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EFFECTS OF FOOTBATH INTERVENTION ON SKELETAL MUSCLE OXYGENATION RECOVERY: GROUP-LEVEL AND INDIVIDUAL-LEVEL ANALYSES USING MDC$_{95}$

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Abstract

Foot bathing (ashiyu) is a traditional and widely practiced recovery method in Japan; however, its physiological effects on skeletal muscle recovery and the sources of inter-individual variability remain unclear. This study investigated the effects of foot bathing on skeletal muscle oxygenation recovery kinetics, focusing on both group-level outcomes and clinically meaningful individual responses. Fifteen healthy young men completed a randomized crossover protocol consisting of a control rest condition and a foot bathing condition following a standardized calf-raise exercise. Muscle oxygenation of the medial gastrocnemius was continuously assessed using near-infrared spectroscopy. Recovery rate (Slope) and recovery half-time (Halftime) were analyzed at both the group and individual levels. Individual responsiveness was classified using the minimal detectable change at the 95% confidence level (MDC_{95}*), assuming an intraclass correlation coefficient of 0.90. Group-level analyses revealed no statistically significant differences between conditions for either Slope or Halftime. In contrast, individual-level analysis demonstrated substantial heterogeneity in responses. Five participants exceeded *MDC_{95}* for improved recovery rate following foot bathing, whereas others showed minimal change or deterioration. No participants exceeded *MDC_{95}* for Halftime improvement. These findings indicate that foot bathing does not exert uniform effects on muscle oxygenation recovery. Incorporating *MDC_{95}*-based individual analysis provides a more* *clinically relevant framework for evaluating recovery interventions and highlights the importance of personalized recovery strategies.*

Keywords:

Foot Bathing, Ashiyu, Muscle Oxygenation, Near-Infrared Spectroscopy

1. Introduction

Effective recovery strategies are increasingly recognized as a critical component of athletic performance and rehabilitation; however, systematic scientific evaluation of recovery interventions remains limited compared with the extensive literature on training load and intensity. Exercise-induced fatigue is a multifaceted phenomenon comprising physical, mental, and nutritional components. While recovery from mental fatigue (Kremenic et al., 2009) and glycogen depletion (Ivy et al., 1988) has been well documented, practical interventions targeting the physiological recovery of skeletal muscle remain insufficiently explored.

Foot bathing (ashiyu) is a traditional thermal intervention in Japan. Unlike full-body immersion, foot bathing imposes minimal cardiovascular load, suggesting its suitability as a safe and accessible recovery modality. Previous studies have reported that foot bathing enhances peripheral blood flow (Uebaba & Xu, 2004) and induces autonomic nervous system modulation, characterized by parasympathetic activation (Kaneko et al., 2009). Despite these promising characteristics, empirical evidence supporting its effectiveness on skeletal muscle recovery remains scarce.

Near-infrared spectroscopy (NIRS) has emerged as a non-invasive and reliable method for assessing skeletal muscle oxygenation and oxidative metabolism (Blasi et al., 1993; Boushel et al., 1998; Ding et al., 2001). Recovery kinetics derived from NIRS, such as recovery rate and half-time, have been validated against phosphorus magnetic resonance spectroscopy and biopsy measures, establishing them as robust indices of mitochondrial oxidative capacity and microvascular function (Ryan et al., 2012; Ryan et al., 2013; Ryan et al., 2014; Brizendine et al., 2013). Thus, NIRS offers a physiological window into the metabolic recovery processes that may be modulated by thermal interventions (Tuesta et al., 2022).

A major limitation of previous recovery studies is their reliance on group-level statistical comparisons. As Neumann et al. (2021) argue, biological systems often exhibit nonergodicity, meaning that group-level results do not necessarily generalize to specific individuals. This "averaging fallacy" may obscure meaningful physiological adaptations occurring in specific "high responders" (Mann et al., 2014). Inter-individual variability in response to exercise and recovery is increasingly recognized as a fundamental characteristic of human physiology rather than random noise, influenced by factors such as baseline fitness and autonomic balance (Bonafiglia et al., 2016; Whipple et al., 2017; Baird & Motl, 2018). To address this gap, the present study investigated the effects of foot bathing on skeletal muscle oxygenation recovery kinetics by integrating group-level analysis with an individual-level framework using the minimal detectable change (MDC_{95}).

