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EXAMINING HEADACHE AND POSTURAL CONTROL VARIABILITY DURING EXPLOSIVE BREACHER TRAINING

A Thesis in

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by

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Abstract

Research investigating the effects of blast on the brain has attempted to elucidate the degree to which low-level blasts can exert an impact on functioning. Military personnel who routinely utilize explosive ordnance to gain access to secured spaces (explosive breachers) are repeatedly exposed to blast overpressure, yet current training protocols are not known to result in diagnosable injury. Survey results from this population have established a symptom profile similar to that observed in post-concussive syndrome including difficulties with headache, sleep, and other complaints, with exacerbated symptom reporting positively associated with increased career breaching exposure and heavy weapons experience. Individuals with diagnosed concussions (with and without persistent headache), have also been shown to have deficits in their postural control, raising the question if such postural deficits are present in those exposed to low-level blasts. We examined headache report and postural control assessed daily in male military personnel across two-week explosive breacher training. Approximate entropy, a non-linear dynamic statistic used to quantify the regularity of time series data, was used to assess center of pressure motion during different postural tasks. Repeated measures ANOVA revealed increased headache report on two days following two consecutive training blast exposures; however, these increases were not associated with deficits in postural control. Symptom and behavioral effects associated with acute exposure to low-level blast may be relatively small, accruing incrementally over time and repeated exposures. Assessments of effortful control of balance may be more sensitive to blast effects (in an undiagnosed population) than more passive assessments of postural control.

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Introduction

Research investigating the effects of blast on the brain has received increased attention in the last two decades due to the U.S. military's involvement in the wars in Iraq and Afghanistan (1). Although the literature often calls blast induced traumatic brain injury (TBI) the "signature" injury of these more recent conflicts, the question of how blast affects the brain predates the modern research interest and has plagued physicians since both World Wars (2,3). In fact, the term *shell shock* originated to identify service members specifically who had suffered some type of injury (as evidenced by symptom report) but without direct evidence of a blunt force event to the brain during World War I (4). The work presented here examines the question of how blast exposure affects the brain. Our use of the term blast refers to overpressure exposures occurring in military training environments, unlike larger exposures experienced in a combat setting (5).

The most frequently identified symptom following mild traumatic brain injury is headache (6,7). The persistent presentation of headache following both diagnosed TBI (7–9), and undiagnosed insults to the head (10–14) makes understanding and considering headache in the context of exposure to blast a salient avenue of investigation. Previous examination of symptomology resulting from repeated low-level blast exposure in 135 breachers and 49 non-breacher controls found that on average, breachers endorsed a higher number of head injury symptoms compared with controls, and also rated these symptoms as more severe (10). Notably, history of breaching exposure, quantified as the number of previous breaching events, was a significant predictor of overall symptomology. Specific symptom complaints in this surveyed cohort included difficulties with headache, sleep, hearing, ringing in the ears, and irritability, with headache being the most frequently endorsed symptom.

Deficits in postural control following head injury have been documented in civilians (15–21) and members of the military (22–25). Cavanaugh et al. (2015), detected subtle changes in postural control in a concussed athletic sample relative to healthy controls 24-48 hours post injury. Examination of vestibular performance in a cohort of blast exposed service members with and without a mild TBI diagnosis, as well as comorbid diagnoses of post-traumatic amnesia (PTA) or post-traumatic stress disorder (PTSD) found differential performance in postural control (23). Haran and colleagues determined that service members with a mild TBI demonstrated worse postural control for two measures of vestibular performance compared with controls, and that these deficits resulted from difficulty integrating both visual and vestibular inputs (24). An association has been demonstrated between headache complaints and decreased postural control (26,27).

