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# Findings from a Randomized Controlled Trial of Sub-Symptom Threshold Exercise Treatment for Persistent Symptoms Related to Mild Traumatic Brain Injury: Efficacy and Moderators of Treatment Response in Service Members

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# Abstract

Persistent mild traumatic brain injury (mTBI)-related symptoms (PMRS) jeopardize operational readiness and can impede recovery in active-duty service members (ADSMs). Sub-symptom threshold aerobic exercise targets physiological dysregulation driving symptom persistence and exercise intolerance (EI). This rehabilitation strategy has shown promise in sports-related concussion, but its effectiveness in treating PMRS in military personnel has been understudied. This prospective, two-armed randomized controlled trial evaluated the efficacy of an 8-week Adaptable Sub-Symptomatic Exercise Treatment (ASSET) rehabilitation program against an active control condition (guided mobility/stretching) in 61 ADSMs with PMRS. The Buffalo Concussion Treadmill Test (BCTT) identified 26 (43%) participants with baseline EI. Primary outcome was global symptom burden (Neurobehavioral Symptom Inventory); secondary outcomes included chronic pain, PTSD, depression, global cognitive functioning, and postural stability. Participants receiving ASSET (n = 29) saw a significant decrease over controls (n = 32) in global symptom burden ($p$ = .030, $\eta p^2$ = .084), pain intensity ($p$ = .004, $\eta p^2$ = .144), and PTSD symptoms ($p$ = .017, $\eta p^2$ = .102). Baseline EI significantly moderated PTSD symptom response ($p$ = .029, $\eta p^2$ = .086), with participants with lower exercise capacity experiencing the greatest benefits from ASSET. These findings support integrating BCTT-based phenotyping into military concussion care.


# Introduction

Persistent mild traumatic brain injury (mTBI)-related symptoms (PMRS) represent a significant and ongoing clinical challenge within the Military Health System [1]. While most injured individuals recover within days to weeks, a clinically meaningful subset experience chronic, heterogeneous symptom burden, including cognitive, somatic and vestibular complaints, as well as higher levels of depression, post-traumatic stress, and pain [2].These deficits have direct implications for active duty service members (ADSMs) health, function, and operational readiness [3].

Traditional approaches to PMRS rehabilitation have largely emphasized symptom management and compensatory strategies, with fewer interventions targeting underlying physiological dysfunction. Sub-symptom threshold exercise has emerged as a promising treatment for PMRS by targeting the autonomic and cerebrovascular dysregulation hypothesized to underpin symptom persistence [4-6]. This dysregulation manifests clinically as exercise intolerance, defined as the inability to exercise to near-maximal heart rate without symptom exacerbation. Exercise intolerance is identifiable via the Buffalo Concussion Treadmill Test (BCTT), a standardized graded exertion protocol [7]. By prescribing individualized aerobic exercise below each patient's heart rate threshold, with progressive intensity advancement over time, sub-symptom threshold exercise aims to restore physiological regulatory capacity and suppress the mechanisms sustaining PMRS.

Exercise intolerance following mTBI remains poorly understood in adults with PMRS, as most prior work focused on young athletes with acute sport-related concussion. There remains limited data in adult populations, particularly in military personnel with disproportionately high levels of repetitive blast and

impact exposure. Emerging evidence suggests that exercise intolerance persists well beyond the acute phase and is associated with greater symptom burden and psychological distress [8, 9], raising the possibility that it may serve as a clinically meaningful phenotype for treatment stratification. Interestingly, adults with PMRS months or even years removed from injury can safely achieve clinically meaningful functional recovery through personalized, heart rate-targeted aerobic exercise programs [10, 11], supporting the application of this approach in the military population.

The present study reports findings from a prospective randomized controlled trial evaluating an 8-week Adaptable Sub-Symptomatic Exercise Treatment (ASSET) program, a hybrid aerobic conditioning and functional resistance training protocol, against an active Mobility Active Control (MAC) condition in ADSMs with PMRS. A secondary aim examined whether baseline exercise tolerance moderates treatment response, as we hypothesized that exercise intolerant participants, ostensibly those with the greatest physiological dysregulation, would derive the greatest benefit from targeted aerobic recalibration.

