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The Effects of Concurrent Resistance and Aerobic Training on Body Composition in Sedentary Young Adults: An 8-Week Randomized Controlled Trial

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ABSTRACT

This randomized controlled trial investigated the effects of an 8-week concurrent resistance and aerobic training on body composition in sedentary young adults. Thirty-eight subjects (18 to 30 years of age) were randomly assigned to a Concurrent Training Group (i.e., the RAG, n = 19) and a Control Group (CG, n = 19). The RA Group completed supervised training 3 times weekly, while the CG maintained habitual activity. Body weight (kg), body fat percentage (%), body mass index (BMI), waist and hip circumferences (cm), waist-to-hip ratio (WHR), and lean body mass were measured at baseline, week 4, and week 8. The data were analyzed using a two-way repeated-measures ANOVA with Bonferroni adjustment. Significant group × time interactions were observed for body weight, body fat percentage, body mass index (BMI), waist and hip circumferences, and lean body mass (all $P < 0.01$). Compared with the CG, the RA Group showed significantly greater improvements in these outcomes (all $P < 0.01$). In the RA Group, body fat percentage, body weight, and 3BMI decreased significantly, while lean body mass increased (all $P < 0.01$). Waist and hip circumferences also declined ($P < 0.01$). No significant changes were observed in the Control Group (all $P > 0.05$), and WHR was not different between the Groups ($P > 0.05$). An 8-week concurrent resistance and aerobic training effectively improved body composition in sedentary young adults and may provide an effective strategy for reducing metabolic risk associated with sedentary behavior.

Keywords: Body Composition, Concurrent Training, Randomized Controlled Trial, Sedentary Behavior

INTRODUCTION

Sedentary behavior, particularly prolonged uninterrupted sitting, has become increasingly prevalent among young adults, and it represents a growing public health concern. It is strongly associated with adverse metabolic outcomes, including impaired glucose regulation, increased adiposity, and chronic low-grade inflammation (9). Sedentary behavior is defined as any waking activity performed in a sitting or reclining posture with an energy expenditure ≤1.5 metabolic equivalents (METs). A growing body of epidemiological evidence indicates that prolonged sedentary time is associated with an increased risk of cardiovascular disease and all-cause mortality. However, the extent to which these associations are independent of regular physical activity remains unclear and warrants further investigation (25).

University students and young adults are considered a high-risk group for sedentary behavior due to their lifestyle patterns (6). With the widespread adoption of digital learning and increasing academic demands, screen time has increased substantially, contributing to reduced daily physical activity and prolonged sitting (39). Sedentary behavior has been associated with increased body fat and reduced muscle mass, suggesting adverse effects on body composition (22). Importantly, lifestyle habits formed during young adulthood often persist into later life and may have lasting effects on long-term health outcomes. Therefore, identifying effective and feasible exercise interventions for this population is of considerable public health importance.

Physical exercise serves as a cornerstone non-pharmacological approach for improving body composition. Common intervention strategies currently used to enhance body composition include dietary control (e.g., energy restriction or nutritional modification), exercise regimens (such as aerobic training, resistance training, or their combination), and comprehensive lifestyle management. Although dietary interventions can effectively lower body weight in the short term, they often suffer from poor long-term adherence and may be accompanied by loss of lean mass. In contrast, exercise-based interventions are considered more sustainable due to their multifaceted benefits on body composition and metabolic health (14).

Different exercise modalities exert effects through distinct physiological mechanisms. Aerobic training effectively reduces body fat and improves abdominal obesity, as reflected by decreases in waist circumference, primarily through increased energy expenditure and enhanced fat oxidation (29,40). Resistance training, on the other hand, stimulates skeletal muscle protein synthesis through mechanical loading and neuromuscular adaptations, thereby increasing lean mass and elevating resting metabolic rate (20,33). Building on these complementary mechanisms, concurrent resistance and aerobic training may offer a more effective strategy for improving body composition. A recent systematic review indicates that, compared to single-mode exercise, concurrent training offers more comprehensive benefits in reducing body fat and improving lean mass (12).

Although the efficacy of concurrent training has been well documented in clinical and older adult populations (2,18), evidence from randomized controlled trials in sedentary yet metabolically healthy young adults remain limited. Existing studies have primarily focused on long-term interventions and physical fitness outcomes, with less attention given to short-term changes in body composition (34). Therefore, it remains unclear whether concurrent training can produce meaningful improvements in body composition within a short intervention period (6 to 8 weeks), particularly under conditions that promote adherence. Although preliminary evidence suggests that adaptations may occur within this time frame (19), confirmation in sedentary young adult populations is still lacking.

Accordingly, this study employed a randomized controlled trial design to evaluate the effects of an 8-week concurrent training program on body composition in sedentary young adults. We hypothesized that, compared with a no-intervention control group, 8-weeks of concurrent training would significantly reduce body weight, body fat percentage, waist and hip circumference, while increasing lean mass, thereby improving body composition.

METHODS

All procedures were conducted in accordance with the Declaration of Helsinki. The study was approved by the Ethics Committee of Khon Kaen University, Thailand (No. HE672183). Written informed consent was obtained from all subjects prior to participation.

2.1 Subjects

The subjects were recruited through official announcements at Jiangxi Institute of Fashion Technology. Eligible individuals were aged 18 to 30 years of age, and they were classified as sedentary based on the International Physical Activity Questionnaire (IPAQ) (8), defined as not meeting the World Health Organization physical activity recommendations (<150 min of moderate-intensity activity or equivalent per week) (5).

The Inclusion Criteria were: (a) age between 18 and 30 years; (b) sedentary status as defined above; (c) no participation in structured exercise training within the past 3 months; and (d) the absence of any medical conditions or medications affecting physical activity or metabolism.

The Exclusion Criteria were: (a) engagement in regular exercise exceeding 60 min per week during the previous 3 months; (b) use of antioxidant supplements or related medications; and (c) a history of cardiovascular or respiratory disease.

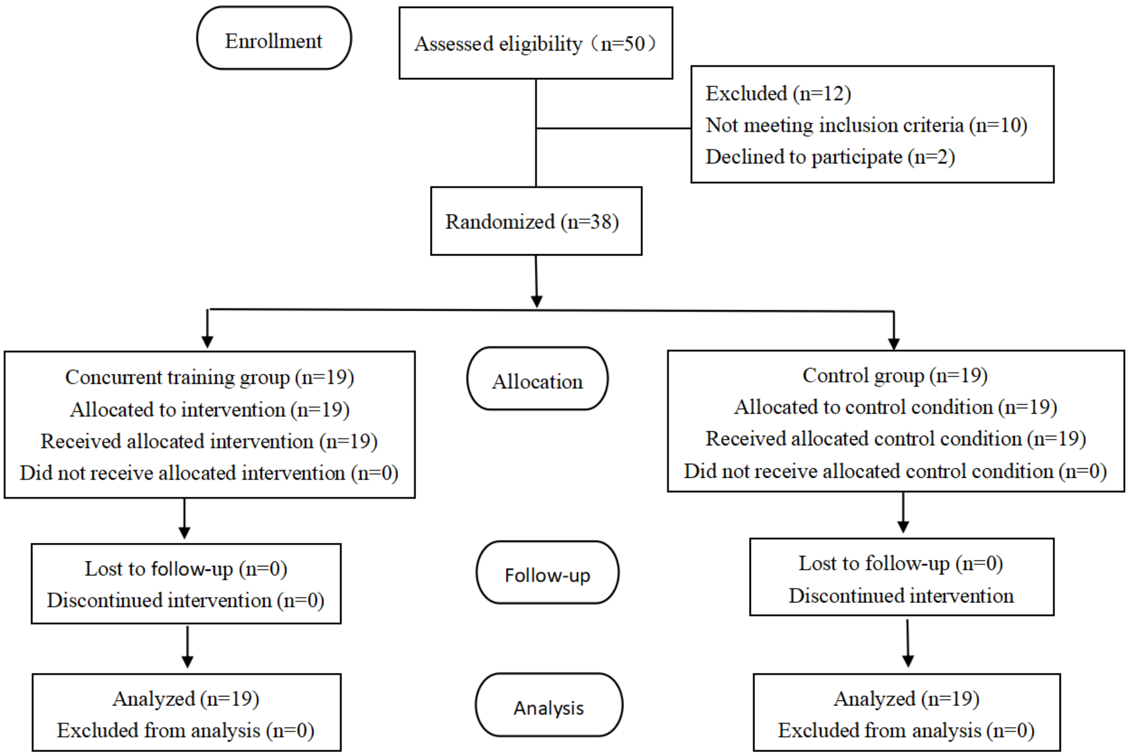
2.2 Sample Size

A priori computations to determine sample size were executed via G*Power software (version 3.1), setting the target effect size at $d = 0.90$, $\alpha = 0.05$, and power = 0.80. Based on these thresholds, the protocol needed a baseline of 16 subjects for each arm. Accounting to offset a projected dropout margin of 15%, 19 subjects were formally enrolled per group, bringing the total sample size to 38 (38).

2.3 Randomization and Blinding

Randomization was conducted by an independent investigator using a computer-generated sequence (Randomized.com), with allocation concealed in sequentially numbered, opaque, and sealed envelopes. Following baseline assessments, the subjects were assigned to groups by a research assistant who was not involved in the randomization process. Blinding of the subjects and trainers was not feasible due to the nature of the intervention. However, outcome assessors and data analyses remained blinded to group allocation. The CONSORT flow diagram is presented in Figure 1.

Figure 1. Participant Recruitment Flowchart.



2.4 Procedures

The subjects assigned to the Concurrent Training Group undertook an 8-week supervised exercise program that combined resistance and aerobic training. The sessions were conducted 3 times per week (Monday, Wednesday, and Friday), with each session lasting approximately 65 minutes. All training sessions were held in the fitness center of Jiangxi Institute of Fashion Technology that utilized standard resistance and aerobic equipment. To ensure safety and compliance, the sessions were supervised by certified exercise professionals with a minimum of 5 years of experience. Each session followed a standardized structure that comprised 4 phases: (a) 10-min warm-up; (b) 15 min resistance training phase; (c) 30 min aerobic phase; and (d) 10-min cool-down. Details of the exercise selection and progression are presented in Table 1. The resistance component included bench press, push-ups, and seated cable rows with progressive overload applied throughout the intervention. During weeks 1 through 4, the subjects performed 3 sets of 10 to 12 repetitions at 40 to 50% of one-repetition maximum (1RM). During weeks 5 through 8, intensity was increased to 75% of 1RM with 3 sets of 4 to 6 repetition. A 60-sec rest interval was maintained between the sets. Aerobic training consisted of stationary cycle ergometry. Exercise intensity was prescribed and monitored using cardiac responses alongside the rating of perceived exertion (RPE). Heart rate was continuously recorded during exercise using chest-worn monitors (Polar Pro Team System, Polar Electro Oy, Finland) (10). Exercise intensity was prescribed based on heart rate reserve (HRR). During weeks 1 through 4, the subjects exercised at 40 to 59% of HRR, which corresponded to an RPE of 8 to 11 on the 6 to 20 Borg Scale. Intensity was progressively increased during weeks 5 through 8 to 60 to 85% of HRR (RPE 12–14) (31). RPE was assessed every 5 min, and the subjects were instructed to adjust cycling speed to maintain the target intensity (Table 1).

Table1. Detailed Intervention Plan (Eight-Week).

Group	Week	Time/Class (65 min)			Class Times	Content
		Warm Up	Training	Cold Down		
RA	1	10	45	10	3	15 minutes of resistance exercise, 1RM: 40-50%; 30 minutes of aerobic exercises, 40-59% HR_{max}
	2	10	45	10	3	
	3	10	45	10	3	
	4	10	45	10	3	
	5	10	45	10	3	15 minutes of resistance exercise, 1RM: 75%; 30 minutes of aerobic exercises, 60-85% HR_{max}
	6	10	45	10	3	
	7	10	45	10	3	
	8	10	45	10	3	

RA, Concurrent Training Group.

The Control Group continued their usual daily activities, refrained from any additional structured physical exercise throughout the study period, and attended a weekly health lecture.

2.5 Outcome Measures

All assessments were conducted at 3 time points: (a) baseline; (b) week 4; and (c) week 8. The measurements were performed in a climate-controlled laboratory (26°C) by trained assessors blinded to group allocation. To ensure consistency, all measurements were carried out by the same team following standardized procedures. Assessors completed training and practice sessions prior to data collection.

2.5.1 Anthropometry

Height and weight were measured using an electronic anthropometric device (University Student Physical Fitness Measurement System, PRC). Body mass index (BMI) was calculated as weight divided by height squared (kg/m^2). Body mass was recorded to the nearest 0.1 kg and height to 0.1 cm. Subjects were measured barefoot and wearing light clothing, maintaining a standard upright posture. This system has been shown to provide reliable and accurate measurements in previous studies (7).

2.5.2 Body Composition

Body fat percentage and lean body mass (LBM) were assessed using a bioelectrical impedance analyzer. Bioelectrical impedance analysis is a reliable and valid method for assessing body composition (26). Subjects were instructed to avoid vigorous exercise and alcohol, and they were instructed to fast for at least 12 hrs prior to testing to minimize the influence of hydration status on measurement outcomes. During testing, subjects stood barefoot on the platform, held the hand electrodes, and remained upright and still for approximately 20–30 sec until measurement was complete. To ensure consistency, all assessments were conducted under standardized conditions at the same time of day.

2.5.3 Local Circumferences

Waist circumference (WC) and hip circumference (HC) were measured using a non-elastic measuring tape. WC was assessed at the midpoint between the lower rib and the iliac crest, and HC at the level of the greater trochanter. The waist-to-hip ratio (WHR) was calculated as WC divided by HC. All measurements were performed by the same trained assessor in accordance with standardized anatomical landmarks. Each measurement was obtained in duplicate, and the mean value was used for analysis. Measurement sites and procedures were standardized across all assessments. The method has demonstrated good reliability in previous studies (1).

2.6 Statistical Analysis

Statistical analyses were performed using SPSS version 29.0 (IBM Corp., Chicago, IL, USA). Data normality was assessed using the Shapiro–Wilk Test, and homogeneity of variances was evaluated with the Levene's Test. Normally distributed data are presented as mean ± standard deviation; whereas, non-normally distributed data are reported as median (interquartile range). A two-way repeated-measures ANOVA was used to examine the effects of group (training vs. control), time (baseline, week 4, and week 8), and their interaction (group × time). When significant interactions were identified, *post hoc* pairwise comparisons were performed using Bonferroni correction. Effect sizes were calculated using partial eta-squared (η^2_p), within thresholds of 0.01, 0.06, and 0.14 indicating small, medium, and large effects, respectively (36). The level of statistical significance was set at $P < 0.05$. Sphericity was assessed using the Mauchly's Test, and when violated, the Greenhouse–Geisser correction was applied.

RESULTS

3.1 Participant Characteristics

All 38 subjects (RA Group: n = 19; CG Group: n = 19) completed the 8-week intervention, with no adverse events reported. No significant differences were observed between the Groups at baseline (P > 0.05). Baseline characteristics are presented in Table 2.

Table 2. Baseline Characteristics.

Parameters	RA (n = 19)	CG (n = 19)	P
	Mean ± SD	Mean ± SD	
Male/Female	9/10	9/10	
Age (yrs)	19.32 ± 1.11	19.79 ± 1.08	0.191
Height (cm)	164.74 ± 7.52	165.21 ± 9.40	0.866
Weight (kg)	65.19 ± 10.69	64.96 ± 10.67	0.947
BMI (kg/m^2)	23.94 ± 2.89	23.76 ± 3.04	0.858
BFP(%)	29.55 ± 6.61	27.78 ± 5.49	0.374
LBM (kg)	45.83 ± 9.49	41.67 ± 11.85	0.240
WC (cm)	77.32 ± 9.01	77.80 ± 7.76	0.862
HC(cm)	98.56 ± 5.62	97.21 ± 6.92	0.514
WH-R	0.78 ± 0.06	0.80 ± 0.06	0.427

Data are presented as mean ± standard deviation. **RA**, Concurrent Training Group; **CG**, Non-Intervention Control Group; **BFP**, Body Fat Percentage; **WC**, Waist Circumference; HC, Hip Circumference; **WH-R**, Waist-to-Hip Ratio; **LBM**, Lean Body Mass. No significant differences were observed between groups at baseline (P > 0.05).

3.2 Changes in Primary Outcomes

As shown in Table 3, significant main effects of time were observed for body weight, BMI, body fat percentage, waist and hip circumferences, and lean body mass (all P < 0.05), indicating significant changes over the intervention period. In contrast, no significant time effect was found for waist-to-hip ratio (WHR) (P > 0.05).

Significant group × time interactions were observed for body weight (F = 87.453, P < 0.001, ${\eta^2}_p$ = 0.708) and BMI (F = 90.675, P < 0.001, ${\eta^2}_p$ = 0.716) (Table 3). *Post hoc* comparisons with Bonferroni correction showed that, in the RA Group, body weight and BMI decreased significantly from baseline to week 4 (both P < 0.05) and showed further reductions at week 8 (both P < 0.01), indicating a progressive decline over time.

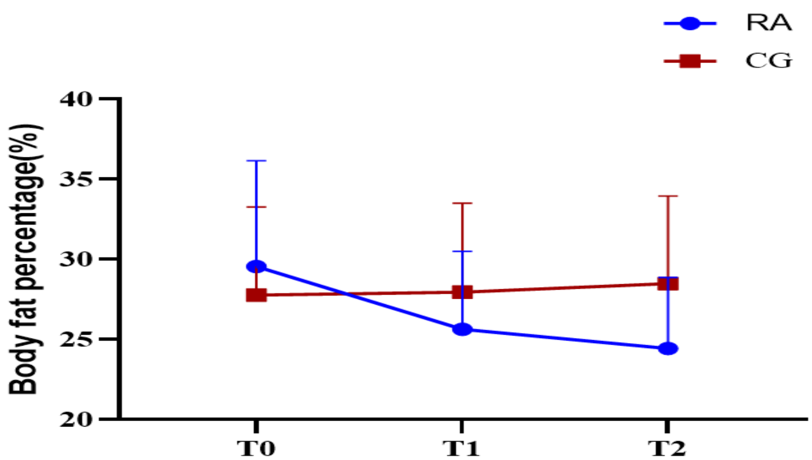
Table 3. Results of Two-Way Repeated Measures ANOVA for Body Composition.

Outcomes	Group	T0	T1	T2	Time Effects			$Time^*$Group Effects		
		Mean ± SD	Mean ± SD	Mean ± SD	F	P	PES	F	P	PES
Weight (kg)	RA	65.19 ± 10.69	63.46 ± 10.12	58.50 ± 9.12	(1.053,37.899) = 61.307	<.001	.630	(1.053,37.899) = 87.453	<.001	.708
	CG	64.96 ± 10.67	65.12 ± 10.67	65.55 ± 10.83						
BMI	RA	23.94 ± 2.89	23.28 ± 2.63	21.45 ± 2.45	(1.055,37.968) = 75.556	<.001	.671	(1.055,37.968) = 90.675	<.001	.716
	CG	23.77 ± 3.04	23.79 ± 3.06	23.89 ± 3.10						
BFP (%)	RA	29.55 ± 6.61	25.65 ± 4.86	24.45 ± 4.42	(1.246,44.855) = 49.872	<.001	.581	(1.246,44.855) = 79.472	<.001	.688
	CG	27.78 ± 5.49	27.96 ± 5.55	28.49 ± 5.47						
WC (cm)	RA	77.32 ± 9.01	75.61 ± 8.44	72.05 ± 7.99	(1.630, 58.681) = 22.894	<.001	.389	(1.63058.681) = 30.639	<.001	.460
	CG	77.80 ± 7.76	78.01 ± 7.57	78.20 ± 7.60						
HC (cm)	RA	98.56 ± 5.62	96.13 ±5.32	93.59 ± 5.60	(2,72) = 19.598	<.001	.352	(2,72) = 35.854	<.001	.499
	CG	97.21 ± 6.92	98.10 ± 5.99	97.97 ± 6.71						
WHR	RA	0.78 ± 0.06	0.79 ± 0.06	0.77 ± 0.05	(1.707, 61.450) = 1.716	.192	.046	(1.707, 61.450) = 2.777	.078	.072
	CG	0.80 ± 0.06	0.80 ± 0.06	0.80 ± 0.06						
LBM (kg)	RA	45.83 ± 9.49	47.15 ± 9.66	49.87 ± 9.71	(1.678, 60.418 = 98.958	<.001	.733	(1.678, 60.418) = 98.376	<.001	.732
	CG	41.6 ± 11.85	41.76 ± 11.87	41.68 ± 11.89						

RA, Concurrent Training Group; **CG**, Control Group; **BFP**, Body Fat Percentage; **WC**, Waist Circumference; **HC**, Hip Circumference; **WHR**, Waist-to-Hip Ratio; **LBM**, Lean Body Mass; **TO**, at Week 1; **T1**, at Week 4; **T2**, at Week 8; P < 0.05 indicates significant.

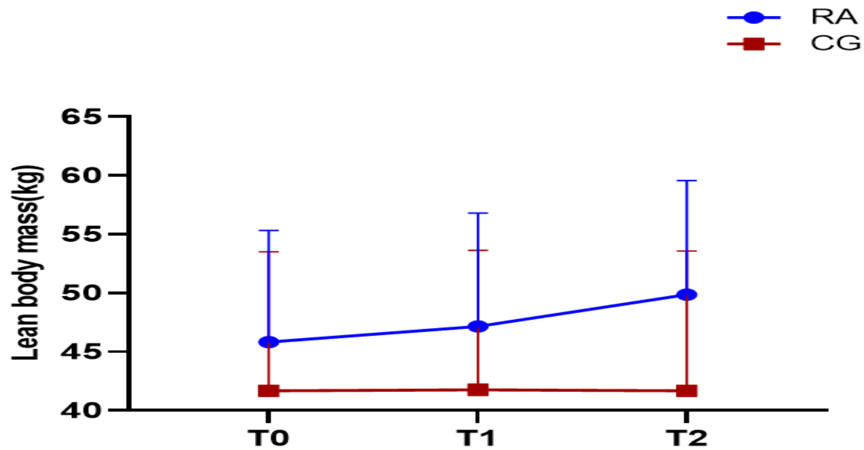
Significant group × time interactions were observed body fat percentage ($F = 79.472$, $P < 0.001$, $\eta^2{}_p = 0.688$) (Table 3). In this RA Group, the decrease in body fat percentage was significant from baseline to week 4 ($P < 0.05$) and it further decreased at week 8 (−17.2%, $P < 0.01$); whereas, no significant changes were observed in the CG Group. At week 8, body fat percentage was significantly lower in the RA Group than in the Control Group ($P < 0.05$). Changes over time are presented in Figure 2.

Figure 2. Trends in Body Fat Percentage in the RA and CG Groups at Different Time Points. (**RA**, Concurrent Training Group; **CG**, Control Group; **T0**, at Week 0; T1, at Week 4; T2, at Week 8)



Significant group × time interactions were observed for waist circumference ($F = 30.639$, $P < 0.001$, $\eta^2{}_p = 0.460$) and hip circumference ($F = 35.854$, $P < 0.001$, $\eta^2{}_p = 0.499$) (Table 3). In the RA Group, waist and hip circumferences decreased significantly at week 4 ($P < 0.05$) and showed further reductions at week 8 ($P < 0.01$); whereas, no significant changes were observed in the Control Group. No significant group × time interactions was found for the waist-to-hip ratio ($F = 2.777$, $P = 0.078$) (Table 3).

Figure 3. Trends in Lean Body Mass in the RA and CG Groups at Different Time Points. (**RA**, Concurrent Training Group; **CG**, Control Group; **T0**, at Week 0; T1, at Week 4; T2, at Week 8)



DISCUSSION

The present study found that an 8-week concurrent training improved body composition in sedentary young adults. Significant reductions were observed in body weight, BMI, body fat percentage, and waist and hip circumferences significantly decreased, while lean body mass increased (all $P < 0.05$); whereas, no changes were detected in the Control Group. These findings corroborate previous evidence indicating that concurrent training effectively improves body composition and reduces metabolic risk (32).

These reductions in body weight, BMI, and body fat percentage may be attributed to the synergistic effects of aerobic and resistance exercise. Aerobic training enhances energy expenditure and promotes lipid oxidation, thereby contributing to a negative energy balance (4,35); whereas, resistance training increases basal metabolic rate through gains in lean body mass (LBM), leading to greater daily energy expenditure (13,16). This synergy increased fat oxidation and enhanced muscle mass, which provides a physiological basis for the observed reductions in fat mass. Previous studies have similarly shown that concurrent training is more effective than single-mode exercise in reducing body fat percentage and BMI, and may also be superior to resistance training alone in decreasing fat mass (15,21). The consistent improvements observed across time points suggest that meaningful metabolic adaptations may occur within a relatively short-term training period.

The observed increase in lean body mass may be explained by resistance training–induced mechanical loading and neuromuscular adaptations, which collectively stimulate muscle protein synthesis and facilitate muscle hypertrophy (28). Although the “interference effect” hypothesis suggests that concurrent training may attenuate strength or hypertrophic adaptations (24), the emerging evidence suggests that when training variables are appropriately controlled, concurrent training may induce comparable gains in lean mass to resistance training alone (12,23). The present study demonstrated an increase of 4.04 kg in lean body mass over 8 weeks. Considering its established association with improved glucose regulation and metabolic health (3), this change may be of clinical importance. Concurrent training integrates the hypertrophic stimulus of resistance exercise with aerobic training–induced improvements in mitochondrial function and oxidative capacity, which together contribute to favorable adaptations in body composition.

The reductions in waist and hip circumferences may reflect decreases in overall adiposity. In particular, waist circumference is a well-established marker of cardiometabolic risk, and its reduction has been consistently associated with improved metabolic outcomes (27). Similarly, the reduction in hip circumference may reflect decreases in peripheral adiposity rather than skeletal muscle mass (11). These findings are in line with previous evidence suggesting that concurrent aerobic and resistance training is effective in reducing central obesity (37). Unlike previous studies that have largely focused on overweight or middle-aged and older populations, the present study specifically targeted sedentary young adults. Although apparently healthy, this population may already present unfavorable body composition profiles and represent an early stage of metabolic risk. Therefore, the present findings support the effectiveness of concurrent training in this population and provides evidence for the implementation of such interventions prior to disease onset, highlighting their potential role in early prevention strategies.

Unlike previous studies that have primarily focused on overweight or middle-aged and older populations, the present study targeted sedentary young adults. Although otherwise healthy, this population may already exhibit unfavorable body composition profiles, suggesting an early stage of metabolic risk development (30). Accordingly, Waist-to-Hip Ratio (WHR) may be less sensitive to short-term changes than absolute anthropometric measures. In addition, compensatory behaviors following exercise initiation, such as increased energy intake or reduced non-exercise physical activity, may partially attenuate fat loss (17). Nevertheless, the consistent improvements across adiposity measures in the training group suggest that the intervention effects likely exceeded the influence of such compensatory mechanisms. Therefore, WHR should be interpreted in the context of absolute changes in waist and hip circumferences.

Key strengths of this study include its randomized controlled design and the high adherence observed throughout the intervention. The inclusion of a mid-intervention assessment (week 4) enabled the evaluation of temporal changes, providing insight into the progression of body composition adaptations and supporting the feasibility of short-term exercise interventions in the time-constrained populations.

Limitations in this Study

This study has some limitations. First, the 8-week intervention period may not be sufficient to capture long-term adaptations or the persistence of training effects. Second, body composition was assessed using bioelectrical impedance analysis rather than more precise methods such as dual-energy X-ray absorptiometry or magnetic resonance imaging, which may have limited measurement accuracy. Third, dietary intake was not rigorously controlled, and variations in energy intake among the participants may have influenced the observed outcomes. Future studies should incorporate longer intervention and follow-up periods, use more accurate assessment methods, and include systematic monitoring of dietary intake and energy expenditure.

CONCLUSION

Concurrent resistance and aerobic training improved body composition in sedentary young adults, characterized by reduced adiposity and increased lean body mass. These adaptations are associated with improved metabolic health and may help reduce the risk of cardiometabolic diseases. Therefore, this training approach represents an effective and practical strategy for early intervention in sedentary young populations.

