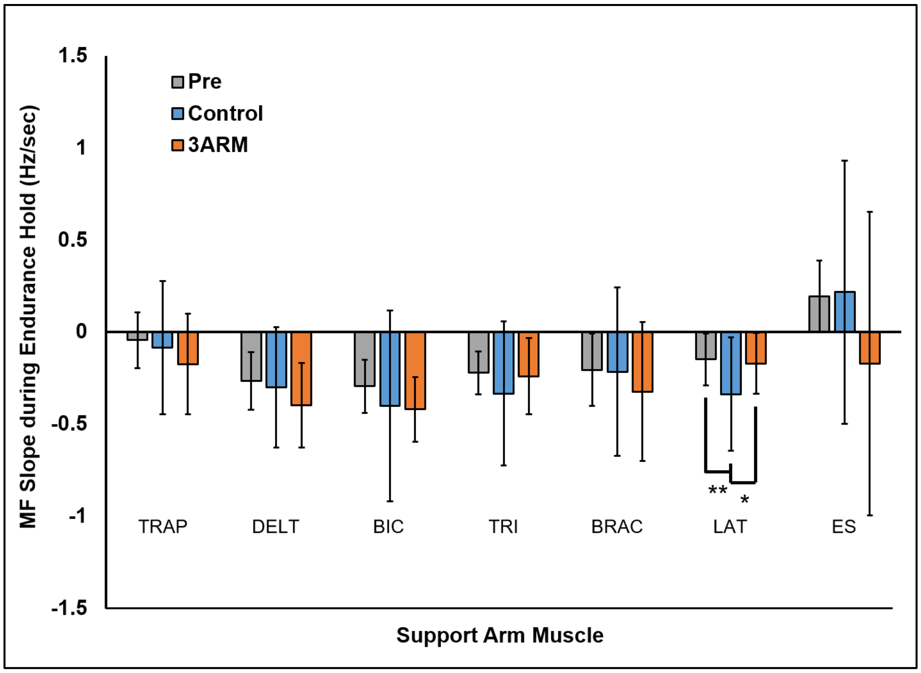


Fig. 9 Mean and SD of MF slope for the support arm muscles during the endurance hold task. The symbols (*) and (**) indicate significant differences between the identified conditions with p-values of 0.055 and 0.027, respectively.

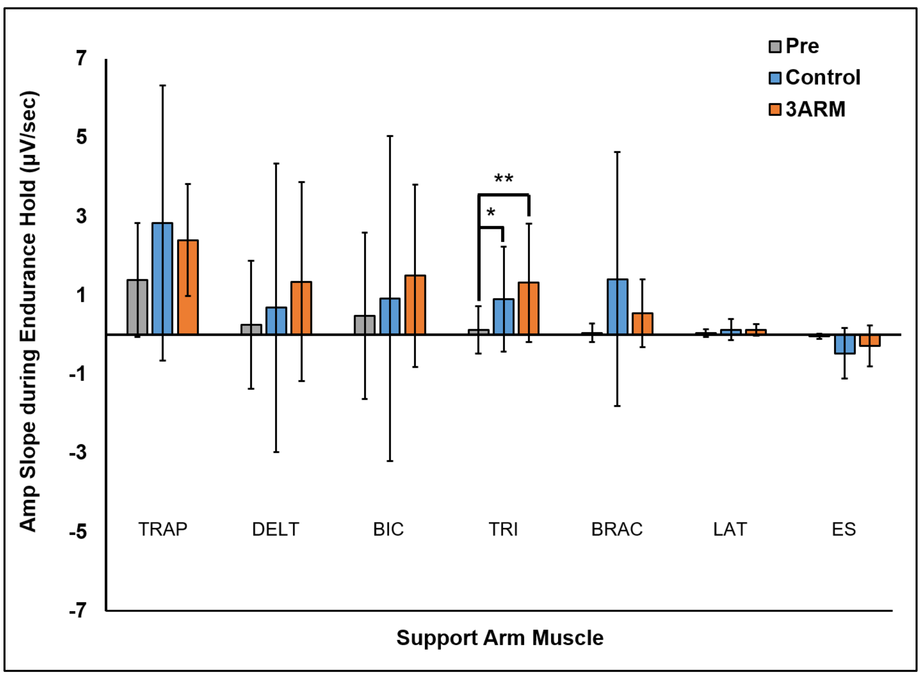


Fig. 10 Mean and SD of Amp slope for the support arm muscles during the endurance hold task. The symbols (*) and (**) indicate significant differences between the identified conditions with p-values of 0.05 and 0.002, respectively.

For the paced live-fire trials, MF and Amp slope measures were calculated for both the supporting and shooting arm. Dependent measures were again submitted to a one-way repeated measures ANOVA with a fixed effect of condition (two levels: Control, 3ARM) and random subject effects. A significant difference ($F_{1,13} = 4.08$, $p = 0.065$) was found between Control and 3ARM conditions for MF slope of the supporting arm DELT muscle (Fig. 11). During the Control condition, participants exhibited a greater decrease in MF (greater negative slope) in the supporting arm DELT compared to the 3ARM condition.

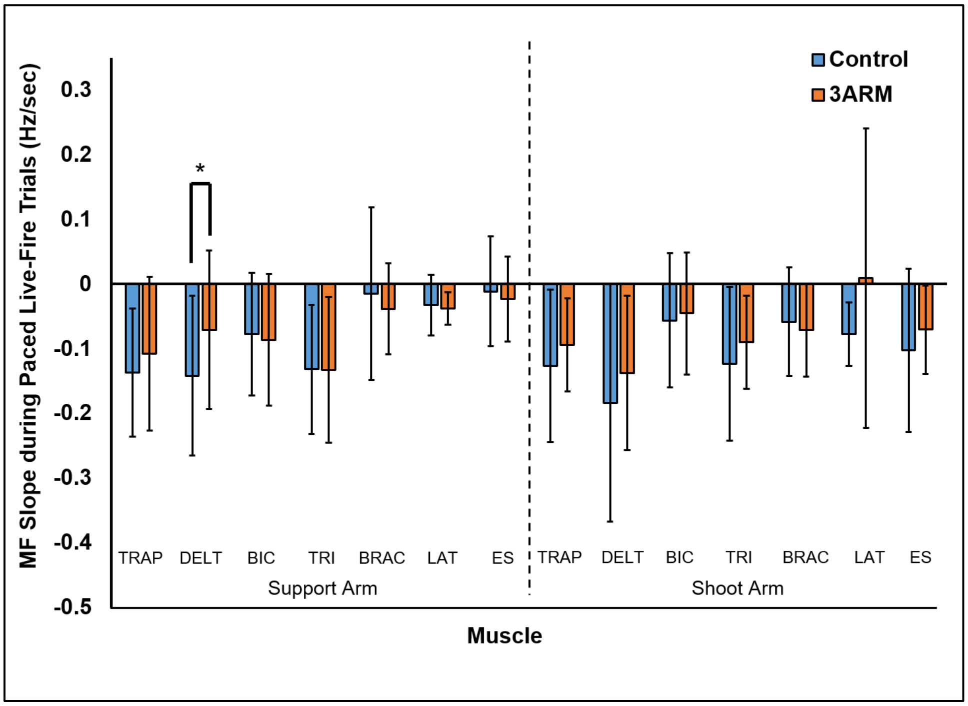


Fig. 11 Mean and SD of MF slope during the paced live-fire trials. The symbol (*) denotes a significant different between the identified conditions with a p-value of 0.065.

Whereas MF slope and Amp slope measures for the endurance hold task and MF slope measures during live fire exhibited the polarities that are consistent with fatigue (negative for MF, positive for Amp), the Amp slope measures during live fire were much more inconsistent. The Amp slope measures for the supporting and shooting arm muscles during the live-fire trials are presented in Fig. 12. The supporting arm DELT and BRAC muscles as well as the shooting arm DELT muscle exhibited significant differences in Amp slope between the Control and 3ARM conditions ($F_{1,26} = 3.04$, $p = 0.093$; $F_{1,12.04} = 4.06$, $p = 0.067$; $F_{1,11.7} = 10.98$, $p = 0.006$, respectively). In each case, the Control condition resulted in a positive mean Amp slope while the 3ARM condition resulted in a negative mean Amp slope. Other muscles resulted in a mean Amp slope that was very nearly 0, indicating no cumulative change in muscle contraction magnitude during the trial.

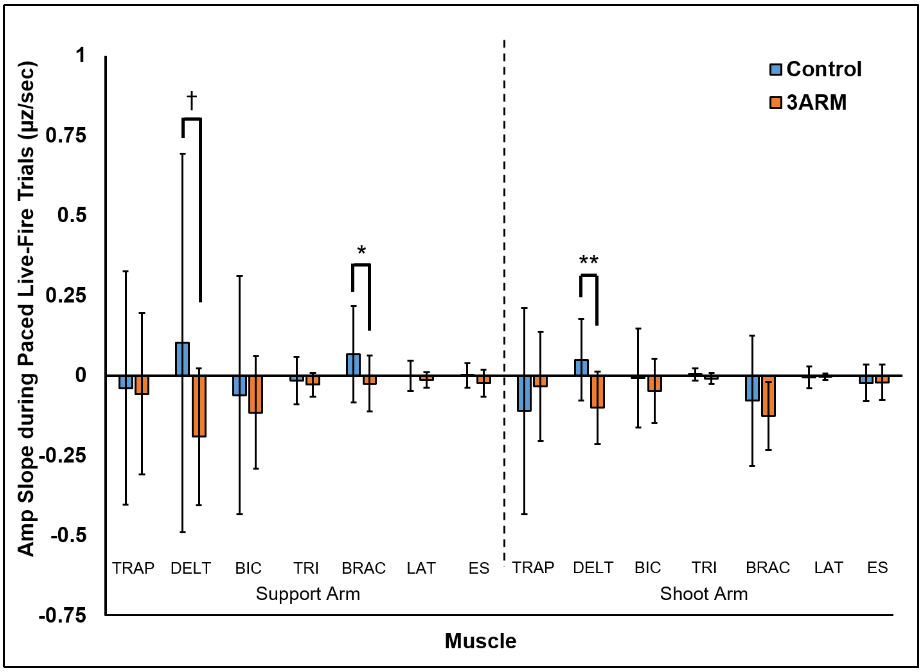


Fig. 12 Mean and SD of Amp slope during the paced live-fire trials. The symbols (†, *, **) denote statistically significant differences between the conditions with p-values of 0.093, 0.067, and 0.006, respectively.

The time series for the course and pitch orientation of the weapon during these paced live-fire trials were submitted to SampEn analysis. The SampEn was calculated for each orientation axis (course, pitch) during the period of static aiming immediately preceding each shot. Participants were cued to fire at the initiation of the trial, so SampEn was not calculated preceding the first shot. SampEn values for weapon orientation preceding live-fire shots 2–30 are shown for a single participant completing both conditions (Fig. 13). As with the EMG measures during live fire, mean SampEn measures were analyzed using a one-way repeated measures ANOVA with a fixed effect of condition (two levels: Control, 3ARM) and a random effect of subject. Along the course (left-right) orientation axis, there was no significant difference in SampEn between conditions ($F_{1,11.8} = 2.46$, $p = 0.14$). Along the pitch (up-down) orientation axis, however, mean SampEn was significantly greater for the Control condition compared to the 3ARM condition ($F_{1,10.4} = 4.95$, $p = 0.049$; Fig. 14).