Approximate entropy (ApEn) is a family of non-linear statistical techniques utilized to detect changes in complex systems; it is useful for quantifying the regularity in time series data, particularly when these changes are anticipated to be subtle (28–30). The method applies a moving window across the time series to determine the likelihood that the series will repeat itself. The ApEn statistic generates a unitless value ranging between 0 and 2 inclusive, with larger values indicating increased irregularity of the time series; conversely ApEn values closer to 0 are typical of time series that are more repeatable, as with sine waves (15,30). Greater irregularity of biological time series has been associated with a healthier system incorporating multiple contributory components (28). Conversely, a more regular time series is thought to be indicative of pathology or aging as complex systems begin to break down or become less effective at integrating previous sensory input components (28). Cavanaugh et al. (2005), utilized ApEn in their analyses of data from the Sensory Organization Test (SOT). They found that the concussed athletes exhibited decreased irregularity in their time series data when compared with not only their own respective baselines but also with healthy controls. More specifically, the greatest changes in irregularity for participants' time series in a front-to-back direction (anterior-posterior, (AP)) occurred between Conditions 1 and 2 (eyes open versus eyes closed both on a firm surface).

Examination of head injuries sustained during combat faces several obstacles when attempting to draw causal links between overpressure exposure and injury as they often result from the combination of blast and blunt forces, which are difficult to disentangle. Overpressure exposure can vary due to several factors, most prominently, the proximity to the blast source, as well as whether the blast exposure occurred in an open environment or an enclosed space (31), which can also be difficult to assess in combat settings. As a result, observations and measurements recorded in training settings can assist investigators to better understand the direct effects of blast overpressure on military operators. Military personnel who routinely utilize explosive ordnance to gain access to secured spaces (explosive breachers) are repeatedly exposed to blast overpressure, yet current training protocols are not known to result in diagnosable injury. Recent research efforts have aimed to assess the effect of overpressure exposure in military operators who routinely use explosive ordnance (explosive breaching), by evaluating these service members while they are in training (11,12). Explosive breaching training paradigms provide a unique opportunity to examine the effects of blast overpressure on the brain in a more controlled scenario in comparison to combat settings and present the field with a challenge to reexamine the ways in which it both conceptualizes brain injury and the measures used to quantify the hypothesized effects. Carr et al. (2015b), systematically observed two-week long advanced explosive breaching training courses at three different sites and collected data on postural stability, overpressure exposure, and self-reported symptomology. A salient contribution specific to this field sample is that the data collection is focused to within a few hours following overpressure exposure, and occurred in the absence of a diagnosable head injury following blast exposure. Furthermore, since operators are evaluated repeatedly over a two-week time period, this affords researchers the possibility to evaluate not only differences within and across participants, but also the impact of routine occupational overpressure exposures, considered to be within current operational safety standards, across several days.

Taken together, these previous studies speak to several key points. First, head injuries can disrupt normal vestibular functioning, both in blast and blunt injury contexts. Second, disruptions to the vestibular system may be detectable through the use of non-linear methods such as ApEn, enabling quicker detection of system perturbations below the threshold of injury and symptom report. Additionally, use of statistical techniques from non-linear dynamics such as ApEn may create opportunities to objectively identify those at risk for future injury independent of self-report. Still, questions remain regarding the sensitivity of these postural sway measures, as well as its specificity to head injury. We examined the symptom report data from Carr et al. (2015b) with specific attention to the most frequently endorsed symptom following mild traumatic brain injury, headache. We then applied non-linear ApEn analysis to the postural sway time series data that were previously examined only by t-test of mean values at baseline and endpoint, rather than daily values across the 2-week period of training with explosives. We hypothesized that service members' anterior-posterior (AP) and medial-lateral (ML) time series (as measured by the approximate entropy values) would become more regular with insult; these increases in regularity will be positively associated with self-report of headache. It was also hypothesized that the regularity of the service members' AP and ML time series will begin a return to baseline values on days where overpressure exposure is absent. Finally, service members' Center of

Pressure (COP) Range and COP Velocity values will increase the day following a blast exposure, and will also begin a return to baseline values on non-blast training days.