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Beetroot Gummy Jelly Increases Plasma Nitrate but Does Not Improve 10-km Running Performance in Hypoxia

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ABSTRACT

JM, NN. The purpose of this study was to examine whether 7 days of dietary nitrate supplementation delivered through a novel beetroot gummy jelly formulation enhances 10-km running performance and physiological responses at sea level (SL) and under simulated hypoxia (SH; ~2500 m). Eleven recreationally trained male runners completed a randomized, placebo-controlled, double-blind crossover trial. The participants performed 4 experimental conditions: (a) beetroot gummy jelly at sea level (BEET-SL); (b) beetroot gummy jelly under simulated hypoxia (BEET-SH); (c) placebo at sea level (PLA-SL); and (d) placebo under simulated hypoxia (PLA-SH). The beetroot gummy jelly provided approximately 8 mmol of nitrate per day for 7 consecutive days, including the testing day. Plasma nitrate concentration, blood glucose, blood lactate, heart rate (HR), peripheral oxygen saturation (SpO_2), muscle oxygenation, rating of perceived exertion (RPE), and 10-km running time-trial performance were assessed. Beetroot gummy jelly supplementation significantly increased plasma nitrate concentrations compared with placebo ($P < 0.001$, $\eta p^2 = 0.912$), confirming effective nitrate delivery through the gummy jelly formulation. However, there were no significant effects of supplementation observed for 10-km running performance or any measured physiological variables at either sea level or under simulated hypoxia ($P = 0.759$, $\eta p^2 = 0.010$). Running performance was significantly impaired under simulated hypoxia compared with sea-level conditions ($P = 0.004$, $\eta p^2 = 0.579$), regardless of supplementation. Seven days of beetroot gummy jelly supplementation effectively increased systemic nitrate availability, but it did not improve the endurance running performance or the physiological responses during a 10-km time trial at SL or under simulated hypoxia. These findings suggest that, under the present supplementation protocol and gummy jelly delivery format, elevated nitrate availability did not translate into measurable ergogenic benefits in recreationally trained runners.

Key Words: Beetroot Gummy Jelly; Dietary Nitrate; Ergogenic Aid; Running Performance; Simulated Hypoxia

INTRODUCTION

Endurance performance is impaired under hypoxic conditions due to the reduction in ambient oxygen pressure that decreases arterial oxygen content and limits oxygen delivery to working muscles. As a result, aerobic energy production is compromised, which leads to a greater reliance on anaerobic metabolism and an accelerated accumulation of fatigue-related metabolites with an earlier onset of fatigue (Amann and Calbet, 2007; Calbet et al., 2009). Consequently, endurance exercise performance progressively decreases with increasing altitude, and reductions in running performance have been consistently reported in both the laboratory and field settings (Hamlin et al., 2015). Even moderate altitudes (~2000 to 3000 m) can negatively affect endurance performance by reducing oxygen availability and increasing physiological strain during prolonged exercise.

Dietary nitrate supplementation has emerged as a nutritional strategy that may partially counteract the physiological limitations associated with hypoxia. Following ingestion, nitrate (NO_3^-) is reduced to nitrite (NO_2^-) by oral bacteria and subsequently converted to nitric oxide (NO) through the nitrate–nitrite–NO pathway. This alternative pathway becomes particularly important under hypoxic and acidic conditions, where endogenous nitric oxide synthesis through nitric oxide synthase may be impaired (Jones et al., 2014). Because nitrite reduction to NO is facilitated in low-oxygen environments, nitrate supplementation has been proposed as a potentially effective ergogenic aid during exercise performed under hypoxic conditions (Shannon et al., 2016).

Increased NO bioavailability may enhance vascular function and improve the matching of oxygen delivery to metabolic demand during exercise. Several studies have reported that dietary nitrate supplementation can reduce the oxygen cost of submaximal exercise, improve exercise efficiency, and enhance endurance performance in some populations (Bailey et al., 2010; Lansley et al., 2011; Jones et al., 2014). However, the ergogenic effects of nitrate supplementation remain inconsistent, with positive effects reported in some studies but not others. Variability in training status, exercise modality, environmental conditions, supplementation protocol, and nitrate delivery format may contribute to these inconsistent findings (Domínguez et al., 2017).

Most previous studies investigating dietary nitrate supplementation have used concentrated beetroot juice as the primary delivery vehicle. Both acute and chronic beetroot juice supplementation have been shown to elevate plasma nitrate and nitrite concentrations and, in some cases, improve endurance exercise performance (Hoon et al., 2014; Jones et al., 2014). However, liquid-based supplements may present practical limitations related to volume, portability, storage, and convenience during training and competition. Alternative delivery systems may improve practicality and user compliance while maintaining the physiological benefits associated with dietary nitrate intake.

Beetroot gummy jelly represents a novel semi-solid nitrate delivery system that may offer several practical advantages over traditional juice-based supplements. Gummy products are compact, easy to transport, stable during storage, and convenient to consume before exercise. In addition, the physical form of a supplement may influence oral processing, gastrointestinal transit, and nitrate bioavailability, suggesting that alternative delivery systems may not necessarily produce identical physiological responses to those observed with liquid-based products. Despite the growing interest in functional sports foods, limited research has examined nitrate supplementation delivered in gummy jelly form, and little is known regarding its effectiveness for increasing nitrate availability and supporting endurance performance.

The potential application of nitrate supplementation may be particularly relevant under hypoxic conditions, where the nitrate–nitrite–NO pathway may become more physiologically active. Nevertheless, studies examining dietary nitrate supplementation during endurance exercise in hypoxia remain limited, and no studies have investigated beetroot gummy jelly supplementation under simulated hypoxic conditions. Therefore, evaluating beetroot gummy jelly as an alternative nitrate delivery system may provide important insights into both the practical and the physiological effectiveness of this supplementation strategy.

A 10-km self-paced running time trial was selected as the exercise model because it represents a practically relevant endurance task and allows assessment of performance under conditions that resemble competitive endurance running. Furthermore, the use of a non-motorized treadmill enables the participants to self-regulate running speed and pacing strategy, thereby providing an ecologically valid assessment of endurance performance.

Therefore, the purpose of this study was to investigate the effects of 7 days of dietary nitrate supplementation provided as beetroot gummy jelly on 10-km running performance and physiological responses at sea level and under simulated hypoxia (~2500 m). It was hypothesized that the beetroot gummy jelly supplementation would increase plasma nitrate concentration and improve endurance running performance compared with the placebo, with greater benefits expected under hypoxic conditions.

METHODS

Subjects

Eleven (N = 11) recreationally trained male runners (age: 22.3 ± 1.8 yrs; BMI: 21.4 ± 2.0 $kg \cdot m^{-2}$; VO_2 max: 54.2 ± 4.6 $mL \cdot kg^{-1} \cdot min^{-1}$) were recruited from local running clubs. The participants had a minimum of 1 year of endurance running experience and regularly engaged in running training at least 2 times per week. All the participants were free from cardiovascular, metabolic, respiratory, and/or musculoskeletal disorders, and they were also not using nitrate-containing supplements during the study period.

Sample size was estimated a priori using G*Power software (version 3.1.9.4; Heinrich Heine University, Düsseldorf, Germany). Based on the effect sizes reported in previous studies investigating beetroot-derived nitrate supplementation and endurance exercise performance (Tirkey et al., 2021), a moderate-to-large effect size (f = 0.50), an alpha level of 0.05, and a statistical power of 0.80 were assumed for the repeated-measures design. The estimated minimum sample size was 8 participants. To account for the potential participant attrition, approximately 20% was added that resulted in a target sample size of 11 participants.

All the participants completed a health screening questionnaire and the Physical Activity Readiness Questionnaire (PAR-Q) prior to participation. Written informed consent was obtained from all the participants before data collection. The study protocol was approved by the Research Ethics Review Committee for Research Involving Human Participants, Chulalongkorn University, Thailand (COA No. 018/68), and all the procedures were conducted in accordance with the Declaration of Helsinki.

Experimental Overview

A randomized, placebo-controlled, crossover design with double-blinding of the supplementation conditions was employed. Each participant completed 4 experimental conditions: (a) beetroot gummy jelly at sea level (BEET-SL); (b) beetroot gummy jelly under simulated hypoxia (BEET-SH); (c) placebo at sea level (PLA-SL); and (d) placebo under simulated hypoxia (PLA-SH). The order of the experimental conditions was determined using a computer-generated randomization sequence to minimize potential order effects.

Blinding of the environmental condition was not feasible because trials were conducted under either normoxic or simulated hypoxic conditions within an environmental chamber. Simulated hypoxia was achieved using a fraction of inspired oxygen (FiO_2) of approximately 15.7%, corresponding to a simulated altitude of ~2500 m; whereas, the sea-level condition was conducted at an FiO_2 of approximately 21.0%.

Each experimental trial included 4 data collection time points: (a)120 min before exercise (prior to ingestion of the final supplement dose); (b) 30 min before exercise (following environmental exposure); (c) immediately before exercise; and (d) immediately after completion of the 10-km running time trial.

Each trial was separated by a minimum 7-day washout period to allow nitrate-related biomarkers to return to baseline and to minimize potential carryover effects between the supplementation conditions (Jones, 2014; Wylie et al., 2013). The participants consumed either beetroot gummy jelly (BEET) or placebo (PLA) daily for 7 consecutive days, including the experimental trial day. The BEET supplement provided approximately 8 mmol nitrate per day. The placebo supplement was matched for appearance, texture, flavor, and packaging but contained negligible nitrate. Supplement distribution and coding were performed by personnel independent of data collection to maintain blinding of the supplementation conditions throughout the study.

Procedures

The participants completed a maximal incremental exercise test at sea level to determine VO_2 max prior to the experimental trials. Following a 2-min standing baseline and a 4-min warm-up at 4.50 $km \cdot h^{-1}$, the test commenced at 4.59 $km \cdot h^{-1}$ with speed increasing by 0.65 $km \cdot h^{-1} \cdot min^{-1}$ and treadmill incline increasing by 0.4%$\cdot min^{-1}$ until volitional exhaustion. A 5-min cool-down at 4.50 $km \cdot h^{-1}$ followed. Then, the participants completed a familiarization session using the non-motorized treadmill (AssaultRunner Pro®, Assault Fitness, USA) and the 10-km time-trial protocol. Experimental trials commenced 7 days later.

The participants reported to the laboratory at 08:00 h for each of the 4 experimental conditions following a minimum 6-hr fast. Baseline measurements that included heart rate (HR), peripheral oxygen saturation (SpO_2), blood glucose, blood lactate, plasma nitrate concentration, and rating of perceived exertion (RPE) were obtained 120 min before exercise. The participants then consumed the assigned supplement and remained under normoxic conditions for 90 min. Thirty minutes before exercise, all measurements except plasma nitrate were repeated.

Then, the participants were exposed for 30 min to either normoxic conditions (FiO_2 ≈ 21.0%) or simulated normobaric hypoxia (FiO_2 ≈ 15.7%; ~2500 m). Near-infrared spectroscopy (NIRS) sensors were positioned over the left vastus lateralis muscle, approximately 15 cm above the patella, because it represents a primary locomotor muscle during running. Sensors were secured using sports tape and covered with a black elastic bandage to minimize ambient light interference. Tissue saturation index (TSI) was recorded during a 1-min resting period before exercise and during the final 3 sec of the time trial. Changes in TSI were calculated as the difference between resting and exercise values. Immediately following the environmental exposure period, all the physiological variables, including plasma nitrate concentration, were assessed before exercise.

Then, the participants completed a standardized warm-up consisting of 1 min of high knees, 1 min of side lunges, and a 5-min jog. The 10-km running time trial commenced immediately thereafter. The participants performed the trial on a non-motorized treadmill at a self-selected pace and they were instructed to complete the distance as quickly as possible. Distance and elapsed time were continuously displayed throughout the trial. Time to completion was recorded as the primary performance outcome.

Immediately upon completion of the time trial, HR, SpO_2, blood glucose, blood lactate, plasma nitrate concentration, muscle oxygenation, and RPE were reassessed. Then, the participants completed a cool-down that consisted of a 2-min jog followed by quadriceps stretching (30 sec per leg). Following the post-exercise measurements, the participants remained in the laboratory for an additional 30 min before dismissal.

Supplementation Procedure

The beetroot gummy jelly (BEET) and placebo gummy jelly (PLA) were produced using identical manufacturing procedures, differing only in the inclusion of beetroot powder in the nitrate-containing product. All the products were prepared by a qualified food scientist under controlled laboratory conditions. Nutritional composition was verified by the Food Research and Testing Laboratory, Faculty of Science, Chulalongkorn University, Thailand. The nutritional characteristics of BEET and PLA were matched as closely as possible for energy, carbohydrate, protein, and fat content to minimize the potential for confounding effects of macronutrient intake.

Each serving of BEET provided approximately 8 mmol of dietary nitrate. The nitrate content of the beetroot powder was independently verified by a third-party laboratory using ion chromatography prior to product production. Gummy jelly was selected as the delivery format because it represents a portable, shelf-stable, and convenient alternative to traditional beetroot juice supplementation, with potential practical applications for athletes during training and competition.

The manufacturing process involved dissolving sugar and glucose syrup in water under controlled heating conditions, followed by incorporation of hydrated gelatin. After cooling the mixture to approximately 55°C, beetroot powder was added and thoroughly mixed before molding and refrigeration overnight. The placebo product was prepared using the same procedure but without beetroot powder. Food-grade coloring was added to maintain visual similarity between products and to preserve participant blinding.

The participants consumed one gummy jelly per day at approximately the same time each day for seven consecutive days, including the day of the experimental trial. Also, they were instructed to maintain their habitual diet and training patterns throughout the study. Dietary intake and physical activity were recorded for 3 days before each experimental condition, and participants were instructed to maintain similar macronutrient intake across trials.

To minimize variation in background nitrate intake, the participants were instructed to avoid nitrate-rich foods, including beetroot, spinach, arugula, celery, and lettuce, during the 3 days preceding each trial. They were also instructed to avoid ergogenic supplements, including caffeine and creatine, throughout the experimental period. Daily reminders were provided to enhance compliance with supplementation and dietary restrictions.

The participants arrived for testing following a minimum 6-hr fast, and they were instructed to avoid oral hygiene practices that may disrupt the oral nitrate–nitrite–nitric oxide pathway prior to testing. Specifically, antibacterial mouthwash and other oral antiseptic products were prohibited because they may impair nitrate reduction by oral bacteria and influence nitrate bioavailability.

Blood Sampling and Analysis

Capillary blood samples were obtained from the fingertip for the assessment of blood glucose and blood lactate concentrations. Blood glucose was measured using a portable glucose analyzer (Accu-Chek Performa, Roche Diagnostics, Mannheim, Germany), while blood lactate concentration was determined using a portable lactate analyzer (Lactate Scout, EKF Diagnostics, Cardiff, UK). Following disinfection of the fingertip with an alcohol swab, a sterile lancet was used to obtain a capillary blood sample, and blood was immediately applied to the respective test strips according to the manufacturers' instructions.

For plasma nitrate analysis, venous blood samples were collected from an antecubital vein into lithium-heparin collection tubes. Samples were centrifuged at 3000 rpm for 10 min at 4°C, and the plasma fraction was aliquoted and stored at −80°C until batch analysis.

Prior to analysis, plasma samples were thawed at room temperature and processed using protein-removal filtration columns. Filtered samples were subsequently centrifuged at 7000 × g for 20 min at 4°C. Plasma nitrate concentration was quantified using a commercially available nitrate/nitrite colorimetric assay kit (NK05, Dojindo Laboratories, Kumamoto, Japan) according to the manufacturer's instructions. Briefly, plasma nitrate was enzymatically reduced to nitrite, followed by colorimetric detection using the Griess reaction. Absorbance was measured at 540 nm, and nitrate concentrations were calculated from a standard curve after blank correction.

Other Measurements

Muscle oxygenation was assessed using a portable near-infrared spectroscopy (NIRS) device (PortaMon, Artinis Medical Systems, Elst, The Netherlands). The device continuously measured tissue saturation index (TSI), which reflects the relative balance between oxygen delivery and oxygen utilization within the monitored muscle tissue. NIRS signals were transmitted wirelessly to a computer at a sampling frequency of 10 Hz and analyzed using Oxysoft software (version 3.0.95; Artinis Medical Systems, Elst, The Netherlands).

Heart rate (HR) and peripheral oxygen saturation (SpO_2) were measured using a fingertip pulse oximeter (Nonin Medical Inc., Plymouth, MN, USA). Rating of perceived exertion (RPE) was assessed using the Borg 6–20 Scale.

All physiological variables and blood samples were collected at the 4 experimental time points described previously. Completion time during the 10-km running time trial was recorded directly from the non-motorized treadmill and was used as the primary performance outcome measure.

Statistical Analyses

The data are presented as mean ± standard deviation (SD). Statistical analyses were performed using IBM SPSS Statistics version 30.1 (IBM Corp., Armonk, NY, USA). Data normality was assessed using the Shapiro–Wilk Test.

For physiological variables measured across multiple time points (plasma nitrate, blood glucose, blood lactate, heart rate, peripheral oxygen saturation, tissue saturation index, and rating of perceived exertion), a 3-way repeated-measures analysis of variance (ANOVA) was performed to examine the effects of supplementation (BEET vs. PLA), environmental condition (SL vs. SH), time, and their interactions. When significant main effects or interaction effects were identified, Bonferroni-adjusted *post hoc* comparisons were performed.

For 10-km time-trial performance, a 2-way repeated-measures ANOVA was used to examine the main effects of supplementation and environmental condition, as well as their interaction.

When assumptions of normality were violated and data transformation was not appropriate, non-parametric analyses were conducted using the Wilcoxon Signed-Rank Test. Effect sizes were reported as partial eta squared (ηp^2) for ANOVA analyses and Cohen's d for pairwise comparisons. Statistical significance was accepted at $P \leq 0.05$.

RESULTS

Plasma Nitrate

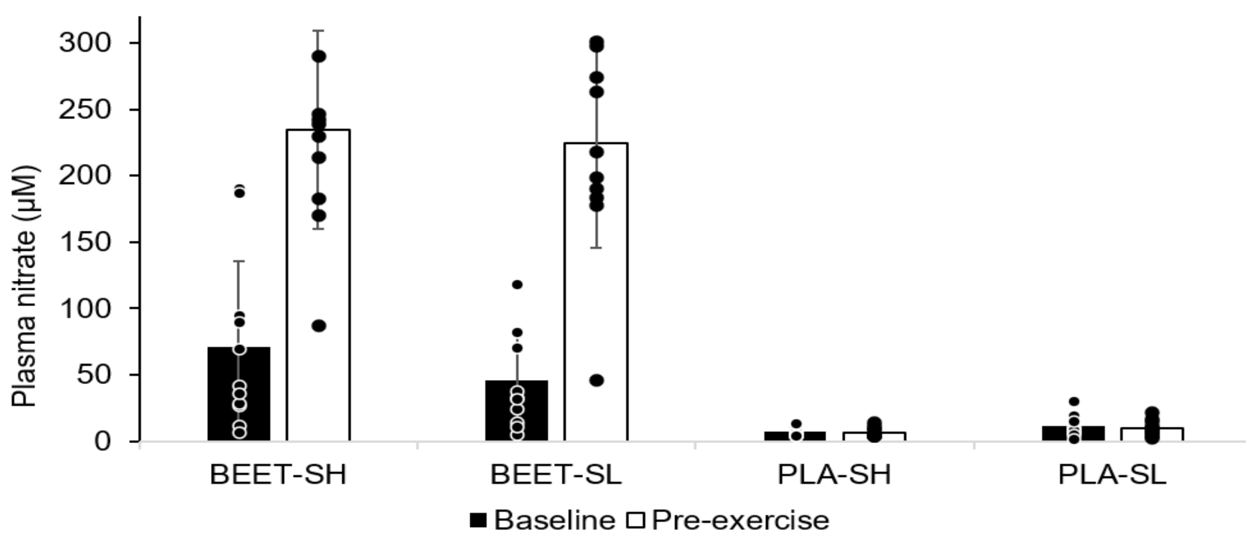

Figure 1. The Change of Plasma Nitrate with BEET Under SL and SH.

Plasma nitrate concentration demonstrated a significant main effect of supplementation ($P < 0.001$, $\eta p^2 = 0.912$) (Table 1). Individual participant responses are presented in Figure 1. In both beetroot supplementation conditions, plasma nitrate concentrations increased substantially across the supplementation period and following the final supplement dose. In the simulated hypoxia condition (BEET-SH), plasma nitrate increased from 71 ± 65 μM at pre-final dose to 235 ± 75 μM at pre-exercise. Similarly, in the sea-level condition (BEET-SL), plasma nitrate increased from 46 ± 37 μM to 225 ± 79 μM over the same period. In contrast, plasma nitrate concentrations remained relatively stable across all measurement time points in both placebo conditions. No significant main effect of environment and no significant supplement × environment × time interaction were observed ($P > 0.05$).

The increase in plasma nitrate concentration following beetroot supplementation was evident after 6 days of supplementation and was further elevated following ingestion of the final supplementation dose prior to exercise.

10-km Time-Trial Performance (TT Performance)

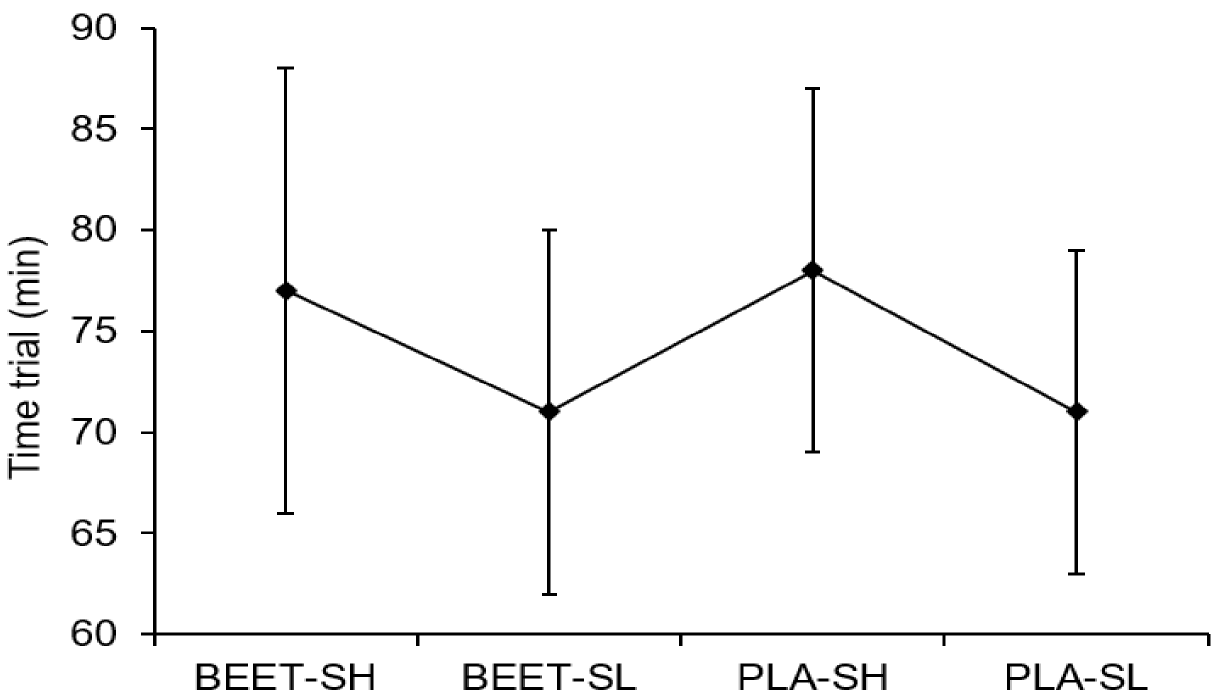

Figure 2. The Change of TT with BEET Under SL and SH.

No significant main effect of supplementation and no significant supplementation × environment interaction were observed for 10-km time-trial performance (Table 1; $P > 0.05$). Time-trial completion times were 77 ± 11 min in BEET-SH, 71 ± 9 min in BEET-SL, 78 ± 9 min in PLA-SH, and 71 ± 8 min in PLA-SL.

A significant main effect of environment was observed ($P = 0.004$, $\eta p^2 = 0.579$), with participants completing the 10-km time trial more slowly under simulated hypoxic conditions compared with sea-level conditions. The individual participant responses are presented in Figure 2.

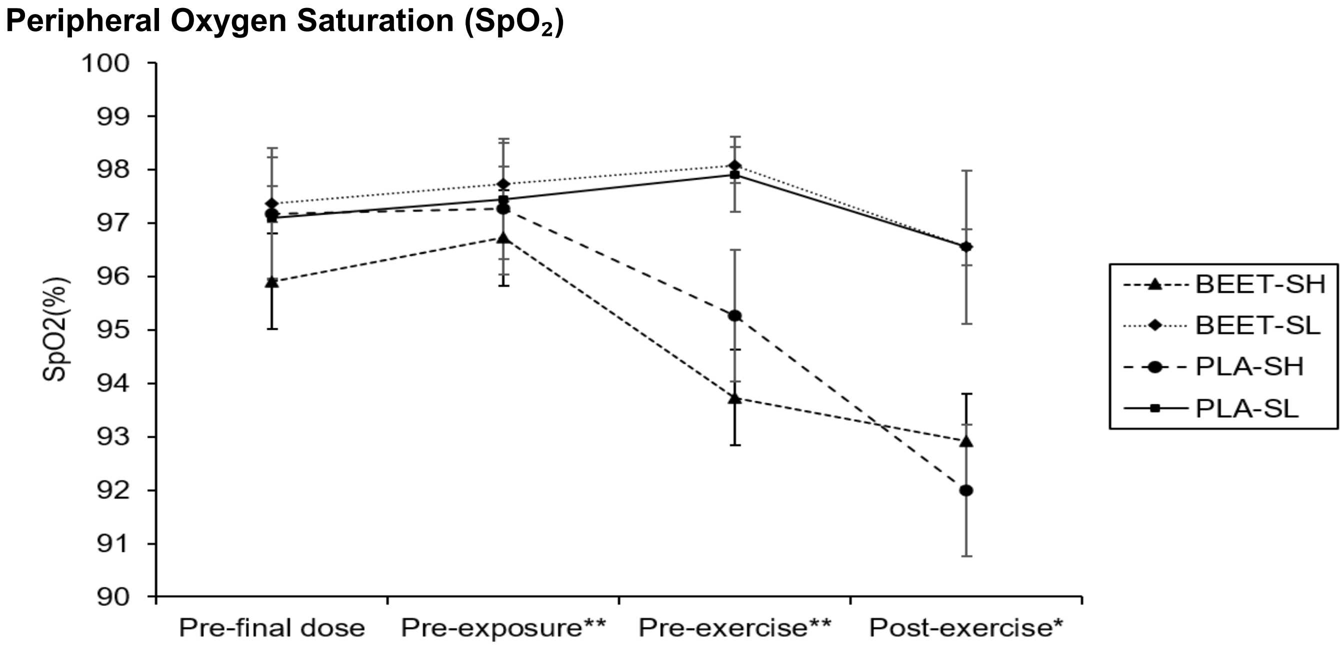

Figure 3. The Change of SpO_2 with BEET Under SL and SH.

Under sea-level conditions, SpO_2 remained relatively stable across all measurement time points (Figure 3). In contrast, simulated hypoxia resulted in a progressive reduction in SpO_2. Values decreased from 97 ± 2% at pre-exposure to 94 ± 2% at pre-exercise and further declined to 93 ± 3% at post-exercise. Post-exercise SpO_2 values were significantly lower than those observed at earlier time points under hypoxic conditions.

A significant main effect of environment was observed for peripheral oxygen saturation (SpO_2) ($P < 0.001$, $\eta p^2 = 0.872$) (Table 1). No significant main effect of supplementation or supplementation × environment interaction was detected ($P > 0.05$).

Table 1. Variable Responses at Different Time Points Under Beetroot and Placebo Supplementation in Sea Level (SL) and Simulated Hypoxia (SH).