2. Methods

2.1 Participants

Fifteen healthy male participants (mean age ± SD: 25 ± 2 years) voluntarily participated in this study. All participants were free from neuromuscular, orthopedic, or cardiovascular disorders. Participants refrained from strenuous activity, caffeine, and alcohol for 24 hours prior to sessions. All procedures were conducted in accordance with the principles of the Declaration of Helsinki.

2.2 Experimental Design

A randomized crossover design was employed to compare control rest (CN) and footbath intervention (FB).

2.3 Exercise Protocol

Participants performed a bilateral standing calf-raise exercise (30 repetitions over 1 minute at 60 bpm) to induce localized fatigue in the medial gastrocnemius muscle without systemic exhaustion.

2.4 Recovery Conditions

Immediately post-exercise, participants underwent a 10-minute recovery phase:

Control rest (CN): Seated rest without immersion.

Footbath intervention (FB): Lower leg immersion in 42 °C water.

2.5 Muscle Oxygenation Measurement

Skeletal muscle oxygenation was continuously monitored using NIRS (Oxy-Pro, Astem, Japan). NIRS allows for the continuous monitoring of tissue oxygen saturation (StO_2) trends during recovery, reflecting the balance between oxygen delivery and utilization (Bhambhani, 2004).

2.6 Outcome Measures

Consistent with established protocols for assessing oxidative capacity (McCully et al., 1994; Kime et al., 2003), two indices were derived from the StO_2 signal (Figure 1).

Muscle reoxygenation kinetics following exercise do not invariably conform to a simple exponential pattern, as the recovery trajectory can vary depending on physiological and experimental conditions (McCully et al., 1994; McCully & Hamaoka, 2000). Accordingly, an exponential model was not applied when quantifying the muscle reoxygenation rate in the present study.

Recovery rate (Slope): The initial slope of StO_2 resaturation immediately following exercise.

Recovery half-time (Halftime): The time required for StO_2 to recover 50% from the nadir to baseline.

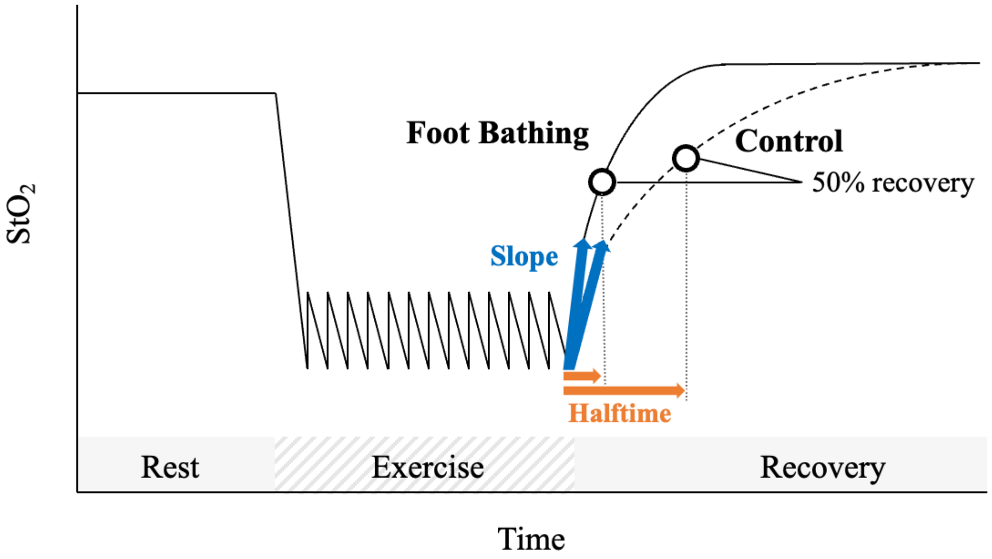

Figure 1. *Schematic Illustration of Muscle Oxygen Saturation (StO_2) Dynamics Measured by Near-Infrared Spectroscopy (NIRS).*

Following a resting period, intermittent exercise induces a marked decrease in StO_2. During recovery, StO_2 progressively increases toward baseline levels. Recovery rate (Slope) represents the initial rate of StO_2 increase immediately after exercise cessation, whereas recovery half-time (Halftime) is defined as the time required to reach 50% of the recovery amplitude from the minimum StO_2 value. The schematic highlights differences in recovery kinetics between the footbath (FB) and control (CN) conditions.