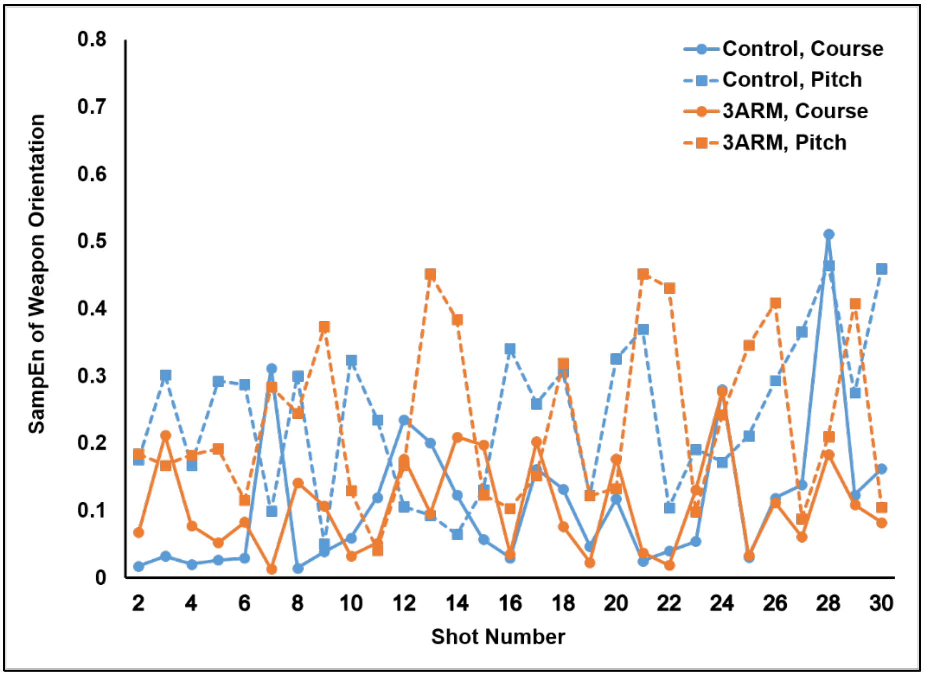


Fig. 13 SampEn for the course and pitch orientations of the weapon immediately preceding each shot during the paced live-fire trials

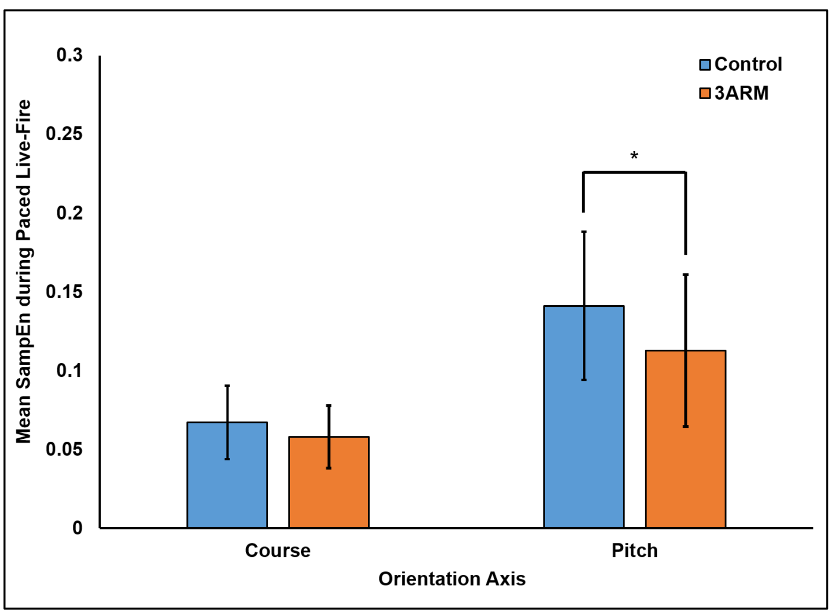


Fig. 14 Mean and SD of SampEn values for the course and pitch orientation of the weapon during paced live fire. The symbol (*) denotes a statistically significant difference between the identified conditions with a p-value of 0.049.

Shooting performance for all participants during the paced scenario is presented in a kernel density plot (Fig. 15) where all shots for a single participant are represented by the same color. Differences in shooting performance can be difficult to distinguish from kernel density plots. Hit percentage (i.e., effectiveness) between conditions was compared using the non-parametric paired samples Wilcoxon signed-rank test, with an a priori significance level set at 0.05. While there was a 1.39% increase in hit percentage when using the 3ARM, the difference was not significant ($p = 0.22$). For the DCSG metric (i.e., accuracy), data from both the Control and 3ARM conditions were normally distributed (Shapiro–Wilk Test for Normality; $p > 0.05$) so a paired samples t-test was used ($\alpha = 0.05$). With a p-value of 0.47, there was no difference in DCSG between the Control and 3ARM conditions. Mean radius, however, did seem to improve with the 3ARM. Using a paired sample t-test, mean radius was significantly different between conditions ($p = 0.02$) with the 3ARM condition resulting in a mean radius that was 0.52 inches less than the Control condition, suggesting greater precision with the 3ARM (Fig. 16).

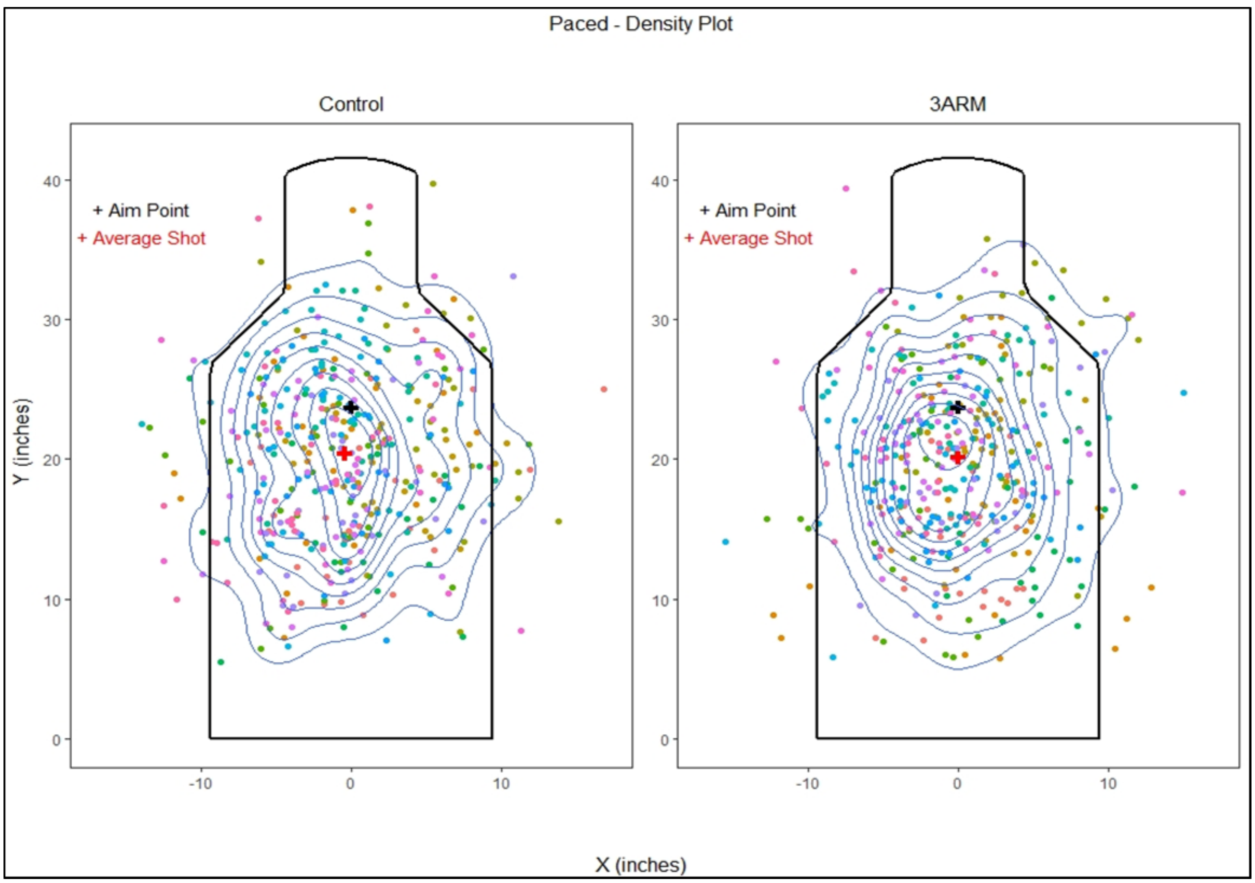


Fig. 15 Kernel density plot for all paced scenario shots overlaid on an outline of an e-silhouette target. The center of mass is represented by a black cross. The mean X and Y coordinate of all shots is represented by a red cross. All shots taken by a single participant are presented in the same color.

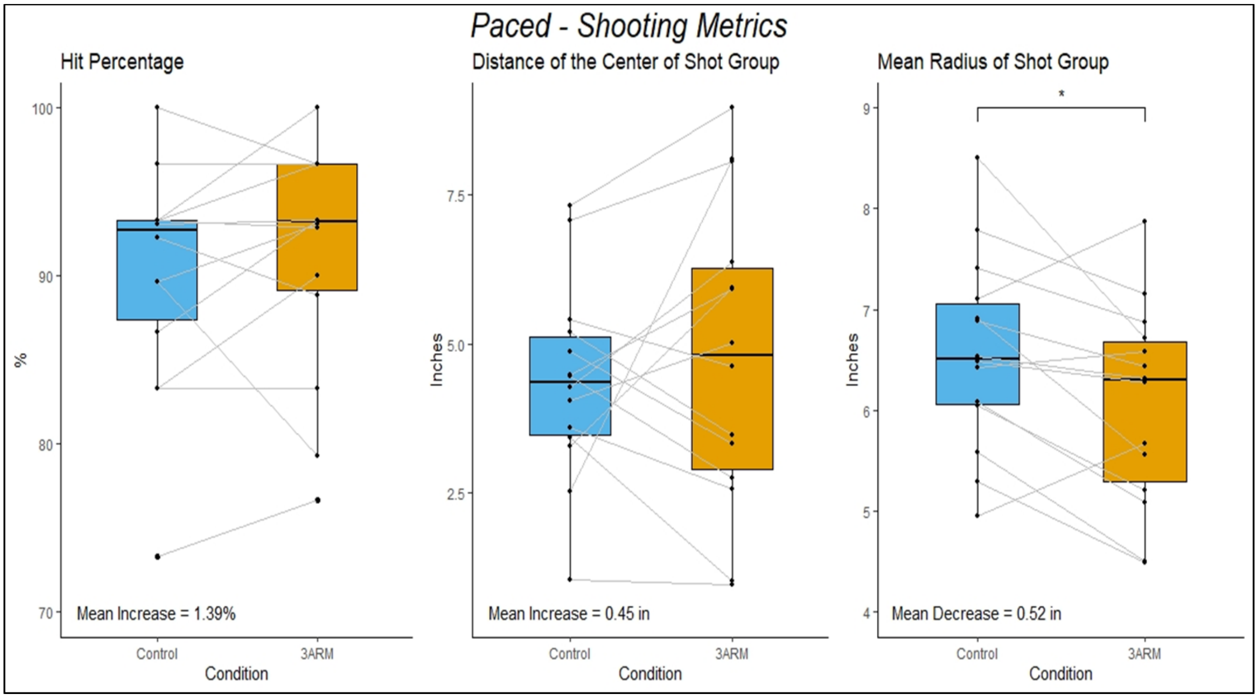


Fig. 16 Box and whisker plots for the comparison of paced shooting metrics between Control and 3ARM conditions. Metrics for individual participants are represented by black dots paired across conditions by gray lines. The symbol (*) indicates a statistically significant difference between conditions.

For the previous analyses, all shots for a particular condition were aggregated, and the shot group was described and used for comparison. However, the paced scenario was designed to test the hypothesis that the 3ARM would mitigate muscular fatigue and thus performance decrement during extended target engagement. Aggregating the shots does not allow for this comparison as there is no distinction between the beginning and end of the trial. To investigate whether the 3ARM improved shooting performance during extended target engagement, we further separated the paced scenario trial into the first five shots ("First") and last five shots ("Last") (Fig. 17).

Data for the DCSG broken out by First and Last shots were not normally distributed, so a Wald Chi Squared Test was run as a non-parametric alternative for within-subjects comparisons. According to the results, there was a non-significant decrease in DCSG at the end of the trial when participants used the 3ARM.

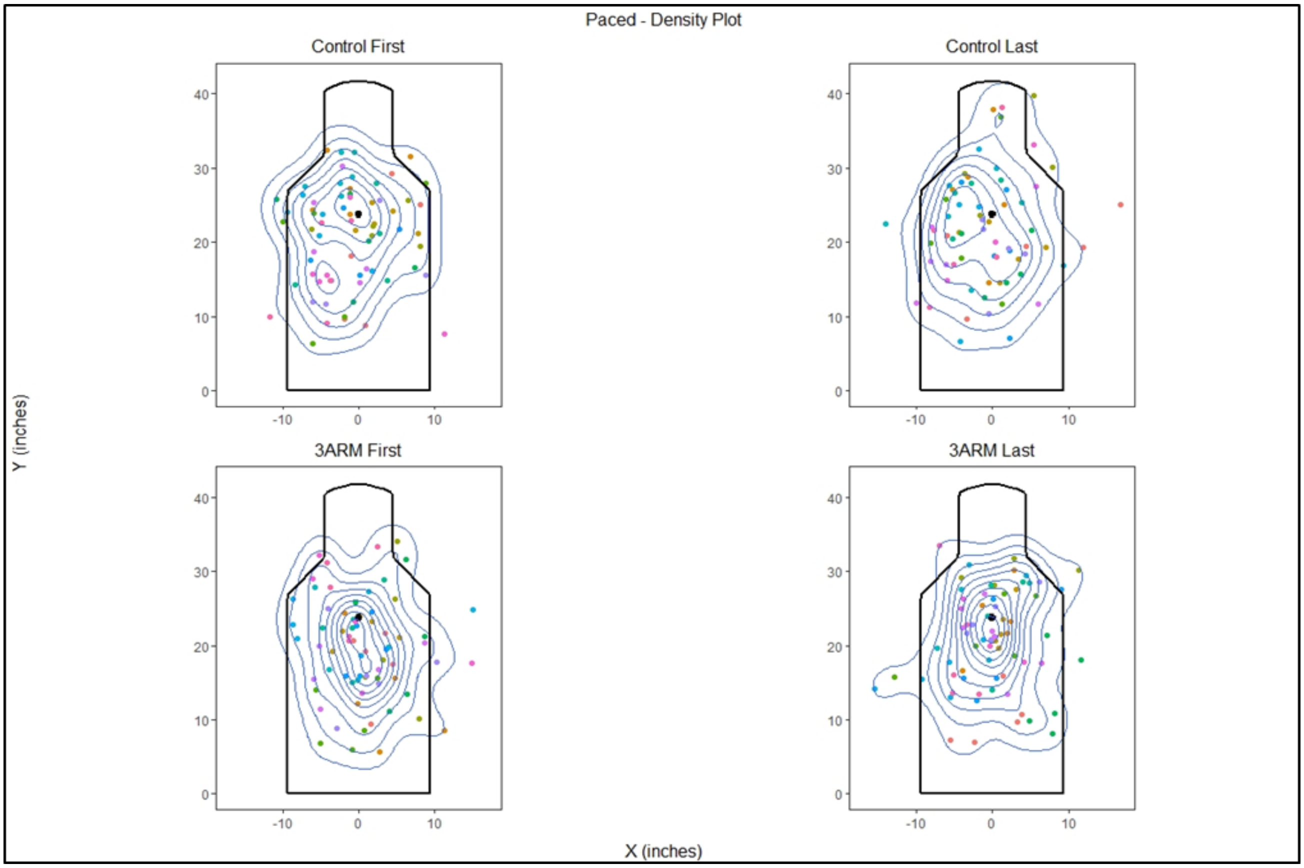


Fig. 17 Kernel density plot for the first five ("First") and last five ("Last") shots taken by all participants for the Control and 3ARM conditions