Variables	Time point	BEET-SH	BEET-SL	PLA-SH	PLA-SL	Supplement	Environment	Interaction
HR (bpm)	Pre-final dose	73 ± 9	65 ± 12	75 ± 15	71 ± 13	F(1, 10) = 0.344 P = 0.570	F(1, 10) = 1.378 P = 0.268	F(3, 8) = 0.061 P = 0.979
	Pre-exposure	76 ± 12	66 ± 14	72 ± 13	65 ± 15			
	Pre-exercise	71 ± 14	63 ± 11	71 ± 17	68 ± 12			
	Post-exercise*	131 ± 15	133 ± 11	128 ± 12	136 ± 16			
Glucose (mg/dL)		100 ± 8	100 ± 6	101 ± 6	103 ± 8			

	Pre-final dose					F(1, 10) = 0.001 P = 0.982	F(1, 10) = 0.366 P = 0.559	F(3, 8) = 1.375 P = 0.318
	Pre-exposure	100 ± 11	100 ± 8	104 ± 12	104 ± 9			
	Pre-exercise	95 ± 9	99 ± 8	98 ± 6	93 ± 9			
	Post-exercise*	112 ± 15	114 ± 14	106 ± 11	111 ± 13			
Lactate (mmol/L)	Pre-final dose	1 ± 0	1 ± 0	1 ± 0	1 ± 0	F(1, 10) = 1.625 P = 0.231	F(1, 10) = 2.276 P = 0.162	F(3, 8) = 0.223 P = 0.878
	Pre-exposure	2 ± 2	2 ± 1	2 ± 1	2 ± 1			
	Pre-exercise	1 ± 0	1 ± 0	1 ± 1	1 ± 1			
	Post-exercise*	10 ± 6	8 ± 3	8 ± 3	7 ± 4			
RPE (scale)	Pre-final dose	8 ± 1	7 ± 1	8 ± 2	8 ± 2	F(1,10) = 0.124 P = 0.732	F(1,10) = 1.249 P = 0.290	F(3,8) = 1.073 P = 0.414
	Pre-exposure	8 ± 1	7 ± 1	8 ± 1	7 ± 1			
	Pre-exercise	8 ± 1	7 ± 1	7 ± 1	7 ± 1			
	Post-exercise*	17 ± 1	16 ± 2	16 ± 2	17 ± 2			
SpO_2 (%)	Pre-final dose	96 ± 3	97 ± 1	97 ± 1	97 ± 1	F(1, 10) = 0.636 P = 0.444	F(1, 10) = 46.956 P < 0.001	F(3, 8) = 1.248 P = 0.355
	Pre-exposure**	97 ± 2	98 ± 1	97 ± 2	97 ± 1			
	Pre-exercise**	94 ± 2	98 ± 1	95 ± 2	98 ± 1			
	Post-exercise*	93 ± 3	97 ± 1	92 ± 3	97 ± 1			

Plasma nitrate (μM)	Pre-final dose	71 ± 65	46 ± 37	7 ± 3	11 ± 8	F(1, 10) = 103.323 P < .001	F(1, 10) = 0.362 P = 0.561	F(1, 10) = 0.260 P = 0.621
	Pre-exercise	235 ± 75	225 ± 79	6 ± 4	10 ± 6			
TT (min)	Post-exercise	77 ± 11	71 ± 9	78 ± 9	71 ± 8	F(1,10) = 0.100 P = 0.759	F(1,10) = 13.754 P = 0.004	F(1,10) = 0.046 P = 0.834
Muscle oxygen (%)	Post-exercise	14 ± 9	13 ± 8	13 ± 4	13 ± 4	F(1, 10) = 0.040 P = 0.845	F(1, 10) = 0.037 P = 0.852	F(1, 10) = 0.183 P = 0.678

* = Significantly different from other time points within the same experimental condition.
** = Significantly different between pre-exposure and pre-exercise within the same experimental condition.

Heart Rate (HR)
No significant supplement × environment × time interaction effect was observed for HR ($P > 0.05$). Likewise, no significant main effects of supplementation or environment were detected (Table 1). A significant main effect of time was observed, with HR increasing from 71 ± 14 beats·min^{-1} at pre-exercise to 131 ± 15 beats·min^{-1} at post-exercise across all conditions.

Blood Glucose
No significant supplement × environment × time interaction effect and no significant main effects of supplementation or environment were observed for blood glucose concentration ($P > 0.05$) (Table 1). A significant main effect of time was identified, with blood glucose concentration increasing to 112 ± 15 mg·dL^{-1} at post-exercise compared with all preceding measurement time points.

Blood Lactate
No significant supplement × environment × time interaction effect and no significant main effects of supplementation or environment were observed for blood lactate concentration ($P > 0.05$) (Table 1). A significant main effect of time was observed, with blood lactate concentration increasing to 10 ± 6 mmol·L^{-1} at post-exercise compared with all earlier time points.

Muscle Oxygenation (Tissue Saturation Index)
No significant supplement × environment × time interaction effect was observed for TSI ($P > 0.05$). Likewise, no significant main effects of supplementation or environment were detected (Table 1). TSI values decreased during the 10-km time trial across all experimental conditions; however, no significant differences were observed between supplementation or environmental conditions.

Rating of Perceived Exertion (RPE)
No significant supplement × environment × time interaction effect was observed for RPE ($P > 0.05$). Similarly, no significant main effects of supplementation or environment were detected (Table 1). A significant main effect of time was observed, with RPE increasing to 17 ± 1 at post-exercise compared with all pre-exercise measurement time points.

Participant Compliance and Adverse Events
All the participants successfully completed the 4 experimental conditions. No adverse events or gastrointestinal complaints were reported throughout the study. Compliance with supplement consumption, pre-trial fasting, dietary recording, and physical activity control was monitored throughout the experimental period and was considered satisfactory.

No participant reported being able to distinguish between the beetroot gummy jelly and placebo supplements, suggesting that blinding of the supplementation conditions was maintained. As expected, the participants were aware of the environmental condition because normoxic and hypoxic trials could not be blinded.

DISCUSSION

The principal finding of the present study was that 7 days of beetroot gummy jelly supplementation substantially increased plasma nitrate concentration under both sea-level and simulated hypoxic conditions, confirming that this novel gummy jelly formulation effectively delivered bioavailable dietary nitrate. Despite the marked increase in systemic nitrate availability, no improvements were observed in the 10-km running performance or any of the physiological variables. These findings indicate that successful nitrate delivery alone may be insufficient to enhance prolonged endurance running performance under the specific exercise, environmental, and supplementation conditions employed in the present study.

A notable observation was the robust increase in plasma nitrate concentration following beetroot gummy jelly supplementation. Plasma nitrate increased approximately 4- to 5-fold from baseline values and remained elevated prior to exercise in both environmental conditions. The magnitude of this response is comparable to values reported following beetroot juice supplementation, suggesting that the gummy jelly formulation was effective in delivering dietary nitrate and increasing systemic nitrate availability (Webb et al., 2008; Jones, 2014; Wylie et al., 2013). Therefore, the absence of performance enhancement cannot be attributed to inadequate nitrate delivery or poor compliance with supplementation.

Despite the marked increase in plasma nitrate concentration, beetroot gummy jelly supplementation did not improve the 10-km running performance. This finding is consistent with several previous studies that reported no significant improvement in endurance exercise performance following nitrate supplementation despite the substantial elevations in nitrate availability (Cermak et al., 2012; De Castro et al., 2018; Vanhatalo et al., 2011). Although dietary nitrate supplementation has demonstrated ergogenic effects in certain exercise models, particularly repeated-sprint exercise, high-intensity intermittent exercise, and selected middle-distance performance tasks, evidence for prolonged endurance exercise remains equivocal (McMahon et al., 2016; Domínguez et al., 2017; Jones et al., 2014). Collectively, current evidence suggests that the effectiveness of nitrate supplementation is influenced by exercise modality, exercise duration, training status, environmental conditions, and the supplementation strategy.

The present study specifically examined dietary nitrate supplementation during exercise performed under simulated hypoxic conditions. As expected, hypoxic exposure significantly reduced peripheral oxygen saturation and impaired 10-km running performance compared with sea-level conditions. These findings confirm that the hypoxic stimulus successfully induced physiological stress and negatively affected endurance performance. In fact, Figure 2 highlights this point, given that it relates to within group variation and high standard deviations. However, beetroot gummy jelly supplementation did not attenuate the reduction in performance associated with hypoxia. Although the nitrate–nitrite–nitric oxide pathway may theoretically become more active under low-oxygen conditions, previous investigations have reported inconsistent performance outcomes following nitrate supplementation in hypoxic environments (Muggeridge et al., 2013; Bourdillon et al., 2015; MacLeod et al., 2015; Shannon et al., 2016).

The discrepancy between elevated plasma nitrate concentrations and unchanged exercise performance may be related to the nature of the exercise task employed in the present study. Previous research suggests that nitrate supplementation may exert greater benefits during exercise requiring repeated recruitment of high-threshold motor units, rapid force production, or repeated-sprint activity (Murphy et al., 2012; Shannon et al., 2016; Casado et al., 2021). In contrast, the 10-km running time trial performed in the present study predominantly relies on sustained aerobic metabolism and pacing regulation over an extended duration. Consequently, any physiological advantages associated with increased nitric oxide availability may have been insufficient to meaningfully influence overall endurance performance.

A unique aspect of the present study was the use of beetroot gummy jelly as an alternative nitrate delivery system. Most previous investigations have administered dietary nitrate in liquid form, particularly concentrated beetroot juice. Comparatively little information is available regarding gummy, chewable, or semi-solid nitrate-containing products. Delivery format may influence gastrointestinal transit, absorption characteristics, user acceptability, and practical application during training and competition. Previous investigations have suggested that physiological responses to nitrate supplementation may differ according to the delivery matrix, even when equivalent nitrate doses are administered (Flueck et al., 2015; Thompson et al., 2018).

Although the present study did not directly compare gummy jelly with beetroot juice, the substantial increase in plasma nitrate concentration observed following supplementation demonstrates that the gummy jelly formulation successfully delivered nitrate into the systemic circulation. Furthermore, all the participants completed the supplementation protocol without adverse events or gastrointestinal complaints, and compliance remained high throughout the study. These observations suggest that beetroot gummy jelly may represent a practical, portable, and well-tolerated alternative to the traditional liquid-based nitrate supplementation strategies.

No supplementation effects were observed for heart rate, blood glucose, blood lactate, muscle oxygenation, peripheral oxygen saturation, or perceived exertion. The absence of physiological alterations despite elevated plasma nitrate concentrations suggests that increased nitrate availability did not meaningfully influence cardiovascular, metabolic, muscular oxygenation, or perceptual responses during prolonged endurance running. These findings further support the concept that increases in nitrate availability do not necessarily translate into measurable improvements in physiological function or endurance performance.

Limitations in this Study

Several limitations should be acknowledged. Although the randomized crossover design reduced inter-individual variability and strengthened the internal validity of the findings, the relatively small sample size may have limited the ability to detect small performance effects. In addition, only recreationally trained male runners were recruited that may limit the generalizability of the findings to elite athletes, female athletes, and other athletic populations.

Although the participants were instructed to avoid nitrate-rich foods before each trial and dietary intake was monitored, complete control of dietary nitrate intake outside of the laboratory was not possible. Furthermore, while plasma nitrate concentration was assessed, plasma nitrite concentration was not measured. Because nitrite is more closely associated with nitric oxide bioavailability, the inclusion of plasma nitrite measurements would have provided additional mechanistic insight.

Although muscle oxygenation was assessed using near-infrared spectroscopy, additional measurements related to vascular function, oxygen utilization, and nitric oxide signaling may have provided a more comprehensive understanding of the physiological responses to supplementation. Finally, the present study did not directly compare beetroot gummy jelly with traditional beetroot juice supplementation. Therefore, the conclusions regarding the relative effectiveness of different nitrate delivery formats should be interpreted with caution.

CONCLUSIONS

Seven days of beetroot gummy jelly supplementation substantially increased plasma nitrate concentrations under both sea-level and simulated hypoxic conditions, which demonstrated that this novel gummy jelly formulation effectively delivered bioavailable dietary nitrate. However, the increase in nitrate availability did not translate into improvements in the subjects' 10-km running performance or associated physiological responses in the recreationally trained runners. These findings suggest that successful nitrate delivery alone may be insufficient to enhance prolonged endurance running performance under the conditions examined in the present study. Nevertheless, beetroot gummy jelly may represent a practical, portable, and well-tolerated nitrate delivery system for future investigation in athletic populations and exercise settings.

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Exercise Frequency and Sleep Quality among Vocational Medical Students in Zigong, Sichuan, China: The Roles of Mental Health and Lifestyle Factors

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ABSTRACT

Yu J, Glangkarn S, Promasatayaprot V, Zeng S. This study examined the association between exercise frequency and sleep quality among vocational medical students in Zigong, Sichuan, China, while considering the roles of mental health and lifestyle factors. A cross-sectional online survey was conducted among 1,007 vocational medical students aged 18 to 24 years of age. Sleep quality was assessed using the Pittsburgh Sleep Quality Index (PSQI), while depressive and anxiety symptoms were measured using the Zung Self-Rating Depression Scale (SDS) and the Self-Rating Anxiety Scale (SAS). Multiple linear and binary logistic regression analyses were performed to identify factors associated with sleep quality. The mean PSQI score was 5.61 ± 3.33, and 48.56% of participants were classified as having poor sleep quality (PSQI > 5). Weekly exercise frequency was significantly associated with better sleep quality ($\beta = -0.123$, $P < 0.001$); whereas, anxiety symptoms ($\beta = 0.311$, $P < 0.001$), depressive symptoms ($\beta = 0.132$, $P < 0.001$), poor parental relationships ($\beta = 0.169$, $P < 0.001$), and harsher family upbringing styles ($\beta = 0.174$, $P < 0.001$) were associated with poorer sleep quality. Logistic regression analysis indicated that anxiety symptoms (AOR = 2.908, 95% CI = 2.208-3.829, $P < 0.001$), depressive symptoms (AOR = 1.346, 95% CI = 1.028-1.763, $P < 0.05$), and alcohol consumption (AOR = 2.462, 95% CI = 1.551-3.909, $P < 0.001$) increased the likelihood of poor sleep quality. In contrast, each one-category increase in weekly exercise frequency was associated with a 26.9% reduction in the probability of poor sleep quality (AOR = 0.731, 95% CI = 0.608-0.878, $P < 0.001$). These findings suggest that poor sleep quality is highly prevalent among vocational medical students and that regular exercise may serve as an important protective factor. Promoting physical activity alongside mental health support may represent an effective strategy for improving sleep quality and overall well-being in this population.

Key Words: Anxiety; Depression; Exercise Frequency; Medical Students, Physical Activity; Sleep Quality

INTRODUCTION

Along with diet and exercise, sleep is considered one of the three fundamental pillars of health. Adequate sleep plays a critical role in maintaining physical, psychological, and cognitive well-being (9,11). Sleep quality generally refers to an individual's subjective satisfaction with sleep and encompasses several dimensions, including sleep duration, sleep latency, sleep maintenance, and sleep efficiency. Despite its importance, sleep disturbances are highly prevalent worldwide. In fact, according to the World Health Organization (WHO), approximately 27% of individuals experience sleep-related problems that negatively influence their daily functioning and overall health (8,24).

Poor sleep quality has been associated with numerous adverse health outcomes. Physiological consequences include an increase in the risk of cardiovascular disease, hypertension, diabetes, endocrine dysfunction, and impaired immune function (7). Furthermore, inadequate sleep has been linked to a variety of psychological conditions that include depression, anxiety, irritability, impaired concentration, and reduced cognitive performance (8,24). Although sleep is essential for maintaining optimal health, many individuals fail to achieve adequate sleep duration or quality (18).

Regular physical activity has emerged as an important modifiable factor influencing sleep quality. Exercise contributes to the regulation of circadian rhythms by helping to synchronize the body's internal biological clock with environmental cues, thereby promoting more consistent sleep–wake cycles (25,27). Physical activity is associated with an increase in melatonin secretion, improved autonomic nervous system balance, enhanced parasympathetic activity, and reduced sympathetic arousal, all of which facilitate sleep initiation and maintenance (9,11). In addition, regular exercise may reduce cortisol levels and attenuate physiological stress responses that commonly interfere with sleep (2). Rhim et al. (21) reported that physically active individuals generally exhibit better sleep efficiency, shorter sleep latency, longer sleep duration, and improved sleep architecture compared with sedentary individuals. Consequently, exercise is increasingly recognized as a practical, non-pharmacological strategy for improving sleep quality and promoting overall health (34).

Among young adults, medical students appear to be particularly vulnerable to disturbances in sleep. Compared with students in other disciplines, medical students are more likely to experience insufficient sleep, delayed bedtimes, and difficulties initiating sleep (1). Studies have reported a high prevalence of sleep problems among medical students worldwide (15). Sleep problems among medical students may result from multiple factors, including depression, anxiety, academic stress, irregular lifestyles, extensive study hours, clinical training requirements, frequent examinations, and financial pressures (3,10). Poor sleep quality may adversely affect academic performance, clinical competence, mental health, and overall quality of life, making it an important concern within medical education (5,14).

In China, vocational medical students account for nearly 30% of the nation’s healthcare workforce training pipeline and constitute an essential component of the primary healthcare system (16). However, relatively little attention has been paid to their sleep quality and related health behaviors. Vocational medical education is characterized by a practice-oriented training model in which students engage in clinical activities early in their education before acquiring comprehensive theoretical knowledge (3). This educational approach, combined with intensive curricula, clinical responsibilities, and rural placement requirements, may contribute to elevated levels of stress, fatigue, and sleep disturbances. Furthermore, preliminary evidence suggests that vocational medical students may experience greater emotional exhaustion than traditional university medical students. Despite these concerns, the systematic investigations examining sleep quality and its associated factors in this population remain limited (15,33).

Therefore, the purpose of this study was to investigate the prevalence of poor sleep quality among vocational medical students in Zigong, Sichuan, China, and to identify its associated predictors. By simultaneously examining mental health status, family environment, lifestyle behaviors, and exercise participation, this study seeks to identify both risk and protective factors related to sleep quality. In particular, regular physical activity is examined as a potentially modifiable behavioral factor that may improve sleep quality and reduce the likelihood of sleep disturbances among vocational medical students. The findings are expected to provide evidence for developing targeted interventions that promote sleep health, psychological well-being, and healthy lifestyle behaviors in vocational medical education.

METHODS

Subjects

This cross-sectional study was conducted among students enrolled at Sichuan Health and Rehabilitation Vocational College in Zigong, Sichuan, China. The data were collected between March and June 2025, using an online questionnaire survey. The study population consisted of first- and second-year vocational medical students from the nursing, rehabilitation, clinical medicine, and pharmacy programs. The eligible participants were between 18 and 24 years of age.

The required sample size was estimated using Daniel's formula for cross-sectional studies, resulting in a minimum sample size of 1,007 participants. A total of 1,007 valid questionnaires were obtained and included in the final analysis. All the participants provided written informed consent prior to participation. The study was approved by the Ethical Committee for Research Involving Human Subjects, Mahasarakham University, Thailand (Approval No. 168-791/2025) and conducted in accordance with the ethical principles of the Declaration of Helsinki.

Procedures

The data were collected using a self-administered questionnaire developed from a review of the relevant literature. The questionnaire consisted of 4 sections: (a) demographic and social characteristics; (b) the Zung Self-Rating Depression Scale (SDS); (c) the Zung Self-Rating Anxiety Scale (SAS); and (d) the Pittsburgh Sleep Quality Index (PSQI). The overall questionnaire demonstrated acceptable reliability (Cronbach's $\alpha = 0.829$), with a Kaiser-Meyer-Olkin (KMO) value of 0.612 and a significant Bartlett's Test of Sphericity ($P < 0.05$).

Sleep quality was assessed using the Pittsburgh Sleep Quality Index (PSQI), which evaluates sleep quality and sleep disturbances during the previous month. The PSQI consists of 19 items grouped into 7 components: (a) subjective sleep quality; (b) sleep latency; (c) sleep duration; (d) habitual sleep efficiency; (e) sleep disturbances; (f) use of sleep medication; and (g) daytime dysfunction. Component scores were summed to obtain a global score ranging from 0 to 21, with higher scores indicating poorer sleep quality. The participants with a PSQI score > 5 were classified as having poor sleep quality.

Depressive symptoms were assessed using the Chinese version of the Zung Self-Rating Depression Scale (SDS), while anxiety symptoms were measured using the Chinese version of the Zung Self-Rating Anxiety Scale (SAS). Both instruments contain 20 items scored on a four-point Likert scale and have been widely used in Chinese populations.

Additional variables included gender, age, academic year, faculty, body mass index (BMI), smoking status, alcohol consumption, psychotropic drug use, exercise frequency per week, monthly disposable income, parental relationship, and family upbringing style. BMI was calculated as weight in kilograms divided by height in meters squared (kg/m^2). Exercise frequency was categorized as never, 1 to 2 times per week, 3 to 4 times per week, and 5 to 7 times per week.

Statistical Analyses

All statistical analyses were performed using IBM SPSS Statistics version 18.0. Descriptive statistics were used to summarize the participant characteristics, sleep quality, depression, and anxiety levels. Continuous variables were expressed as mean ± standard deviation (SD); whereas, the categorical variables were presented as frequencies and percentages.

Independent-samples *t*-tests and one-way analysis of variance (ANOVA) were used to compare PSQI scores across the participant characteristics. Multiple linear regression analysis was performed to identify factors associated with sleep quality using the continuous PSQI score as the dependent variable (6,23,28).

To further examine the influence of modifiable behavioral factors on sleep quality, binary logistic regression analysis was conducted using sleep quality status (good vs. poor sleep quality) as the dependent variable. Odds ratios (ORs) and 95% confidence intervals (CIs) were calculated to estimate the strength of associations between predictor variables and poor sleep quality. Statistical significance was established at $P < 0.05$.

RESULTS

Characteristics of the Study Sample

Among the 1,007 participants, 160 (15.89%) were male and 847 (84.11%) were female. The mean age was 19.14 ± 0.98 years, and the mean BMI was 20.81 ± 2.81 kg/m^2. The mean SDS and SAS scores were 48.36 ± 8.86 and 42.66 ± 8.54, respectively. Overall, 51.14% of the participants reported depressive symptoms (SDS > 49), while 40.52% reported anxiety symptoms (SAS > 44).

To facilitate the analysis of factors associated with sleep quality, the variables were classified into modifiable and non-modifiable factors. Modifiable factors included alcohol consumption, smoking status, psychotropic drug use, weekly exercise frequency, depressive symptoms, and anxiety symptoms. Non-modifiable factors included gender, age, academic year, and faculty. Additional socioeconomic and family-related variables included monthly disposable income (RMB), parental relationship, and family upbringing style.

Prevalence of Sleep Quality

The mean PSQI score among vocational medical students was 5.61 ± 3.33. In addition, 38.37% of students reported falling asleep after midnight, and 64.65% reported sleeping less than seven hours per night. Based on the PSQI classification criteria, 48.56% of the participants were classified as having poor sleep quality (PSQI > 5) (Table 1).

As shown in Table 1, 51.44% of students demonstrated good sleep quality, whereas 40.12%, 7.75%, and 0.70% experienced mild, moderate, and severe sleep difficulties, respectively.

Table 1. Descriptive Statistics of Sleep Quality Among Vocational Medical Students (N = 1,007).

Variable	Mean ± SD	Sleep Quality Category	n	%
PSQI Score	5.61 ± 3.33	Good Sleep Quality (0–5)	518	51.44
		Mild Sleep Difficulties (6–10)	404	40.12
		Moderate Sleep Difficulties (11–15)	78	7.75
		Severe Sleep Difficulties (16–21)	7	0.70

Note. PSQI = Pittsburgh Sleep Quality Index. Higher PSQI scores indicate poorer sleep quality.

Multiple Linear Regression Analysis of Sleep Quality

To identify factors associated with sleep quality among vocational medical students, a multiple linear regression analysis was conducted using the total PSQI score as the dependent variable. Fourteen variables, including gender, age, academic year, faculty, BMI, smoking status, alcohol consumption, psychotropic drug use, weekly exercise frequency, monthly disposable income, parental relationship, family upbringing style, SDS score, and SAS score, were entered as independent variables. The regression model was statistically significant ($F = 37.997$, $P < 0.001$) and explained 34.0% of the variance in PSQI scores (Adjusted $R^2 = 0.340$).

Alcohol consumption, weekly exercise frequency, and monthly disposable income were significantly associated with PSQI scores (all $P < 0.001$). In addition, parental relationship ($\beta = 0.169$, $P < 0.001$), family upbringing style ($\beta = 0.174$, $P < 0.001$), depressive symptoms ($\beta = 0.132$, $P < 0.001$), and anxiety symptoms ($\beta = 0.311$, $P < 0.001$) were significantly associated with poorer sleep quality. Among all predictors, anxiety symptoms demonstrated the strongest association with PSQI scores.

Faculty was also significantly associated with sleep quality ($\beta = -0.076$, $P = 0.045$), although the magnitude of this association was relatively small. No significant associations were observed for gender, age, academic year, BMI, smoking status, or psychotropic drug use (Table 2).

Table 2. Multiple Linear Regression Analysis Predicting Sleep Quality (PSQI Score).

Predictor	B	β	t	p
Gender (1 = male)	0.477	0.053	1.853	0.064
Age (years)	0.004	0.001	0.025	0.980
BMI (kg/m²)	-0.019	-0.016	-0.606	0.545
Academic Year	-0.087	-0.013	-0.309	0.757
Faculty	-0.211	-0.076	-2.009	0.045*
Smoking Status (1 = yes)	-0.656	-0.040	-1.475	0.140
Alcohol Consumption (1 = yes)	-1.511	-0.145	-5.155	<0.001***
Psychotropic Drug Use (1 = yes)	-0.677	-0.027	-1.012	0.312
Weekly Exercise Frequency	-0.563	-0.123	-4.554	<0.001***
Monthly Disposable Income	-0.449	-0.092	-3.425	0.001**
Parental Relationship	0.718	0.169	5.803	<0.001***
Family Upbringing Style	0.539	0.174	6.146	<0.001***
Depressive Symptoms (SDS)	0.045	0.132	4.478	<0.001***
Anxiety Symptoms (SAS)	0.121	0.311	9.908	<0.001***

Model Statistics: F = 37.997, P < 0.001, Adjusted R^2 = 0.340
Note. PSQI = Pittsburgh Sleep Quality Index; BMI = Body Mass Index; SDS = Self-Rating Depression Scale; SAS = Self-Rating Anxiety Scale. P < 0.05, **P < 0.01, ***P < 0.001.

Logistic Regression Analysis of Sleep Quality

Binary logistic regression analysis was conducted to examine the associations between modifiable factors and poor sleep quality. Smoking status, alcohol consumption, psychotropic drug use, weekly exercise frequency, depressive symptoms, and anxiety symptoms were included as independent variables. The results indicated that students with depressive symptoms were more likely to experience poor sleep quality than those without depressive symptoms (AOR = 1.346, 95% CI = 1.028–1.763, P < 0.05). Likewise, students with anxiety symptoms were significantly more likely to report poor sleep quality (AOR = 2.908, 95% CI = 2.208–3.829, P < 0.001). The magnitude of association was greater for anxiety symptoms than for depressive symptoms.

Alcohol consumption was significantly associated with poor sleep quality. Students who consumed alcohol were 2.462 times more likely to experience poor sleep quality than non-drinkers (95% CI = 1.551–3.909, P < 0.001). Weekly exercise frequency emerged as a significant protective factor. Each one-category increase in exercise frequency was associated with a 26.9% reduction in the odds of poor sleep quality (AOR = 0.731, 95% CI = 0.608–0.878, P < 0.001). Smoking status and psychotropic drug use were not significantly associated with poor sleep quality (Table 3).

Table 3. Binary Logistic Regression Analysis of Factors Associated with Poor Sleep Quality.

Predictor	Adjusted Odds Ratio (AOR)	95% CI	p
Smoking Status	1.260	0.633–2.508	0.510
Alcohol Consumption	2.462	1.551–3.909	<0.001***
Psychotropic Drug Use	2.134	0.565–8.058	0.263
Weekly Exercise Frequency	0.731	0.608–0.878	<0.001***
Depressive Symptoms (SDS)	1.346	1.028–1.763	0.031*
Anxiety Symptoms (SAS)	2.908	2.208–3.829	<0.001***

Note. Odds ratios greater than 1 indicate an increased likelihood of poor sleep quality, whereas odds ratios less than 1 indicate a protective effect. SDS = Self-Rating Depression Scale; SAS = Self-Rating Anxiety Scale. P < 0.05, **P < 0.01, ***P < 0.001.

DISCUSSION

The present study investigated sleep quality and its associated factors among vocational medical students in Zigong, Sichuan, China. The findings indicate that 48.56% of the participants experienced poor sleep quality, indicating that sleep disturbances are highly prevalent in this population. This prevalence is higher than that reported in several studies of Chinese university students and supports the previous evidence that suggested medical students are particularly vulnerable to sleep-related problems due to academic demands, clinical training requirements, psychological stress, and lifestyle challenges (31). Furthermore, more than one-third of the students reported falling asleep after midnight, and nearly two-thirds slept less than 7 hours per night, highlighting a widespread pattern of insufficient sleep (32).

Among all predictors examined, anxiety symptoms demonstrated the strongest association with poor sleep quality. Students with anxiety symptoms were nearly 3 times more likely to experience poor sleep quality than students without anxiety symptoms (26). This finding is consistent with previous research showing that anxiety disrupts normal sleep processes through increased physiological arousal, excessive cognitive activity, and heightened activation of the stress response system. Anxiety may impair both sleep initiation and sleep maintenance, resulting in poorer overall sleep quality (12). Similarly, depressive symptoms were significantly associated with poor sleep quality, although the magnitude of the association was smaller than that observed for anxiety. These findings support the close relationship between sleep and mental health among young adults and emphasize the importance of psychological well-being in sleep promotion programs (20).