## Methods

# Design and Setting

This study analyzed data from a prospective, two-arm randomized controlled trial conducted at a military treatment facility specializing in mTBI rehabilitation [12]. Participants were randomized to ASSET or MAC and assessed at baseline and immediately following the 8-week intervention period. The study was reviewed and approved by the Naval Medical Center, San Diego (NMCSD) Institutional Review Board (IRB). All study procedures were conducted in accordance with applicable institutional requirements and written informed consent was obtained from all participants prior to enrollment. The trial is registered at ClinicalTrials.gov (NCT06561100).

# Participants

ADSMs were recruited from the Intrepid Spirit Center, a military treatment facility specializing in mTBI rehabilitation. Inclusion criteria were: (1) at least one mTBI meeting DoD/VA diagnostic criteria; (2) more than three months out from last injury; (3) age 18–55 years; and (4) medical clearance for graded exercise. Exclusion criteria included moderate or severe TBI, active suicidal ideation, current substance use disorder, neurological conditions other than mTBI, and medical contraindications to exercise testing.

# Exercise Tolerance Assessment

Baseline exercise tolerance was assessed using the Buffalo Concussion Treadmill Test (BCTT), a standardized graded exertion protocol in which speed and incline/resistance are incrementally increased until the participant reaches volitional exhaustion or reports a clinically significant worsening of

symptoms (≥3-point increase on the symptom severity rating scale [13]). Participants were classified as exercise intolerant if symptom exacerbation occurred prior to volitional exhaustion, and exercise tolerant if they completed the protocol without symptom provocation. Heart rate at the point of exacerbation or test completion was used to individualize ASSET programming. BCTT final stage achieved was retained as a continuous index of physiological capacity for exercise in all analytic models.

# Interventions

## ASSET: Adaptable Sub-Symptomatic Exercise Treatment

ASSET consisted of an individualized, progressively advanced exercise program prescribed below each participant's BCTT-derived symptom-exacerbation heart rate threshold [12]. The program integrated aerobic conditioning (treadmill, cycle ergometer, or elliptical) and functional resistance training organized around fundamental movement patterns (hip hinge, squat, lunge, push, pull, and loaded carry). Participants completed two supervised 60-minute sessions per week (1:1 therapist-to-participant ratio) and three independently performed sessions per week (45–60 minutes) over 8 weeks. Heart rate targets were advanced incrementally (∼5–10 bpm) at each supervised session provided no symptom exacerbation was reported.

## MAC: Mobility Active Control

The MAC condition controlled for nonspecific effects of structured clinical engagement and physical activity while avoiding the aerobic conditioning and resistance training stimulus central to ASSET. Sessions consisted of guided stretching, joint mobility exercises, and low-intensity movement, with heart rate maintained below 60% of age-predicted maximum. Session frequency and duration were matched to ASSET across the 8-week period.

# Outcome Measures

The Neurobehavioral Symptom Inventory (NSI) served as the primary outcome, a 22-item self-report instrument assessing cognitive, affective, somatic, and vestibular post-concussive symptoms (range 0–88; higher = greater burden). A reliable change index (RCI) value of ≥ 8 was based on published recommendations [14]. Secondary outcomes included: PTSD symptoms (PTSD Checklist-Military Version [PCL-M]; range 17–85; probable PTSD defined as PCL-M > 44 [15]), and meaningful clinical change threshold of ≥ 10 based on recommendations from the National Center for PTSD [16], depressive symptoms (Patient Health Questionnaire-8 [PHQ-8]; range 0–24; probable depression defined as ≥10), postural stability (Sensory Organization Test [SOT] composite score; range 0–100; higher = better stability), global cognitive functioning (Global Deficit Scale [GDS]; probable impairment defined as ≥ 0.50 [17]), and pain intensity assessed using a 0–10 Numerical Rating Scale (NRS; 0 = "no pain", 10 = "worst

pain imaginable"); a change threshold of ≥ 2 was applied according to published recommendations [18, 19].

# Statistical Analysis

# Analysis of Covariance (ANCOVA)

ANCOVA modeling was used to examine Intervention main effects and Interaction (Intervention x BCTT Final Stage) effects. A consistent two-model analytic approach was applied across all outcomes. Model 1 examined the primary intervention effect with a standard covariate set. Model 2 introduced interaction terms to test whether physiological capacity for exercise moderated treatment response (Intervention × BCTT Final Stage).