3.2 Prone Target Engagement Scenario

Prone trials produced a number of time-based measures of performance. Measures of between-shot times for the prone and standing groups and P2S transition time were analyzed using a two-way repeated measures ANOVA with fixed effects of condition (two levels: Control, 3ARM) and observation (three levels: Observation 1, 2, and 3) and with random subject effects. The S2P transition time measure was analyzed using the same repeated measures ANOVA model, but the observation number had only two levels for the analysis of S2P. The total engagement time was analyzed using the one-way repeated measures ANOVA described earlier in the paced scenario results section (3.1).

No interaction effects between condition and observation were observed for any of the time measures, so results are presented as grand means for each condition (Table 2). There was no effect of condition on between-shot times recorded for either the prone or standing shot groups ($F_{1,58.2} = 0.0011$, $p = 0.97$; $F_{1,58.2} = 1.57$, $p = 0.22$, respectively). Analysis of P2S transition time did reveal a significant difference between groups ($F_{1,58.2} = 13.80$, $p < 0.001$) with the 3ARM condition resulting in a significantly longer transition time from the prone to standing position. Interestingly, the S2P transition time was not found to be significantly different between conditions ($F_{1,32.8} = 2.13$, $p = 0.15$), although the condition means suggest that the 3ARM transition time between standing and prone positions was nearly 5 s longer than the transition time for the Control condition. Lastly, total engagement time was found to be significantly different between conditions ($F_{1,10.2} = 14.19$, $p = 0.003$), with the Control condition being completed in about 78 s while the 3ARM condition was completed in about 100 s.

Table 2 Grand mean (SD) of shot measures for each condition and the associated p-value for the effect of condition

Measure (s)	Control	3ARM	p-value
Between-shot time, prone	1.55 (0.80)	1.61 (0.68)	0.97
Between-shot time, standing	1.68 (0.57)	1.88 (0.67)	0.22
P2S transition time	7.71 (2.12)	10.95 (3.40)	< 0.001*
S2P transition time	8.06 (2.60)	12.52 (4.29)	0.15
Total engagement time	77.55 (26.49)	99.52 (27.29)	0.003*

The symbol (*) indicates a significant difference between conditions.

Visual depiction of the differences in prone shooting performance between Control and 3ARM can be seen in the kernel density plot in Fig. 18. Summary statistics are displayed in Fig. 19. For hit percentage, a Wilcoxon signed rank test revealed no differences between conditions ($p = 0.75$), while a paired samples t-test revealed that there was a significant ($p = 0.01$) 0.9-inch decrease in DCSG with the 3ARM compared to Control. An outlier in the mean radius can be seen in the box plot in Fig. 20. This was caused by a single errant shot by a single participant and was subsequently removed from the statistical analysis. Normality was confirmed after outlier removal, and the subsequent paired samples t-test revealed no differences between conditions.

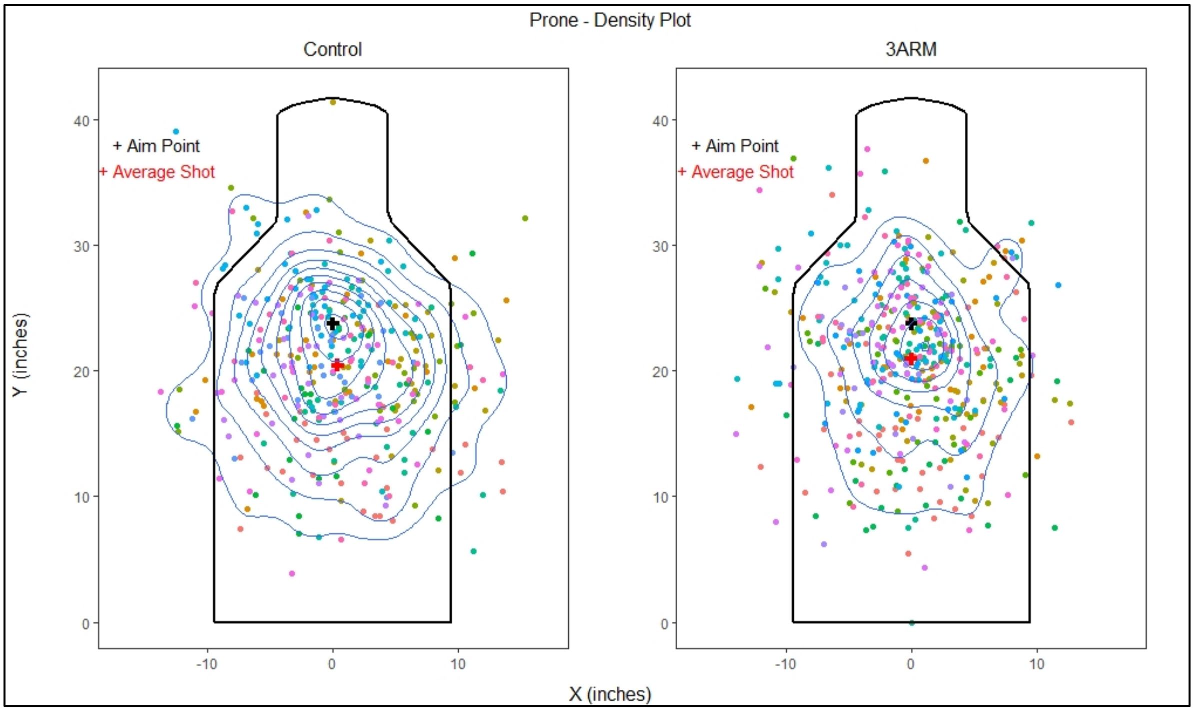


Fig. 18 Kernel density plot for all prone shots overlaid on an outline of an e-silhouette target. The target center of mass is represented by a black cross. The mean X and Y coordinate of all shots is represented by a red cross. All shots taken by a single participant are presented in the same color.

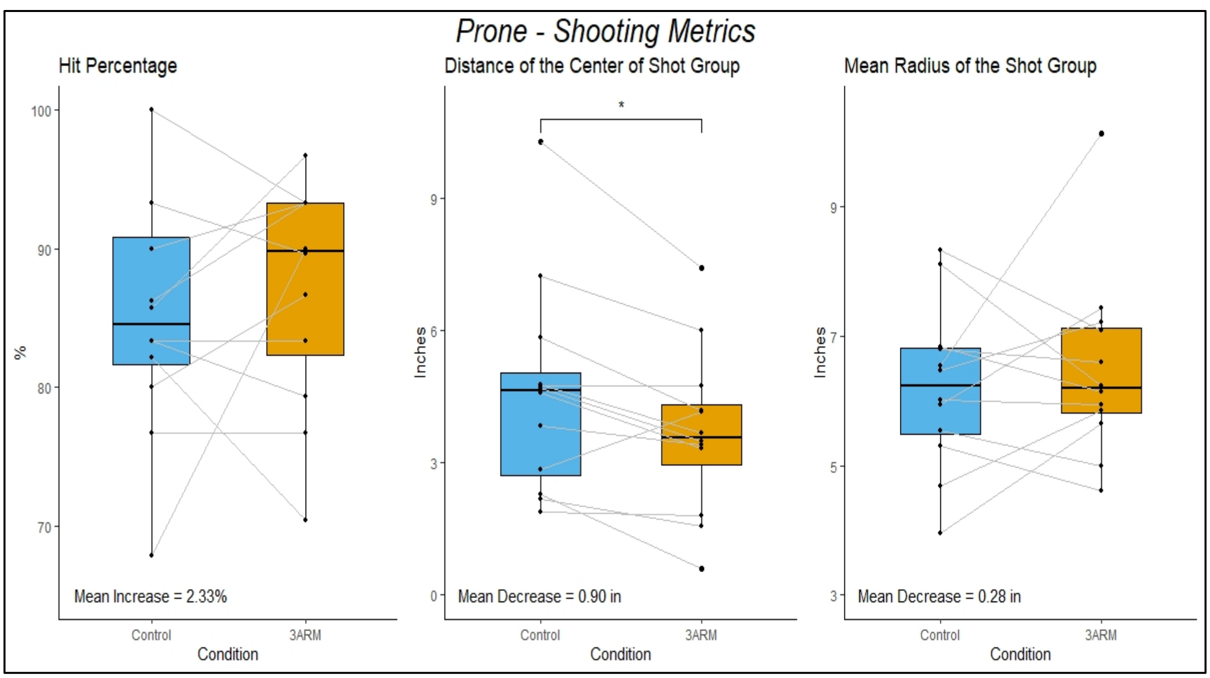


Fig. 19 Box and whisker plots for the comparison of prone shooting metrics between Control and 3ARM conditions. Metrics for individual participants are represented by black dots paired across conditions by gray lines. The symbol (*) indicates a statistically significant difference between conditions.

3.3 Lateral Target Engagement Scenario

For each live-fire trial, half (15) of the targets were presented to the participant's left, and the other half (15) were presented to the user's right. The sequence of left and right target presentation was randomized to remove the effect of anticipation on response time. Lateral response time was analyzed using a two-way repeated measures ANOVA with main factors of condition (two levels: Control, 3ARM) and direction (two levels: Left, Right) and a random effect of subject. No significant differences in lateral response time were found between conditions ($F_{1,709.4} = 0.18$, $p = 0.66$) or between directions of target presentation ($F_{1,704.2} = 0.71$, $p = 0.40$) (Fig. 20). Additionally, there was no significant interaction effect between condition and direction ($F_{1,704.2} = 0.67$, $p = 0.41$). Mean response time for all conditions and directions ranged between 1.84 ± 0.56 s and 1.91 ± 0.71 s (Fig. 20).

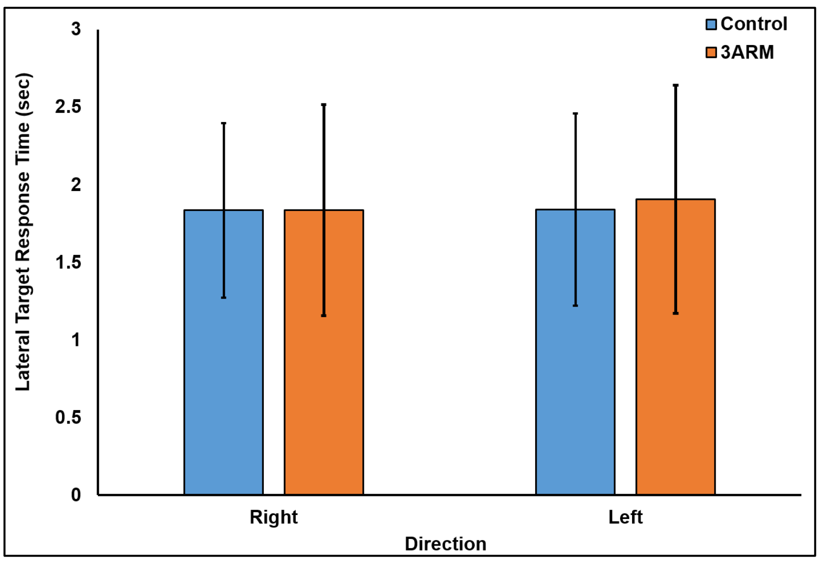


Fig. 20 Mean and SD of lateral target response time presented by condition and direction of target. No significant main or interaction effects of condition and direction were observed for lateral target response time.