An important finding of this study was the protective effect of regular exercise. Weekly exercise frequency was significantly associated with better sleep quality in both the linear and logistic regression analyses. Specifically, each one-category increase in exercise frequency was associated with a 26.9% reduction in the likelihood of poor sleep quality. This finding supports previous research indicating that regular physical activity contributes to improved sleep outcomes through several physiological mechanisms. Exercise has been shown to enhance circadian rhythm regulation, improve autonomic nervous system balance, increase parasympathetic activity, and reduce physiological stress responses (29). Regular physical activity may also facilitate melatonin secretion, reduce sleep latency, improve sleep efficiency, and increase restorative slow-wave sleep.

From an exercise physiology perspective, the present findings suggest that exercise represents an effective and accessible non-pharmacological strategy for improving sleep quality among vocational medical students (19). Given the high prevalence of sleep disturbances observed in this study, encouraging regular participation in physical activity may provide substantial benefits for both physical and psychological health (4). Exercise promotion programs integrated into vocational medical education may therefore serve as an important component of student health interventions.

Alcohol consumption was another significant predictor of poor sleep quality. Students who reported alcohol consumption were more than twice as likely to experience poor sleep quality than non-drinkers (22). Although alcohol is sometimes perceived as a sleep aid because it may facilitate initial sleep onset, previous studies have demonstrated that alcohol disrupts normal sleep architecture, reduces rapid eye movement (REM) sleep, and increases sleep fragmentation (17). These effects may contribute to poorer overall sleep quality and reduced daytime functioning.

Family-related factors also played an important role in sleep quality. Poor parental relationships and harsher family upbringing styles were significantly associated with higher PSQI scores. These findings suggest that family environments may influence emotional regulation, stress management, and coping strategies, all of which can affect sleep quality (13). Students who experience supportive family relationships may be better equipped to manage academic and personal stressors, thereby promoting healthier sleep patterns.

Limitations in this Study

Several limitations should be considered when interpreting these findings. First, the cross-sectional design prevents causal inferences regarding the relationships between exercise, mental health, and sleep quality. Second, all the data were collected through self-report questionnaires, which may be subject to recall bias and social desirability bias. Third, exercise was assessed only by frequency and did not include information regarding exercise intensity, duration, or type. Future studies should incorporate objective measures of physical activity and sleep, as well as longitudinal or experimental designs, to better clarify the causal mechanisms underlying these relationships.

CONCLUSIONS

Poor sleep quality was highly prevalent among vocational medical students in Zigong, Sichuan, China, affecting nearly half of the participants. Anxiety symptoms, depressive symptoms, alcohol consumption, and adverse family environments were significantly associated with poorer sleep quality. In contrast, regular exercise emerged as a significant protective factor, with higher exercise frequency associated with a lower likelihood of poor sleep quality. These findings highlight the importance of promoting physical activity, mental health support, and healthy lifestyle behaviors to improve sleep quality and overall well-being among vocational medical students.

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The Effects of Otago Exercise Program with Weight Sandbags on Balance, Muscle Strength, and Reaction Time in Older Adults

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ABSTRACT

Manlika Boonprem, Achariya Anek The objectives of this research were to examine and compare the effects of the Otago exercise program with weight sandbags on balance, muscle strength, and reaction time in older adults. The participants included 30 older adults (mean age = 65.07 ± 2.84 years), who were randomly assigned into the Experimental Group and the Control Group. The Experimental Group participated in the Otago exercise program with weighted sandbags for 50 minutes per session, twice a week for 8 weeks. Both Groups were assessed before and after the intervention. The outcome measures included Balance Tests, namely Single-Leg Stance on a Firm Surface, the Single-Leg Stance on a Soft Surface, and the Timed Up and Go (TUG) Test. Muscle strength was assessed using the 30-Second Sit-to-Stand Test. Reaction time was evaluated using the 30 second light ~~R~~ reaction time for both the right side and the left side. After intervention, the results showed that the Experimental Group demonstrated significant improvements in balance, muscle strength, and reaction time (P < 0.01) compared to their pre-test scores. Furthermore, when compared with the Control Group, the Experimental Group showed significantly better performance in all measured outcomes (P < 0.01). In conclusion, the Otago exercise program with weighted sandbags effectively improved balance, muscle strength, and reaction time in the older adults. This program can be applied as an effective strategy for promoting health and preventing falls among older adults.

Key Words: Balance, Muscle Strength, Otago, Older Adults, Reaction Time, Weight Sandbags

INTRODUCTION

Population aging is an increasing global public health concern, particularly because advancing age is strongly associated with functional decline, reduced independence, and increased risk of falls (20). Thailand is one of the most rapidly aging countries in Southeast Asia, and it currently has the second-highest proportion of older adults among The Association of Southeast Asian Nations (ASEAN) (8). Although the overall population of Thailand is declining, the number and proportion of older adults continue to increase (13). Older adults aged 60 to 69 years account for approximately 7.94 million individuals, representing 55.74% of the total older population (8). Accordingly, Thailand has already entered a complete-aged society, and it is projected to become a super-aged society by 2033 (13).

Aging is accompanied by progressive deterioration of the musculoskeletal and neuromuscular systems. Reductions in skeletal muscle mass, muscular strength, muscular endurance, and bone mineral density contribute to decreased mobility and increased susceptibility to injury (6). In parallel, age-related neurological changes, including slower information processing, reduced neuromuscular coordination, delayed reaction time, and impaired motor control have a negative influence on the ability to respond effectively to postural disturbances (18).

Postural control depends on the integration of visual, vestibular, and somatosensory inputs within the central nervous system, followed by appropriate motor responses to maintain the body's center of mass within the base of support (18). In older adults, deterioration of vestibular function, proprioception, sensory feedback, and lower-extremity muscle performance reduces the ability to maintain postural stability during both static and dynamic tasks (10,18). As a result, falls are associated with very serious consequences that include fractures, disability, loss of independence, and mortality (20).

Exercise training is one of the most effective non-pharmacological strategies to improve physical function and reduce fall risk among older adults (17). The Otago Exercise Program (OEP), originally developed by Campbell and Robertson, is a widely recognized evidence-based intervention for reducing falls among older adults (3). Previous studies (5,9) have demonstrated that the OEP improves lower-limb strength, balance ability, functional mobility, physical fitness, and fall-prevention behaviors among older adults.

Furthermore, exercise interventions involving mechanical loading and weight-bearing activities have been shown to induce favorable musculoskeletal adaptations. Anek and Mitranun (1) reported that weight-bearing aerobic exercise significantly improved osteogenic responses in premenopausal women, which suggest that external loading may provide an effective stimulus for enhancing musculoskeletal function.

Although the benefits of the OEP have been well established, limited evidence is available regarding the effects of modifying the program with additional external resistance. Evidence supporting the role of mechanical loading in promoting musculoskeletal adaptation (1) further suggests that the incorporation of weighted sandbags into the OEP may enhance training effectiveness. However, to the authors' knowledge, no previous studies have examined the effects of an Otago Exercise Program combined with weighted sandbags on balance, muscle strength, and reaction time in older adults.

Therefore, the purpose of this study was to investigate the effects of an 8-week Otago Exercise Program combined with weighted sandbags on balance performance, muscle strength, and reaction time in older adults. It was hypothesized that the participants in the Experimental Group would demonstrate significantly greater improvement in balance, muscular strength, and reaction time compared with the participants in the Control Group.

METHODS

Participants and Study Design

Thirty (N = 30) healthy community-dwelling older adults (men and women; aged 60 to 69 years) from Nonthaburi Province, Thailand, voluntarily participated in this study. Prior to enrollment, all the participants were screened for eligibility according to predefined inclusion and exclusion criteria. The eligible participants were required to be free from severe musculoskeletal, neurological, cardiovascular, and/or cognitive impairments that could interfere with exercise participation or outcome assessments.

The required sample size was determined using G*Power software (Version 3.1.9.4; Heinrich Heine University Düsseldorf, Germany). The calculation was based on a paired-samples *t*-test with an alpha level of 0.05, statistical power of 0.90, and an effect size derived from a previous study conducted by Eaungpulsawat W. (7). The minimum sample size required was estimated to be 22 participants. To compensate for an anticipated dropout rate of 40%, the final sample size was increased to 30 participants.

A randomized controlled trial design was employed. The participants were randomly assigned to either the Control Group (CON; n = 15) or the Experimental Group (Otago; n = 15) using a computer-generated randomization sequence created through the Versakit Web Application. The participants allocated to the Control Group continued their usual daily physical activities without participation in a structured exercise program. The participants in the Experimental Group completed a modified Otago Exercise Program combined with ankle-weighted sandbags.

All the participants received a detailed explanation of the study objectives, procedures, potential risks, and benefits before participation and they subsequently a provided written informed consent. The study protocol was reviewed and approved by the Human Research Ethics Committee (Approval No. AF 19-03-03.1). All the study procedures were conducted in accordance with the ethical standards of the Declaration of Helsinki for research involving human participants.

Procedures

The intervention period lasted 8 weeks. All the participants completed physical performance assessments before and after the intervention period. Static balance was assessed using the Single-Leg Stance Test on both a firm surface and a soft surface using a Get Moving foam pad. Dynamic balance was assessed using the Timed Up and Go (TUG) Test. Reaction time was evaluated using a 30-Second Optical Response Time Test for both the right and left sides, using a ReactionX brand device.

All assessments were conducted under standardized testing conditions before and after the 8-week intervention period. The same testing procedures were applied to all the participants to ensure consistency across pre- and post-intervention measurements.

Exercise Intervention
The participants in the Experimental Group completed a modified Otago Exercise Program for 50 to 60 minutes per session, twice weekly, for 8 consecutive weeks. The content of the training program was validated by 5 experts in sports science for content validity and item-objective congruence, yielding an Index of Item-Objective Congruence (IOC) of 0.92. The program was designed to elicit a moderate level of perceived exertion, corresponding to a Rating of Perceived Exertion (RPE) of 4 to 7 on a scale of 1 to 10, with 1 = no effort and 10 = maximal effort. Throughout the intervention period, the participants wore ankle-weighted sandbags weighing 1 kg on each leg during the exercise sessions.

The 8-week intervention was divided into 2 phases. Phase 1 (Weeks 1–4) consisted of supervised training sessions conducted under the direct supervision of the principal investigator and 2 research assistants. Each session included a dynamic warm-up consisting of 5 exercises performed for 10 repetitions each, followed by the main training protocol that consisted of 7 balance exercises performed for 10 steps each and 7 strengthening exercises performed for 10 repetitions each. All the exercises were completed for 2 sets, with a 1-minute rest interval between the sets. Each session ended with a cool-down period that consisted of 5 static stretching exercises performed for 10 repetitions each. Phase 2 (Weeks 5–8) consisted of home-based training. During this phase, the participants independently performed the same exercise program using instructional videos provided by the research team. The videos included an auditory rhythm set at 120 beats per minute (BPM) to standardize exercise cadence and promote consistency of movement performance across training sessions.

Statistical Analyses
The data are presented as mean ± standard deviation. Paired *t*-tests were used to assess within-group changes, while independent *t*-tests were used to compare post-intervention differences between groups. Statistical significance was set at $P < 0.05$. Analysis was performed using Statistical Product and Service Solutions version 25.

RESULTS

Table 1. The Participants' Characteristics in Both Groups (N = 30).

Group	EXPERIMENTAL GROUP (OTAGO) n = 15	CONTROL GROUP n =15
Age (yr)	65.33 ± 2.58	64.80 ± 3.14
Weight (kg)	67.50 ± 8.60	67.45 ± 12.52
Height (cm)	157.80 ± 7.57	163.07 ± 8.23
BMI (kg/m^2)	27.19 ± 3.61	25.22 ± 3.20

Table 1 presents the baseline characteristics of the participants in both the Experimental Group and the Control Group prior to the intervention. The data indicate that the physical attributes of subjects in the 2 Groups are generally comparable, with no significant differences observed ($P > 0.05$). This suggests that the random selection process was effective in ensuring group equivalence at the outset of the study.

Balance

The subjects in the Experimental Group combined with Weighted Sandbags (Otago) showed significant improvement in the Single-Leg Stance on a Firm Surface Test, Single-Leg Stance on a Soft surface Test, and Timed Up and Go after the intervention ($P < 0.01$), while the subjects in the Control Group (CON) showed no significant change (Table 2). After the intervention, the subjects in the Experimental Group had significantly better Balance ($P < 0.01$) than the subjects in the Control Group.

Table 2. Changes in Balance Before and After Week 8 of the Experiment Between The Control Group and The Otago Program (i.e., the Experimental Group combined with Weighted Sandbags).

	EXPERIMENTAL GROUP (OTAGO)		CONTROL GROUP	
	Pre-Test	Post-Test	Pre-Test	Post-Test
Single-Leg Stance on a Firm Surface Test (sec)	10.25 ± 7.23	10.59 ± 6.72	11.92 ± 5.63	32.17 ± 12.93^{+*}
Single-Leg Stance on a Soft Surface Test (sec)	4.05 ± 2.59	4.71 ± 3.08	5.68 ± 9.84	17.50 ± 11.56^{+*}
Timed Up and Go (sec)	10.50 ± 0.33	10.53 ± 0.54	10.49 ± 0.32	8.23 ± 0.58^{+*}

The data are presented as mean ± SD. $^{+}$Significant difference between Pre-Test and Post-Test ($P < 0.01$). *Significant difference between the Otago Program (i.e., the Experimental Group) and the Control Group ($P < 0.01$).

Muscle Strength

The Otago Group, combined with Weighted Sandbags (Otago), showed statistically significant improvements in the 30-Second Sit-to-Stand Test ($P < 0.01$) while there were no significant changes in the Control Group (Table 3). Also, after the intervention the Otago Group had significantly ($P < 0.01$) better Muscle Strength than the subjects in the Control Group.

Table 3. Changes in Muscle Strength Before and After Week 8 of the Experiment Between the Control Group and the Experimental Group (i.e., the Otago Program Combined with Weighted Sandbags).

	EXPERIMENTAL GROUP (OTAGO)		CONTROL GROUP	
	Pre-Test	Post-Test	Pre-Test	Post-Test
30-Second Sit-to-Stand Test (t)	15.73 ± 3.61	16.53 ± 1.83	15.07 ± 2.84	20.93 ± 2.15^{+*}

The data are presented as mean ± SD. $^{+}$Significant difference between the Pre-Test and the Post-Test (P < 0.01). *Significant difference between the Otago Program and the Control Group (P < 0.01).

Reaction Time

The Experimental Group, combined with Weighted Sandbags (Otago), showed significant improvements (P < 0.01) in the 30 second light Reaction time for both the right side and the left side, but not in the Control Group (Table 4). After the intervention, the Experimental (Otago) Group had significantly better Reaction Time (P < 0.01) than the Control Group.

Table 4. Changes in Reaction Time Before and After Week 8 of the Experiment Group (Otago Program Combined with Weighted Sandbags) were Significant Compared to No Changes in the Control Group.

Group	OTAGO		CON	
	Pre-Test	Post-Test	Pre-Test	Post-Test
30 Second Light Reaction Time, Right Side (t)	16.13 ± 2.75	17.47 ± 3.60	16.07 ± 2.43	23.27 ± 1.98^{+*}
30 Second Light Reaction Time, Left Side (t)	16.00 ± 2.95	17.07 ± 2.84	15.93 ± 2.87	23.13 ± 1.60^{+*}

The data are presented as mean ± SD. $^{+}$Significant difference between the Pre-Test and the Post-Test (P < 0.01). *Significant difference between the Experimental (Otago Program) Group and the Control Group (P < 0.01).

DISCUSSION

The primary finding of the present study was that participation in an 8-week Otago Exercise Program (OEP) combined with ankle-weighted sandbags significantly improved static balance, dynamic balance, lower-extremity muscle strength, and neuromuscular reaction time in community-dwelling older adults. These findings support the study hypothesis and they are consistent with previous evidence demonstrating that OEP-based interventions effectively improve physical performance, balance, muscle strength, and fall-related outcomes among older adults (5,9,10). In contrast, no significant changes were observed in the Control Group, suggesting that habitual daily activities alone may be insufficient to attenuate age-related declines in neuromuscular function.

Balance

Static Balance

Static balance was assessed using the Single-Leg Stance Test performed on both firm and foam surfaces. The significant improvements observed following the intervention may be attributed to the combined effects of isometric and isotonic muscle contractions incorporated within the OEP. The addition of ankle-weighted sandbags increased external loading and likely enhanced proprioceptive stimulation through greater activation of muscle spindles, Golgi tendon organs, and joint mechanoreceptors. Enhanced proprioceptive feedback improves body-position awareness and contributes to more effective postural control.

Furthermore, improvements in sensory integration and neuromuscular coordination may have enhanced the participants' ability to maintain the center of mass within a reduced base of support during the single-leg stance tasks. Similar findings have been reported in previous studies demonstrating that exercise interventions targeting sensory-motor integration significantly improve postural stability and balance performance in older adults (15,16,18). Therefore, the observed improvements in static balance may reflect both musculoskeletal and neurosensory adaptations induced by the intervention.

Dynamic Balance

Dynamic balance was evaluated using the Timed Up and Go (TUG) Test. Significant improvements in TUG performance were observed following the intervention that indicated enhanced functional mobility and balance control. The additional resistance provided by the ankle-weighted sandbags likely increased muscular demand during exercise, resulting in greater improvements in lower-extremity strength and movement efficiency.

Muscle strength is a critical determinant of functional mobility and balance performance in older adults. Previous studies have demonstrated that participation in OEP significantly improves balance ability, walking performance, and confidence during daily activities (4,14). Therefore, improvements in dynamic balance observed in the present study likely resulted from enhanced muscular strength, postural control, and movement coordination. These adaptations may have practical implications for reducing fall risk and improving functional independence among older adults.

Muscle Strength

Lower-extremity muscle strength was assessed using the 30-Second Sit-to-Stand Test. The participants in the Experimental Group demonstrated significant improvements following the intervention. The use of ankle-weighted sandbags transformed the exercise program into a progressive resistance-training intervention that increased mechanical loading of the lower-extremity musculature.

The training protocol specifically targeted major muscle groups involved in postural control and locomotion, including the quadriceps, hamstrings, hip abductors, and ankle stabilizers. It is likely that the increase in weight resulted in neuromuscular adaptations and improvement in force-generating capacity. These findings are consistent with previous reports demonstrating that OEP effectively enhances lower-extremity muscle strength and functional performance in older adults (16).

Reaction Time

A significant reduction in reaction time was observed following participation in the modified Otago Exercise Program. The 30-second optical reaction time assessment using a ReactionX device demonstrated improved neuromuscular responsiveness following the intervention. The addition of ankle-weighted resistance may have increased motor unit recruitment and neuromuscular activation during training that led to an improvement in communication efficiency between the nervous system and the muscular system.

Repeated exposure to coordinated movement tasks promotes motor learning and facilitates the development of more efficient movement patterns. As neuromuscular coordination improves, reaction time is reduced and responsiveness to environmental stimuli is enhanced. These findings are consistent with the report by Wang and Kim (19), who demonstrated that exercise interventions emphasizing neuromuscular control improved reaction time and motor performance in older adults.

In addition, repetitive balance and functional movement training have been reported to facilitate neural adaptation and movement pattern stabilization through motor learning processes (2). Cadore et al. (2) also suggested that multicomponent exercise programs simultaneously stimulate neuromuscular, sensory, and musculoskeletal adaptations that result in substantial improvements in functional performance and fall prevention. Likewise, Chiu et al. (5) reported that combined strength and balance training significantly reduced fall risk while improving neuromuscular function in older populations.

Collectively, these findings suggest that incorporating ankle-weighted sandbags into the Otago Exercise Program may provide an additional training stimulus that enhances proprioceptive function, muscle strength, postural control, and neuromuscular responsiveness. Such adaptations are likely to contribute to improved balance performance and reduced fall risk among community-dwelling older adults.

Limitations in this Study

Several limitations in this study should be noted. The general good health of the young-old cohort (aged 60 to 69 years) combined with specific screening criteria (including a Timed Up and Go (TUG) Test threshold of 10 to 15 seconds and explicit volunteer interest) resulted in an extended timeline for sample recruitment.

CONCLUSIONS

The findings of the present study demonstrated that participation in an 8-week Otago Exercise Program combined with ankle-weighted sandbags significantly improved balance performance, lower-extremity muscle strength, and neuromuscular reaction time in older adults. These improvements are clinically meaningful because enhanced muscle strength, postural control, and reaction time are important factors associated with preventing falls and improving functional independence. In particular, the results suggest that incorporating ankle-weighted resistance into the Otago Exercise Program provides an effective strategy for enhancing physical function and reducing fall-related risk factors and related adverse health problems among community-dwelling older adults.

Practical Applications

The present findings indicate that health professionals, exercise specialists, and community-based elderly care programs may consider incorporating ankle-weighted resistance into the Otago Exercise Program to enhance balance, lower-extremity strength, and neuromuscular responsiveness in older adults. Because the program can be performed safely at home with minimal cost and equipment, it may represent a practical approach for promoting healthy aging and reducing fall-related risk factors in community-dwelling older populations.

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Effects of Blood Flow Restriction Combined with Proprioceptive Neuromuscular Facilitation on Recovery from Lower-Limb Fatigue in Collegiate Basketball Athletes

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ABSTRACT

Wei Rusong, Witid Mitranun, Supaporn Silalertdetkul, Achariya Anek. This study examined whether blood flow restriction (BFR) combined with proprioceptive neuromuscular facilitation (PNF) improves recovery from lower-limb exercise-induced fatigue in male collegiate basketball athletes. Two sequential studies were conducted. Study 1 compared the effects of BFR at 80 mmHg and 140 mmHg. Fourteen athletes completed a randomized crossover comparison of 80 and 140 mmHg BFR with a 7-day washout period. Study 2 applied the favorable BFR pressure identified in Study 1. BFR and PNF following simulated game-induced fatigue in 32 athletes randomly assigned to 4 Groups: BFR, PNF, BFR+PNF, and Control (n = 8 per Group). Recovery was assessed by perceived exertion, rectus femoris biomechanical characteristics, quadriceps electromyographic indicators, vertical jump height, 10-m sprint time, and T-test agility time. The results indicated that 80 mmHg produced better recovery of subjective fatigue, muscle tension, stiffness, elasticity, vertical jump height, and sprint performance than 140 mmHg. No adverse reactions occurred under 80 mmHg; whereas, mild numbness and pain occurred under 140 mmHg. The combined 80 mmHg BFR+PNF Group showed the most favorable recovery across subjective fatigue, muscle biomechanical characteristics, neuromuscular function, and basketball-specific performance ($P < 0.05$). PNF showed greater immediate neuromuscular recovery; whereas, 80 mmHg BFR showed better delayed recovery of muscle elasticity and sprint performance. In conclusion, the 80 mmHg condition produced more favorable recovery outcomes and was better tolerated than the 140 mmHg condition. Combining 80 mmHg BFR with PNF may provide a practical strategy for immediate and sustained recovery following basketball-specific fatigue.

Key Words: Basketball Athletes, Blood Flow Restriction, Exercise-Induced Fatigue, Proprioceptive Neuromuscular Facilitation

INTRODUCTION

Basketball requires repeated high-intensity movements, including sprinting, jumping, acceleration, deceleration, physical contact, and rapid changes of direction. During training and competition, athletes frequently perform these movements with limited recovery intervals that places substantial physiological and neuromuscular demands on the lower limbs (26). Such demands can lead to exercise-induced fatigue, which may reduce muscle force production, impair movement control, and decrease basketball-specific performance, including vertical jumping, sprinting, and agility (22,26). When recovery between training sessions or matches is insufficient, fatigue and training load may accumulate, which increases the likelihood of performance deterioration and lower-limb injury (8,22).

Exercise-induced fatigue is accompanied by alterations in the biomechanical and neuromuscular properties of skeletal muscle. Following repeated high-intensity activity, muscle tension and stiffness may increase while elasticity and force-generating capacity may decrease (5,13). These alterations can impair shock absorption, joint stability, and coordination during explosive movements. Fatigue may also be reflected by changes in average electromyographic amplitude (AEMG) and reductions in mean power frequency (MPF) that indicate altered neuromuscular activation and muscle fatigue status (1,5). Therefore, post-exercise recovery should be evaluated using a combination of subjective fatigue, muscle biomechanical characteristics, neuromuscular function, and sport-specific performance rather than a single indicator (1).

Proprioceptive neuromuscular facilitation (PNF) is widely used to improve flexibility and joint range of motion. This technique typically combines passive stretching, isometric contraction, relaxation, and assisted stretching. Previous studies have shown that appropriately applied PNF can improve muscle extensibility and range of motion (12,23). These effects may be related to mechanisms such as autogenic inhibition, reciprocal inhibition, and increased stretch tolerance, although the immediate effects of PNF on strength and neuromuscular performance may depend on stretching duration and protocol (11,25,28). These characteristics suggest that PNF may assist the immediate restoration of muscle extensibility following exercise-induced fatigue.

Blood flow restriction (BFR) has also received increased attention as a potential recovery strategy. BFR involves applying external pressure to the proximal portion of a limb to partially restrict arterial inflow and substantially restrict venous outflow (15,19). Following cuff release, reperfusion and reactive hyperemia may alter local circulation and potentially support the restoration of muscle function, although the underlying recovery mechanisms remain unclear (18,19). Unlike active recovery strategies that impose additional mechanical loading, passive BFR can be administered with minimal movement, which may be advantageous for fatigued athletes (15,18).

However, the physiological and perceptual effects of BFR depend considerably on the applied pressure. Insufficient pressure may provide an inadequate restriction stimulus while excessive pressure may increase ischemic stress, pain, numbness, and muscle discomfort (3,16). Although individualized pressures based on arterial or limb occlusion pressure are generally recommended to account for differences in limb size, cuff characteristics, and vascular responses, fixed absolute pressures remain common because they are simpler to administer (15,17,19). Nevertheless, limited evidence is available regarding the fixed BFR pressure that provides an appropriate balance between recovery effectiveness and safety in basketball athletes.

PNF and BFR may contribute to recovery through different but complementary pathways. PNF may produce relatively rapid improvements in muscle extensibility and range of motion (12,23,25). In contrast, post-exercise BFR may influence local circulation and the subsequent recovery of muscle function and physical performance (18). Combining the two interventions may provide broader recovery benefits than either method alone. However, most previous research has examined PNF and BFR separately, and direct comparisons among BFR alone, PNF alone, combined BFR and PNF, and passive rest following basketball-specific fatigue remain scarce.

In addition, previous studies have predominantly examined selected recovery indicators or assessed outcomes at a limited number of post-exercise time points (6,21). Basketball fatigue research has included performance, physiological, athlete-reported, and neuromuscular outcomes, but few studies have simultaneously evaluated subjective fatigue, muscle biomechanical characteristics, neuromuscular function, and basketball-specific performance across immediate, 24-hr recovery period, and 48-hr recovery period. Because central and peripheral components of neuromuscular fatigue can recover at different rates, assessments conducted at only one time point may not distinguish an acute response from sustained functional recovery (4).

For basketball athletes who may be required to train or compete repeatedly within a short period, identifying a safe and effective recovery strategy is important for restoring lower-limb function and maintaining performance. Therefore, this research comprised two sequential studies. Study 1 identified an appropriate BFR pressure for recovery from lower-limb exercise-induced fatigue; whereas, Study 2 examined the recovery effects of BFR alone, PNF alone, combined BFR and PNF, and passive rest following simulated basketball game-induced fatigue.

METHODS

Participants and Study Design

Two sequential studies were conducted with male collegiate basketball athletes 19 to 22 years of age. Sample size was estimated using G*Power 3.1.9.6 with $\alpha = 0.05$ and power = 0.80. The minimum required sample sizes were 12 participants for Study 1 based on a within-subject crossover design ($f = 0.30$) and 7 participants per group for Study 2 based on a four-group between-subject design ($f = 0.35$). Allowing for potential dropout, 14 athletes were recruited for Study 1 and 32 athletes were recruited for Study 2. In Study 1, 14 athletes completed a randomized crossover trial comparing blood flow restriction (BFR) at 80 mmHg and 140 mmHg, with a 7-day washout period between the conditions. In Study 2, 32 athletes were randomly assigned to a BFR Group, proprioceptive neuromuscular facilitation (PNF) Group, combined BFR+PNF Group, or passive-rest Control Group (n = 8 per Group). The participants had no lower-limb injury during the previous 6 months and no contraindications to BFR (3,19). The study was approved by the Human Research Ethics Committee of Xiamen Institute of Technology (approval no. XIT-2025BS0110001), and it was conducted in accordance with the Declaration of Helsinki. All the participants provided written informed consent.

Procedures

Before testing, the participants completed a standardized warm-up. In Study 1, fatigue was induced using repeated 20-m sprints and maximal vertical jumps. Fatigue was confirmed when Rating of Perceived Exertion (RPE, 6-20) reached ≥17 (2), vertical jump height decreased to ≤70% of baseline, and 10-m sprint time increased by ≥0.5 sec. Then, the participants received either 80 mmHg or 140 mmHg BFR applied to the proximal thigh (19). The BFR cuffs were applied for 10 min while the participants remained seated quietly.