Based on known confounds in the military mTBI recovery literature, four covariates were identified *a priori* and included across all models: baseline score for the respective outcome, BCTT Final Stage (continuous index of physiological capacity for exercise), premorbid cognitive reserve (Test of Premorbid Functioning [TOPF]), and injury chronicity (years since last TBI). Ethnicity (Hispanic vs. non-Hispanic) was included as a fixed factor in all self-report outcome models (NSI, PCL-M, PHQ-8, and NRS), given documented symptom reporting disparities across ethnic groups in the military health system [20]. Ethnicity was excluded from models examining objective performance-based outcomes (GDS, SOT) because these measures are not subject to the same self-report bias.

# Clinical Response Analyses

Published reliable change index (RCI) and minimal clinically important difference (MCID) thresholds were applied to classify individual treatment response, and between-group differences in responder rates were compared using Fisher's Exact Test.

All statistical analyses were two-tailed with significance defined as $p < .05$ and corresponding 95% confidence intervals are reported where appropriate. All statistical analyses were performed using SPSS (Version 29).

## Results

# Sample Characteristics

Participant demographic, injury, service, and baseline clinical characteristics are presented in **Table 1**. Sixty-one ADSMs with PMRS enrolled and completed the study protocol (ASSET: n = 29; MAC: n = 32). Of the 61 participants, 26 (43%) were classified as EI (ASSET: 45%; MAC: 41%) and 35 (57%) as ET. Despite active-duty status and medical clearance for exercise, more than half of the full sample met criteria for

probable PTSD (54%) and probable depression (61%), and 38% demonstrated clinically meaningful cognitive impairment (GDS ≥ .50), underscoring the severity of this population's clinical profile. No significant between-group differences were observed on any baseline variable across intervention conditions.

# Primary Outcome: Global Symptom Burden (NSI)

The primary ANCOVA (Model 1) revealed a significant main effect of Intervention on post-intervention NSI total scores, $F(1, 54) = 4.95$, $p = .030$, $\eta p^2 = .084$; $R^2 = .72$, indicating that ASSET produced superior reductions in overall PMRS burden compared to MAC. After controlling for baseline symptom severity and covariates, ASSET participants reported significantly lower post-intervention global symptom burden indicating greater response to treatment (ASSET: $M = 31.05$, $SE = 1.81$; MAC: $M = 36.50$, $SE = 1.75$; mean difference = 5.45, 95% CI [0.54, 10.37], $p = .030$; see **Table 2**). Model 2 revealed that exercise tolerance did not moderate treatment response (Intervention × BCTT Final Stage: $p = .610$), indicating that the benefits of ASSET on global symptom reduction are robust regardless of a patient's baseline exercise capacity (see **Table 3**).

# Secondary Outcomes: Pain Intensity, PTSD symptoms, Depression, Global Cognitive Functioning, and Postural Stability

# Pain Intensity (NRS)

Model 1 revealed a significant main effect of Intervention on post-intervention pain intensity, $F(1, 54) = 9.05$, $p = .004$, $\eta p^2 = .144$; $R^2 = .40$, representing the largest intervention effect observed across all outcomes in this study. Relative to pre-treatment pain levels, ASSET participants reported significantly less pain post-intervention than those in MAC (ASSET: $M = 2.45$, $SE = .24$; MAC: $M = 3.47$, $SE = .25$; mean difference = 1.03, 95% CI [.35, 1.71], $p = .004$; see **Table 2**). Model 2 revealed treatment response was not moderated by exercise tolerance (Intervention × BCTT Final Stage: $p = .437$), indicating that the pain reduction benefit conferred by ASSET was robust and not contingent on physiological capacity for exercise (see **Table 3**).

# PTSD Symptoms (PCL-M)

Model 1 revealed a significant Intervention main effect on post-intervention PCL-M scores, $F(1, 54) = 6.12$, $p = .017$, $\eta p^2 = .102$; $R^2 = .64$, with ASSET participants reporting significantly lower PTSD symptoms than those in MAC (ASSET: $M = 39.86$, $SE = 1.86$; MAC: $M = 46.34$, $SE = 1.94$; mean difference = 6.49, 95% CI [1.23, 11.75], $p = .017$; see **Table 2**). Model 2 revealed a significant Intervention × BCTT Final Stage

interaction, $F(1, 53) = 5.01$, $p = .029$, $\eta p^2 = .086$, indicating that physiological capacity for exercise moderated PTSD treatment response (see **Table 3**). As depicted in **Figure 1**, the relationship between baseline exercise capacity and post-intervention PTSD symptoms differed significantly between ASSET and MAC. Probing the interaction revealed that the therapeutic benefit of ASSET was greatest for individuals with the lowest physiological capacity for exercise (i.e., greater exercise intolerance) at baseline. For these participants, ASSET was associated with markedly reduced PTSD symptom severity compared to the MAC condition, whereas this benefit diminished as baseline exercise capacity increased. Importantly, no significant difference between intervention arms was observed for those with higher baseline exercise capacity.