Methods

Data for these analyses were drawn from the existing protocol completed by Carr et al. (2015b). The protocol for this study was reviewed and approved by the Institutional Review Boards of both the Naval Medical Research Center and Walter Reed Army Institute of Research. Across all three sites, all service members present for the explosive breacher training course who wished to enroll in the research, provided informed consent. On days where training included use of explosive ordnance, the 108 service members were fitted with sensors- on the left and right sides of their helmets.

All service members were evaluated at the end of each training day using the Biosway Clinical Test for Sensory Integration of Balance (CTSIB; Biodex Medical Systems 2014, Biodex Medical Systems, Inc., Shirley, NY, USA). Service members completed four of the six possible conditions while wearing combat boots: eyes open and eyes closed, evaluated on both a firm and dynamic surface (Conditions 1-4). At the start of each individual assessment, service members were instructed to stand on the firm testing surface and place both feet side by side and centered on the platform until the testing software confirmed that the service member's feet were centered appropriately. After recording the heel positions and angles for both feet with the testing software, the assessor instructed the service member that he should remain as still as possible and quiet while completing each of the four conditions; each condition was tested for 30 seconds, with a ten second rest period between each condition. They also completed a 32 item self-report of symptoms typically associated with head injury. Headache severity was assessed on a 5-level Likert scale, ranging from 0- "not experienced at all" to 4- "a severe problem" (11). Detailed documentation regarding other study procedures across the two-week training programs has been described previously (11).

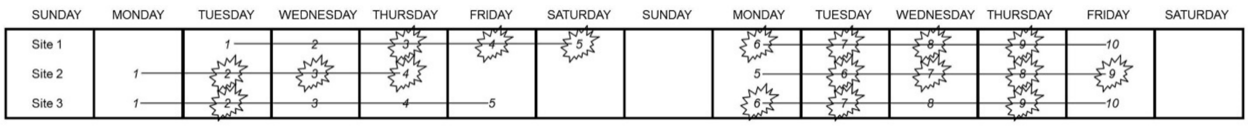

Figure 1: schematic of blast training paradigms at each explosive breacher training site. Blast days are denoted by the starburst graphic. Borrowed from Carr et al., (2015) and reprinted with permission.

The CTSIB provides the center of pressure COP data for each testing session of each service member for each of the four conditions examined during the breacher training paradigm on each testing session. The COP data provides the intersection of the vertical ground reaction force vector with the support surface in the anterior-posterior (AP) and medial-lateral (ML) directions. The COP data were low-passed filtered at 5 Hz using a bi-directional Butterworth filter. The following COP metrics were determined: ApEn values in both AP and ML directions, COP Range in both AP and ML directions, and COP Velocity in Conditions 1 and 4. For ApEn there are two required parameters: the size of the moving window (m), and a difference threshold (r). The window was set to 2, and the threshold set to 0.2 of the standard deviation of the time series (Pincus, 1995).

Data Analyses

Statistical analyses were conducted in RStudio, Version 3.5.1 (32). Descriptive analyses for all variables of interest (including headache report and COP measures) were conducted, along with bivariate correlations. The current analyses focused on Site 3 (N = 33) from Carr et al. (2015b); this site experienced a large overpressure exposure on Day 7, 400% larger than any other exposure recorded at this site as well as in the overall study. Service members ranged in age from 25 to 42 years old (*Mean* = 31), with an average of 13.1 years of education. Just under half of service members at this site (42%) endorsed sustaining at least one head injury prior to participation in the training course. Pilot analyses determined mean values of headache report across all service members appeared to increase the day following overpressure exposure. To expand on these primary findings and others previously established in the literature, the current study sought to examine trends and predictors of both headache report and measures of postural control across the duration of the training program.