Study 2 adopted the BFR pressure selected from Study 1. The participants completed a 10-min basketball-specific fatigue protocol involving repeated sprints, jumps, rapid stops, lateral movements, and changes of direction. After fatigue induction, the BFR Group received 80 mmHg BFR for 10 min, based on the optimal pressure identified in Study 1; the PNF group received contract–relax stretching of the major lower-limb muscles (12,23,25). The PNF protocol targeted the rectus femoris, hamstrings, gastrocnemius, and other major lower-limb muscles using hold–relax and contract–relax techniques. Each target muscle group was stretched for 2 sets, with a 30-sec interval between sets, and the total PNF intervention lasted approximately 15 min. The Combined Group received BFR followed by PNF, and the Control Group rested passively.

In Study 1, the measurements were obtained at baseline, after fatigue induction, immediately after intervention, and at 24 and 48 hrs. Outcomes included RPE, rectus femoris muscle tension, stiffness, and elasticity measured using a MyotonPro device (27), vertical jump height, 10-m sprint time, and adverse responses. In Study 2, the measurements were obtained at the same time points. Outcomes included RPE, rectus femoris stiffness and elasticity, quadriceps average electromyographic amplitude (AEMG), and mean power frequency (MPF) (10), vertical jump height, 10-m sprint time, and T-test agility time (20).

Statistical Analyses

The data are presented as mean ± SD. Normality and homogeneity of variance were examined using the Shapiro–Wilk and Levene Tests, respectively (14,24). Paired-samples *t* tests were used to compare outcomes before and after fatigue induction. For the intervention comparison, a mixed two-way repeated-measures ANOVA was used to examine the effects of intervention group, post-fatigue recovery time, and their interaction (9). *Post hoc* comparisons were conducted when significant main or interaction effects were detected. A Chi-Square Test was used to compare the incidence of adverse reactions between pressure conditions. Statistical significance was set at $P < 0.05$.

RESULTS

Study 1: Selection of the Optimal BFR Pressure

Effectiveness of Fatigue Induction

All 14 the participants completed both BFR conditions without dropout. Following the fatigue protocol, all the participants met the predefined fatigue criteria, including an RPE score ≥ 17, a reduction in vertical jump height to ≤ 70% of baseline, and an increase in 10-m sprint time of ≥ 0.5 sec. Compared with baseline, RPE, rectus femoris tension, and rectus femoris stiffness increased significantly; whereas, muscle elasticity and vertical jump height decreased significantly. The 10-m sprint time also increased significantly (all $P < 0.001$), confirming successful induction of lower-limb fatigue (Table 1).

Table 1. Changes in Selected Outcomes Before and After Fatigue Induction in Study 1 (N = 14).

Outcome	Before Fatigue	After Fatigue	Change (%)	P Value
RPE (points)	8.3 ± 1.2	18.6 ± 0.6	124.1	<0.001
Rectus Femoris Tension (Hz)	24.6 ± 1.1	29.9 ± 1.4	21.5	<0.001
Rectus Femoris Stiffness (N/m)	326.5 ± 20.1	390.2 ± 25.3	19.5	<0.001
Rectus Femoris Elasticity	0.32 ± 0.03	0.28 ± 0.02	−12.5	<0.001
Vertical Jump Height (cm)	62.5 ± 2.0	43.2 ± 1.7	−30.9	<0.001
10-m Sprint Time (sec)	1.61 ± 0.04	2.17 ± 0.06	34.8	<0.001

Values are presented as M ± SD. **RPE** = Rating of Perceived Exertion.

Subjective Fatigue

Significant effects of BFR pressure, recovery time, and their interaction were observed for RPE, $F(1,13) = 31.256$, $F(3,39) = 168.532$, and $F(3,39) = 8.364$, respectively (all, $P < 0.001$). Immediately after the intervention, RPE decreased to 11.2 ± 1.0 in the 80 mmHg condition and 10.7 ± 0.9 in the 140 mmHg condition, with no significant between-condition difference ($P = 0.186$). At 24 hrs, RPE was significantly lower under 80 mmHg than under 140 mmHg (8.4 ± 1.1 vs. 9.7 ± 1.2, $P = 0.003$). At 48 hrs, RPE under 80 mmHg was not significantly different from the baseline (8.2 ± 1.0, $P = 0.425$); whereas, RPE under 140 mmHg remained significantly elevated (8.8 ± 1.1, $P = 0.021$).

Muscle Biomechanical Characteristics

The 80 mmHg condition produced better recovery of muscle tension, stiffness, and elasticity than the 140 mmHg condition. At 48 hrs, rectus femoris tension under 80 mmHg was not significantly different from baseline (24.8 ± 1.0 Hz, $P = 0.356$); whereas, it remained significantly elevated under 140 mmHg (26.4 ± 1.2 Hz, $P = 0.008$).

A significant pressure-by-time interaction was observed for muscle stiffness, $F(3,39) = 7.628$, $P < 0.001$. Immediately after the intervention, stiffness decreased to 341.8 ± 21.5 N/m under 80 mmHg and 366.5 ± 23.8 N/m under 140 mmHg ($P = 0.012$). At 48 hrs, stiffness under 80 mmHg was not significantly different from baseline (327.6 ± 19.6 N/m, $P = 0.482$) while stiffness under 140 mmHg remained significantly elevated (346.3 ± 21.2 N/m, $P = 0.015$).

Muscle elasticity also recovered more completely under 80 mmHg. At 48 hrs, elasticity under 80 mmHg was not significantly different from baseline (0.32 ± 0.03, $P = 0.518$); whereas, it remained below baseline under 140 mmHg (0.30 ± 0.02, $P = 0.028$).

Sports Performance
A significant pressure-by-time interaction was observed for vertical jump height, $F(3,39) = 9.256$, $P < 0.001$. Immediately after the intervention, vertical jump height was significantly greater under 80 mmHg than under 140 mmHg (57.1 ± 2.1 vs. 55.3 ± 1.8 cm, $P = 0.023$). At 48 hrs, vertical jump height under 80 mmHg was not significantly different from baseline (62.3 ± 2.0 cm, $P = 0.385$); whereas, it remained significantly reduced under 140 mmHg (58.5 ± 2.2 cm, $P = 0.006$).

The 10-m sprint time recovered more rapidly under 80 mmHg at all measurement points ($P < 0.05$). At 48 hrs, sprint time under 80 mmHg was not significantly different from baseline (1.62 ± 0.04 sec, $P = 0.452$), while sprint time under 140 mmHg remained significantly longer than baseline (1.74 ± 0.05 sec, $P = 0.003$).

Adverse Reactions and Pressure Selection
No participants reported numbness or pain under 80 mmHg. Under 140 mmHg, 3 of the participants (21.4%) reported mild numbness, and 1 participant (7.1%) reported mild pain immediately after the intervention. All the symptoms were resolved within 24 hrs. The incidence of adverse reactions differed significantly between the 2 pressures ($\chi^2 = 4.667$, $P = 0.031$). Based on the recovery and safety outcomes, 80 mmHg was selected as the BFR pressure for Study 2.

Study 2: Effects of Different Recovery Interventions

Baseline Comparability and Fatigue Induction
In Study 2, 32 participants were randomly assigned to the BFR, PNF, BFR+PNF, or Control Group (n = 8 per Group). No significant differences were observed among the Groups in age, height, body mass, training experience, or baseline outcome values ($P > 0.05$). Following fatigue induction, all 4 Groups met the predefined fatigue criteria, with no significant between-Group differences ($P > 0.05$).

To illustrate the physiological and performance changes induced by the fatigue protocol, pre- and post-fatigue outcomes in the combined Group are presented in Table 2. In this Group, RPE, rectus femoris stiffness, 10-m sprint time, and T-test agility time increased significantly after fatigue, while rectus femoris elasticity, quadriceps AEMG, quadriceps MPF, and vertical jump height decreased significantly (all $P \leq 0.002$; Table 2).

Table 2. Changes Before and After Simulated Game Fatigue in the Combined Group (n = 8).

Outcome	Before Fatigue	After Fatigue	Change (%)	P Value
RPE (points)	8.2 ± 1.1	18.4 ± 0.7	124.4	<0.001
Rectus Femoris Stiffness (N/m)	325.3 ± 19.6	379.5 ± 24.2	16.7	<0.001
Rectus Femoris Elasticity Index	0.33 ± 0.03	0.29 ± 0.02	−12.1	0.001
Quadriceps AEMG (μV)	126.5 ± 10.1	99.2 ± 8.5	−21.6	<0.001
Quadriceps MPF (Hz)	85.6 ± 6.1	76.8 ± 5.7	−10.3	0.002
Vertical Jump Height (cm)	62.3 ± 2.1	49.1 ± 1.8	−21.2	<0.001
10-m Sprint Time (sec)	1.60 ± 0.04	2.14 ± 0.05	33.8	<0.001
T-Test Agility Time (sec)	10.1 ± 0.3	12.7 ± 0.4	25.7	<0.001

Note. Values are presented as M ± SD. **AEMG** = Average Electromyographic Amplitude; **MPF** = Mean Power Frequency; **RPE** = Rating of Perceived Exertion.

Subjective Fatigue

Significant effects of intervention, recovery time, and their interaction were observed for RPE, $F(3,28) = 132.568$, $F(3,84) = 226.345$, and $F(9,84) = 19.652$, respectively (all $P < 0.001$). The Combined Group showed significantly lower RPE than the other 3 Groups at all post-intervention measurement points ($P < 0.05$). At 48 hrs, RPE had decreased substantially in all 3 Intervention Groups; whereas, it remained significantly higher in the Control Group (Table 3).

Table 3. RPE Values Following Different Recovery Interventions in Study 2 (n = 8 per Group).

Group	After Fatigue	Immediately	24 hours	48 hrs
BFR	18.5 ± 0.6	11.4 ± 0.9	9.1 ± 1.0	8.3 ± 1.1
PNF	18.3 ± 0.7	11.7 ± 1.0	9.4 ± 1.1	8.4 ± 1.0
BFR+PNF	18.4 ± 0.7	10.1 ± 0.8*	8.2 ± 1.0*	8.1 ± 0.9*
Control	18.6 ± 0.6	16.4 ± 0.8	13.5 ± 1.0	11.1 ± 1.0

Note. Values are presented as M ± SD. **BFR** = Blood Flow Restriction; **PNF** = Proprioceptive Neuromuscular Facilitation; **RPE** = Rating of Perceived Exertion. * $P < 0.05$ compared with the **BFR**, **PNF**, and Control Groups at the corresponding time point.

Muscle Biomechanical Characteristics

A significant intervention-by-time interaction was observed for rectus femoris stiffness, $F(9,84) = 23.568$, $P < 0.001$. Immediately after the intervention, stiffness was significantly lower in the Combined Group (331.6 ± 20.1 N/m) than in the BFR Group (347.8 ± 22.3 N/m), PNF group (351.5 ± 23.0 N/m), and control group (370.2 ± 24.1 N/m) ($P < 0.01$). At 48 hrs, rectus femoris stiffness in the Combined Group was not significantly different from baseline (326.5 ± 19.5 N/m, $P = 0.425$); whereas, stiffness remained higher than baseline in the BFR, PNF, and Control Groups.

The Combined Group also demonstrated the greatest recovery in muscle elasticity. At 48 hrs, rectus femoris elasticity in the Combined Group was not significantly different from baseline (0.33 ± 0.03, $P = 0.518$), compared with 0.32 ± 0.02 in the BFR Group, 0.31 ± 0.02 in the PNF Group, and 0.29 ± 0.02 in the Control Group ($P < 0.001$).

Neuromuscular Function

A significant intervention-by-time interaction was observed for quadriceps AEMG, $F(9,84) = 18.652$, $P < 0.001$. Immediately after intervention, AEMG was significantly higher in the PNF Group than in the BFR Group (117.8 ± 9.0 vs. 111.5 ± 8.6 μV, $P = 0.021$). At 24 and 48 hrs, the Combined Group showed the greatest recovery. At 48 hrs, AEMG in the Combined Group was not significantly different from baseline (125.8 ± 10.0 μV, $P = 0.452$) and was significantly higher than in the BFR and PNF Groups ($P < 0.05$).

A similar pattern was observed for MPF. Immediately after intervention, MPF was significantly higher in the PNF Group than in the BFR Group (82.3 ± 5.5 vs. 79.1 ± 5.2 Hz, $P = 0.028$). At 48 hrs, MPF in the Combined Group was not significantly different from baseline (85.3 ± 6.0 Hz, $P = 0.486$); whereas, MPF in the Control Group remained significantly reduced (78.3 ± 5.8 Hz, $P = 0.008$).

Sports Performance

A significant intervention-by-time interaction was observed for vertical jump height, $F(9,84) = 25.682$, $P < 0.001$. The Combined Group showed significantly greater vertical jump height than the other Groups at all post-intervention time points ($P < 0.05$). At 48 hrs, vertical jump height in the Combined Group was not significantly different from baseline (62.1 ± 2.1 cm, $P = 0.385$; Table 4).

Table 4. Vertical Jump Height Following Different Recovery Interventions in Study 2 (n = 8 per Group).

Group	After Fatigue	Immediately	24 hrs	48 hrs
BFR	48.8 ± 1.7	55.9 ± 1.8	59.2 ± 2.0	60.5 ± 2.1
PNF	49.3 ± 1.8	55.5 ± 1.9	58.8 ± 2.1	60.2 ± 2.0
BFR+PNF	49.1 ± 1.8	58.6 ± 2.0*	61.2 ± 2.1*	62.1 ± 2.1*
Control	48.9 ± 1.7	50.1 ± 1.6	53.5 ± 1.8	56.8 ± 1.9

Note. Values are presented as M ± SD. **BFR** = Blood Flow Restriction; **PNF** = Proprioceptive Neuromuscular Facilitation. * $P < 0.05$ compared with the BFR, PNF, and Control Groups at the corresponding time point.

At 24 and 48 hrs, 10-m sprint recovery was significantly greater in the BFR Group than in the PNF Group ($P < 0.05$), while the Combined Group demonstrated the most favorable recovery.

At 48 hrs, sprint time in the Combined Group was not significantly different from baseline (1.61 ± 0.04 sec, $P = 0.425$), compared with 1.67 ± 0.05 sec in the BFR Group, 1.71 ± 0.06 sec in the PNF Group, and 1.94 ± 0.07 sec in the Control Group ($P < 0.001$).

The Combined Group also demonstrated the greatest recovery in T-test agility performance. At 48 hrs, agility time in the Combined Group was not significantly different from baseline (10.2 ± 0.3 sec, $P = 0.458$); whereas, it remained significantly prolonged in the Control Group (11.7 ± 0.4 sec, $P = 0.003$). Overall, the combined intervention produced the greatest recovery across subjective fatigue, muscle biomechanical characteristics, neuromuscular function, and basketball-specific performance.

DISCUSSION

The present study found that moderate-pressure BFR at 80 mmHg was associated with more favorable recovery outcomes and fewer adverse reactions than high-pressure BFR at 140 mmHg following lower-limb exercise-induced fatigue. In addition, the combined BFR+PNF intervention resulted in the greatest overall improvements in subjective fatigue, muscle biomechanical characteristics, neuromuscular function, and basketball-specific performance. Collectively, these results indicate that moderate-pressure BFR may provide a more appropriate balance between recovery effectiveness and tolerability, while combining BFR with PNF may offer broader recovery benefits than either intervention alone or passive rest.

Effects of BFR Pressure

Both BFR pressures reduced RPE immediately after the intervention, indicating that BFR may support short-term recovery after exercise-induced fatigue. However, the subsequent recovery patterns differed between the two pressure conditions. At 24 and 48 hrs, the 80 mmHg condition was associated with more complete recovery of RPE, rectus femoris tension, stiffness, elasticity, vertical jump height, and 10-m sprint performance. In contrast, several outcomes remained different from baseline following 140 mmHg BFR.

The divergent recovery patterns may reflect pressure-dependent vascular and perceptual responses to BFR. BFR partially restricts arterial inflow and limits venous return, thereby altering local hemodynamics (19). Following cuff release, reactive hyperemia may increase local blood flow and potentially facilitate post-exercise metabolic recovery (18). Moderate pressure may provide sufficient vascular stimulation while limiting excessive ischemic or mechanical stress. In contrast, higher pressure may increase tissue compression, discomfort, and strain on neural and vascular structures that may reduce the potential recovery benefit (3,16).

The adverse-reaction findings further support this interpretation. No participants reported numbness or pain under 80 mmHg, whereas mild numbness and pain occurred under 140 mmHg. These findings indicate that greater restriction pressure was not associated with superior recovery. Rather, 80 mmHg appeared to provide a more favorable balance between recovery and safety in the present sample.

Subjective Fatigue and Muscle Biomechanical Recovery

The combined BFR+PNF Group showed the greatest reduction in RPE across all post-intervention time points. Perceived fatigue reflects the combined influence of metabolic stress, muscle discomfort, neuromuscular fatigue, and perceived effort (1). PNF may reduce muscular tightness through contraction-relaxation procedures and inhibitory neuromuscular mechanisms (11,25); whereas, BFR may support local circulatory and metabolic recovery following cuff release (18). The additive influence of these mechanisms may partly explain the greater reduction in subjective fatigue observed in the Combined Group.

Fatigue induction also increased rectus femoris stiffness and reduced muscle elasticity. These changes may impair shock absorption, force transmission, and movement efficiency during explosive lower-limb actions (13). The combined intervention was associated with the greatest recovery of these biomechanical characteristics, with stiffness and elasticity showing no significant differences from baseline at 48 hrs.

PNF may improve muscle extensibility by increasing stretch tolerance and reducing resistance to muscle lengthening through autogenic and reciprocal inhibition (11,25). In comparison, the effects of BFR may be more closely related to vascular and metabolic processes that develop over time (18). This interpretation is consistent with the finding that BFR alone was associated with greater delayed recovery of muscle elasticity than PNF alone. Thus, combining PNF with BFR may integrate the immediate effects of neuromuscular relaxation with the delayed recovery effects associated with post-occlusion vascular responses.

Neuromuscular Function

The simulated basketball fatigue protocol reduced AEMG and MPF, indicating impaired neuromuscular activation and increased muscle fatigue. Lower AEMG may reflect reduced motor unit recruitment or firing activity; whereas, lower MPF is commonly associated with reductions in muscle fiber conduction velocity during fatigue (5).

Immediately after the intervention, the PNF Group showed higher AEMG and MPF than the BFR Group. This finding indicates that PNF may facilitate more immediate neuromuscular recovery. PNF involves passive stretching, isometric contraction, relaxation, and assisted stretching, all of which provide proprioceptive input and may influence neuromuscular coordination through inhibitory and afferent mechanisms (11,25).

In contrast, the effects of BFR appeared to become more evident during later recovery. This pattern may reflect the time required for vascular and metabolic responses to influence muscle function (18). At 24 and 48 hrs, the combined group showed the greatest neuromuscular recovery, and both AEMG and MPF were not significantly different from baseline. These results suggest that the immediate neuromuscular effects of PNF and the delayed recovery effects of BFR may be complementary.

Basketball-Specific Performance

The fatigue protocol reduced vertical jump height and increased 10-m sprint and T-test agility times, indicating impaired explosive power, acceleration, and change-of-direction ability. These capacities are central to basketball performance, which requires repeated jumping, sprinting, braking, and rapid changes of direction during training and competition (22,26).

The combined intervention was associated with the greatest recovery across all 3 performance outcomes. Vertical jump height was higher in the Combined Group than in the other Groups at all post-intervention time points and was not significantly different from baseline at 48 hrs. Similarly, 10-m sprint and T-test agility performance showed the most favorable recovery in the Combined Group.

Recovery of vertical jump performance depends on the restoration of muscle elasticity, force production, and neuromuscular activation (7). Improvements in stiffness, elasticity, AEMG, and MPF may partly account for the superior recovery of vertical jump performance observed after the combined intervention. Sprint and agility performance also require rapid force production, braking control, coordination, and repeated neuromuscular responses. By influencing several components of lower-limb function, the combined intervention may have supported more comprehensive recovery than either intervention alone.

The BFR Group showed better 10-m sprint recovery than the PNF Group at 24 and 48 hrs. This finding suggests that BFR may be more relevant to delayed performance recovery, while PNF may provide greater immediate neuromuscular benefits. From an applied perspective, the selection of a recovery method may therefore depend on the available recovery period. PNF may be useful when immediate neuromuscular restoration is required, while BFR may be more beneficial when recovery is monitored over the following 24 to 48 hrs. The combined protocol may be preferable when both immediate and sustained recovery are important.

Comparison With Passive Rest and Practical Implications

The Control Group showed slower recovery than the Intervention Groups. At 48 hrs, several outcomes remained different from baseline, including RPE, muscle biomechanical characteristics, neuromuscular indicators, and basketball-specific performance. These findings suggest that passive rest alone may be insufficient for rapid recovery following high-intensity basketball-specific fatigue.

From a practical perspective, the findings support the potential use of 80 mmHg BFR combined with PNF as a recovery strategy for male collegiate basketball athletes. The combined intervention may be especially applicable in congested training or competition schedules, where restoration of lower-limb function within 24 to 48 hrs is required.

However, fixed BFR pressure should be applied cautiously because physiological responses to a given pressure may vary according to limb circumference, cuff width, blood pressure, and individual vascular characteristics (17,19). Practitioners should therefore monitor discomfort and adverse reactions and consider individualized occlusion pressure when appropriate equipment and expertise are available (3,17).

Limitations and Future Directions

Several limitations should be acknowledged. The relatively small sample size and inclusion of male collegiate basketball athletes only may limit the generalizability of the findings. Additionally, fixed BFR pressures were used, and recovery was assessed only through 48 hrs. Future research should include larger and more diverse samples, compare fixed and individualized occlusion pressures, and examine the longer-term effects of repeated BFR+PNF interventions.

Summary

The present study demonstrates that moderate-pressure BFR at 80 mmHg results in more favorable recovery outcomes and fewer adverse reactions than high-pressure BFR at 140 mmHg, while the combined BFR+PNF intervention produces the greatest overall recovery of subjective fatigue, muscle biomechanical characteristics, neuromuscular function, and basketball-specific performance.

CONCLUSIONS

Moderate-pressure BFR at 80 mmHg resulted in more favorable recovery outcomes and fewer adverse reactions than high-pressure BFR at 140 mmHg, while the combined BFR+PNF intervention produced the greatest improvements in subjective fatigue, muscle biomechanical characteristics, neuromuscular function, and basketball-specific performance. The findings support combined BFR+PNF as a practical recovery strategy for basketball athletes, particularly in response to the repeated high-intensity demands of training and competition. From an exercise physiology perspective, the observed recovery pattern may reflect complementary biomechanical, neuromuscular, and vascular-metabolic mechanisms. These findings underscore the potential value of combined recovery interventions for restoring lower-limb function and maintaining performance in athletes exposed to repeated high-intensity activity.

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Physiological Responses under Comfort-Selected and Grip Performance-Selected Pillow Conditions: Cervical Muscle Activity and Local Oxygenation

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ABSTRACT

Sauto BP, Sirirat Kiatkulanusorn S, Suttawong N, Aewzipo S, Kleawyothatis W, Sukkho O. This study investigated the effects of pillow selection based on perceived comfort and grip performance on muscle activity and oxygenation of the sternocleidomastoid (SCM) and upper trapezius (UT) in a supine position. Thirty (n = 30) healthy participants 18 to 45 years of age were included. Muscle activity was assessed using electromyography (%MVC), and muscle oxygen saturation (SmO_2) was measured using near-infrared spectroscopy. Measurements were obtained from the SCM and UT under 2 pillow selection conditions (comfort-based and grip performance-based) across rest, wrist extension, and recovery phases. No significant differences were observed between the 2 pillow selection methods for either muscle activity or oxygenation across all phases ($P > 0.05$). However, very strong positive correlations were found between the methods for both %MVC and SmO_2 ($r = 0.78 – 1.00$, $P < 0.001$), indicating highly consistent physiological responses. The SCM demonstrated higher muscle activity; whereas, the UT exhibited higher oxygen saturation across all conditions ($P < 0.05$). Significant differences between muscle activity and oxygenation were observed in all phases ($P < 0.001$), with weak-to-moderate correlations were primarily identified in the SCM during the rest phase. No significant associations were found during wrist extension, and only weak and inconsistent correlations were observed during recovery. These findings suggest that pillow selection based on subjective comfort and grip performance produces comparable physiological outcomes, with muscle-specific and phase-dependent responses reflecting the complex interaction between neuromuscular activation and oxygen dynamics.

Key Words: Cervical Support, Grip Strength, Perceived Comfort, Pillow Selection

INTRODUCTION

Pillows are essential for maintaining appropriate head and cervical spine alignment during prolonged supine rest and sleep (5,19). Adequate support helps to preserve neutral cervical posture, minimize unnecessary muscular activity, and maintain local tissue perfusion in the neck and shoulder region (2,5). In contrast, insufficient or inappropriate pillow support may alter cervical alignment, increase muscular demand, and impair local circulation, which potentially contributes to discomfort, sleep disturbance, and the development or persistence of musculoskeletal symptoms, particularly in the cervical region (11). Individually selected pillows that provide suitable contour, comfort, and cervical lordosis support may improve sleep-related outcomes by reducing neck pain and headache, thus enhancing perceived sleep quality (17).

In both clinical practice and consumer settings, pillow selection is predominantly based on perceived comfort. In fact, comfort is a major determinant of user preference and long-term adherence, thus representing a multidimensional construct shaped by sensory input, prior experience, and individual expectations (12). However, comfort remains inherently subjective and may not necessarily reflect biomechanical or physiological optimization. A pillow perceived as comfortable may still impose an excessive muscular demand or provide suboptimal cervical support. Hence, reliance on comfort alone may be insufficient for identifying the most physiologically favorable pillow condition (24).

An alternative approach is to incorporate functional performance measures into pillow selection. Handgrip strength is a simple, reliable, and widely accepted indicator of neuromuscular function (1,13,21). Distal force production depends partly on proximal stability, postural control of the upper limb and trunk, and efficient neuromuscular coordination (21). Moreover, complex neural coupling between the distal and the proximal upper extremity musculature may influence grip force control during movements (21). From this perspective, the assessment of grip performance in the supine position under different pillow conditions may indirectly reflect the adequacy of head and neck support (16). A pillow associated with greater grip strength may indicate a more favorable neuromuscular and biomechanical state that supports its potential use as an objective adjunctive criterion for pillow selection (4,25).

To evaluate the physiological consequences of different pillow selection strategies, objective outcome measures are required. Surface electromyography (EMG) provides information regarding muscular activation and loading demand; whereas, near-infrared spectroscopy-derived muscle oxygen saturation (SmO_2) reflects the balance between local oxygen delivery and utilization (6,23). These measures provide complementary insights. For example, the EMG characterizes neuromuscular effort, while the SmO_2 captures the underlying physiological conditions related to perfusion and metabolic demand (6,23). Assessing these responses in the key cervical muscles, that is, the sternocleidomastoid (SCM) and the upper trapezius (UT), may provide a comprehensive understanding of cervical support under different pillow conditions (2,3,7).

Despite the practical relevance of both subjective comfort and functional performance, it remains unknown whether pillow conditions selected according to maximal comfort and those selected according to maximal grip performance produce comparable physiological responses. In addition, the extent to which responses under these two selection strategies are associated within individuals has not been established. Addressing these gaps may help to facilitate the development of a more objective, individualized, and physiologically informed approach to pillow selection.

Therefore, the primary purpose of this study was: (a) to compare SCM and UT muscle activity and local oxygen saturation (SmO_2) between comfort-selected and grip performance-selected pillow conditions; and (b) to examine correlations in the physiological responses between the 2 selection methods. Also, the secondary purpose of this study was (a) to explore the relationship between the SCM responses and the UT responses; and (b) to investigate associations between the muscle activity and local oxygenation.

METHODS

Participants

This study was conducted in a cohort of healthy adults to isolate the physiological effects of pillow conditions without interference from underlying musculoskeletal or systemic disorders. A total of 30 participants 18 to 45 years of age were enrolled.

The participants were eligible if they had been free from neck pain and related conditions, such as cervical spondylosis, office syndrome, or frozen shoulder for at least 3 months. Additional requirements included a body mass index between 18.0 and 24.9 kg/m² and the ability to remain in a supine position for a minimum of 30 minutes without discomfort.

Individuals were excluded if they reported a history of cervical trauma, spinal infection, surgery, or congenital spinal abnormalities. Additional exclusion criteria included hematological conditions that could influence muscle oxygenation (SmO_2), use of medications known to alter heart rate, tobacco or vaping use, and allergy to adhesive materials or latex. All the participants provided written informed consent prior to their participation.