Visual depiction of the differences in lateral shooting performance between the Control and 3ARM conditions can be seen in the kernel density plot in Fig. 21. Summary statistics are displayed in Fig. 22. A Wilcoxon signed rank test determined the difference in hit percentage only approached significance ($p = 0.09$), with 3ARM resulting in a mean hit percentage that was 4.35% greater than the Control condition. Data for the DCSG was not normally distributed according to a Shapiro–Wilk test. A log-transformation was implemented to return the data to normality, and a paired samples t-test was used. A non-significant difference of 0.08 in mean DCSG was found between conditions. Similarly, no significant difference in mean radius was found between conditions.

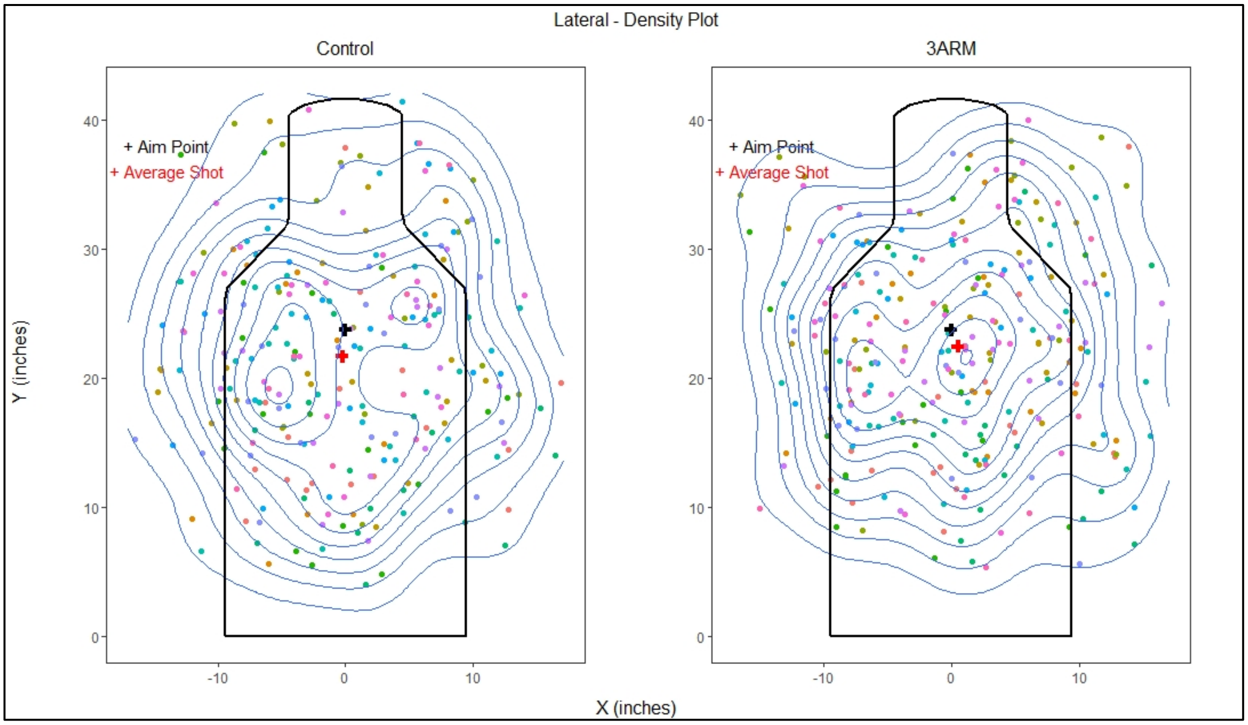


Fig. 21 Kernel density plot for all lateral scenario shots overlaid on an outline of an E-silhouette target. The center of mass is represented by a black cross. The mean X and Y coordinate of all shots is represented by a red cross. Colors of individual dots are indicative of a specific participant.

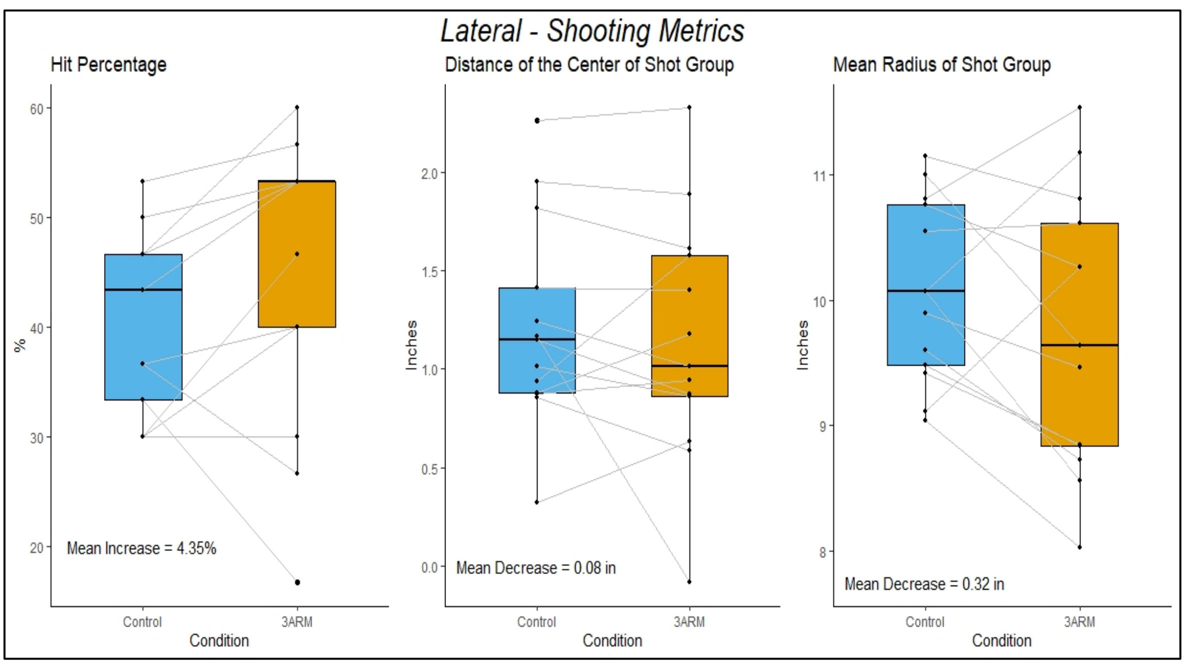


Fig. 22 Box and whisker plots for the comparison of lateral shooting metrics between Control and 3ARM conditions. Metrics for individual participants are represented by black dots paired across conditions by gray lines. The symbol (*) indicates a statistically significant difference between conditions.

3.4 Questionnaire Responses

Following each live-fire trial, participants completed a CQ (Appendix A) consisting of a series of Likert-scale questions to rate their experience following each live-fire scenario and condition as well as a Pain, Soreness, and Discomfort (PSD) questionnaire in which they reported and rated discomfort during the trial. Results for the CQ responses are presented by shot scenario. Following all live-fire trials, participants completed an AAQ (Appendix B) in which they compared the Control and 3ARM conditions and provided critical feedback regarding the 3ARM design and function.

3.4.1 Paced Shot Scenario Condition Questionnaire

For paced live-fire trials, there were five Likert scale questions:

- Q1: I developed no fatigue or discomfort throughout the trial.
- Q2: I was easily able to maintain my aim point throughout the trial.
- Q3: I was able to hold the weapon comfortably.
- Q4: I felt that I was easily able to control the orientation of the weapon.
- Q5: My confidence in my shot placement was unchanged between first and last shot.

Participants responded to these questions using a seven-point Likert scale ranging from Strongly Disagree to Strongly Agree, and the responses were coded such that Strongly Disagree = –3, Disagree = –2, Somewhat Disagree = –1, Neutral = 0, Somewhat Agree = 1, Agree = 2, and Strongly Agree = 3. Figure 23 illustrates the distribution of responses recorded for each question. These results were analyzed using a Wilcoxon signed rank test to determine if the median of the response for each question differed between conditions. For each question, there was a significant difference in response between conditions (Q1: $Z = -2.06$, $p = 0.04$; Q2: $Z = -3.02$, $p = 0.002$; Q3: $Z = -3.29$, $p < 0.001$; Q4: $Z = -2.61$, $p = 0.02$; Q5: –2.43, $p = 0.01$).

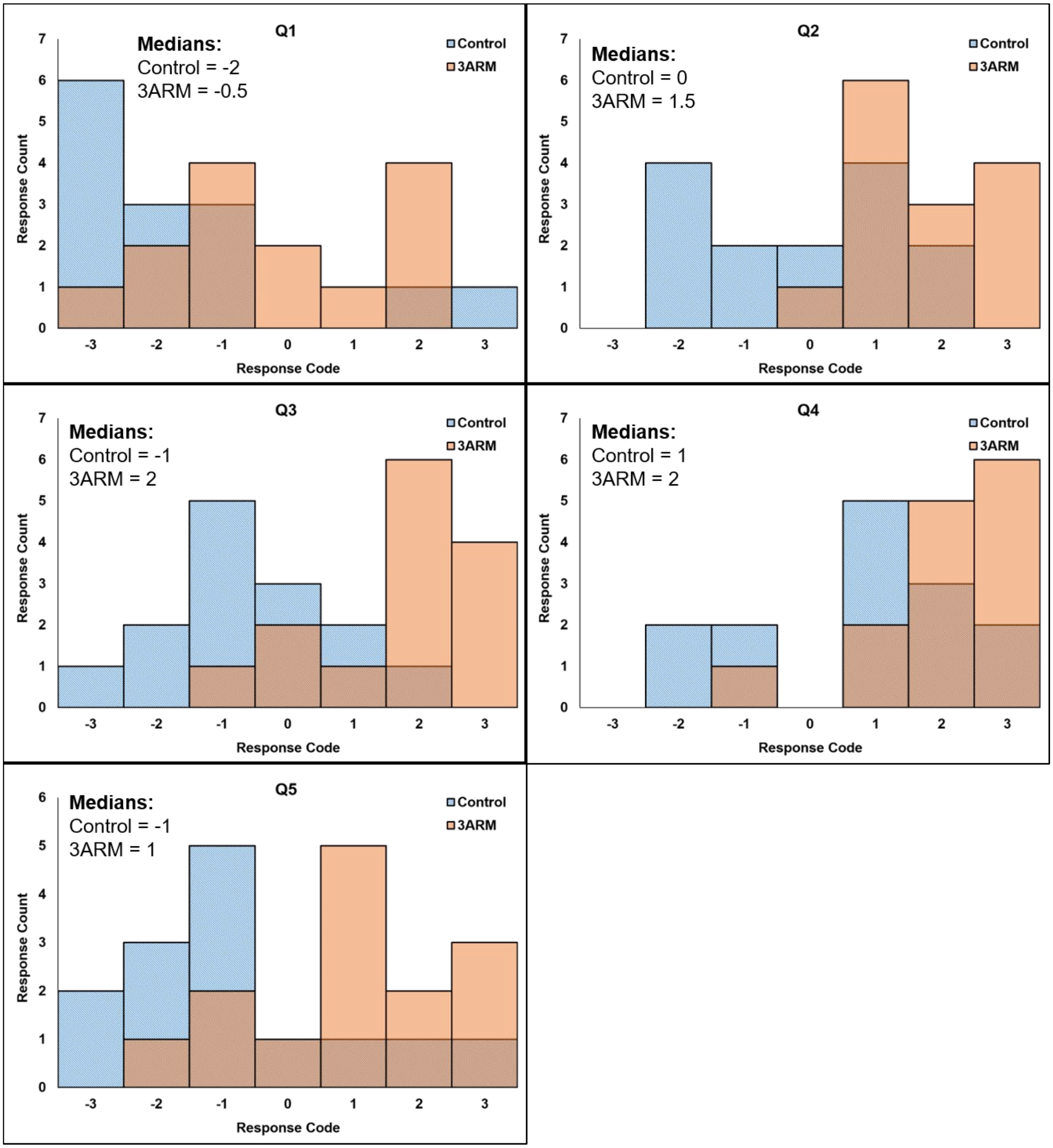
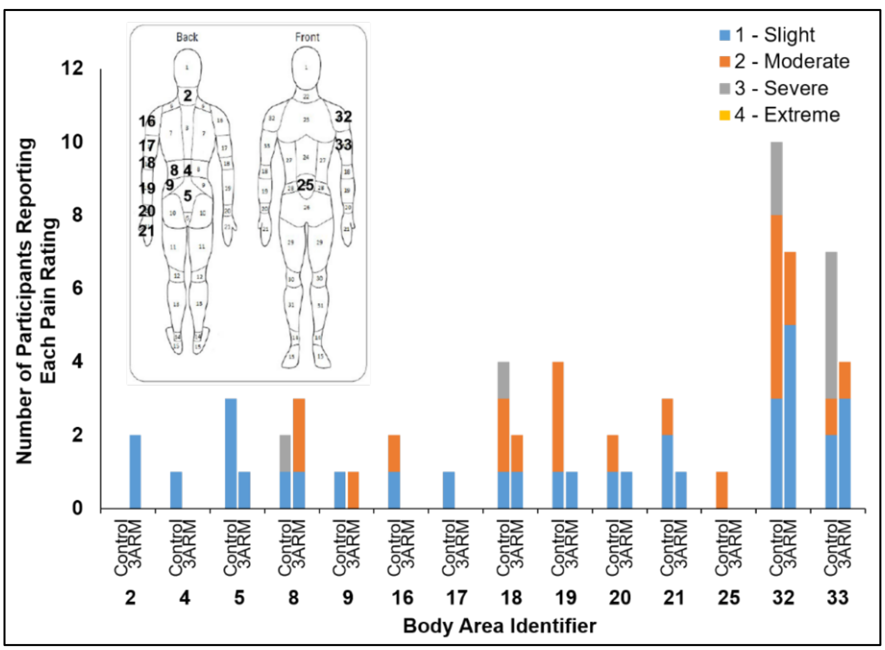


Fig. 23. Response counts for each question (identified in title bar) on the CQ following the paced live-fire trials. Colors are used to distinguish responses between conditions, and the gray shaded regions show an overlap in response count. Response codes: –3 = Strongly Disagree, –2 = Disagree, –1 = Somewhat Disagree, 0 = Neutral, 1 = Somewhat Agree, 2 = Agree, and 3 = Strongly Agree.