2.7 Statistical Analysis

2.7.1 Group-Level Analysis

Group-level comparisons were conducted using paired t-tests ($p < 0.05$) using SPSS Statistics 30 (IBM SPSS Japan, Tokyo, Japan). In addition to group-level analyses, individual-level changes were evaluated using a minimal detectable change framework.

2.7.2 Individual-Level Analysis and Minimal Detectable Change

To identify clinically meaningful individual responses beyond measurement error, the minimal detectable change at the 95% confidence level (MDC_{95}) was calculated using the following equation:

$$\mathrm{MDC}_{95} = 1.96 \times \sqrt{2} \times SEM$$

where the standard error of measurement (SEM) was estimated as:

$$\mathrm{SEM} = SD \times \sqrt{1 - ICC}$$

An intraclass correlation coefficient (ICC) of 0.90 was assumed, consistent with previous reliability reports of NIRS-derived muscle oxygenation measures (Ryan et al., 2012).

Individual change scores were calculated as FB − CN for Slope and CN − FB for Halftime, such that positive values indicated improved recovery. Participants were classified as above, within, or below MDC_{95} thresholds.

3. Results

3.1 Group-Level Analysis

Mean recovery rate (Slope) was higher in the footbath condition (FB: 5.37 ± 4.02, n = 15) than in the control condition (CN: 3.95 ± 2.87, n = 15); however, this difference did not reach statistical significance (paired t-test: t(14) = −1.03, p = 0.319, 95% CI of the mean difference: −4.35 to 1.52; Figure 2). The standardized effect size was small (Cohen’s d = −0.27, 95% CI: −0.78 to 0.25; Hedges’ g = −0.25).

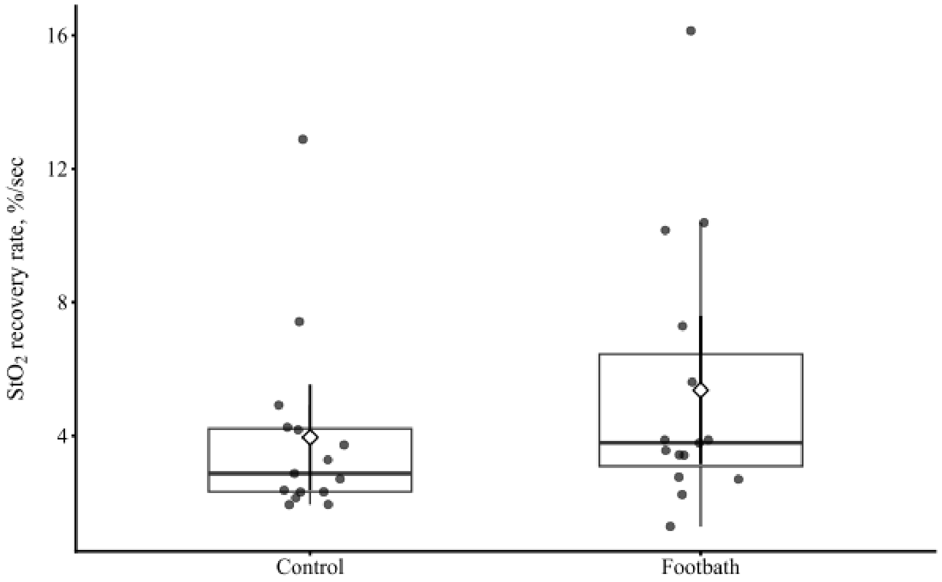

Figure 2. *Distribution of StO_2 recovery rate under Control and Footbath conditions.*

Boxplots represent the median and interquartile range, with whiskers indicating the range excluding outliers.