Sample size was determined using pilot data for SCM muscle SmO_2 measured under 2 pillow conditions (52.12 ± 17.67 vs. 88.62 ± 19.12). Based on an effect size of 0.426, with $\alpha = 0.05$ and statistical power set at 0.80, a minimum of 25 participants was required. To mitigate potential data loss, 30 individuals were recruited.

Study Design

A within-subject, repeated-measures design was employed to evaluate the physiological responses under the 2 pillow conditions. Each participant was tested using 2 pillows (A and B), enabling direct within-individual comparisons while minimizing between-subject variability. Based on individual responses, conditions were later classified as comfort-selected and grip performance-selected for analysis. The study was conducted in accordance with the principles of the Declaration of Helsinki (1964, revised) and received ethical approval from the Human Ethics Committee of Burapha University (Protocol No. HS078/2567(C2); Approval No. IRB1-116/2567). Written informed consent was obtained from all the subjects prior to participation.

Experimental Procedure

A 3-phase protocol (rest, active, and recovery) was used to evaluate neuromuscular and physiological responses under different pillow conditions, reflecting low-load cervical demands typical of pre-sleep activities. The rest phase established baseline values, the active phase elicited cervical muscle engagement, and the recovery phase assessed reoxygenation and return toward baseline.

Testing was conducted in a standardized supine position on a treatment table, with the arms resting alongside the body. The pillow conditions were applied in randomized order. Pillow placement was adjusted to support the cervical curve, with the lower edge aligned to the C7 spinous process and the midline centered along the sagittal axis. Body alignment was standardized using markers at key anatomical landmarks to ensure consistent positioning across trials.

Each trial began with 5 controlled breathing cycles combined with gentle isometric head contact to standardize posture. The protocol consisted of a 5-minute rest (Rest Phase), followed by 90 seconds of low-load wrist extension using a 0.25 kg dumbbell at 30 beats per minute (Wrist Extension Phase), and a 3-minute recovery period (Recovery Phase). The participants maintained visual fixation to minimize head movement and performed light cognitive engagement (backward counting) to prevent drowsiness.

To minimize carryover effects, a washout period (1 minute sitting, 1 minute treadmill walking, and 1 minute sitting) was applied between conditions to restore circulation and neuromuscular baseline. Both conditions were completed within a single session under controlled environmental conditions (22–25 °C, dim lighting, and minimal noise).

Following the recovery phase, grip strength was measured in the supine position using a digital dynamometer (Takei Scientific Instruments, Japan). The participants performed 3 maximal contractions with the arm positioned alongside the body, and the mean value was used for analysis. Perceived comfort was then assessed using a 100-mm visual analog scale (VAS). Based on these measures, conditions were classified at the individual level: the comfort-selected condition corresponded to the higher VAS score; whereas, the grip performance-selected condition was defined by the higher mean grip strength.

Instrumentation and Measure

Pillow Conditions

Two conditions were derived from a single pillow design to isolate the effect of height. The base pillow consisted of Elasta Fiber™ polyester filling within a 100% cotton cover (19 × 29 inches; unloaded height: 6 inches). In the second condition, an additional polyester insert (~1.5 inches) was introduced to increase thickness without altering external appearance. Mechanical characteristics were evaluated through a compression test. A 12 N static load was applied centrally using a 12 cm diameter flat acrylic plate for 3 minutes. Each condition was tested 3 times, and mean compressed height was used as an index of firmness. Mean compressed heights were 4.7 ± 0.2 inches for the standard condition and 5.7 ± 0.2 inches for the augmented condition. External materials and surface features were identical across conditions to minimize visual and tactile cues.

Muscle Oxygenation (SmO_2)

Muscle oxygen saturation (SmO_2) was continuously measured using a wireless near-infrared spectroscopy device (Moxy, Fortiori Design LLC, USA), reflecting the balance between local oxygen delivery and utilization. Sensors were positioned over the left sternocleidomastoid (SCM) and upper trapezius (UT) following skin preparation with alcohol, aligned parallel to the muscle fibers, and secured with an opaque covering to minimize ambient light interference. Signals were sampled at 2 Hz and recorded across all phases. The data were averaged over 10-second windows within predefined segments: the middle 3 minutes of the rest phase, the middle 60 seconds of the active (wrist extension) phase, and the middle 2 minutes of the recovery phase. The device was calibrated prior to each session according to the manufacturer guidelines.

Electromyographic Data
Surface electromyography (EMG) signals were recorded from the sternocleidomastoid (SCM) and upper trapezius (UT) muscles on the right side using a wireless telemetry system (TELEMyo DTS, Noraxon Inc., Scottsdale, AZ, USA) at a sampling rate of 1500 Hz. A video camera (Intel® RealSense™ 3D Camera, Front F200 RGB, Dell Inc., USA; resolution: 1920 × 1080) was used to monitor posture during testing. Data acquisition and analysis were performed using MyoResearch XP software (version 3.8.3). Right-sided placement was selected to minimize electrocardiographic interference, while near-infrared spectroscopy (NIRS) was recorded on the contralateral side to avoid signal cross-talk. Hand dominance was determined by self-report. No significant differences in EMG or SmO_2 were observed between dominance groups ($P > 0.10$).

Electrode placement followed SENIAM guidelines. After shaving (if necessary) and cleaning the skin with alcohol, bipolar Ag/AgCl electrodes (Blue Sensor, Ambu A/S, Denmark) were applied with an interelectrode distance of 20 mm and secured with adhesive tape. Electrodes were positioned at one-third of the distance from the sternal notch to the mastoid process (SCM) and midway between the acromion and C7 spinous process (UT). A video camera was used to monitor posture and ensure consistency during testing.

Maximum voluntary contraction (MVC) was assessed for normalization. Participants performed two 3-second maximal isometric contractions against manual resistance, with at least 2 minutes of rest between trials. The highest value was used for normalization (%MVC). SCM MVC was obtained during ipsilateral lateral flexion with contralateral rotation against resistance, while UT MVC involved scapular elevation against resistance in a seated position. EMG signals were band-pass filtered (20–500 Hz), full-wave rectified, and processed to calculate root mean square (RMS) using a 50-ms moving window. For analysis, normalized EMG data were extracted from the middle portions of each phase: 3 minutes of rest, 60 seconds of the active phase, and 3 minutes of recovery.

To reduce potential bias, data extraction and processing were conducted by a researcher blinded to the pillow conditions. Pillow configurations were visually indistinguishable, and coded identifiers were used during analysis to maintain blinding.

Statistical Analysis
All statistical analyses were performed using appropriate statistical software. Statistical significance was set at $\alpha = 0.05$. Muscle activity was normalized and expressed as a percentage of maximum voluntary contraction (%MVC). Prior to analysis, data distribution was assessed for normality.

Comparisons between the comfort-selected and grip performance-selected conditions were conducted using paired *t*-tests for all primary variables, including SCM and UT muscle activity (%MVC) and SmO_2. Statistical analyses were performed for both overall values and phase-specific segments (rest, active, and recovery). Pearson correlation coefficients were used to examine relationships between variables under the two selection conditions, as well as associations between SCM and UT responses and between muscle activity (%MVC) and SmO_2. Correlation analyses were conducted using both pooled data and phase-specific values.

RESULTS

The participant characteristics are presented in Table 1. The data are presented as mean ± standard deviation (SD) for continuous variables and frequency (percentage) for categorical variables.

Table 1. Participant Characteristics.

Characteristic	Mean ± SD f(%)
Age (yr)	20.00 ± 1.31
Female	20 (66.7%)
Right Dominant Hand	30 (100%)
Weight (kg)	58.28 ± 7.55
Height (cm)	165.43 ± 7.12
BMI (kg/m²)	21.27 ± 1.98

Pillow selection outcomes are summarized in Table 2. The participants showed equal preference when selecting pillows based on comfort; whereas, a greater proportion selected the standard pillow when selection was based on grip performance.

Table 2. Pillow Selection Based on Perceived Comfort and Grip Performance.

Pillow Selection	Standard Pillow		Standard Pillow + Insert Pad	
	f(%)	Mean ± SD	f(%)	Mean ± SD
Better Comfort	15 (50%)	8.49 ± 0.89	15 (50%)	8.37 ± 0.79
Better Grip	21 (70%)	24.81 ± 7.45	9 (30%)	21.17 ± 5.04

The data are presented as frequency (percentage) and mean ± standard deviation (SD) for each pillow condition.

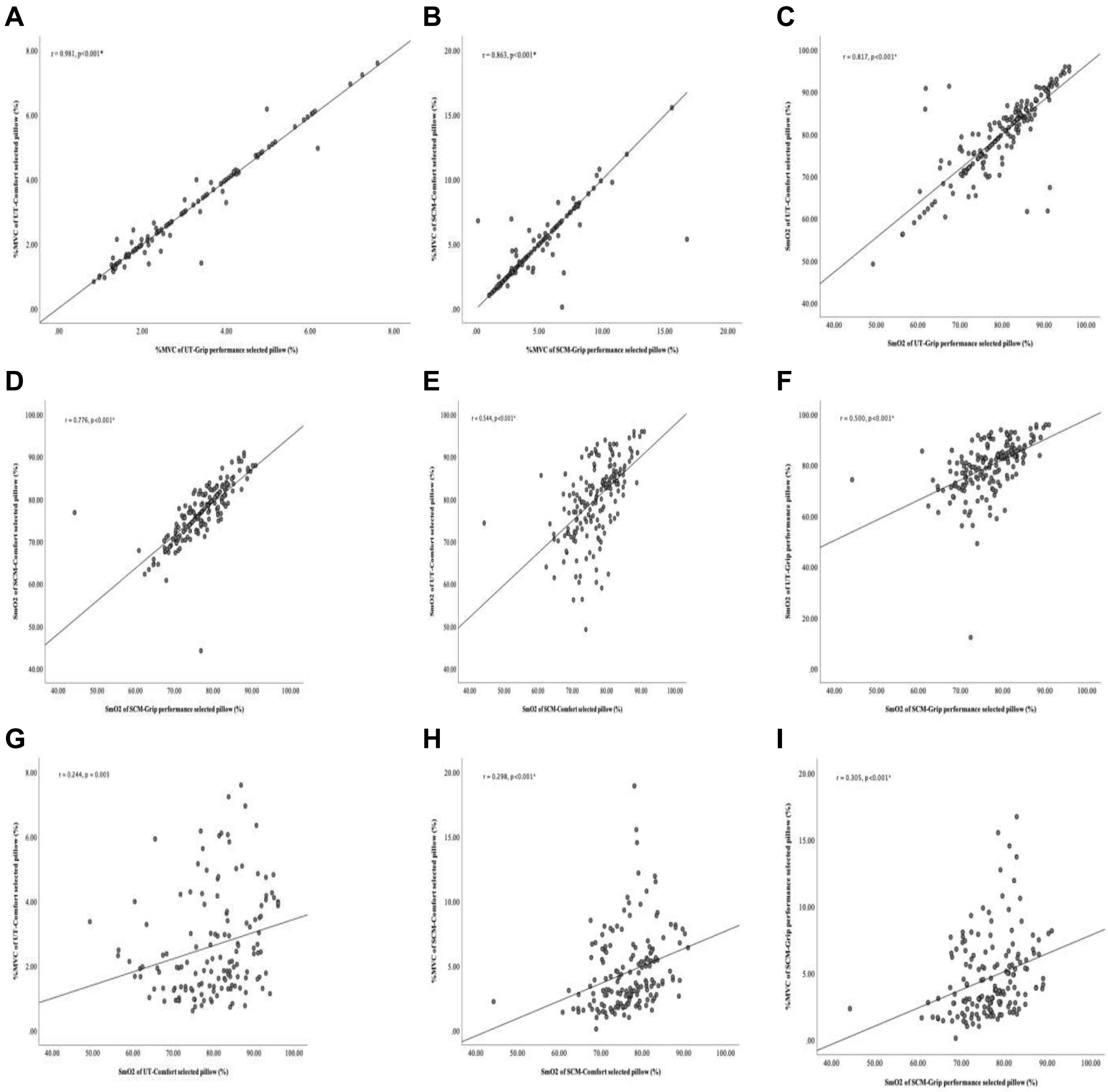

Figure 1. Correlation Between Comfort-Based and Grip Performance-Based Pillow Conditions Across All Phases.

Scatter plots illustrate the relationships in muscle activity (%MVC) and muscle oxygen saturation (SmO_2) for the upper trapezius (UT) and sternocleidomastoid (SCM). Each point represents an individual participant. Pearson correlation coefficients (r) indicate the strength of association between the 2 pillow selection methods.

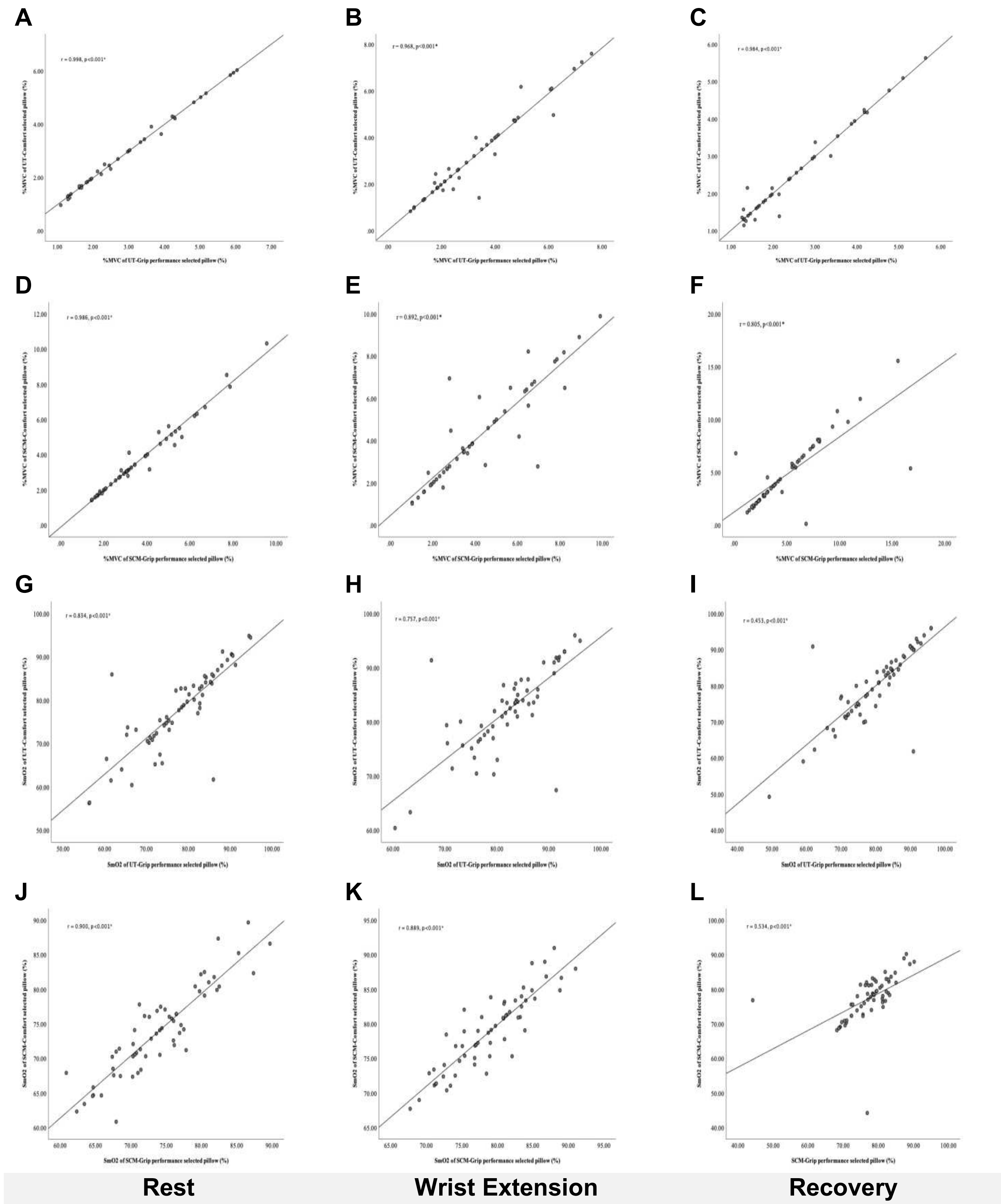

Figure 2. Correlation Between Comfort-Based and Grip Performance-Based Pillow Conditions Across Individual Phases.

Scatter plots show the relationships in muscle activity (%MVC) and muscle oxygen saturation (SmO_2) for the upper trapezius (UT) and sternocleidomastoid (SCM) during the rest, wrist extension, and recovery phases. Each point represents an individual participant. Pearson correlation coefficients (r) are presented for each phase.

Comparisons and relationships between comfort-based and grip-based pillow conditions are presented in Table 3. No significant differences were observed in muscle activity (%MVC) or muscle oxygen saturation (SmO_2) across all phases. However, very strong positive correlations were identified between the two selection methods for both variables, indicating highly consistent physiological responses.

Table 3. Comparison and Correlation Between Comfort-Based and Grip-Based Pillow Conditions Across Phases.

Phase	Parameter	Muscle	Comfort Pillow	Grip Performance Pillow	Comparison				Correlation	
			Mean ± SD	Mean ± SD	Mean dif. ± SD	95% CI	t	P	r	P
Overall	%MVC	UT	2.88 ± 1.55	2.90 ± 1.54	-0.02 ± 0.30	-0.07 to 0.03	-0.73	0.465	0.98	<0.001*
		SCM	4.33 ± 2.54	4.39 ± 2.72	-0.07 ± 1.39	-0.29 to 0.16	-0.58	0.566	0.86	<0.001*
	SmO_2	UT	80.08 ± 9.15	80.08 ± 9.15	0.00 ± 5.54	-0.82 to 0.82	0.00	0.999	0.82	<0.001*
		SCM	76.77 ± 6.55	76.77 ± 6.55	0.00 ± 4.39	-0.65 to 0.64	0.00	0.999	0.78	<0.001*
Rest	%MVC	UT	2.85 ± 1.47	2.86 ± 1.46	-0.01 ± 0.09	-0.04 to 0.02	-0.65	0.523	1.00	<0.001*
		SCM	3.76 ± 1.94	3.72 ± 1.85	0.03 ± 0.33	-0.06 to 0.13	0.70	0.490	0.99	<0.001*
	SmO_2	UT	77.82 ± 9.36	77.82 ± 9.36	0.00 ± 5.40	-1.39 to 1.40	0.00	0.999	0.83	<0.001*
		SCM	73.97 ± 6.4	73.96 ± 6.39	0.00 ± 2.86	-0.74 to 0.74	0.00	0.999	0.90	<0.001*
Wrist Extension	%MVC	UT	3.18 ± 1.80	3.22 ± 1.79	-0.04 ± 0.45	-0.18 to 0.09	-0.64	0.527	0.97	<0.001*
		SCM	4.28 ± 2.34	4.28 ± 2.34	0.00 ± 1.09	-0.31 to 0.32	0.01	0.996	0.89	<0.001*
	SmO_2	UT	82.39 ± 7.71	82.39 ± 7.71	0.00 ± 5.37	-1.40 to 1.40	0.00	1.000	0.76	<0.001*
		SCM	78.89 ± 5.43	78.89 ± 5.43	0.00 ± 2.56	-0.66 to 0.66	0.00	1.000	0.89	<0.001*
Recovery	%MVC	UT	2.54 ± 1.21	2.54 ± 1.21	0.00 ± 0.21	-0.07 to 0.07	-0.12	0.904	0.98	<0.001*
		SCM	4.91 ± 3.08	5.13 ± 3.49	-0.22 ± 2.09	-0.80 to 0.36	-0.75	0.454	0.81	<0.001*
	SmO_2	UT	80.07 ± 9.80	80.07 ± 9.80	0.00 ± 5.91	-1.53 to 1.53	0.00	0.999	0.45	<0.001*
		SCM	77.45 ± 6.85	77.45 ± 6.85	0.00 ± 6.61	-1.71 to 1.71	0.00	0.998	0.53	<0.001*

Muscle activity (%MVC) and muscle oxygen saturation (SmO_2) of the upper trapezius (UT) and sternocleidomastoid (SCM) are presented as mean ± SD. Between-condition comparisons and Pearson correlation coefficients (r) are reported for each phase (overall, rest, wrist extension, and recovery).

Differences and relationships between the upper trapezius (UT) and sternocleidomastoid (SCM) muscles are shown in Table 4. SCM demonstrated significantly higher muscle activity, while the UT exhibited significantly higher oxygen saturation across all phases. Moderate positive correlations in SmO_2 were observed between the muscles, while correlations in %MVC were generally weak or non-significant.

Table 4. Comparison and Correlation Between Upper Trapezius (UT) and Sternocleidomastoid (SCM) Muscles Under Different Pillow Selection Conditions.

Phase	Parameter	Pillow selection	UT	SCM	Comparison				Correlation	
			Mean ± SD	Mean ± SD	Mean dif ± SD	95% CI	t	P	r	P
Overall	%MVC	Comfort	2.60 ± 1.59	4.26 ± 3.09	-1.66 ± 3.30	-2.24 to -1.08	-5.71	<0.001*	0.12	0.189
		Grip	3.19 ± 1.88	4.72 ± 3.15	-1.53 ± 3.49	-2.16 to -0.90	-4.79	<0.001*	0.11	0.252
	SmO2	Comfort	80.08 ± 9.15	76.79 ± 6.56	3.29 ± 7.84	2.13 to 4.44	5.61	<0.001*	0.54	<0.001*
		Grip	79.71 ± 10.43	76.77 ± 6.55	2.94 ± 9.13	1.59 to 4.28	4.32	<0.001*	0.50	<0.001*
Rest	%MVC	Comfort	2.67 ± 1.64	3.63 ± 1.84	-0.96 ± 2.09	-1.65 to -0.26	-2.79	0.008*	0.28	0.089
		Grip	2.97 ± 1.72	3.86 ± 1.87	-0.89 ± 2.07	-1.58 to -0.20	-2.61	0.013*	0.33	0.044*
	SmO2	Comfort	77.82 ± 9.36	73.97 ± 6.40	3.85 ± 7.82	1.83 to 5.87	3.82	<0.001*	0.56	<0.001*
		Grip	77.82 ± 9.36	73.96 ± 6.39	3.86 ± 7.81	1.84 to 5.87	3.82	<0.001*	0.56	<0.001*
Wrist extension	%MVC	Comfort	2.93 ± 1.77	4.30 ± 3.00	1.37 ± 3.51	-2.39 to -0.35	-2.70	0.010*	-0.02	0.888
		Grip	3.45 ± 2.05	4.64 ± 3.03	-1.20 ± 3.47	-2.26 to -0.13	-2.26	0.029*	0.11	0.488
	SmO2	Comfort	82.39 ± 7.71	79.00 ± 5.41	3.40 ± 6.49	1.71 to 5.09	4.02	<0.001*	0.56	<0.001*
		Grip	81.23 ± 11.84	78.89 ± 5.43	2.34 ± 10.42	-0.35 to 5.03	1.74	0.087	0.48	<0.001*
Recovery	%MVC	Comfort	2.19 ± 1.24	4.76 ± 3.89	-2.57 ± 3.74	-3.70 to -1.43	-4.55	<0.001*	0.28	0.069
		Grip	3.12 ± 1.85	5.59 ± 3.95	-2.47 ± 4.34	-3.86 to -1.08	-3.60	0.001*	0.01	0.933
	SmO2	Comfort	80.07 ± 9.80	77.45 ± 6.85	2.62 ± 9.06	0.28 to 4.96	2.24	0.029*	0.45	<0.001*
		Grip	80.07 ± 9.80	77.45 ± 6.85	2.62 ± 9.06	0.28 to 4.96	2.24	0.029*	0.45	<0.001*

Muscle activity (%MVC) and oxygen saturation (SmO_2) are presented as mean ± SD. Between-muscle comparisons and Pearson correlation coefficients (r) are reported across all phases.

The comparison between muscle activity and oxygenation is presented in Table 5. Significant differences between %MVC and SmO_2 were observed across all phases and conditions. Correlation analysis revealed weak-to-moderate associations, with significant relationships primarily observed in the SCM during the rest phase under both conditions, and to a lesser extent in the UT under the comfort condition. In contrast, correlations during wrist extension were not significant, and those during recovery were generally weak and inconsistent.

Table 5. Comparison and Correlation Between Muscle Activity (%MVC) and Muscle Oxygen Saturation (SmO_2).

Phase	Parameter	Pillow Selection	%MVC	SmO2	Comparison				Correlation	
			Mean ± SD	Mean ± SD	Mean dif ± SD	95% CI	t	P	r	P
Overall	UT	Comfort	2.64 ± 1.60	80.02 ± 9.56	-77.38 ± 9.30	-78.92 to -75.84	-99.11	<0.001*	0.24	0.003*
		Grip	3.27 ± 1.91	79.81 ± 11.04	-76.54 ± 10.91	-78.36 to -74.72	-82.98	<0.001*	0.15	0.077
	SCM	Comfort	4.53 ± 3.03	76.51 ± 6.67	-71.97 ± 6.45	-72.98 to -70.97	-141.98	<0.001*	0.30	<0.001*
		Grip	4.67 ± 3.01	76.64 ± 6.74	-71.97 ± 6.48	-73.00 to -70.95	-139.07	<0.001*	0.31	<0.001*
Rest	UT	Comfort	2.72 ± 1.60	77.93 ± 9.99	-75.22 ± 9.63	-78.14 to -72.29	-51.82	<0.001*	0.30	0.048*
		Grip	3.04 ± 1.69	77.68 ± 9.49	-74.64 ± 9.23	-77.41 to -71.87	-54.24	<0.001*	0.24	0.108
	SCM	Comfort	3.79 ± 1.94	73.33 ± 6.44	-69.54 ± 5.88	-71.22 to -67.87	-83.61	<0.001*	0.42	0.002*
		Grip	4.00 ± 2.25	73.49 ± 6.40	-69.49 ± 5.82	-71.11 to -67.87	-86.11	<0.001*	0.42	0.002*
Wrist extension	UT	Comfort	2.97 ± 1.82	82.20 ± 7.89	-79.22 ± 7.68	-81.41 to -77.04	-72.95	<0.001*	0.23	0.106
		Grip	3.60 ± 2.15	81.12 ± 12.66	-77.52 ± 12.65	-81.11 to -73.92	-43.33	<0.001*	0.09	0.538
	SCM	Comfort	4.75 ± 3.12	78.67 ± 5.49	-73.92 ± 5.62	-75.43 to -72.42	-98.49	<0.001*	0.24	0.07
		Grip	4.69 ± 2.88	78.99 ± 5.44	-74.30 ± 5.72	-75.91 to -72.69	-92.81	<0.001*	0.17	0.246
Recovery	UT	Comfort	2.21 ± 1.25	79.66 ± 10.44	-77.45 ± 10.27	-80.43 to -74.47	-52.27	<0.001*	0.20	0.182
		Grip	3.15 ± 1.82	80.50 ± 10.45	-77.35 ± 10.37	-80.47 to -74.24	-50.06	<0.001*	0.13	0.392
	SCM	Comfort	4.98 ± 3.61	77.17 ± 6.98	-72.19 ± 7.09	-74.09 to -70.30	-76.24	<0.001*	0.23	0.089
		Grip	5.29 ± 3.62	77.46 ± 7.10	-72.17 ± 7.00	-74.08 to -70.25	-75.72	<0.001*	0.28	0.039

Data are presented as mean ± SD for each muscle and pillow condition. Paired comparisons between %MVC and SmO_2 and Pearson correlation coefficients (r) are reported across all phases.

DISCUSSION

The present study investigated the effects of pillow selection based on perceived comfort and grip performance on neck muscle activity and oxygenation. The primary finding was that no significant differences ($P = 0.05$) were observed between the comfort-based and the grip-based pillow conditions. However, very positive correlations were identified between the 2 methods across all phases (Table 5). This alignment confirms that subjective comfort is not merely a preference, but rather a reliable proxy for physiological neutrality, given that the best perception of comfort is consistently associated with low muscle activity that results from better head and shoulder alignment (20). This suggests that both approaches yield consistent physiological responses, indicating that subjective comfort perception may closely reflect optimal neuromuscular conditions. In other words, individuals may intuitively select pillow conditions that promote favorable cervical alignment (19,20) and muscular function even without objective performance measures (20). Furthermore, the use of grip performance as a valid selection criterion is supported by the fact that hand grip strength is greatest in the head-neck neutral position (9,25).