## Depression (PHQ-8)

Model 1 revealed a non-significant Intervention main effect on post-intervention PHQ-8 scores, $F(1, 54) = 2.79$, $p = .101$, $\eta p^2 = .049$; $R^2 = .59$; ASSET: M = 9.22, SE = .64; MAC: M = 10.71, SE = .66; mean difference = 1.49, 95% CI [–0.30, 3.28]; see **Table 2**. Model 2 revealed a non-significant Intervention × BCTT Final Stage interaction for post-intervention PHQ-8 scores, $F(1, 53) = 2.77$, $p = .102$, $\eta p^2 = .050$; see **Table 3**.

# Global Cognitive Functioning (GDS)

Model 1 revealed a non-significant Intervention main effect on post-intervention PHQ-8 scores, $F(5, 55) = .07$, $p = .792$, $\eta p^2 = .001$; $R^2 = .57$; ASSET: M = .36, SE = .07; MAC: M = .38, SE = .06, mean difference = .02, 95% CI [-.16, .21]; see **Table 2**. Model 2 revealed a non-significant Intervention × BCTT Final Stage interaction for post-intervention GDS scores, $F(6, 54) = 1.29$, $p = .260$, $\eta p^2 = .023$; see **Table 3**.

# Postural Stability (SOT)

Model 1 revealed a non-significant Intervention main effect on post-intervention SOT composite scores, $F(5, 55) = .01$, $p = .906$, $\eta p2 = .049$; $R^2 = .42$; ASSET: M = 74.26, SE = 1.27; MAC: M = 74.05, SE = 1.20, mean difference = -.21, 95% CI [-3.73, 3.31]; see **Table 2**. Model 2 revealed a non-significant Intervention × BCTT Final Stage interaction for post-intervention SOT composite scores, $F(6, 54) = .03$, $p = .864$, $\eta p^2 = .001$; see **Table 3**.

# Clinical Response Analyses: Clinically Important Differences

To complement the continuous outcome analyses and evaluate treatment effects at the level of individual clinical significance, we examined between-group differences in the proportion of participants achieving published clinical change threshold scores (see **Table 4**). ASSET participants were

significantly more likely than MAC participants to achieve minimal clinically meaningful improvement in post-traumatic stress (45% vs. 16%, $p$ = .023) and pain (45% vs. 9%, $p$ = .003). For global symptom burden, the proportion achieving the NSI RCI threshold favored ASSET (59% vs. 34%, $p$ = .075), falling just short of significance; however, this pattern may simply reflect limited statistical power at the current sample size. Response rates for depression, postural stability, and global cognitive functioning were comparable across conditions (all $p$'s > .50), consistent with the null continuous-outcome findings for those domains.

# Discussion

This RCT provides evidence that ASSET produces clinically meaningful improvements across multiple symptom domains in ADSMs with PMRS. The pattern of findings supports four overarching conclusions. First, ASSET produced robust, sample-wide improvements in overall post-concussive symptom burden, PTSD symptoms, and pain, establishing its multidomain efficacy as a rehabilitation program. Second, exercise tolerance significantly moderated the PTSD symptom response, such that ADSMs with the lowest physiological capacity for exercise experienced the greatest reduction in PTSD symptoms after treatment with ASSET. Third, cognitive functioning and postural stability showed no significant intervention effect within 8 weeks, suggesting these domains may require a longer recovery runway than other domains. Fourth and lastly, a consistent pattern emerged across psychiatric, symptom, cognitive, and pain outcomes in this dataset: lower physiological capacity for exercise at baseline predicted more favorable post-intervention status across multiple domains.