Open diamonds indicate the mean, and vertical lines represent the mean ±95% confidence interval.

Individual data points are shown with slight horizontal jitter for visualization.

Recovery half-time (Halftime) showed substantial overlap between conditions, with no significant difference observed between FB (12.19 ± 3.66, n = 13) and CN (11.11 ± 4.26, n = 13) (paired t-test: t(12) = −1.02, p = 0.327, 95% CI of the mean difference: −3.38 to 1.22; Figure 3). The effect size was likewise small (Cohen’s d = −0.28, 95% CI: −0.83 to 0.28; Hedges’ g = −0.27).

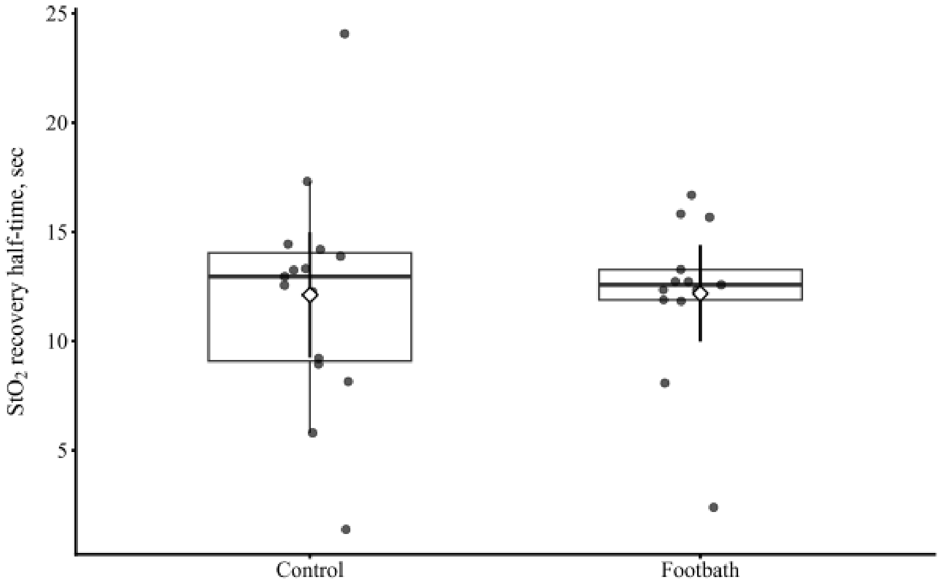

Figure 3. *Distribution of StO_2 recovery half-time under Control and Footbath conditions.*

Boxplots represent the median and interquartile range, with whiskers indicating the range excluding outliers.

Open diamonds indicate the mean, and vertical lines represent the mean ±95% confidence interval.

Individual data points are shown with slight horizontal jitter for visualization.

3.2 Individual-Level Analysis

Despite minimal group-level differences, individual responses varied markedly.

For recovery rate, five participants exceeded MDC_{95}, indicating clinically meaningful improvement following foot bathing. Eight participants remained within MDC_{95}, and two exhibited deteriorations beyond MDC_{95}.

For recovery half-time, no participants exceeded MDC_{95} for improvement, while one participant demonstrated deterioration beyond MDC_{95}. The remaining participants showed changes within measurement error (Figures 4 and 5).