Examining Changes in Headache Report

One-way repeated measures analysis of variance (RM-ANOVA; Lawrence, 2016) was used to examine headache ratings across the two-week training course, and to assess delayed presentation of headache stimuli. Post-hoc pairwise comparisons were conducted using dependent t-tests with a Bonferroni correction to assess delayed presentation of headache symptoms one day following a training blast exposure, defined as change in headache report from headache ratings provided on Day 2. Service members participating in this breacher training course were home based at locations across the country and were still traveling to the training site during the first day of the assessment (Day 1), with some arriving the day before Day 1 and some arriving on Day 1, increasing the likelihood of variability in symptom report in comparison to Day 2 of the training course. Utilizing the second day of training as a baseline value instead of Day 1 was considered a more accurate representation of service members' symptom reports. Effect sizes (*d*) were also computed for pairwise comparisons that emerged as significant ($p < 0.05$).

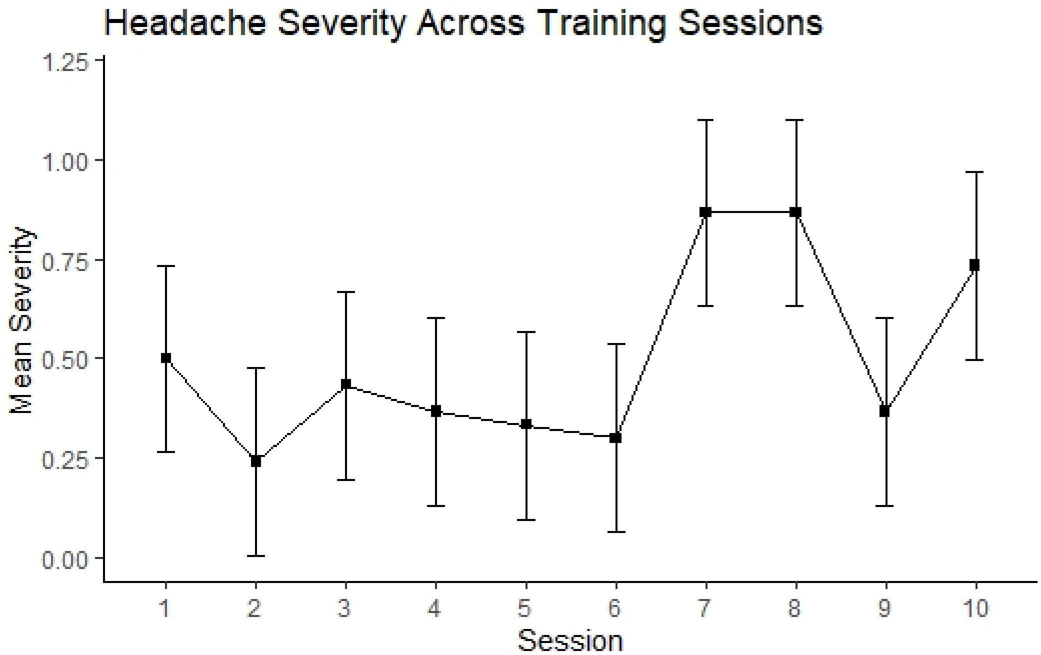

Figure 2: Mean report of headache, for all service members across all ten training days. Error bars represent standard deviation of the mean.

Examining Changes in Postural Control

Similar to analyses conducted on headache ratings, one-way RM-ANOVA were implemented to examine postural control in Conditions 1 and 4 across the two-week training course, and also to examine if performance on these assessments declined the day following blast exposure. These two conditions were chosen to contrast the most familiar postural control condition, standing on a stable surface with eyes open (Condition 1), with the most difficult one, standing on a dynamic surface with eyes closed (Condition 4), given that Condition 4 is an atypical activity. For COP Range and ApEn values, the one-way RM-ANOVA was conducted for values both in the AP and ML directions. Post-hoc comparisons were again computed; effect sizes were calculated for pairwise comparisons that met post-hoc testing statistical criterion ($p < 0.05$).