General Efficacy: Global Symptoms, PTSD, and Pain

ASSET produced a significant 5.5-point reduction in overall post-concussive symptom burden. This clinically notable difference, given published thresholds, was detectable even after controlling for baseline severity, ethnicity, physiological capacity for exercise, time since injury, and premorbid cognitive ability. The robustness of this effect across this covariate set speaks to the consistency of ASSET's efficacy rather than its dependence on favorable analytic conditions. The significant reduction in PTSD symptoms extends the therapeutic scope of exercise-based concussion rehabilitation into trauma-related psychopathology. The practical significance of this effect is reinforced by the clinical response analyses that showed ASSET participants were nearly three times more likely than MAC participants to achieve a clinically meaningful reduction in post-traumatic stress (45% vs. 16%, $p$ = .023). For clinicians treating ADSMs with co-occurring PTSD and PMRS, this finding suggests that ASSET may address both conditions simultaneously through shared pathways, specifically the autonomic and cerebrovascular dysregulation that underlies both exercise intolerance following mTBI and the chronic hyperarousal state characteristic of PTSD [21].

ASSET also produced a large reduction in pain, with ASSET participants five times more likely to achieve a clinically meaningful pain reduction relative to MAC (45% vs. 9%, $p$ = .003). The absence of any

exercise tolerance moderation for pain indicates that this benefit is broadly available, regardless of a service member's physiological profile at baseline.

Targeted Rehabilitation: Exercise Intolerance as a Moderator of PTSD Treatment Response

One of the most novel clinical findings of this study was the interaction between baseline physical fitness and the efficacy of graded exercise for reducing post-traumatic stress symptoms (see Table 3). Plotting the interaction (see **Fig. 1**) identified a critical threshold for clinical decision-making around BCTT stage 15. For service members with lower baseline exercise intolerance (BCTT stage < 15), ASSET substantially reduced PTSD symptom severity compared to MAC, whereas for ADSMs with higher tolerance for exercise at baseline (BCTT stage ≥ 15), ASSET offered no additional benefit over MAC. From a clinical translation perspective, this crossover effect strongly supports the implementation of BCTT-based physiological phenotyping to tailor care.

The reasons for this differential treatment response are likely multi-faceted. One potential explanation is the well-established relationship between post-traumatic stress and ANS dysfunction. Autonomic dysregulation has long been recognized as a core physiological feature of PTSD and is characterized by increased sympathetic arousal and reduced parasympathetic regulation [22, 23]. It is possible that ASSET exerts its therapeutic effects, at least in part, through improvements in ANS regulation, thereby producing benefits for both post-traumatic stress symptoms and persistent post-concussive symptoms. Under this framework, lower baseline physiological capacity may serve as a proxy indicator of greater ANS dysfunction, providing a larger opportunity for clinical improvement. Furthermore, this finding is a straightforward confirmation that the intervention works best for those it was designed to serve. ASSET was developed specifically for individuals who cannot sustain exercise without symptom provocation; therefore, it makes sense that the greatest therapeutic gains are seen in participants with the most physiological ground to cover. Future studies should directly evaluate this hypothesis using objective measures of autonomic function.

Limitations

Several limitations should inform interpretation of these findings. The small sample size recruited from a single specialized medical facility may limit statistical power for some findings (e.g., RCI improvement on the NSI) and generalizability (e.g., veterans, non-specialty settings). The 8-week assessment window also limits conclusions about optimal treatment dose, thus whether fewer sessions would suffice or longer program would produce greater gains remains an open question. Finally, reliance on self-report instruments for PMRS and psychiatric symptoms introduces reporting bias and precludes mechanistic inferences about the physiologic pathways underlying effects of ASSET.

# Conclusions

We report that ASSET produces clinically meaningful improvements in overall PMRS burden, PTSD symptoms, and pain in ADSMs that exceed those of an active control condition. A consistent pattern of

preferential benefit for participants with the lowest baseline physiological capacity for exercise suggests that BCTT-based phenotyping can prospectively identify treatment responders. Considering ASSET was designed precisely to serve this population, with the greatest physiologic dysregulation, this pattern across analytic approaches and outcome domains supports the construct validity of BCTT-based patient stratification and reinforces the argument for a targeted rehabilitation approach. Thus, these findings argue for integrating BCTT-based exercise tolerance assessment into routine military concussion rehabilitation intake protocols and position ASSET as a targeted, scalable, and clinically impactful intervention for this population.