More specifically, in each case the median score was greater for the 3ARM condition than for the Control condition. For Q1, discomfort and fatigue were reported for both conditions, but participants disagreed more strongly during the

Control condition, indicating a greater sensation of discomfort during the Control compared to the 3ARM condition. For Q2, participants were neutral on their ability to maintain a consistent aim point during the Control condition, but agreed more strongly that they were able to maintain their aim using the 3ARM. Q3, the ability to hold the weapon comfortably, resulted in the greatest disparity between conditions. The median result for the Control condition was –1, indicating that they somewhat disagreed that they were able to comfortably hold the weapon. The median result for the 3ARM condition, however, was 2, meaning they agreed that they were able to comfortably hold the weapon with 3ARM. Q4 revealed that for both conditions, participants agreed that they were easily able to control the orientation of the weapon, although they agreed more strongly for the 3ARM condition. Finally, the results for Q5 suggest that their confidence in shot placement over the duration of the trial was unchanged between first and last shot for the 3ARM condition, but that their confidence in shot placement did change over the duration of the Control trial.

To report PSD, participants were asked to reference a numbered diagram and report the number corresponding to the specific area of the body that experienced discomfort. They were also asked to rate that discomfort on a scale of 1 to 4 in which 1 = Slight, 2 = Moderate, 3 = Severe, and 4 = Extreme. The PSD questionnaire results following the paced live-fire trials are presented in Fig. 24.



Fig, 24 PSD questionnaire results following the paced live-fire trials as a function of body part and the reported rating. A reference diagram is provided for the body area identifier numbers. For visibility, the body area identifier numbers reported for a given shot scenario are only highlighted on one side of the diagram, but note that the numbers labeling each body part are symmetric left-to-right.

During the paced live-fire trials, discomfort was reported for the neck (2), middle and lateral lower back (4 and 8), hips (9), pelvis/sacrum (5), posterior shoulder (16), tricep (17), elbow (18), forearm (19), wrist (20), hand (21), abdomen (25), anterior shoulder (32), and bicep (33). The shoulder and bicep received the greatest number of reports of PSD during the paced trials and also received higher ratings for PSD severity than other areas. For 11 of the 14 body parts reported (4, 5, 16, 18, 19, 20, 21, 32, and 33), a greater number of PSD reports were recorded for the Control trial compared to the 3ARM trial. A single participant reported discomfort in area 9 for each condition, but the severity was slightly greater with the 3ARM than for the Control condition. Areas 2 and 8 received more reports of discomfort with the 3ARM than without it.

3.4.2 Prone Shot Scenario Condition Questionnaire

For prone live-fire trials, there were seven Likert scale questions:

- Q1: I developed no fatigue or discomfort throughout the trial.
- Q2: I was easily able to acquire the target each time.
- Q3: I was able to hold the weapon comfortably.
- Q4: I was able to move freely during target engagement.
- Q5: I felt that I was easily able to control the orientation of the weapon.
- Q6: I was satisfied with the speed with which I could engage the targets.
- Q7: My confidence in my shot placement was unchanged between first and last shot.

The distribution of responses to these questions is provided in Fig. 25. Significant differences were observed between conditions in the responses to Q1 and Q4 ($Z = -2.18$, $p = 0.047$; $Z = 2.81$, $p = 0.004$, respectively). Despite a significant finding, the median responses for Q1 were the same (2) between the two groups and likely resulted from the distribution of two responses that fell outside the otherwise tightly grouped scores. Thus, it is reported here that participants did not express significantly different perceptions of fatigue or discomfort between the two conditions. For Q4, however, the median score for the Control condition was 3 while the median score for the 3ARM condition was 1. Considerably more responses ranging from –2 to 0 were recorded for the 3ARM while none were recorded for the Control condition. This suggests that the participants felt strongly that they could move more freely during the Control trial than during the 3ARM trial. No significant differences in between conditions were found for Q2, Q3, Q5, Q6, or Q7. This suggests that participants felt that the two conditions were not substantially different in terms of the ability to acquire the target, hold the weapon comfortably, control the orientation of the weapon, control the speed of target engagement, or control their shot placement over the duration of the trial.

PSD results (Fig. 26) indicate that the prone trials resulted in pain, soreness, or discomfort of the neck (2), middle and lateral upper back (3 and 7), middle and lateral lower back (4 and 8), hips (9), pelvis/sacrum (5), posterior shoulder (16), elbow (18) forearm (19), hand (21), anterior shoulder (32), and biceps (33). The severity of PSD was reported as either slight or moderate for all body areas identified. The Control condition resulted in more reports of PSD for the lateral lower back, elbow, forearm, posterior and anterior shoulder, and bicep. The 3ARM condition resulted in more reports of PSD for the middle lower back, pelvis/sacrum, and hips. Similar responses for PSD were recorded for both conditions for the neck, upper back, and hand.

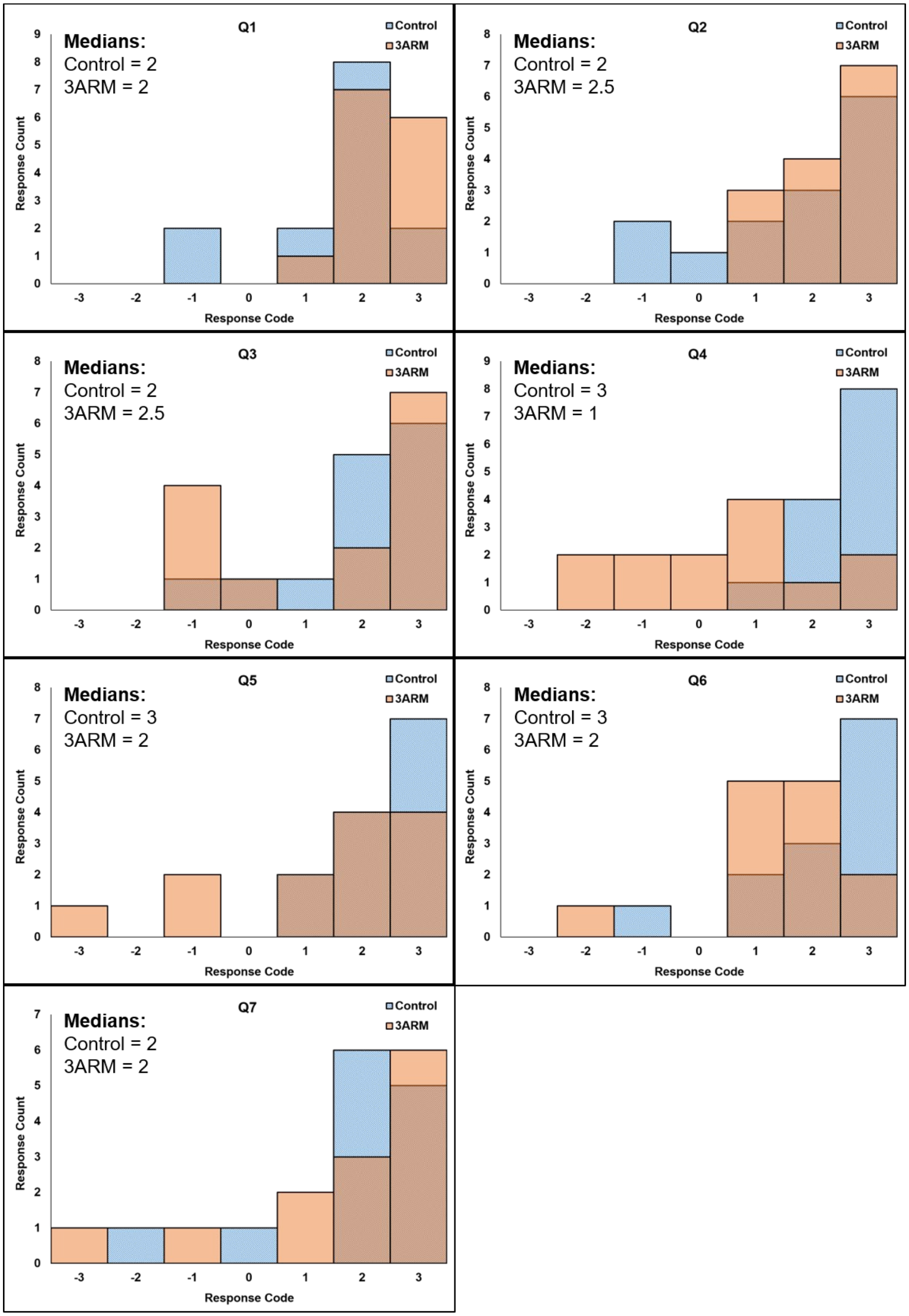


Fig. 25 Response counts for each question (identified in title bar) on the CQ following the prone live-fire trials. Colors are used to distinguish responses between conditions, and the gray shaded regions show an overlap in response count. Response codes: –3 = Strongly Disagree, –2 = Disagree, –1 = Somewhat Disagree, 0 = Neutral, 1 = Somewhat Agree, 2 = Agree, and 3 = Strongly Agree.

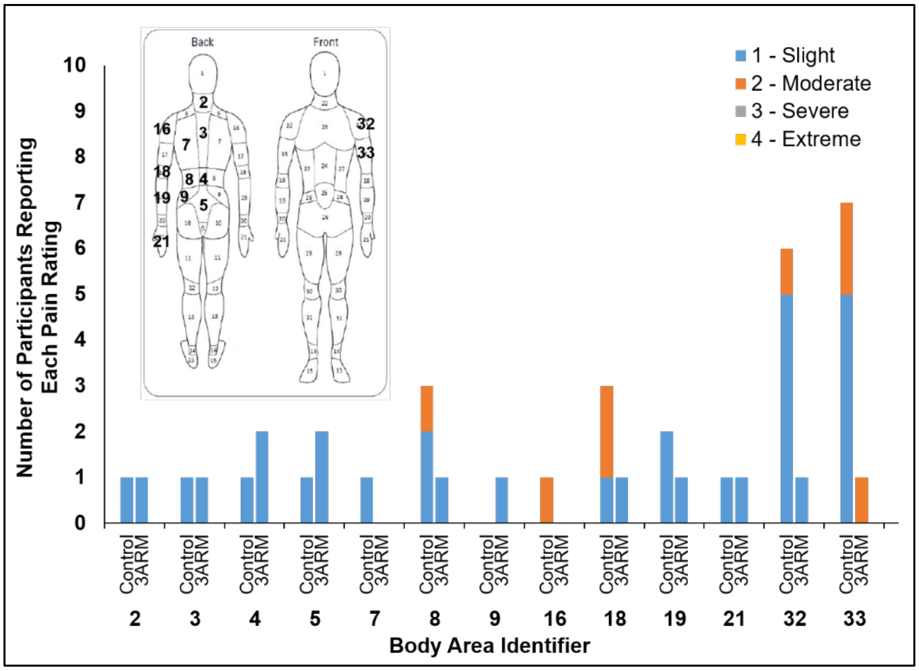


Fig. 26 PSD questionnaire results following the prone live-fire trials as a function of body part and the reported rating. A reference diagram is provided for the body area identifier numbers. For visibility, the body area identifier numbers reported for a given shot scenario are only highlighted on one side of the diagram, but note that the numbers labeling each body part are symmetric left-to-right.

3.4.3 Lateral Shot Scenario Condition Questionnaire

For lateral live-fire trials, participants completed the same seven Likert scale questions:

- Q1: I developed no fatigue or discomfort throughout the trial.
- Q2: I was easily able to acquire the target each time.
- Q3: I was able to hold the weapon comfortably.
- Q4: I was able to move freely during target engagement.
- Q5: I felt that I was easily able to control the orientation of the weapon.
- Q6: I was satisfied with the speed with which I could engage the targets.
- Q7: My confidence in my shot placement was unchanged between first and last shot.