Results

Changes in Headache Report

One service member had to withdraw after the fourth training day and was omitted from the analyses. An additional two service members were missing individual headache ratings and were similarly excluded from the headache analyses, leaving 30 service members for analyses. Throughout the two weeks spent in training, mean report of headache severity appeared to increase from the Day 2 baseline during the second half of the training course. Specifically, mean headache reports were significantly increased on Day 7 (p = .027, d = - .62) and on Day 8 (p = .022, d = - .67) compared with Day 2. Both of these days were preceded by training blasts. An additional comparison that approached statistical significance was the mean headache ratings from Day 6 to Day 7 (p = .055). The remaining pairwise comparisons did not meet statistical significance.

Changes in Postural Control

All service members completed all conditions on the CTSIB battery for all days during the training course (N = 30). The hypothesized effects on service members' ApEn values (increased regularity in their time series) were not observed in either the AP or ML directions in either Condition 1 or 4. Analyses of the COP Range values also yielded null results, again in both conditions and in both AP and ML directions. COP Velocity, however, produced statistically significant differences based on condition, but in the opposite direction to that hypothesized. Specifically, Condition 4 Velocity values decreased over the two weeks in the training course, notably on Days 4 (p = .016, d = .65), 7 (p = .0004, d = .84), and 10 (p = .045, d = .59) in comparison to Day 2. COP Velocity values in Condition 1, however, did not demonstrate changes over the training course as a result of blast exposure.

Discussion

The headache results here revealed subtle, yet meaningful findings in understanding the emergence of headache across a two-week explosive breacher training program. Specifically, reports of headache increased during the second week of training (Days 6-10), rather than during the first few days of training. The finding that service members reported experiencing headaches significantly more on Days 7 and 8 are important in two key aspects. Not only do the data support the hypothesized increase in response on the day following a blast exposure, but they also infer a cumulative effect of blast exposures occurring two days in a row (on Days 6 and 7). Furthermore, the observed effect sizes on Days 7 and 8 (d = .61 and d = .69 respectively) represent a meaningful change from the baseline (Day 2) rating. The cumulative impact of repeated blast exposures on symptomology has been observed elsewhere, namely in a survey of military and law enforcement breachers (10). Furthermore, the emergence of headache over the course of explosive breacher training has also been observed previously with those endorsing more problems with this symptom reporting greater career history of explosive breaching (12,13).

Despite the elevated headache reports on two consecutive training days, it should be noted that two other days subsequent to blast exposure did not elicit the same elevated headache report (Day 3 and Day 10). It is likely that the blast exposures on Days 2 and 9 were not large enough to result in symptom report, in contrast to the large blast on Day 7 that was 400% larger than any other training blast. Blast exposure magnitude in military training associated with behavioral effects among a comparable population has recently been reported LaValle and colleagues (2019) (33). Alternatively, given that military populations are well-known under-reporters of symptoms (13), it is conceivable this reporting bias persisted in the presence of non-consecutive blast days, especially at lower magnitude exposures. It should also be noted that 11

(36%) of the 30 service members reported no headache for the entire training course, reinforcing that any effects resulting from primary blast exposure will likely be transient and susceptible to individual differences in sensitivity to blast. Whether the dichotomy in reporting or non-reporting is due to resilience factors, the restricted range of the reporting scale, or under-reporting frequently observed in military populations remains unknown.