## Declarations

# Conflicts of Interest:

The authors declare that they have no conflicts of interest, financial disclosures, or competing commercial interests to report.

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# Disclaimer

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# Author Contribution

A.J.D. writing- original draft; formal analysis; visualization.J.M.B.: conceptualization; funding acquisition; supervision; validation.M.N.H., J.J.L., K.R.K.: conceptualization; methodology.M.R.A. and G.E.B.: visualization.G.E.B., K.S.P., and J.D.B.: writing - review and editing.J.J.L. and M.R.A.: data curation.L.K.K.: methodology; resources; writing - review and editing.L.K.K., J.R.B., J.J.L., M.R.A., and A.G.B.: investigation.J.J.L. and A.G.B.: project administration.All authors reviewed the manuscript.

# Data Availability

To protect participant privacy and in accordance with Department of Defense policies, the de-identified data from this study are not publicly available. Specific de-identified data may be made available to qualified researchers for academic purposes upon reasonable request, contingent upon institutional approvals and a formal Data Sharing Agreement (DSA) with the sponsoring military entities.

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# Tables

Table 1. Participant characteristics by intervention arm.

| Variable | Total (N = 61) | ASSET (n = 29) | MAC (n = 32) |
|---|---|---|---|
| Age, yrs, M ± SD | 34.54 ± 7.98 | 34.10 ± 7.85 | 34.94 ± 8.20 |
| Gender, % (n) male | 93% (57) | 90% (26) | 97% (31) |
| Race, % (n) Caucasian | 79% (48) | 75% (21) | 84% (27) |
| Ethnicity, % (n) non-Hispanic | 69% (42) | 59% (17) | 78% (25) |
| Lifetime mTBIs, M ± SD | 4.38 ± 2.79 | 4.41± 2.81 | 4.34 ± 2.81 |
| Years since injury, M ± SD | 5.82 ± 5.79 | 5.86 ± 6.05 | 5.78 ± 5.64 |
| Deployment mTBIs, M ± SD | 0.92 ± 1.35 | 0.72 ± 1.25 | 1.09 ± 1.42 |
| BCTT HR threshold, M ± SD | 145.89 ± 19.23 | 144.86 ± 20.63 | 146.81 ± 18.16 |
| BCTT Final Stage, M ± SD | 10.97 ± 3.53 | 10.83 ± 3.72 | 11.09 ± 3.40 |
| Exercise intolerant, % (n) | 43% (26) | 45% (13) | 41% (13) |
| TOPF, M ± SD | 107.03 ± 9.63 | 105.86 ± 11.02 | 108.09 ± 8.22 |
| NSI, M ± SD | 37.33 ± 14.15 | 37.14 ± 14.91 | 37.50 ± 13.66 |
| GDS, M ± SD | 0.60 ± 0.75 | 0.62 ± 0.78 | 0.59 ± 0.74 |
| Impairment (GDS ≥ .50), % (n) | 38% (23) | 41% (12) | 34% (11) |
| PCL-M, M ± SD | 46.11 ± 16.09 | 44.90 ± 15.73 | 47.22 ± 16.58 |
| PHQ-8, M ± SD | 11.51 ± 5.40 | 11.07 ± 5.14 | 11.91 ± 5.68 |
| SOT, M ± SD | 69.48 ± 12.40 | 70.52 ± 11.93 | 68.53 ± 12.93 |
| Pain, M ± SD | 3.39 ± 1.27 | 3.62 ± 1.45 | 3.19 ± 1.06 |

M = Mean, SD = Standard deviation. ASSET = Adaptable Sub-Symptomatic Exercise Treatment; MAC = Mobility Active Control; TOPF = Test of Premorbid Functioning; BCTT = Buffalo Concussion Treadmill Test; HR = heart rate; NSI = Neurobehavioral Symptom Inventory; GDS = Global Deficit Scale; PCL-M = PTSD Checklist-Military Version; PHQ-8 = Patient Health Questionnaire-8; SOT = Sensory Organization Test; Pain = Numerical Rating Scale (NRS). Significance markers reflect tolerance group comparisons (exercise intolerant vs exercise tolerant).