The distribution of responses to these questions for the lateral shot scenario is provided in Fig. 27. Significant differences were found for Q1 and Q7 ($Z = -3.01$, $p = 0.002$ and $Z = -2.15$, $p = 0.03$, respectively). These results reveal that the Control condition resulted in greater feelings of fatigue development during the lateral live-fire trials than the 3ARM condition. Additionally, participants had less confidence in their shot placement over the duration of the trial during the Control condition compared to the 3ARM condition. The remaining questions (Q2–Q6) did not reveal any significant differences in the recorded responses regarding target acquiring time, comfortability of holding the weapon, ability to move freely, ability to control orientation of the weapon, or the speed with which they could engage targets.

The lateral shot scenario resulted in the highest number of body regions reported on the PSD questionnaire (Fig. 28). This may be attributable to the lateral trials being of longer duration than either of the other shot scenarios. The body areas reported to experience discomfort during these trials include the neck (2), mid and lateral upper and lower back (3, 4, 7, and 8), pelvis/sacrum (5), hips (9), trapezius (6), posterior shoulder (16), tricep (17), elbow (18), forearm (19), wrist (20), hand (21), abdomen (25), anterior shoulder (32), and bicep (33). The Control condition resulted in more reports of PSD to the neck, pelvis, trapezius, lateral lower back, hips, posterior shoulder, elbow, forearm, anterior shoulder, and bicep. The 3ARM condition resulted in more reports of PSD in the mid and lateral upper back, hand, and abdomen. The lower back, tricep, and wrist each received the same number of PSD reports between conditions and were of similar severity.

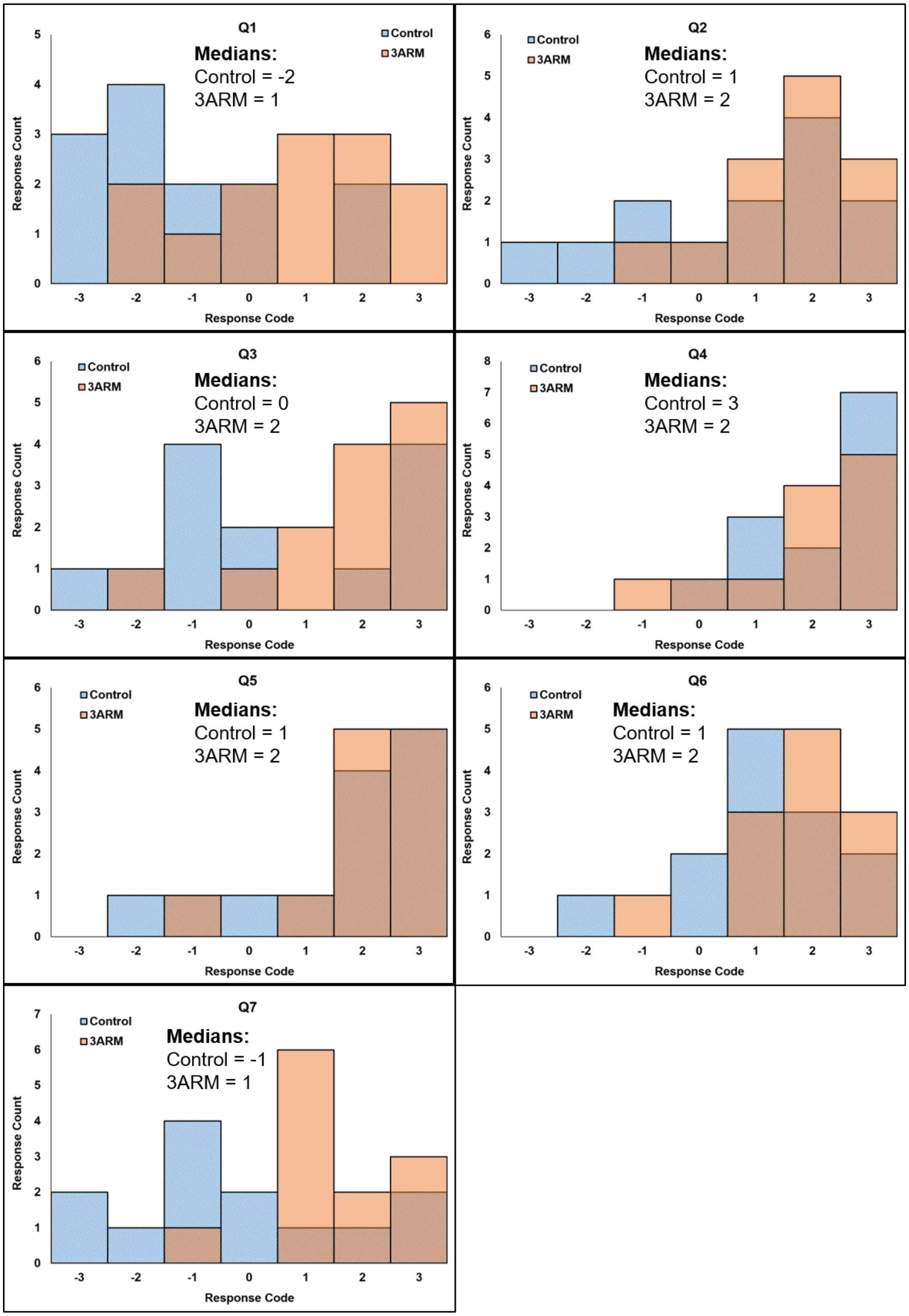


Fig. 27 Response counts for each question (identified in title bar) on the CQ following the lateral live-fire trials. Colors are used to distinguish responses between conditions, and the gray shaded regions show an overlap in response count. Response codes: –3 = Strongly Disagree, –2 = Disagree, –1 = Somewhat Disagree, 0 = Neutral, 1 = Somewhat Agree, 2 = Agree, 3 = Strongly Agree.

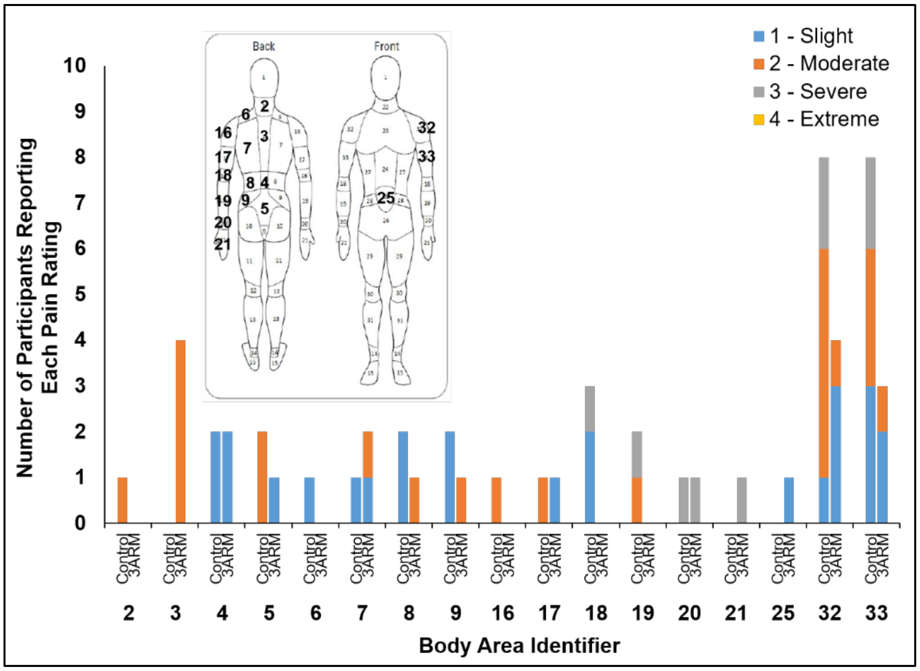


Fig. 28 PSD questionnaire results following the lateral live-fire trials as a function of body part and the reported rating. A reference diagram is provided for the body area identifier numbers. For visibility, the body area identifier numbers reported for a given shot scenario are only highlighted on one side of the diagram, but note that the numbers labeling each body part are symmetric left-to-right.

3.4.4 After-Action Questionnaire

The AAQ asked participants to compare the 3ARM to the Control condition and gave participants the opportunity to provide critical feedback on the design and function of the 3ARM. Participants rated their experiences regarding eight aspects of marksmanship:

- Q1: Fatigue development or discomfort
- Q2: Ability to maintain weapon aim point throughout the trial
- Q3: Ability to hold weapon comfortably
- Q4: Ability to acquire the target each time during self-paced shots
- Q5: Ability to control the orientation of the weapon
- Q6: Ability to move freely during target engagement
- Q7: Satisfaction with speed of target engagement during self-paced shots
- Q8: Confidence in shot placement

For each of these questions, participants were asked to rate their preference between conditions on a seven-point Likert-type scale, which was then coded for analysis as follows:

- "Control was MUCH BETTER than 3ARM" = –3

- "Control was BETTER than 3ARM" = –2
- "Control was SLIGHTLY BETTER than 3ARM" = –1
- "No difference between 3ARM and Control" = 0
- "3ARM was SLIGHTLY BETTER than Control" = 1
- "3ARM was BETTER than Control" = 2
- "3ARM was MUCH BETTER than Control" = 3

The scores for each question were analyzed as a categorical variable using a single sample Wilcoxon signed rank test to determine whether the group median response was significantly different from 0. Significant differences in response median were found for Q1, Q2, Q4, Q5, and Q8 (Fig. 29; $W = 94.5$, $p = 0.01$; $W = 74.5$, $p = 0.04$; $W = 33.5$, $p = 0.03$; $W = 66$, $p = 0.036$; and $W = 63$, $p = 0.01$, respectively). For each of these questions, the median ranged from 1 to 2.5, indicating that the group generally felt that the 3ARM was slightly to much better than the Control condition regarding fatigue development, weapon aim control, target acquisition, control of weapon orientation, and confidence in shot placement. Median group response was not significantly different from 0 for Q3, Q6, and Q7. These results indicate that the 3ARM and Control conditions were not perceived to be different in terms of the ability to hold the weapon comfortably, the ability to move freely during engagement, or the satisfaction of their speed during target engagement.

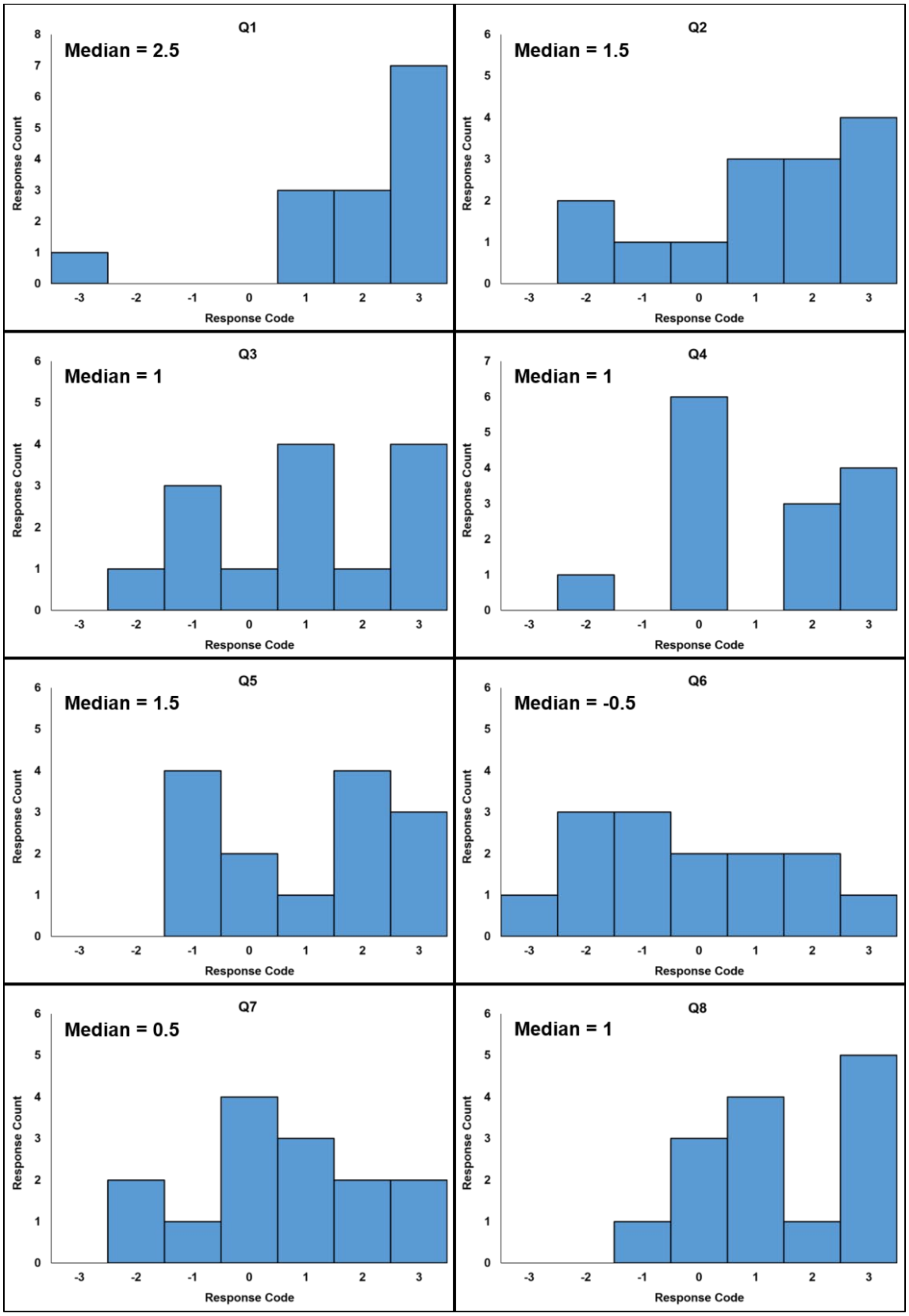


Fig. 29 Response counts for each question (identified in title bar) on the AAQ rating eight different aspects of marksmanship performance. Response codes of –3, –2, and –1 indicate that the Control condition was perceived to be Much Better, Better, or Slightly Better than the 3ARM condition, respectively. Similarly, response codes of 1, 2, and 3 indicate responses that the 3ARM was perceived to be Slightly Better, Better, or Much Better, respectively, than the Control condition. A response of 0 indicates that the participant perceived no difference between the Control and 3ARM conditions.