Contrary to our hypotheses drawn from sports concussion research, postural control did not appear to be consistently or strongly impacted the day following blast, and was not associated with headache report as has been demonstrated in other research (15,26). Similarly, the potential clinical utility of ApEn in differentiating time series data of concussed individuals from those absent an injury was not observed here, in contrast to previous findings. Although one postural control measure, COP Velocity, demonstrated changes when compared to performance on Day 2, the effect was in the opposite proposed direction (values decreased over the course, rather than increasing). The absence of an observed decline in postural control here could be due to a variety of factors. It is possible that ApEn is not well suited to evaluate changes in the regularity of time series data in field settings. Service members completed these assessments while wearing their combat boots (not barefoot); footwear is not typically worn in the assessment of postural control. Service members completed these assessments in pairs, which introduced the potential for inter-subject influence. Combat boots and testing by pairs were necessary accommodations for the field setting and were expected to have equal influence (if any) across all 10 time points and, therefore, not bias the analyses, but those factors may have diminished sensitivity in analyses. They also repeatedly completed these assessments over a total of ten days, introducing the likelihood of practice effects. In line with this perspective, it is also possible that service members utilized unique strategies while completing these postural control assessments. Previous findings in the athletic literature have suggested that the environments in which athletes train, combined with the specific postural demands of their respective sports may impart differential strategies to maintain balance throughout training (34).

It is possible that the balance assessment tasks utilized here were not sufficiently challenging to produce an effect reflecting the hypotheses. In populations diagnosed with mild TBI the changes were in line with the hypotheses, for example in athletes (15,26) and military personnel (23,25,35). These prior findings describe balance deficits in individuals formally diagnosed with a mild TBI and contrasted with healthy controls. A comparison with a control group of truly blast naïve service members was not feasible here. The assessment of postural control following blast exposure in the field is likely best suited by direct evaluations of effortful control of balance, given the possibility that subtle effects can be masked or confounded by field conditions, including footwear.

Conclusion

In the analyses presented here, we assessed the impact of low-level blast on headache report and postural control in 30 service members engaged in a two-week explosive breaching training course. We observed an increase in headache report from baseline on two consecutive days following two consecutive blast days, including a large magnitude blast. However, two other days subsequent to blast did not yield the same elevated report of headache. Our hypothesized effects of postural control deficits following blast exposure did not emerge in the analyses presented here. Of note, to our knowledge, this is the first study to utilize ApEn in the assessment of postural control following blast exposure in explosive breacher training. Direct assessment of effortful control of balance appears better suited to detect changes in postural control resulting from primary blast forces. Additionally, blast exposure in training may exert other effects on symptoms not examined here, and within a time frame that extends beyond the two weeks of the training course observed here. Based on these findings, it appears that changes in symptom report or any deficits in postural control consequent to blast may emerge over time with repeated exposures (5,11,12), particularly when blasts occur on consecutive days and include exposures above a threshold yet to be defined.

Author Contributions Statement KD contributed to analyses and drafting of the manuscript, WC assisted with data collection, analyses, and drafting the manuscript, JC contributed to data analyses and drafting the manuscript, PA contributed to drafting the manuscript and supervision of the project, ML assisted with data collection and drafting the manuscript, AY assisted with data collection and drafting the manuscript, GK assisted with data collection and drafting the manuscript, and FH assisted with drafting the manuscript and supervision of the project.

Conflict of Interest Statement Material has been reviewed by the Walter Reed Army Institute of Research. There is no objection to its presentation and/or publication. The opinions or assertions contained herein are the private views of the authors, and are not to be construed as official, or as reflecting true views of the Department of the Army or the Department of Defense.

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Contribution to the Field Statement Military personnel who routinely utilize explosive ordnance to gain access to secured spaces (explosive breachers) are repeatedly exposed to blast overpressure, yet current training protocols are not known to result in diagnosable injury. We assessed the impact of low-level blast on headache report and postural control in 30 service members engaged in a two-week explosive breaching training course. We observed an increase in headache report from baseline on two consecutive days following two consecutive blast days. However, two other days subsequent to blast did not yield the same elevated report of headache. Our hypothesized effects of postural control deficits following blast exposure did not emerge in the analyses presented here. Of note, to our knowledge, this is the first study to utilize ApEn in the assessment of postural control following blast exposure in explosive breacher training. Direct assessment of effortful control of balance appears better suited to detect changes in postural control resulting from primary blast forces. Additionally, blast exposure in training may exert other effects on symptoms not examined here, and within a time frame that extends beyond the two weeks of the training course observed here.

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