Table 2. Primary and secondary outcomes summary: Intervention main effects and estimated marginal means.

| Measure | ASSET EMM | MAC EMM | Δ | *p-value* | $\eta p^2$ | Clinical interpretation |
|---|---|---|---|---|---|---|
| Primary Outcome | | | | | | |
| **NSI (Global symptom burden)** | **31.05** | **36.50** | **5.45** | **.030** | **.084** | **Medium effect; ASSET reduced global PMRS burden** |
| Secondary Outcomes | | | | | | |
| **NRS (Pain intensity)** | **2.45** | **3.50** | **1.05** | **.004** | **.144** | **Large effect; ASSET reduced pain intensity** |
| **PCL-M (PTSD symptoms)** | **39.86** | **46.34** | **6.49** | **.017** | **.102** | **Medium effect: ASSET reduced PTSD symptom severity** |
| PHQ-8 (Depressive symptoms) | 9.22 | 10.71 | 1.49 | .101 | .049 | Small effect in expected direction; did not reach significance |
| GDS (Global cognitive functioning) | 0.36 | 0.38 | 0.02 | .792 | .001 | Negligible effect; no meaningful difference between arms |
| SOT (Postural stability) | 74.26 | 74.05 | -0.21 | .906 | .049 | Negligible effect; no meaningful difference between arms |

*N* = 61. NSI = Neurobehavioral Symptom Inventory; NRS = Numerical Rating Scale (pain intensity); PCL-M = PTSD Checklist-Military Version; PHQ-8 = Patient Health Questionnaire 8-item; GDS = Global Deficit Scale; SOT = Sensory Organization Test. EMM = estimated marginal means derived from Model 1 (Main Effects) of respective outcome analyses. Δ = EMM difference MAC - ASSET; $\eta p^2$ = partial eta squared.

Table 3. Moderation effects of BCTT final stage on treatment outcomes.

| Measure | B | SE | *F(df)* | *p-value* | $\eta p^2$ |
|---|---|---|---|---|---|
| Primary Outcome | | | | | |
| NSI (Global symptom burden) | -.37 | .72 | .26 (1, 53) | .610 | .005 |
| Secondary Outcomes | | | | | |
| NRS (Pain intensity) | .06 | .11 | .28 (1, 53) | .601 | .005 |
| **PCL-M (PTSD Symptoms)** | **-1.64** | **.73** | **5.01 (1, 53)** | **.029** | **.086** |
| PHQ-8 (Depressive symptoms) | -.42 | .18 | 2.77 (1, 53) | .102 | .050 |
| GDS (Global cognition) | .03 | .03 | 1.29 (1, 54) | .260 | .023 |
| SOT (Postural stability) | .09 | .54 | .03 (1, 54) | .864 | .001 |

*N* = 61. NSI = Neurobehavioral Symptom Inventory; NRS = Numerical Rating Scale (pain intensity); PCL-M = PTSD Checklist-Military Version; PHQ-8 = Patient Health Questionnaire 8-item; GDS = Global Deficit Scale; SOT = Sensory Organization Test. B = beta coefficient, or interaction estimate; SE = standard error; F(df) = F-statistic (degrees of freedom); $\eta p^2$ = partial eta squared.

Table 4. Proportion of participants achieving established clinical change thresholds by intervention arm.

| Domain | Measure | Threshold | Responders, % (n) | | *p* |
|---|---|---|---|---|---|
| | | | ASSET | MAC | |
| Global symptom burden | NSI[a] | ≥ 8.0 | 59% (17) | 34% (11) | .075 |
| **Pain intensity** | **NRS[b]** | **≥ 2.0** | **45% (13)** | **9% (3)** | **.003** |
| **PTSD symptoms** | **PCL-M[b]** | **≥ 10.0** | **45% (13)** | **16% (5)** | **.023** |

*N* = 61. NSI = Neurobehavioral Symptom Inventory; PCL-M = PTSD Checklist-Military Version; NRS = Numerical Rating Scale. PTSD = Post-traumatic Stress Disorder. [a]Reliable change index (RCI), [b]Minimal Clinically Threshold Difference (MCID).