The remainder of the AAQ consisted of Yes/No responses and short answer questions to which the participants could provide feedback regarding the comfort, fit, and utility of the 3ARM. Most (10) participants responded that they would wear the 3ARM if given the choice. Three others indicated that they would not preferentially wear the 3ARM, and single participant responded "Yes" and "No" clarifying that they would wear it if they were using a heavier weapon but not for standard dismounted patrols. When asked if there were particular engagement scenarios for which the 3ARM might be helpful, 12 participants responded "Yes", one responded "No", and a single participant opted not to respond. Among the scenarios for which participants felt that 3ARM would be helpful was "close range urban environments where targets appear quickly and need to be engaged from a standing position." Other participants expressed similar ideas stating that it would be useful for military operations in urban terrain (MOUT) and raiding/room clearance. At least one participant suggested that future testing of the 3ARM might include MOUT scenarios to determine whether it creates any performance issues in movement through the city, through buildings, and while mounting or dismounting a vehicle. Other participants suggested that 3ARM might be useful for traffic control points; entrance to Forward Operating Bases (FOBs); during oversight or overwatch requiring surveillance from a stable, invisible area; posts in which target engagements may occur above or below the Soldier's position; or for conditions that require lateral prone firing. Other more general suggestions for 3ARM use were for heavier weapons or tools; during assignments when the Soldier can expect prolonged periods of holding the weapon at the ready; when patrolling in open areas (it is thought that the 3ARM may become entangled in dense forests); and during kneeling fire. Participants felt that the 3ARM did help to alleviate the fatigue in the arms and that the structure of the 3ARM may provide some added stability when engaging targets from a kneeling position. One participant indicated that they would not use 3ARM in its current state but suggested that it could be useful for urban operations once it was improved.

Participants were also asked if they found the 3ARM system to be comfortable. Eight participants responded "Yes", four responded "No", and two responded either "Yes/No" or opted out of responding. Despite the distribution of Yes/No responses, the majority of short answer explanations following this prompt described discomfort issues. A common critique was that the 3ARM alleviates the weight in the arms and neck but directs it to the back, so over time the user's back and shoulders may feel sore or fatigued. Similarly, a participant stated that there was minor discomfort due to the sensation of the ballistic plates being pushed into their back. Discomfort in the elbow was reported when pushing the 3ARM away from the body to get into the prone position, and at least one participant found it difficult to shoulder the weapon properly when prone. More generally, a participant noted that the 3ARM was comfortable for the lateral shot scenario but found the transition from standing to prone and vice versa to be uncomfortable. Another stated that they felt as though they had to strain their neck to get a good sight picture. One participant who felt that the 3ARM was otherwise comfortable disliked the way the weapon hangs when not actively firing.

All participants responded “Yes” to the question of whether or not the 3ARM could be improved. The participants provided a variety of insights toward improving its design and utility. Many improvement suggestions reiterated concerns related to the prone firing position. It was repeatedly suggested that the 3ARM be better designed to allow the user to drop to the prone position. One participant stated that in its current state, the user is “not really dropping into prone, you’re making them get down into prone”. The ability to drop to prone smoothly and quickly is critical to survival, and it should be redesigned to be more effortless (e.g., removing the need to push the 3ARM away from the body with the elbow). Several participants noted that it is difficult to complete side-to-side lateral firing in the prone position. The system should be redesigned to allow easier transition between sectors of fire when prone, and the system should be designed to allow the user to perform the low crawl maneuver. One participant also stated that the larger Q arm can partially obscure the sight picture when the user is prone. Despite the reports of discomfort in the act of transitioning from standing to prone, a few participants remarked that once down in the prone position, the 3ARM essentially functions as a stand to help them stabilize their weapon. That is, when in the prone position, the carbon fiber linkage supporting the weapon rests directly on the ground and provides support and stability.

Another common suggestion was to redesign 3ARM to allow it to support weight above parallel to the ground. Participants felt that this would address issues of craning the neck for a sight picture, and it could eliminate the sensation that the user is pulling up against 3ARM to engage targets above 90° from the ground. Another suggestion was to design the vertical arm to allow forward motion. Many participants believed that the 3ARM could be useful for larger, heavier weapons or crew-served weapons. Larger weapons sit farther away from the body, so allowing forward movement of the arm would accommodate these weapons, get the 3ARM and weapon a little farther away from the user, and open up the field of view. It was also suggested that perhaps the 3ARM could have a brace or bracket at the elbow so 3ARM moves naturally with the user’s arm. Similarly, the designers might consider moving the point of attachment of the 3ARM to the upper back or arm instead of its current position. It was thought that this new configuration might alleviate some of the current pain or discomfort associated with its use.

Other suggestions included redesigning the way the weapon hangs or is stored against the body when not being used. It was observed that if the 3ARM were to be used with mounted operations, the user could easily hit his chin off the buttstock during egress from a vehicle. It was suggested that future designs be evaluated by cavalry scouts who frequently mount and dismount Stryker vehicles and High-Mobility Multipurpose Wheeled Vehicles. Regarding other practical implementation issues, participants emphasized that depending on a Soldier's role within his unit (e.g., rifleman, grenadier, team leader, or squad-designated marksman), the Soldier's body armor will be outfitted with other supplies. This full kit will make movement of the 3ARM even more difficult and present a lot of interaction issues with necessary equipment.

Final design suggestions included designing a quick release and/or quick attachment mechanism to allow users to employ 3ARM on other equipment such as a belt. This flexibility in configuration may allow for better target engagement out of plane with the user (e.g., above or below). It was recommended that the 3ARM be redesigned to have fewer hinges, bolts, and pinch points. It was noted that the existing joints and hardware will get dirty very quickly, particularly given the climate and terrain of current theaters, and the joints will become increasingly difficult to move. Participants also suggested reducing the bulk and weight of 3ARM system and counterbalancing its load so the plates do not push into the user's back.

4. Discussion

Only in the recent years has traditional biomechanical analysis been integrated into the study of marksmanship and shooting performance (Era et al. 1996; Ball et al. 2003; Lakie 2010; Causer et al. 2011; Mullineaux et al. 2012; Sattlecker et al. 2014). Postural stability measures as well as measures of weapon aim point and biofeedback have all been used to study the physical performance associated with marksmanship. In this study, we used EMG and IMU-based analysis techniques to quantify differences in marksmanship performance with and without the 3ARM system. The paced prolonged marksmanship task was selected as a shooting scenario for this study because it is representative of the type of marksmanship tasks for which the 3ARM was specifically designed to assist. This shooting scenario also lent itself well to traditional biomechanical analyses because the action of prolonged marksmanship is similar to the submaximal isometric muscle contractions that are often used to study fatigue development. Additionally, the combination of bipedal stance, the weight of the weapon, and the extended posture of the support arms makes the prolonged standing shooting posture a worst-case scenario for stability. If the 3ARM provided assistance with weapon stabilization, it would be most evident in a shooting posture that required prolonged, static target engagement.

The 3ARM did provide greater muscle endurance compared to the Control condition as evidenced by a greater muscular endurance time following the shooting trials. Endurance time was still greatest, however, for the Pre condition, indicating that some fatigue still developed when using 3ARM. Analysis of MF and Amp slope measures revealed that during the endurance hold task, participants largely developed fatigue at similar rates in the support arm muscles. MF slope indicated a greater rate of fatigue development in the LAT muscle following the Control condition, and Amp slope indicated that both conditions resulted in a greater rate of fatigue development in the TRI muscle than the Pre condition. The MF and Amp slope during the live-fire trials revealed differences between Control and 3ARM conditions for the supporting arm DELT and BRAC muscles and the shooting arm DELT. In each case, the differences were indicative of greater muscle fatigue for the Control condition than for the 3ARM condition. Most muscles exhibited the expected negative polarity of MF slope during the live-fire trials, but the Amp slope measure, in many cases, also exhibited a negative polarity. Submaximal isometric contractions typically elicit a decrease in MF and an increase in Amp as the muscle shifts to a slower contraction frequency but recruits more motor units to maintain force output (Hakkinen and Komi 1983; Merletti et al. 1984; Krogh-Lund and Jorgensen 1991; Alison and Fujiwara 2002; Phinyomark et al. 2012). There exist a few possibilities to explain the unexpected negative polarity of Amp slope measures during live-fire with 3ARM. First, it is possible that the recoil events provided momentary relief and required postural adjustment that prevented the MF and Amp slope measures from demonstrating the changes expected of purely isometric muscle contractions. Another possibility is that the force output requirement was met by a decrease in contraction frequency without the need for recruiting additional motor units. This would further support the idea that 3ARM did provide some resistance to fatigue, but caution is required in this interpretation as motor unit recruitment was not specifically quantified in this study.

The use of EMG as an analysis tool for marksmanship is still relatively novel. The sample size required for strong statistical power regarding these metrics for a marksmanship application is still difficult to estimate. The relatively large standard deviations in EMG measures may be attributed to individual differences in muscle contraction patterns employed to support a weapon. For example, some individuals may naturally engage their support arm deltoid more to support the weapon while others may engage the bicep. While their posture may appear similar, the physiological process affording control of that posture is different. Averaging the values associated with these muscle data would then result in a mean closer to zero with a larger standard deviation. More pronounced group differences may have been observed if participants were required to adhere to a rigidly defined shooting posture. As this study was intended to describe the effects of the 3ARM relative to an individual's normal shooting ability, only minimal instruction was provided regarding marksmanship posture. Namely, the participants were requested to use the standard military-instructed support position for the weapon rather than the "C" grip support approach. The "C" grip is defined by a completely outstretched support arm that clamps the side or the top of the barrel for support. This technique is often employed by those with greater experience in close-quarters battle or shoot-on-the-move engagement scenarios. The more standard underhand barrel grip posture was used in this study. While individual differences in contraction patterns may have affected the results, those significant differences observed in this study are expected to be indicative of the "common denominator" changes that would occur for most users of the 3ARM.

The prolonged static aiming task performed during the paced trials also afforded an analysis of weapon control. IMUs were used to track the course, pitch, and roll orientations of the weapon, and the course and pitch orientations describing the weapon motion relative to the target were used to calculate a surrogate measure of stability. SampEn in the pitch orientation, corresponding to the vertical aim of the weapon, was significantly lower for the 3ARM condition than the Control. Lower SampEn is consistent with less random, more predictable control of the weapon. Given that the 3ARM system attached to the weapon on the top of the barrel and that it is intended to offset the burden of weapon weight, it follows that vertical control of the weapon would more likely be augmented than the lateral control. These results also suggest that the 3ARM was able to augment weapon stability relevant to marksmanship performance. The 3ARM provided some improved weapon stability in the vertical direction during this prolonged paced marksmanship task.

There was an expectation that improved weapon control would translate to improved hit percentage or shot accuracy. Only the mean radius, however, was found to be significantly different between the Control and 3ARM conditions. Mean radius, a measure of shot precision, was improved with 3ARM, but hit percentage and shot accuracy were unaffected. A possible explanation for this is that weapon control was only improved in the vertical and not the horizontal direction. It may be that the improvement in vertical control of the weapon contributed to improved precision but did not provide enough augmented control to substantially influence hit percentage. A second possibility is that the 75-m target range was close enough that most shots still hit the e-silhouette or were within range of the shot scoring system. This could account for a similar hit percentage with or without 3ARM. A target positioned farther away may have more effectively discriminated hit percentage between conditions. Choosing a target distance, however, is a matter of trade-offs. Farther target distances naturally produce greater errors and shot spread. This could provide more definitive results pertaining to hit percentage but would also decrease the available number of shots scored for which precision and accuracy measures could be determined. The 75-m target distance was selected because pilot testing suggested it was challenging enough to produce some misses but close enough to capture coordinates for the majority of shots, thus enabling comparisons of hit percentage, accuracy, and precision metrics.