A notable finding of this study is the distinct behavior observed between the sternocleidomastoid (SCM) muscle and the upper trapezius (UT) muscle, reflecting region-specific physiological sensitivity (9). The SCM consistently demonstrated higher muscle activity; whereas, the UT exhibited higher oxygen saturation levels across all phases. This pattern suggests different functional roles of these muscles during supine positioning. The SCM, as a key cervical flexor and stabilizer, is likely contribute more to active neuromuscular control that results in higher activation levels (8,10). Conversely, the UT functions primarily as a compensatory stabilizer and appears more sensitive to posterior pressure redistribution rather than active movement (8,9). In contrast, the UT may play a more supportive or postural role (19), maintaining adequate perfusion with relatively lower metabolic demand (8,9). These findings highlight the importance of considering muscle-specific responses when evaluating cervical biomechanics and pillow ergonomics (9).

The relationship between muscle activity and oxygenation further provides insight into underlying physiological mechanisms. The observed weak-to-moderate correlations between %MVC and SmO_2 indicate that neuromuscular activation and local oxygen dynamics are not directly proportional. While EMG reflects neural activation and motor unit recruitment, SmO_2 represents the balance between oxygen delivery and utilization within the muscle (9). The partial independence of these measures suggests that increased muscle activation does not necessarily correspond to reduced oxygenation, particularly under low-load or static conditions (9). This distinction is important for interpreting muscle function in ergonomic and rehabilitation contexts (9).

Phase-dependent variations were also evident in the present study. Stronger and more consistent correlations were observed during the rest phase while no significant relationships were found during wrist extension, and correlations during recovery were weak and inconsistent. These findings suggest that under stable conditions, such as rest, neuromuscular and metabolic responses are more closely coupled (9). However, during dynamic tasks (such as wrist extension), additional factors including motor coordination, neural control, and biomechanical interactions (9,13) may obscure the relationship between muscle activation and oxygenation. Specifically, muscle contractions may cause interference with arterial inflow, leading to increased intramuscular pressure that induces transient ischemia, which complicates the linear relationship between EMG and SmO_2 (14). Furthermore, active phases may involve a higher reliance on deep or compensatory muscles that are not fully captured by surface electrodes (9). During recovery, variability in circulatory and metabolic processes may further contribute to inconsistent associations (9). This highlights the complexity of neuromuscular regulation during functional tasks (15,18).

Another important implication of this study is the potential functional link between cervical positioning and upper extremity performance. The use of grip performance as a selection criterion, along with observed responses during the wrist extension phase, supports the concept of regional interdependence (12,22). This concept proposes that dysfunction or misalignment in one region of the body can influence function in another. In support of this, evidence shows that hand grip strength is significantly influenced by head-neck positions, reaching its peak when the cervical spine is in a neutral alignment (25). In this context, appropriate cervical support may contribute to improved neuromuscular efficiency in the upper limb, possibly through optimized neural and biomechanical pathways (9,25).

From a clinical perspective, these findings emphasize the importance of proper pillow selection in maintaining cervical health and function. The results suggest that pillows perceived as comfortable may also promote favorable physiological conditions, including improved muscle oxygenation and efficient neuromuscular activity. Therefore, subjective comfort may serve as a practical and accessible indicator for selecting appropriate cervical support. This has implications for the prevention and management of musculoskeletal disorders, particularly those related to prolonged supine positioning or sleep ergonomics.

Limitations in this Study

The study included only healthy young adults, which may limit generalizability to clinical populations or older individuals. Additionally, measurements were conducted in a controlled laboratory setting, which may not fully reflect real-world sleep conditions. Future studies should investigate long-term effects, include symptomatic populations, and explore additional factors such as pillow material, height, and spinal alignment. Incorporating biomechanical and imaging assessments may also provide a more comprehensive understanding of cervical support mechanisms.

CONCLUSIONS

This study demonstrates that pillow selection based on perceived comfort and grip performance produces comparable physiological outcomes, as evidenced by the absence of significant differences and the presence of strong correlations between conditions. Distinct muscle-specific responses were observed, with the sternocleidomastoid muscle showing greater activation and the upper trapezius muscle exhibiting higher oxygen saturation, reflecting their differing functional roles.

The relationship between muscle activity and oxygenation was generally weak to moderate and varied across phases, indicating that neuromuscular activation and local metabolic responses are partially independent and influenced by task conditions. Overall, these findings highlight the importance of appropriate cervical support in optimizing neuromuscular function. Subjective comfort may serve as a practical indicator for pillow selection, with potential implications for improving sleep ergonomics and reducing the risk of musculoskeletal disorders

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Interpretation of Fatigue-Induced Neuromuscular Responses from Performing Maximal Intended Velocity Dynamic Leg Extensions Using Mechanomyographic Wavelet Transformation

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ABSTRACT

Pioske JS, Arnett JE, Roberts TD, Ortega DG, Schmidt RJ, Bergstrom HC, Housh TJ. The purpose of this study was to apply an alternative signal processing technique to appropriately quantify and qualitatively analyze neuromuscular the responses associated with maximal intended velocity (MIV) dynamic muscle actions. Eleven (n = 11) men (aged 21.55 ± 1.57yrs) performed MIV unilateral leg extension repetitions to failure at 40% 1RM. Peak performance variables were collected using a linear transducer. Mechanomyographic (MMG) signals were recorded from the vastus lateralis (VL), vastus medialis (VM), and rectus femoris (RF). These signals were decomposed to 11 wavelet bands for First repetition and the Last repetition. A repeated measures ANOVA was used to assess the MMG total intensity and wavelet band intensities for the VL, and VM, and RF between repetitions, while contour plots qualitatively characterized the time-resolved mechanical events. Paired *t*-tests were used to assess mean changes in peak performance variables. MMG intensity was greatest in wavelet bands 2, 3, 5, and 6 (P = 0.029), with no muscle- or repetition-specific differences (P = 0.118 to 0.430). MMG total intensity (P = 0.043) and peak performance variables (P < 0.001) decreased from the First repetition to the Last repetition. Contour plots revealed greater MMG intensities in wavelet bands 5 and 6 preceding, but not following, the moment of peak force. The decline in MMG total intensity with fatigue may have reflected reduced motor unit firing rates consistent with the muscle wisdom hypothesis. Meanwhile, the contour plots potentially illustrated the recruitment of high-threshold motor units responsible for the rapid force production. These findings extend the muscle wisdom hypothesis to include maximal effort tasks and highlight the utility of wavelet-based analyses for resolving neuromuscular events.

Key Words: Motor Units, Quadriceps Femoris, Rate of Force Development, Resistance Exercise

INTRODUCTION

Dynamic constant external resistance (DCER) exercises are commonly used by strength and conditioning coaches, physical therapists, and personal trainers to improve an individual's physical performance and quality of life (68,73,85). The traditional DCER exercise recommendations follow those outlined by Delorme (27), which include performing repetitions at a slow, controlled pace. In addition, Delorme (27) suggested that training with a low number of repetitions and heavy loads improves muscular power while training with a high number of repetitions and light loads improves muscular endurance, and that neither training prescription produces the muscular adaptations that are obtained by the other.

Current recommendations by the American College of Sports Medicine (23) suggest that both heavy (force dominant) and light (velocity dominant) DCER loads improve muscle power adaptations. Furthermore, the early research of Behm and Sale (15) suggested that the intent to exert maximal velocity rather than the external movement velocity drives improvements in the rate of force development and peak force production. Recent studies have provided support for this hypothesis and reported more favorable improvements in one-repetition maximum (1RM) strength (29,63), sprint speed (47,77), countermovement jump height (29,63), rapid force capacity (45), and movement velocity across both light and heavy loads (34,58) following DCER training with maximal intended velocity (MIV) compared to training with slow or self-selected velocities, despite both groups having identical DCER training loads and volumes.

Furthermore, MIV DCER exercise is characterized by a greater rate of rise in electromyographic (EMG) amplitudes than controlled velocity contractions during DCER leg extensions across a range of light and heavy loads (75). It has been hypothesized, however, that specific neuromuscular adaptations underlying the rate of force development are not fully realized following heavy resistance training alone (25). For example, Del Vecchio et al. (25) reported no changes in tibialis anterior motor unit recruitment or initial discharge rates during MIV ankle dorsiflexion contractions following heavy resistance training. The authors (25) concluded that maximal force production and intended contraction speed are governed by different motor unit behavior adaptations, with increased recruitment speed serving as the primary neuromuscular mechanism for improving the rate of force development.

Mechanomyography (MMG), the mechanical counterpart of motor unit action potentials measured by EMG (37), involves recording and quantifying the summed mechanical activities of the unfused, activated skeletal muscle fibers at the surface of the skin (14). The recording of the MMG signal is generated by: (a) The gross lateral movement of the non-simultaneous activation of skeletal muscle fibers at the beginning of a contraction; (b) smaller subsequent lateral oscillations of the muscle fibers at their resonant frequency; and (c) dimensional changes of the active fibers (3,55). Previous studies have demonstrated that the content of the MMG signal is primarily generated by muscle activity required to perform static and dynamic tasks, including tracking force (6,20) and power output (65).

Furthermore, Orizio et al. (57,58) suggested that the MMG signal may contain additional information about the relative motor unit activation strategies modulating force production that cannot be determined solely from interpreting the EMG signal. For example, Orizio et al. (59) demonstrated that the amplitude (AMP) of the MMG increases with force up to 80% maximal voluntary isometric contraction (MVIC) and suggested that the AMP of the MMG signal is closely related to the motor unit recruitment threshold. In addition, the frequency content of the MMG signal has been suggested to provide qualitative information regarding the global firing rates of the unfused, activated motor units (10,11,57). It has been demonstrated that increasing the firing rates of individual motor units, thereby the global firing rate, results in a higher frequency of the MMG signal (48,52,60,86). Furthermore, Orizio (55) attributed the increased frequency content of the MMG signal to the recruitment of high-threshold motor units, which are characterized with short contraction times, resulting in "… shorter MUSS [motor unit sound spikes]" (p. 227). Therefore, the content of the MMG signal has been previously used to describe the fatigue-induced motor unit activation strategies during isometric and dynamic muscle actions (21,28,43,61,72).

The root mean square (rms) and Fourier-based algorithms are the most widely used signal processing techniques to quantify the time and frequency domains of the MMG signal, respectively (40). The rms of a signal, which is commonly used to quantify the AMP, involves calculating the mean of the squared values within the selected epoch of the raw signal and then calculating the squared root of the mean of the squared values (40). Fourier-based algorithms, such as fast Fourier or discrete Fourier transformations are used to estimate the frequency spectrum of the MMG signal and are used to calculate the weighted mean frequency (MPF) (40).

Although these signal processing techniques have been widely used to make inferences about motor unit activation strategies (21,28,43,61,72), there are limitations to their use during dynamic muscle actions (19,35). For example, algorithms utilizing the Fourier-based transformations assume signal stationarity (19,35). However, during dynamic muscle actions the mechanical properties of the muscle as well as the number of active motor units vary depending on the joint angle (69,78,79). Therefore, the changes in muscle length may generate "fast non-stationarities" that result in rapid changes in the time and/or frequency content of the MMG signal and can mask the physiological interpretation of the signal (19). Furthermore, epochs shorter than 250 ms result in high variability in calculating the parameters of the signals power density spectrum (35), thus limiting the ability to analyze the neuromuscular mechanisms such as those characterizing rapid force production. Considering these limitations, previous studies (14,80) have developed wavelet-based transformation algorithms to analyze non-stationary MMG and EMG signals during dynamic muscle actions.

The wavelet transformation for EMG signals was developed by von Tscharner (80) and was later rescaled by Beck et al. (14) to align with the frequency range of the MMG signal. Specifically, the wavelet transformations filter the EMG or MMG signal onto sets of 11 Cauchy wavelets that decompose the signal into time-resolved events. Therefore, the short bursts of oscillatory activity that occur during non-stationary MMG signals were resolved without compromising the frequency or time resolution (14), which provides a distinct advantage over traditional time-frequency parameters (AMP and MPF) during very short epochs (14). In addition, wavelet-based analyses decompose the signal into instantaneous intensity coefficients within a given epoch, which allows for the development of contour plots to qualitatively describe the mechanical (MMG) or electrical (EMG) events that characterize the muscle contraction (7,81,82).

Previous studies have used the MMG wavelet analysis to examine the neuromuscular responses of non-fatiguing dynamic and isometric muscle actions (7,9,12–14) as well as fatiguing isometric muscle actions (16,62). For example, Benitez et al. (16) examined the MMG wavelet band intensity of the vastus lateralis (VL) of the non-dominant leg during sustained, unilateral leg extensions anchored to MVIC force in men and women. There were no sex related differences, but there were fatigue-induced wavelet band-specific differences at task termination. Benitez et al. (16) reported that the medium and high frequency bands decreased with fatigue, but the low frequency bands remained unchanged. Similarly, Ortega et al. (62) reported fatigue-induced decreases in medium and high frequency bands as well as the total intensity of the MMG signal during sustained, isometric forearm flexion tasks anchored to low and high rating of perceived effort. The authors (62) suggested that the fatigue-induced decreases in MMG intensities may be attributable to the de-recruitment of high- but not low-threshold motor units.

Furthermore, previous studies by Beck et al. (7,14) and Beck and von Tscharner (13) demonstrated muscle-specific wavelet band differences between the superficial muscles of the quadriceps femoris during isometric and isokinetic leg extensions, which may relate to muscle-specific motor unit activation strategies. However, no previous study has applied the MMG wavelet transformation (13) to investigate the fatigue-induced or the muscle-specific neuromuscular responses during DCER exercise performed at MIV. Furthermore, because MIV resistance training has previously been shown to improve aspects of muscular power (15,29,45,63) and is characterized by different adaptions in motor unit behavior than heavy resistance training (25), investigating the fatigue-induced neuromuscular responses that occur immediately before and after the moment of peak force may provide valuable information regarding the mechanisms governing rapid force production during fatiguing dynamic exercise.

Therefore, the purpose of the present study was to use the wavelet-based MMG transformation to quantitatively and qualitatively examine the fatigue-induced neuromuscular responses during MIV DCER leg extensions at a light relative load, as well as the muscle-specific wavelet band responses for the rectus femoris (RF), vastus lateralis (VL), and vastus medialis (VM). It was hypothesized that the MMG intensities would decrease at the medium and high frequency bands, remain unchanged at lower frequency bands, and decrease in total MMG intensity during the MIV DCER task (16,62), as well as present muscle-specific wavelet band differences between the RF, VL, and VM (7,13,14).

METHODS

Study Design

The subjects visited the laboratory on 2 separate occasions within a 7-day period. During the first visit, the subjects completed a Health History Questionnaire, signed the written Informed Consent form, and were familiarized with performing MVICs and DCER leg extensions performed at MIV. Following familiarization with the testing equipment, the subjects' 1RM was assessed with their non-dominant leg (contralateral to the subject's preferred kicking leg). During the second visit, the subjects performed the fatiguing task, which consisted of MIV repetitions performed to failure with their non-dominant leg at load that corresponded to 40% of their 1RM. Prior to the fatiguing task, the subjects performed a MVIC that was used to normalize the MMG signals during the fatiguing task. Before the testing and fatiguing tasks, all subjects completed a standardized warm-up on a stationary cycle ergometer, which consisted of continuous cycling for 5 minutes at a self-selected pace and resistance.

Subjects
Twelve men volunteered to participate in this study. However, 2 men were excluded from the final analyses due to measurement issues with their MMG signals that invalidated the wavelet intensity values. Therefore, 11 (mean ± SD: age = 21.55 ± 1.57 yr, height = 179.57 ± 5.35 cm, body mass = 79.85 ± 14.52 kg) recreationally active men (51) participated in the present study. The subjects reported participating in resistance exercise 3.82 ± 2.14 days per week and aerobic exercise 4.09 ± 1.70 days per week. The subjects in the present study were part of a larger, multiple-independent and dependent variable investigation, however, none of the current data have been previously published. All subjects reported no lower body pathologies or injuries that would affect their performance in the present study. Furthermore, all subjects were informed about the experimental procedures, potential risks of participating, and provided written informed consent prior to any data collection. The Institutional Review Board for Human Subjects (IRB approval #: 20250524627FB) approved the ethical procedures in this study

One-Repetition Maximum (1RM)
During the first laboratory visit, the subjects' non-dominant, unilateral DCER leg extension 1RM test was conducted. The unilateral leg extension 1RM was performed on a plate-loaded Hammer Strength Iso-Lateral resistance machine (Hammer Strength, Cincinnati, OH). Following the cycling warm-up, the subject's maximal leg extension range of motion was determined using a ruler fastened to an adjustable tripod (Figure 1A). The height of the ruler was recorded and used to standardize the subject's range of motion for the subsequent visit. The 1RM testing protocol followed the guidelines of the National Strength and Conditioning Association (50). To be considered a successful 1RM attempt, the shin pad bar of the leg extension machine was required to reach the height indicated by the ruler. A change in load between 1RM attempts ranged from 1.13 to 4.54 kg. The subjects were provided strong verbal encouragement during all 1RM attempts.

Figure 1. Leg Extension Set Up. (A) Tripod with Ruler to Determine Maximal Range of Motion. (B) Load Cell Strapped from the Base of the Machine to the Plate Sleeve. (C) Buckle Strap to Secure Subject's Leg to the Machine's Lever Arm. (D) Linear Transducer Placed Directly Under, and With the Tether Attached to the Plate Sleeve.

Maximal Voluntary Isometric Contraction (MVIC)
During the second visit and following the cycling warm-up, the subjects performed two 3-second isometric leg extension muscle actions at 50% and 70% of perceived maximal effort separated by 30 seconds of rest. Then, the subjects performed two, 3-second MVICs following 1-2 minutes of rest. The MVIC attempts were separated by 30 to 60 seconds of rest. The MMG signal associated with the attempt that produced the greatest MVIC force was used to normalize the MMG signals recorded during the fatiguing task. The MVIC force was recorded using a portable dynamometer (Tindeq Processor 150, Leknes, Norway) that was secured to the base and plate sleeve of the leg extension machine (Figure 1B). Consistent with previous studies (6,16,38), the MVICs were performed at a knee angle of 120°.

Fatiguing Task
During the second visit and following MVIC testing, the subjects completed 2 DCER warm-up sets, which included 5 to 10 repetitions at 15% 1RM and 3 to 5 repetitions at 30% 1RM that were separated by approximately 1 minute of rest. Then, the subjects performed the fatiguing task with 40% of their 1RM and were instructed to "kick as fast as possible" for every concentric leg extension repetition throughout the fatiguing task. During each repetition, the subjects were instructed to control the eccentric phase of the movement to avoid bouncing the leg extension lever arm, which would have assisted the subsequent concentric movement. A buckle strap was used to secure the subject's shin to the shin pad of the leg extension machine (Figure 1C), ensuring consistent contact between the subjects' leg and the lever arm when performing MIV repetitions. The shin pad bar was required to reach the height of the ruler for each repetition to be considered successful. Task failure occurred when the subjects missed the ruler on 2 consecutive repetitions, or they voluntarily terminated the task. Strong verbal encouragement was provided during the fatiguing task to ensure the subjects performed each repetition as fast as possible and reached their maximum number of repetitions. Peak force, peak velocity, and peak power were collected during the fatiguing task via a linear transducer (Tendo Sports Machines and Technologies, London, UK) that was securely fastened to the plate sleeve of the leg extension machine with a Velcro strap (Figure 1D). The Tendo linear position transducer has previously been reported to yield valid estimates for the angular movements throughout a 120° range of motion (46) In the present study, the subjects did not exceed 90° range of motion when performing the leg extension movement.

Mechanomyography (MMG) Procedures and Signal Processing
During the second visit, MMG signals were collected using a miniature accelerometers (Model: 352A24, PCB Piezotronics, Depew, NY, resolution: 1 to 10k Hz, frequency range: 1 to 8k Hz, dimensions: 12.2 x 7.1 x 4.8 mm, mass: 0.8 gm, sensitivity: 100.8 to 103.1 $mV \oplus g^{-1}$) that were placed over the muscle bellies of the RF, VL, and VM of the non-dominant leg using double-sided adhesive tape. Placement of each MMG accelerometers followed the recommendations of the Surface Electromyography for the Non-Invasive Assessment of Muscles (39). The accelerometer for the RF was placed at 50% of the distance between the anterior superior iliac spine (ASIS) and the superior border of the patella. The accelerometer for the VL was placed at 66.67% of the distance between the ASIS and the lateral border of the patella. The accelerometer for the VM was placed at 80% of the distance from the ASIS to the joint space in front of the anterior border of the medial ligament. A 12-bit analog-to-digital converter (Model: MP150, Biopac Systems Inc., Goleta, CA, USA) was used to digitize the MMG signals at 2000 samples per second. The signals were then processed and digitally band-pass filtered (fourth-order Butterworth, 5-100 Hz) using a custom written LabVIEW program (Version 2025 Q3,

National Instruments, Austin, TX, USA) and stored on a personal computer (Surface Pro 6, Windows 11 Pro, Microsoft Corp., Remond, WA, USA).

Table 1. Wavelet Band Features of the MMG Wavelet Transformation Described by Beck et al. (14).

Wavelet Band	Center Frequency (Hz)	Bandwidth (Hz)
2	5.79	7
3	11.31	10
4	18.63	13
5	27.71	15
6	38.54	18
7	51.12	21
8	65.42	24
9	81.45	26
10	99.19	29
11	118.63	32

MMG = **M**echanomyography

The filtered MMG signals were decomposed into intensities as a function of time and frequency using a custom, MMG-specific wavelet transformation written in R (The R Foundation for Statistical Computing, version 4.4.1, Vienna, Austria). Specifically, the MMG signals were decomposed onto 11 Cauchy wavelets bands as described by Beck et al. (14). The wavelet bandwidth and center frequencies for each wavelet band are presented in Table 1. However, the MMG signal's power within wavelet band 1 has previously been suggested to reflect movement artifact (16,22,53). Therefore, wavelet band 1 was excluded from further analyses. The total intensity (i.e., the sum of all intensities across all wavelet bands over time) of the signal and the wavelet intensity spectra (i.e., the distribution of intensity across 11 wavelet bands) were derived from the intensity patterns (14).

Repetition Selection and Normalization

The MMG signals recorded from the fastest of the first 3 repetitions (First) and the last successful repetition (Last) during the fatiguing task were processed using the wavelet transformation. Fatigue results in a slower movement velocity and, therefore, longer duration of the leg extension movement (4,41). Thus, in the present study, the MMG signal during the Last repetition included more data points than the First repetition, despite an approximately equal range of motion. Since total intensity and the intensity values for each wavelet band are derived by summing the intensity values across all data points, the number of data points included for analysis can influence the calculated intensity value, independent of the effects of fatigue.

Therefore, following the wavelet decomposition of each signal, the number of data points for the First repetition and the Last repetition were standardized relative to peak force by selecting 100 data points immediately before (50 ms) and 100 data points immediately after (50 ms) the data point where peak force occurred. This procedure resulted in an MMG signal epoch of approximately 101.5 ms and included 201 data points for both the First and Last repetition. To normalize the MMG intensities of the First repetition and the Last repetition, a 1 second epoch from the center of the 3 second MVIC measured prior to the fatiguing task was wavelet transformed. From the 1 second MVIC epoch, total intensity was calculated as the sum of all the intensities across all data points for each muscle and was used to normalize the MMG intensities from the RF, VL, and VM for the First and Last repetitions.

Intensity Patterns

The intensity patterns from the wavelet transformation provided 2 quantities, total intensity and the wavelet intensity spectrum, which may provide unique information regarding the fatigue-induced neuromuscular responses (13,14,62). The total intensity values were calculated as the sum of all normalized intensities across all data points. The total intensity of a signal is approximately equal to the square of the root mean square (rms^2) of the amplitude, or the power of a signal, within a given time window (7). The wavelet intensity spectra were determined as the sum of the normalized intensities within a given wavelet band across all data points (14). The intensity patterns from the wavelet transformation were represented as contour plots in a scale of warm and cool colors (DataGraph, version 5.5; Visual Data Tools Inc., Chapel Hill, NC, USA; Figure 2).

Separate contour plots were developed for the normalized (% of MVIC total intensity) MMG intensity patterns for the First repetition and the Last repetition as well as the difference (First repetition – Last repetition) intensity patterns for the RF (top row, Figure 2), VL (middle row, Figure 2), and VM (bottom row, Figure 2). The color scale of the contour plots presents the level of intensity as a function of time (x-axis) and wavelet band (y-axis) (14,80). The color scales of the difference contour plots represent the fatigue-induced changes in MMG intensity patterns from the First to Last repetition (14). It has been suggested (13,14,62) that difference in contour plots represent intensity pattern changes as a result of fatigue, which may provide insight related to fatigue-induced changes in motor unit activation strategies.

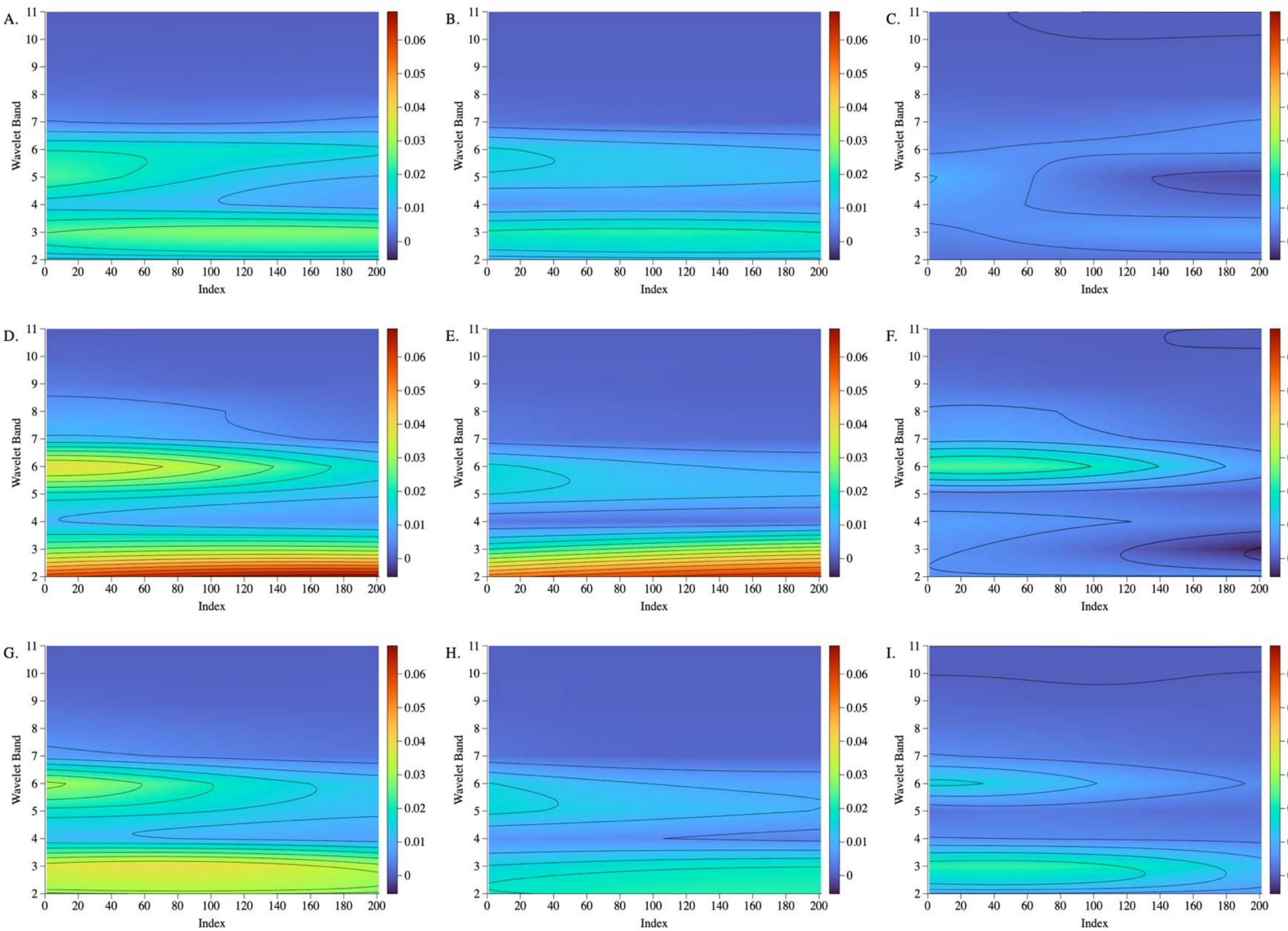

Figure 2. Normalized (% of MVIC total intensity) mechanomyographic intensity patterns for the First (a, d, g) repetition and the Last (b, e, h) repetition as well as the difference (First repetition – Last repetition) intensity patterns (c, f, i) for the rectus femoris (top row), vastus lateralis (middle row), and vastus medialis (bottom row). The moment of peak force occurred at data point 101. the range of motion within the 201 data point epoch was approximately 98° to 115° and 97° to 108° for the First repetition and the Last repetition, respectively. MVIC = maximal voluntary isometric contraction.