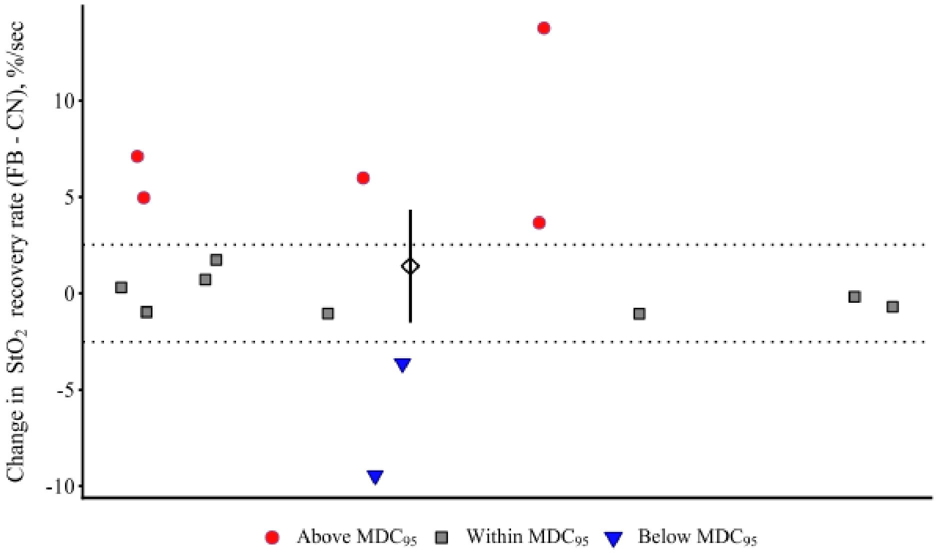

Figure 4. *Individual changes in StO_2 recovery rate following Footbath intervention relative to Control.*

Each point represents an individual change score (FB − CN). Positive values indicate faster reoxygenation in the footbath condition compared to control. Dotted horizontal lines indicate the minimal detectable change at the 95% confidence level (MDC_{95}). Symbols denote individuals above, within, or below MDC_{95}. The open diamond and vertical line indicate the mean change and its 95% confidence interval. Individual data points are shown with slight horizontal jitter for visualization.

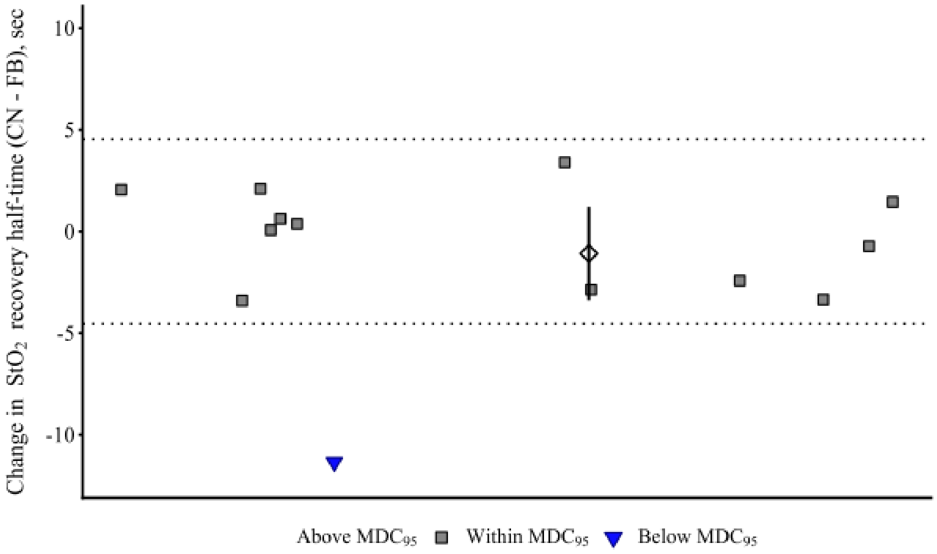

Figure 5. *Individual changes in StO₂ recovery half-time following Footbath intervention relative to Control.*

Each point represents an individual change score (CN - FB). Positive values indicate a reduction in recovery half-time, signifying improved recovery kinetics in the footbath condition. Dotted horizontal lines indicate the minimal detectable change at the 95% confidence level (MDC_{95}). Symbols denote individuals above, within, or below MDC_{95}. The open diamond and vertical line indicate the mean change and its 95% confidence interval. Individual data points are shown with slight horizontal jitter for visualization.

4. Discussion

The primary finding of this study is that foot bathing does not produce uniform improvements in skeletal muscle oxygenation recovery across all individuals. The clinical significance of this study lies in demonstrating that, despite minimal group-level effects, meaningful improvements can be identified at the individual level using an MDC_{95}-based analytical framework. This approach provides critical insights that are frequently overlooked by conventional group-averaged analyses, aligning with the growing consensus that group-level results do not inherently generalize to individuals (Neumann et al., 2021).