# Figures

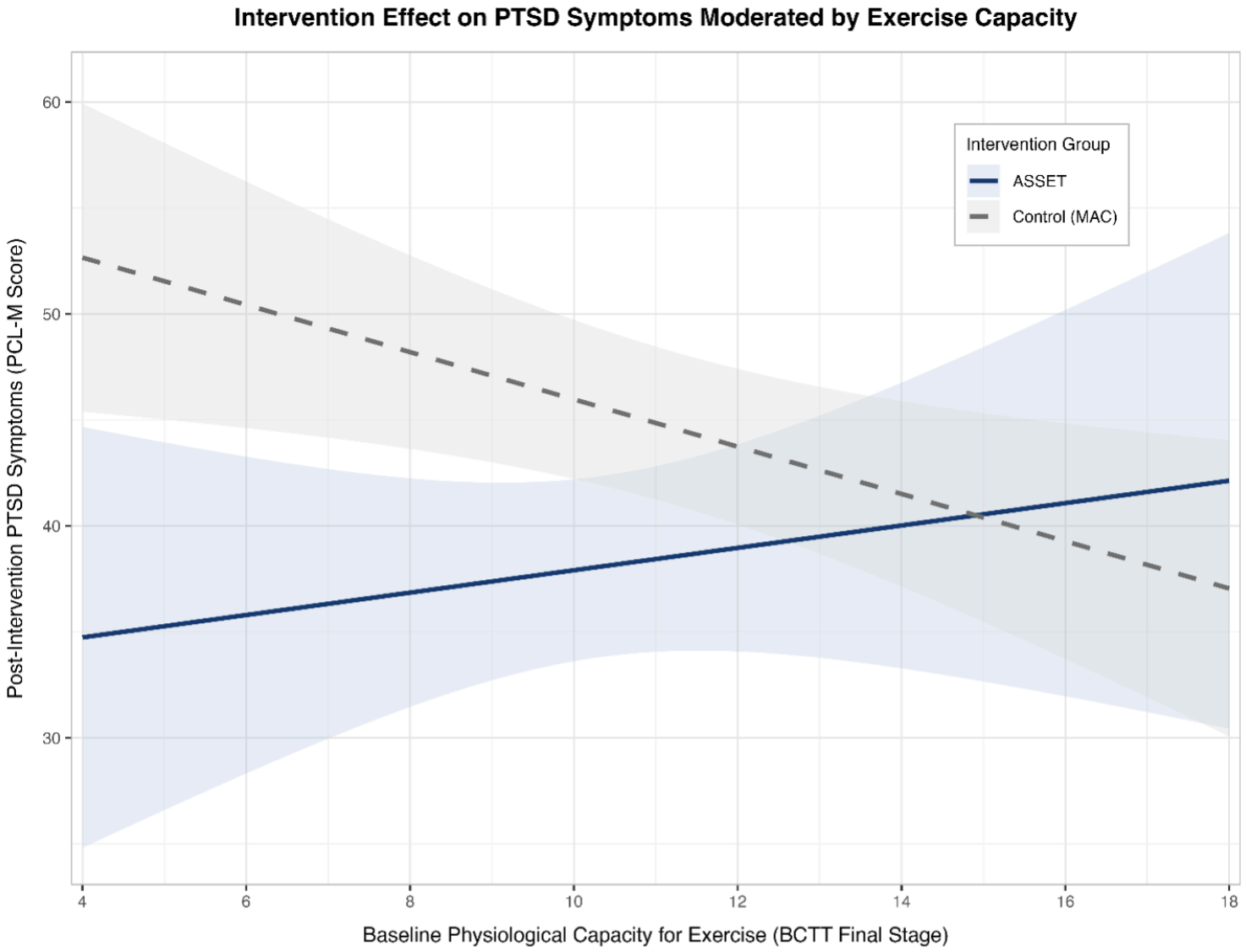



**Figure 1**

Moderating effect of baseline exercise capacity on PTSD symptom response to intervention. The regression lines depict the relationship between baseline physiological capacity for exercise (BCTT Final Stage) and post-intervention PTSD symptom severity (PCL-M score, adjusted for covariates) for both ASSET (solid blue line) and MAC (dashed gray line). A significant Intervention × BCTT Final Stage interaction ($p$ = .029) was observed, demonstrating that the therapeutic benefit of ASSET was greatest for ADSMs with lower exercise capacity at baseline (i.e., greater exercise intolerance). PCL-M = PTSD Checklist-Military Version; BCTT = Buffalo Concussion Treadmill Test; ASSET = Adaptable Sub-Symptomatic Exercise Treatment; MAC = mobility active control. Shaded areas around the regression lines represent 95% confidence intervals of the predicted means.