While the paced shooting scenario provided the opportunity for objective biomechanical assessment of shooting performance, the prone and lateral scenarios were used to challenge other capabilities of the 3ARM system. The 3ARM was designed with several degrees of freedom permitting relatively free motion, but the prone scenario was used to determine whether 3ARM affects the user's ability to transition between postures and quickly engage targets. During the prone scenario, P2S transition time was longer with the 3ARM, indicating that participants needed more time to return to a standing posture and fire on target. Although other component times (S2P and Between-Shot) were not individually significantly different between conditions, differences between conditions summed to a total engagement time that was significantly longer (~22 s) for the 3ARM than for the Control condition. Neither target hit percentage nor shot precision (mean radius) were significantly different between groups. DCSG, however, was significantly better for the 3ARM condition than the Control condition. Marksmanship effectiveness is a function of both speed and accuracy. While 3ARM did cause a substantial delay in postural transition and task completion time, it compensated somewhat in providing an improved shot accuracy. In operational use, however, the relative importance of speed versus accuracy is highly dependent on battle conditions. The slightly improved accuracy (0.9 inches) afforded by 3ARM may not justify the potential risk of being substantially slower to maneuver in a combat environment.

The lateral shooting scenario investigated whether 3ARM affects the user's ability to slew the weapon and engage laterally presented targets. Neither shot timing nor metrics of shooting performance was substantially affected by the use of the 3ARM. Unchanged marksmanship performance must be considered both ways. First, the 3ARM has the ability to reduce some of the physical burden of marksmanship without resulting in a detriment to marksmanship performance. This could have implications of improved or preserved Soldier resilience and readiness on the battlefield. On the other hand, if the 3ARM is not substantially improving marksmanship, one must consider whether it is worth the added weight and encumbrance to the user, depending on their specific MOS or their role within their unit.

Subjective survey responses were used to assess whether participants had generally positive or negative feelings regarding the use of 3ARM. The perception of 3ARM's effectiveness appears to be influenced by shooting scenario. For the paced trials, the 3ARM resulted in improved perceptions of fatigue development, ability to hold the weapon comfortably, ability to control the weapon, and confidence in shot placement. Similarly, the lateral trials elicited responses indicating that the 3ARM lessened fatigue development and improved confidence in shot placement. For the prone trials, however, the participants indicated a greater perception of freedom of movement for the Control condition. These findings are corroborated by the timing results reported for the prone trials—namely that postural transition times and total target engagement times were longer with 3ARM and for the Control. Together, these results suggest that 3ARM does alleviate fatigue development and improve the perception of weapon control, but it may also decrease the freedom of movement users experience under normal firing conditions. Regardless of the shooting scenario, the anterior deltoid, biceps, and back were cited as the areas of the body experiencing the most pain and discomfort. The frequency of these reports and the severity of discomfort were typically lower for trials in which the 3ARM was employed. However, as will be defined in the discussion of the AAQ, 3ARM may still require design modifications to improve mobility limitations and address discomfort that may be specific to its current design.

The AAQ challenged participants to compare the Control and 3ARM conditions directly and also to provide critical feedback regarding the use of the 3ARM system. When comparing the 3ARM to the Control condition, participants largely felt that the 3ARM condition was better than the Control condition in regards to fatigue development, weapon aim control, target acquisition, control of weapon orientation, and confidence in shot placement. Despite this positive assessment, however, the participants were able to provide valuable critiques of the 3ARM system. The general opinion was that the 3ARM did alleviate weight and fatigue in the arms and helped to stabilize the weapon. Standing and standing lateral (side-to-side) target engagement was fairly seamless with the 3ARM, but several individuals reported that when the weapon is mounted to the 3ARM, the rear body armor plate is sometimes pressed uncomfortably into the user's back. It was suggested that the system be redesigned to balance the distribution of weight across the user's back. Another suggestion was to redesign 3ARM to permit weight bearing of the weapon above 90° from vertical. If targets are presented at an elevated position, the user would need to pull up against 3ARM and possibly also have to crane their neck to get a sight picture.

Although it is possible to transition to the prone position, participants found the transition difficult compared to the Control condition. One participant stated succinctly that he was "not dropping into prone but being made to get down into prone." The implication there is that they could not drop into the protective and offensive position as quickly as they need to. Once participants were in the prone position, however, several reported that the 3ARM functioned as a stand to support and stabilize the weapon because of its contact with the ground. They did recommend, however, that the system be designed to allow for better lateral movement to engage different sectors of fire and to allow low crawl maneuverability.

Several participants indicated that they would wear the 3ARM if given the choice, but others cautioned that when a Soldier is in full kit, the 3ARM would interact with other equipment that is typically attached to the body armor vest. Some participants suggested that the 3ARM may not be necessary for an M4 but would be useful for larger or crew-served weapons. The larger size and weight of these weapons makes fatigue a bigger issue, and 3ARM could help to alleviate that. In order to accommodate larger or crew-served weapons, the 3ARM may need to be designed to allow forward translation of the weapon. Participants indicated that this function may also serve to open up the user's field of view when scanning for targets. It was also suggested that 3ARM could be useful when serving at traffic control points, FOB entrances, or other duties for which the Soldier can reasonably expect to have to hold the weapon for an extended period of time. Others believe that 3ARM would be useful in MOUT operations, close range urban environments, and raiding/room clearance because in those scenarios, the Soldier must maintain a ready position and engage targets quickly from a standing position. Some participants indicated that it may be useful for mounted units to help stabilize the weapon during target engagement, but they cautioned that the way in which the weapon is stowed against the user's body would need to be improved. As is, users thought it likely that they could hit their chin on the buttstock during vehicle egress. Overall, there was a variety of positive and negative responses to the 3ARM. Continued development and design improvements may help to address some of the concerns identified during this evaluation. Additionally, the user's feedback has provided insight on a number of potential use case scenarios for which the 3ARM may be helpful.

5. Limitations

Outdoor live-fire studies are subject to weather cancellations and unexpected range closures. Due to these extenuating circumstances, some data was lost due to incomplete data collection sessions. All usable data was retained for analysis, but some statistical tests were performed with uneven sample sizes due to missing data.

Another limitation of this study is the gender distribution of the participants. Although it was not intended in the study design, all participants who were successfully recruited for this study self-identified as male. As such, the subjective reports of system fit and comfort may only apply to male users. The evaluation does not document any specific issues that may arise due to use of the system by someone identifying as female. As females are now permitted to serve in combat units, future evaluations should strive to include female participants to identify any complications that exist due to sub-optimal compatibility with female anthropometry.

6. Conclusion

Results suggest that the current design of the 3ARM alleviates some fatigue development during prolonged marksmanship tasks and may also augment vertical weapon control. The 3ARM may cause delays in transition time between shooting postures, but it allows relatively unencumbered slewing for lateral target engagement. Although a farther target distance may have revealed greater disparities in shot performance, the 75-m target range used in this study only revealed small differences in marksmanship performance between the Control and 3ARM conditions. As 3ARM design improvements are made, trade-offs between improvements in fatigue development and weapon stability must be carefully weighed against the potential cost of a loss in maneuverability, especially if shot performance is not substantially improved by its use. Consideration of these trade-offs may help to identify the most appropriate use cases for 3ARM (e.g., overwatch or guard duty). Users expressed some concern over comfort and mobility with 3ARM. In particular, back pain was a common observation with the 3ARM as were limitations to dropping into the prone position and the sensation of pulling against 3ARM to acquire an appropriate sight picture. Design improvements to 3ARM that enable better weight distribution and improved mobility may result in a system which could serve Soldiers assigned to a variety of MOSs and aid in preserved Soldier readiness in combat environments.

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Appendix A. Condition Questionnaire

Subject Number: ____________________ Date: ________________________

Condition: Control / 3ARM Task: Static / Prone / Lateral

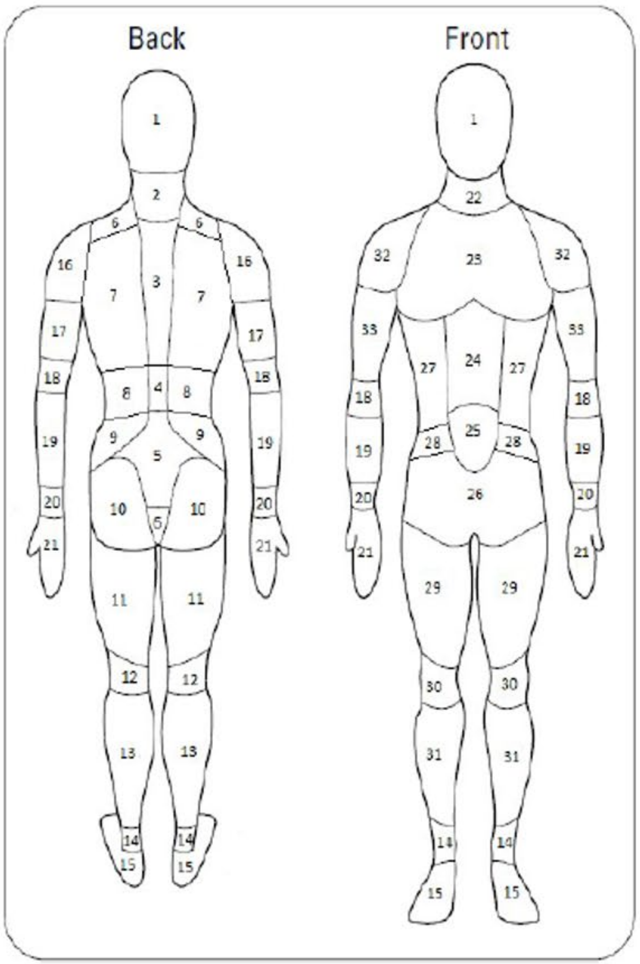
CONDITION QUESTIONNAIRE

Please check one box for each row to indicate the level to which you agree or disagree with each statement.

	Strongly Disagree	Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Agree	Strongly Agree
For paced shots:							
I developed no fatigue or discomfort throughout the trial.							
I was easily able to maintain my aim point throughout the trial.							
I was able to hold the weapon comfortably.							
I felt that I was easily able to control the orientation of the weapon.							
My confidence in my shot placement was unchanged between first and last shot.							
For self-paced shots:							
I developed no fatigue or discomfort throughout the trial.							
I was easily able to acquire the target each time.							
I was able to hold the weapon comfortably.							

I was able to move freely during target engagement.							
I felt that I was easily able to control the orientation of the weapon.							
I was satisfied with the speed with which I could engage the targets.							
My confidence in my shot placement was unchanged between first and last shot.							

CONDITION QUESTIONNAIRE, CONTINUED



Area of the body	Slight	Moderate	Severe	Extreme
	①	②	③	④
	①	②	③	④
	①	②	③	④
	①	②	③	④
	①	②	③	④
	①	②	③	④
	①	②	③	④
	①	②	③	④
	①	②	③	④
	①	②	③	④
	①	②	③	④
	①	②	③	④
	①	②	③	④
	①	②	③	④
	①	②	③	④
	①	②	③	④

Appendix B. After-Action Questionnaire

Subject Number: ____________________ Date: ______________________

AFTER ACTION QUESTIONNAIRE

You are asked to consider your experience with 3ARM compared to the control condition. Please check one box for each row to indicate how you feel the 3ARM compared to the control for each

	Control was MUCH BETTER than 3ARM	Control was BETTER than 3ARM	Control was SLIGHTLY BETTER than 3ARM	No difference between 3ARM and Control	3ARM was SLIGHTLY BETTER than Control	3ARM was BETTER than Control	3ARM was MUCH BETTER than Control
Fatigue development or discomfort							
Ability to maintain weapon aim point throughout trial							
Ability to hold weapon comfortably							
Ability to acquire target each time during self-paced shots							
Ability to control the orientation of the weapon							
Ability to move freely during target engagement							
Satisfaction with speed of target engagement during self-paced shots							
Confidence in shot placement							

1) Would you wear the 3ARM if given the choice?

Yes / No

2) Are there engagement scenarios or use-case scenarios for which you think the 3ARM would be helpful?

Yes / No

Please describe:

____
____
____
____
____
____

3) Did you find the device to be comfortable?

Yes / No

If no, please explain:

____
____
____
____
____
____

3) Could the 3ARM be improved?

Yes / No

Please provide any suggestions for improvement:

____
____
____
____
____
____
____
____
____

List of Symbols, Abbreviations, and Acronyms

3ARM	Third Arm
AAQ	After-Action Questionnaire
Amp	amplitude
BIC	biceps brachii
BRAC	brachioradialis
CAD	computer-aided design
CQ	Condition Questionnaire
DCSG	distance of the center of the shot group
DELT	deltoid
EMG	electromyography
ES	erector spinae
FOB	Forward Operating Base
IMU	inertial measurement unit
LAT	latissiumus dorsi
MF	median frequency
MOS	Military Occupational Specialty
MOUT	military operations in urban terrain
P2S	prone-to-standing
PSD	Pain, Soreness, and Discomfort
RMS	root mean square
S2P	standing-to-prone
SampEn	Sample entropy
TRAP	trapezius
TRI	triceps brachii

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Y CHEN
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K OIE
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FCDD RLH FA
A DECOSTANZA
FCDD RLH FB
D BOOTHE (A)
C HAYNES
A TWEEDELL
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