While group-level comparisons indicated substantial overlap between conditions, individual-level evaluation revealed significant "response heterogeneity" (Bonafiglia et al., 2016). Specifically, a subset of participants showed improvements in recovery rate exceeding the threshold of measurement error. These findings underscore the inherent limitations of relying solely on group means when evaluating recovery interventions and emphasize the importance of identifying "high responders" (Mann et al., 2014).

Recovery from physical fatigue involves complex interactions among vascular, metabolic, and autonomic mechanisms, all of which exhibit considerable inter-individual variability. Previous studies have established that foot bathing enhances peripheral circulation and modulates autonomic activity—specifically increasing parasympathetic tone—without imposing excessive cardiovascular stress (Kaneko et al., 2009; Uebaba & Xu, 2004). However, our data suggest that the extent to which these systemic responses translate into localized muscle-level recovery differs markedly between individuals. This variability should not be regarded as random noise, but as a fundamental characteristic of physiological recovery processes, potentially influenced by baseline microvascular function, thermoregulatory sensitivity, or autonomic balance (Li et al., 2015; Hinder et al., 2014). This is consistent with evidence that systemic circulatory stimuli can alter oxygen dynamics even in non-exercising muscle, depending on individual physiological profiles (Nagasawa et al., 2009).

Notably, improvements exceeding MDC_{95} were primarily observed in the recovery rate (Slope), whereas recovery half-time (Halftime) remained largely within measurement error. This discrepancy can be explained by the distinct physiological determinants of these two indices. As demonstrated by Ryan et al. (2013, 2014), the initial slope of NIRS-derived reoxygenation is highly sensitive to convective oxygen delivery and local perfusion pressure. The thermal stress from foot bathing likely induced local vasodilation and increased microvascular blood volume (Uebaba & Xu, 2004), thereby accelerating the early "filling phase" of the vascular bed immediately post-exercise.

In contrast, recovery half-time is more strongly constrained by intrinsic mitochondrial respiratory capacity and the rate of phosphocreatine resynthesis, both of which are governed by enzymatic kinetics rather than oxygen availability alone (Ryan et al., 2014; Brizendine et al., 2013). While mild hyperthermia can optimize oxygen delivery, it is unlikely to acutely alter mitochondrial enzyme density or efficiency within a 10-minute window. Thus, our findings suggest that foot bathing functions primarily as a "hemodynamic primer," facilitating rapid oxygen supply (Slope), but does not necessarily accelerate the metabolic restoration processes (Halftime) that are rate-limited by mitochondrial capacity.

5. Limitations and Future Directions

Several limitations should be considered when interpreting the present findings. First, the relatively small sample size limits statistical power and the generalizability of group-level conclusions. Second, although autonomic and vascular mechanisms are likely contributors to individual responsiveness, direct measurements of autonomic nervous system activity or vascular function were not included.

In addition, the intraclass correlation coefficient (ICC) used for MDC_{95} calculation was assumed based on commonly accepted values rather than empirically derived from repeated baseline measurements. While this approach is methodologically reasonable, future studies should establish protocol-specific ICC values to refine estimates of clinically meaningful change.

Future research should aim to identify predictors of responsiveness to foot bathing, such as baseline vascular function, autonomic balance, or thermal sensitivity. Incorporating mechanistic measures alongside muscle oxygenation outcomes would help clarify the physiological pathways underlying heterogeneous recovery responses. Furthermore, systematic examination of dose–response relationships—including water temperature, immersion duration, and timing relative to exercise—will be essential for optimizing individualized recovery prescriptions.

6. Conclusion

Foot bathing does not produce consistent group-level improvements in skeletal muscle oxygenation. However, individual-level analysis using MDC_{95} reveals that some individuals experience clinically meaningful improvements in early-phase muscle reoxygenation. These findings highlight the importance of integrating individual responsiveness into recovery research (Neumann et al., 2021) and support MDC_{95}-based evaluation as a practically relevant framework.

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