Statistical Analyses

Paired *t*-tests were used to examine the mean differences between the First Repetition and the Last Repetition for peak force, peak velocity, peak power, time to peak force, and joint angle at peak force. A three-way (Repetition [First, Last] · Muscle [RF, VL, VM] · Wavelet Band [2-11]) repeated measures ANOVA was used to examine the mean differences for the normalized (% of MVIC total intensity) MMG wavelet band intensity values. In addition, a 2-way (Repetition · Muscle) repeated measures ANOVA was used to examine the mean differences for the normalized (% of MVIC total intensity) MMG total intensity values. Partial eta squared ($^{2}_{p}$) and

Cohen's *d* were calculated to quantify the effect sizes for the ANOVA and *t*-tests, respectively. Statistical significance for all analyses was set at P = 0.05 and the Greenhouse-Geisser adjustment was used to correct for sphericity violations. All statistical analyses were completed using IBM SPSS version 29 (SPSS Inc., Armonk, NY, USA).

RESULTS

Performance Measures

The paired *t*-tests for peak force, peak velocity, and peak power revealed significant (P < 0.001, *d* = 4.116 to 5.217) decreases from the First repetition to the Last repetition. The paired *t*-test for time to peak force revealed no significant difference between the First repetition (200.27 ms) and the Last repetition (213.70 ms, P = 0.529, *d* = 0.197). The paired *t*-test for joint angle at peak force revealed a significant decrease from the First repetition (105.16°) to the Last repetition (102.02°, P< 0.001, *d* = 2.417). The results of the paired *t*-tests as well as the percent change for peak force, peak velocity, peak power, time to peak force, and joint angle at peak force are presented in Table 2.

Table 2. Results of the Peak Performance Variables for the First and Last Repetitions.

Variable	First Repetition	Last Repetition	Percent Change	P-value	*d*
Peak Force (N)	934.64 ± 142.85	693.55 ± 113.27	-34.76%	< 0.001	4.461
Peak Velocity ($m \cdot s^{-1}$)	2.16 ± 0.16	1.34 ± 0.16	-37.96%	< 0.001	5.217
Peak Power (W)	1484.55 ± 264.66	694.27 ± 143.81	-53.23%	< 0.001	4.155
Time to Peak Force (ms)	200.27 ± 73.21	213.70 ± 39.95	6.71%	0.529	0.197
Joint Angle at Peak Force (°)	105.16 ± 1.57	102.03 ± 1.49	-2.98%	< 0.001	2.427

Values are presented as the mean ± standard deviation. **N** = Newtons; $\mathbf{m \cdot s^{-1}}$ = meters per second; **W** = watts; **ms** = milliseconds, ***d*** = Cohen's effect size for the comparison.

Wavelet Bands

For normalized MMG wavelet intensity, the 2 (Repetition) · 3 (Muscle) · 10 (Wavelet Band) repeated measures ANOVA revealed no significant 3-way or 2-way interactions (P = 0.118 to 0.430, η_p^2= 0.070 to 0.210). There were, however, significant main effects for Repetition (P = 0.043, η_p^2 = 0.349) and Wavelet Band (P = 0.029, η_p^2= 0.346). The *post-hoc* pairwise comparison for the main effect for Repetition (collapsed across Muscle and Wavelet Band) revealed a significant decrease (P = 0.043, *d* = 1.912) from the First (2.53% of MVIC total intensity) repetition to the Last (1.49% of MVIC total intensity) repetition. The *post-hoc* pairwise comparisons for the main effect for Wavelet Band (collapsed across Repetition and Muscle) are presented in Table 3.

Table 3. ***Post-Hoc*** **Pairwise Comparisons for Normalized MMG Intensity (Collapsed Across Repetition and Muscle) Between Wavelet Bands.**

Wavelet Band	Significant Comparisons
2	> 4, 7-11
3	> 4, 7-11
4	> 8-11; < 2, 3, 5, 6
5	> 4, 7-11
6	> 4, 7-11;
7	> 8-11; < 2, 3, 5, 6
8	> 9-11; < 2-7
9	> 10, 11; < 2-8
10	> 11; < 2-9
11	< 2-11

There was no significant 3- or 2-way interaction (P = 0.118 to 0.430, h_p^2 = 0.070 to 0.210) for Muscle (RF, VL, VM) or Repetition (First, Last). There was a significant main effect for Wavelet Band (P = 0.029, h_p^2 = 0.346) and the *post-hoc* pairwise comparisons for the normalized MMG intensity for each wavelet band are presented above. A P-value of ≤ 0.05 was considered statistically significant for all comparisons. **MMG** = Mechanomyography; **>** = Greater Than; **<** = Less Than.

Total Intensity

For normalized MMG total intensity, the 2 (Repetition) · 3 (Muscle) repeated measures ANOVA revealed no significant interaction (P= 0.431, η_p^2 = 0.070), however, there was a significant main effect for Repetition (P = 0.043, η_p^2 = 0.349). The *post-hoc* pairwise comparison for the main effect for Repetition (collapsed across Muscle) revealed a significant decrease in normalized MMG total intensity from the First repetition (25.25%) to the Last Repetition (14.89%, P = 0.043, *d.*= 0.698).

DISCUSSION

The results of the present study demonstrated fatigue-induced decreases in peak force, peak velocity, peak power, and the joint angle at which peak force occurred from the First repetition to the Last repetition. However, there were no fatigue-induced changes in the time to peak force between the First repetition and the Last repetition (Table 2). Moreover, there were no MMG wavelet band intensity changes from the First repetition to the Last repetition for the RF, VL, or VM. Also, there were no MMG total intensity or wavelet band intensity differences between the 3 superficial muscles of the quadriceps femoris. However, there were MMG intensity differences among the wavelet bands that were consistent across muscles and repetitions (Table 3). Furthermore, there were parallel decreases in MMG total intensity (i.e., the intensity summed across wavelet bands and data points) for the RF, VL, and VM (Figure 3) from the First repetition to the Last repetition of the fatiguing task.

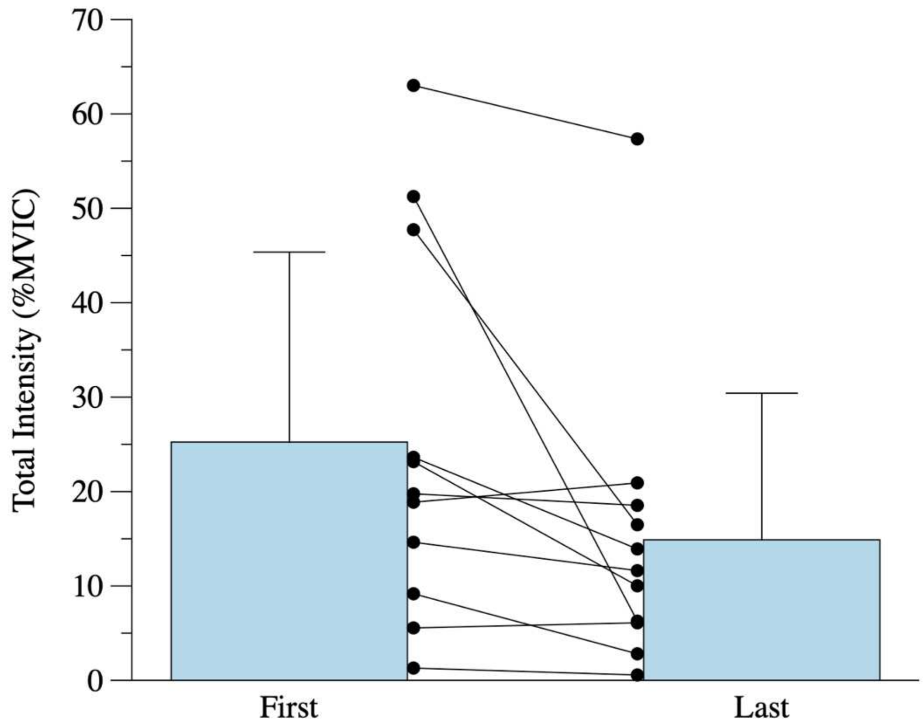

Figure 3. Mean (SD) and Individual Spaghetti Plots for Mechanomyographic (MMG) Normalized Total Intensity (Collapsed Across Muscle) for the First Repetition and the Last Repetition.

Task-Specific Wavelet Band Responses

In contrast to the previous studies, which identified muscle-specific wavelet bands differences between the 3 superficial muscles of the quadriceps femoris (7,13,14), the present study found no differences in MMG wavelet band intensities between the RF, VL, and VM. For example, Beck et al. (7) reported that the RF had the greatest MMG intensities in the middle frequency bands (wavelet bands 5 and 6), while the VL had the greatest intensities in lower frequency bands (wavelet bands 2 to 4) during 40, 60, 80, and 100% MVIC. Furthermore, Beck and von Tscharner (13) reported that the middle frequency bands (wavelet bands 5 and 6) demonstrated the greatest MMG intensities during maximal, isokinetic, concentric leg extension muscle actions; whereas, during maximal isokinetic, eccentric leg extension muscle actions, the lower frequency bands (wavelet bands 2 and 3) were characterized with the greatest MMG intensities.

However, in the present study, the lower frequency (wavelet bands 2 and 3) and the middle frequency bands (wavelet bands 5, and 6) demonstrated the greatest MMG intensities for the RF, VL, and VM (Table 3) during MIV leg extension muscle actions. The differences between the present study and those of Beck et al., (7,14) and Beck & von Tscharner (13) may have been due to the differences in the tasks performed (DCER versus isometric versus isokinetic, respectively), muscle action (concentric versus eccentric), as well as the joint angle evaluated (DCER = 98° to 115° versus isometric = 90° versus isokinetic = 120° to 150°). Collectively, these findings suggest that the observed MMG wavelet band characteristics may reflect task-dependent frequency patterns rather than muscle-specific frequency patterns. Future research should further evaluate the effects of contraction type and joint angle on the MMG wavelet band characteristics.

Interpretation of Contour Plots and Wavelet Bands

The present study used a wavelet-based analysis for MMG signals, which offers improved frequency resolution during very short epochs without compromising the time resolution, thereby providing a distinct advantage over traditional time-frequency techniques during dynamic muscle actions where the MMG signal is non-stationary (14). Furthermore, the contour plots developed from the intensity patterns of the wavelet transformation provide unique information regarding key muscular events that occur across time (81,82). For example, contour plots provide a visual, qualitative representation of the non-stationarity of the MMG signal across time, thereby allowing for the identification of task- and fatigue-related intensity pattern responses across time that are not interpretable from traditional statistical analyses, which collapse the signal (across time) into a single value (14).

In the present study, the contour plots represent the intensity distribution across wavelets bands during the 50 ms immediately before and 50 ms immediately after the moment of peak force. The contour plots for the First repetition qualitatively display greater MMG intensities in wavelet bands 5 and 6 during the initial 50 ms before peak force compared to the last 50 ms after peak force, while the intensities in wavelet bands 2 and 3 remained constant throughout the epoch (Figure 2A, D, and G). Although there is conflicting evidence (8), it is possible that the intensities in wavelet bands 5 and 6 prior to the moment of peak force reflected the neuromuscular activity responsible for producing force rapidly (24,26). For example, it has been hypothesized that the frequency content of the MMG signal is influenced by fiber type composition, whereby higher and lower frequency signals reflect the recruitment of fast-twitch (high-threshold) and slow-twitch (low-threshold) motor units, respectively (48,52,60,86). Therefore, the greater intensities in wavelet bands 5 and 6 during the initial 50 ms compared to the last 50 ms may have reflected the rapid recruitment of fast-twitch (high-threshold) motor units that contribute to the rate force development (24,26).

The results of the statistical analysis revealed that the MMG intensities were not different between wavelet bands 2, 3, 5, and 6 for the RF, VL, or VM (Table 3). Therefore, the approximately equal MMG intensities between wavelet bands 2, 3, 5, and 6 may suggest that both low- and high-threshold motor units were recruited during fast velocity movements for the 3 superficial muscles of the quadriceps femoris. However, these findings are not consistent with those of Blake and Wakeling (18), who utilized an EMG specific wavelet analysis to examine the signals from the medial gastrocnemius during fast-cycling velocities. The authors (18) reported reduced low-frequency EMG content during the slow-cycling velocities (40 to 120 revolutions per minute) compared to the fast-cycling velocities (140 to 180 revolutions per minute) and suggested that the medial gastrocnemius demonstrated a selective motor unit recruitment strategy that resulted in the decruitment of low-threshold motor units during the fast-cycling velocities.

Given the controversy regarding the interpretation of the spectral properties of the EMG signal (34,83), a wavelet-based MMG analysis, such as that in the present study, may provide an expanded physiological assessment of motor unit activation strategies from the mechanical oscillations of muscle fibers associated with the recruitment and firing rates of motor units (56,57,60). Future research should incorporate both EMG and MMG wavelet-based analyses during fatiguing tasks, thereby providing complementary interpretations regarding the fatigue-induced motor unit activation strategies.

Interpretation of Fatigue-Induced Responses

The contour plots for the Last repetition represent the intensity pattern distribution across wavelet bands and across time and may reflect fatigue-induced neuromuscular responses from performing a fatiguing set of MIV leg extension repetitions. Unlike the First repetition, the Last repetition exhibited nearly equal MMG intensities in wavelet bands 5 and 6 during the 50 ms immediately before and the 50 ms immediately after the moment of peak force for RF, VL, and VM (Figure 2B, E, and H).

In addition, the results of the present study revealed no changes in the MMG intensity among the wavelet bands from the First to the Last repetition; however, there was a decrease in MMG total intensity (sum of all intensities across wavelet bands and across all data points) from the First repetition to the Last repetition (Figure 3). Although there were no significant changes in the individual wavelet bands between the First and Last repetition, the qualitative evaluation of the difference contour plots (Figure 2F and I) suggest that the decrease in MMG total intensity was the result of the reduced MMG intensity in wavelet bands 5 and 6 during the initial 50 ms of the Last repetition compared to the First repetition. Because the total intensity from the wavelet transformation is analogous to traditional measures of signal power (14), mechanisms that influence the amplitude (AMP) of the MMG signal similarly affect the MMG total intensity. For example, the fatigue-induced decreases in MMG AMP during maximal isokinetic muscle actions (5,66) and maximal sprint cycling (67) have been partially attributed to increases in muscle thickness, intra- and extracellular fluid, and/or intramuscular pressure during prolonged static and dynamic muscle actions (2,42,70,71), which can restrict the lateral oscillations of the muscle fibers and decrease the intensity of the MMG signal.

However, later studies demonstrated a lack of change in MMG AMP under simulated conditions that reflected increased intramuscular pressure (73) or intra- and extracellular fluid content (33), and suggested that the MMG signal reflects the intrinsic contractile properties of the muscle. Therefore, it is possible that the decreases in MMG total intensity in the present study reflected the fatigue-induced alterations in motor unit firing behavior and contractile dynamics (57) rather than increases in intramuscular pressure and/or intra- and extracellular fluid content.

Previous studies hypothesized that the fatigue-induced decreases in MMG AMP from maximal isokinetic muscle actions (5,66) and maximal sprint cycling (67) may result from decreases in motor unit firing rates and/or fusion of motor unit twitches. Similarly, in the present study the fatigue-induced decreases in MMG total intensity (Figure 3) and the unchanged MMG intensity in wavelet bands 5 and 6 across all data points for the Last repetition (Figure 2B, E, H) may also reflect changes in motor unit activation strategies. Specifically, the fatigue-induced pattern of responses in the present study are consistent with those of the “muscle wisdom” hypothesis of fatigue (17), which proposes that during prolonged maximal contractions, motor unit firing rates are decreased to compensate for the fatigue-induced decrease in muscle fiber relaxation rates, while mitigating the loss in force production via fusion of motor unit twitches (30,32,49,87).

Although the muscle wisdom hypothesis has traditionally been discussed in the context of maximal force-producing contractions (i.e., 100% MVIC), the present findings suggest that it may also characterize maximal effort tasks performed with submaximal loads. For example, the leg extension muscle actions in the present study were performed with a submaximal load (i.e., 40% 1RM), however, the subjects were instructed to perform each repetition at a maximal effort to produce MIV repetitions. Furthermore, in the present study there were fatigue-induced decreases in peak velocity and joint angle of peak force (Table 2), which are consistent with the slowed contraction dynamics that characterize the muscle wisdom hypothesis. It has been hypothesized that MIV contractions are characterized by rapid recruitment of high-threshold motor units at the onset of the task (15,26,83), which are highly inefficient due to their high ATP turnover rates and, therefore, have greater rates of inorganic phosphate and ADP accumulation compared to low-threshold motor units (44). Therefore, the fatigue-induced decreases in movement velocity in the present study were likely due to increased inorganic phosphate and ADP concentrations, which interfered with the excitation-contraction dynamics, including the calcium release and reuptake by the sarcoplasmic reticulum, actin-myosin binding affinity, and troponin-calcium binding affinity (1). Furthermore, the fatigue-induced decrease in movement velocity may have allowed for a greater number of motor unit twitches to fuse (i.e. muscle wisdom), thereby reducing the mechanical oscillations of the muscle fibers and decreasing the total intensity of MMG signal (10).

However, the time to peak force did not change across the fatiguing set of MIV leg extensions despite the decrease in peak force (Table 2), which may suggest an economical motor unit activation strategy to mitigate the loss in the rate of force production during fatiguing maximal effort task (30) and provide support for the muscular wisdom hypothesis during MIV DCER muscle actions. Therefore, the findings of the present study extend the muscular wisdom hypothesis by suggesting that the modulation of motor unit firing rates is not exclusive to maximal force conditions, but rather occurs during maximal effort tasks, where the central nervous system reduces the motor unit firing rate to meet the task demands regardless of the external load during MIV DCER muscle actions.

The results of the present study are not consistent with those of Neltner et al. (54), who reported no changes in MMG AMP or MPF during MIV DCER forearm flexion muscle actions at 30% 1RM and suggest that there were no alternations in motor unit recruitment or firing rates for the biceps brachii in response to fatigue. The inconsistencies between the MMG responses of the present study and those of Neltner et al. (54) may be due to the violation of Fourier's assumption of signal stationarity with dynamic muscle actions, muscle architecture (pennate versus fusiform) and/or the muscle action (extension versus flexion) performed. For example, MIV DCER muscle actions performed with a light relative load produces high movement velocities (47,54,63,77), which results in limited epoch windows (14) and high variability in calculating MPF from the MMG power density spectrum (35).

Therefore, the MMG signal recorded from Neltner et al. (54), may not have accurately represented the frequency responses during MIV muscle actions. Regarding muscle architecture, pennate muscles (leg extensors) allow for more sarcomeres in parallel, therefore, can generate greater forces than fusiform muscles (i.e., forearm flexors) (31), which can result in greater muscle fiber oscillations that are captured in the MMG signal (76). Furthermore, assistance from synergist muscles (i.e., brachialis or brachioradialis) may explain the lack of fatigue-induced changes in MMG responses from the biceps brachii during forearm flexion MIV task (64). Therefore, future research should further evaluate the fatigue-induced effects of MIV muscle actions of fusiform muscles (i.e., biceps brachii, brachialis, and/or brachioradialis) while applying the MMG wavelet-based analyses to better examine the time and frequency responses.

Limitations in this Study

Although the present study provides novel insights into neuromuscular responses during MIV DCER exercise, several limitations should be considered when interpreting the findings. For example, the present study examined the fatigue-induced responses during MIV muscle actions in men, thus the results cannot be extrapolated to women. In addition, the present study analyzed the MMG intensity responses of the 3 superficial muscles of the quadriceps femoris during leg extension muscle actions. Future research should consider analyzing the MMG intensity responses of other pennate muscles, fusiform muscles, and/or different muscle actions (e.g., flexion). Furthermore, it is important to remember that the results of the present study are limited to only MMG intensity responses during MIV DCER muscles actions with a submaximal load. Therefore, future research should consider simultaneously examining the EMG and MMG signals during MIV DCER muscle actions, thereby providing complementary interpretations regarding the fatigue-induced motor unit activation strategies. Future research should also consider investigating the fatigue-induced responses throughout a range of light and heavy loads during MIV DCER muscle actions.

In addition, the present study did not examine the time course of neuromuscular responses throughout the fatiguing task. For example, previous studies using submaximal DCER loads performed to failure reported nonlinear patterns for MMG AMP and MMG mean power frequency (28,72). Therefore, future research should include one or more mid-set MMG measurements to better characterize the fatigue-induced patterns of motor unit activation strategies during MIV DCER muscle actions.

Another limitation of the present study included the complex study design involving several factors (i.e., repetition number, wavelet bands, and muscle), which together with a modest sample size (n = 11) may have limited the detection of some interaction effects. However, a prior analysis (G*Power version 3.1.9.7, Düsseldorf, Germany) for a within-factors repeated measures ANOVA indicated that a sample size of 9 subjects was required based on an alpha of 0.05, power of 0.8, and an estimate medium effect size of 0.5 (62).

CONCLUSIONS

The findings of the present study demonstrated that MMG wavelet analysis provided novel insights for characterizing neuromuscular activation strategies during DCER muscles actions performed at MIV. There were no differences in MMG wavelet band intensity between the 3 superficial muscles of the quadriceps femoris, which suggested that the wavelet band characteristics reflected task-dependent frequency patterns rather than muscle-specific frequency patterns. However, the absence of muscle-specific differences were inconsistent with previous studies (7,13,14), which may be due to the differences in the joint angle and/or muscle contractions that were investigated.

Furthermore, the improved time-frequency resolution of the wavelet transformation allowed for the characterization of non-stationary features of the MMG signal throughout a very short epoch (101.5 ms) (14), thus providing unique contour plots regarding muscular events (81,82). In the present study, the contour plots qualitatively displayed intensity differences between the 50 ms prior to and the 50 ms following the moment of peak force in wavelet bands 5 and 6, which may reflect the recruitment of high-threshold motor units that characterize the rate of force development (24).

Also, there were fatigue-induced decreases in MMG total intensity, peak velocity, peak force, peak power, and joint angle of peak force. The reduction in MMG total intensity (summed intensities across all wavelet bands and data points), despite no changes in individual wavelet bands, may reflect a global decrease of motor unit firing rates in response to the increased muscle fiber relaxation rates, thus allowing for a greater fusion of motor units twitches and providing an economical motor unit activation strategy to mitigate the loss in force production (49,87). The findings in the present study suggest that the muscle wisdom hypothesis of fatigue may not be exclusive to maximal force conditions, but also includes maximal effort tasks (30), such as the effort to produce MIV repetitions.

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JSP, JEA, and TJH conceived and designed the research. JSP and TDR performed data collection, JSP analyzed the data, and JSP interpreted the results of the experiments, prepared the tables and figures, and drafted the manuscript. JSP and TJH edited and revised the manuscript while JEA, DGO, TDR, RJS, HCB, and TJH approved the final version of the manuscript. The authors would like to thank the subjects for their participation in this study.

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Effects of a Four-Posture Rusie Dutton Exercise on Pain in Individuals with Chronic Non-Specific Neck Pain

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ABSTRACT

Khamhaeng T, Sa-ardluan T, Mompanao, Sungkamanee S, Maharan S, Ladawan S Chronic non-specific neck pain (CNSNP) is a common cause of pain and disability. Although exercise is recommended as first-line treatment, complex programs may reduce adherence. The effectiveness of a simplified four-posture Rusie Dutton program for pain reduction in CNSNP remains unclear. Therefore, this study investigated the effects of a four-posture Rusie Dutton exercise program on pain in chronic non-specific neck pain. Twenty-eight participants 20 to 59 years of age were assigned either to a Rusie Dutton Group (n = 14) or a Control Group (n = 14). The Rusie Dutton Group completed 4 selected Rusie Dutton postures 3 times weekly for 3 weeks; whereas, the Control Group continued their usual daily activities. Pain Numeric Rating Scale (NRS), Neck Disability Index (NDI) score, and Pressure Pain Threshold (PPT) were assessed before and after the intervention. At the end of the intervention, the Rusie Dutton Group demonstrated significantly greater improvements in NRS and NDI than both their baseline values and those of the Control Group. PPT significantly increased from baseline at the bilateral trapezius muscles and the left levator scapulae in the Rusie Dutton Group. However, no significant between-group differences were observed for PPT at all muscle sites. A 3-week Rusie Dutton exercise program consisting of 4 selected postures effectively improved NRS and NDI in individuals with chronic non-specific neck pain. Although PPT improved within the intervention (i.e., the Rusie Dutton Group), no significant between-group differences were observed. A longer-duration, progressively dosed Rusie Dutton program may be necessary to elicit clinically meaningful changes in pain modulation and sensory processing.

Key Words: Chronic Non-Specific Neck Pain, Pain, Rusie Dutton Exercise

INTRODUCTION

Neck pain is a common global health problem, affecting an estimated 203 million people in 2020, with a stable age-standardized prevalence since 1990. The burden is projected to rise to 269 million cases by 2050, largely driven by population growth and aging (35). The most common type of neck pain is nonspecific neck pain (6,14,17). Chronic nonspecific neck pain is defined as persistent pain or discomfort in the region between the upper cervical spine and the upper thoracic spine that last for more than 3 months without a clearly identifiable pathology, injury, or neurological involvement. (1,16,30). The pain is associated with restricted cervical mobility, functional impairment, myofascial pain syndrome of the neck muscles, and work-related stress. These interrelated factors may collectively contribute to reduced health-related quality of life (5).

Exercise-based interventions are considered a first-line non-pharmacological approach for the management of chronic neck pain. Different types of therapeutic exercises, including Yoga, Pilates, Tai Chi, and Qigong were shown to help reduce pain and improve disability (8).

Rusie Dutton is a traditional exercise practice that has been widely performed in Thailand for centuries. It is characterized by low-impact movements of light to moderate intensity, incorporating a range of motion alongside elements of muscular strength, balance, flexibility, and postural alignment. The practice also integrates meditative components with slow, controlled, and graceful movements, combined with deep breathing and relaxation techniques (24,32). A previous study found that Rusie Dutton produced similar benefits to yoga and strengthening exercises for reducing neck and shoulder pain and improving quality of life (QoL) among office workers (32). It has also been shown to improve health and well-being among older adults (24), as well as pain, Neck Disability Index questionnaire (NDI), and QoL in individuals with text neck syndrome (21).

Although Rusie Dutton has been shown to be effective in reducing neck pain, it encompasses a wide range of postures with varying levels of difficulty, which may limit accessibility for beginners and individuals with physical limitations. Consequently, performing a full set of Rusie Dutton poses safely and consistently may not be feasible for these populations. Therefore, the purpose of this study was to evaluate the effects of 4 selected Rusie Dutton postures drawn from 15 fundamental poses and focused on movements of the neck, shoulders, and upper back on pain in chronic non-specific neck pain. The findings are expected to inform the development of a simplified, targeted Rusie Dutton protocol that is safer, more accessible, and easier to implement for individuals with chronic non-specific neck pain.

METHODS

Subjects

The required sample size of 12 participants per group was calculated based on a previous study (21), using a significance level of 0.05 (α) and statistical power of 0.80. To account for an anticipated dropout rate of approximately 10%, 14 participants were recruited per group, resulting in a total of 28 participants who were then randomly allocated to either the Rusie Dutton Group or the Control Group. The participants were included if they met the following **Inclusion Criteria**: (a) adults of either sex between 20 and 59 years of age; (b) a history of nonspecific neck pain persisting for at least 12 weeks; (c) a pain intensity score of ≥3 on the Numeric Rating Scale (NRS); and (d) a Neck Disability Index (NDI) score of ≥5. The **Exclusion**

Criteria included: (a) a prior history of traumatic injury or fracture involving the cervical spine; (b) clinical signs of cervical radiculopathy or myelopathy; and (c) evidence of serious underlying pathology (e.g., infection or inflammatory disorders). The participants were recruited in this study through face-to-face contact. All of the participants were informed of the study protocol and possible risks before signing the consent form. The study protocol was approved by University of Phayao Human Ethics Committee, reference number HEC-UP-HSST 1.2/096/67.

Procedures

The participants in the Rusie Dutton Group were asked to perform Rusie Dutton exercise for 3 weeks. The Control Group were given the information of Rusie Dutton exercise after the end of study. All the participants were asked to continue their routine activities of daily living as before participating in the study. The main outcomes were assessed before and at the end of the exercise program.

Intervention

Four of 15 patterns of Rusie Dutton associated with neck, shoulders, and upper back movement include: (a) stomach ache and headache; (b) headache and blurred eyes; (c) trunk, knee, and leg trouble; and (d) chest and body discomfort (19). The Rusie Dutton exercise program consisted of 10 repetitions per pose, performed as 1 set per day, 3 days per week for 3 weeks.

Measurements

Pain numeric rating scale (NRS) was used to evaluate pain intensity. It was a score of 0-10, where 0 was no pain while 10 was the worst possible pain (25).

Neck Disability Index (NDI) is a validated patient-reported outcome measure commonly employed to quantify functional impairment associated with neck disorders. The questionnaire consists of 10 sections that assess the influence of neck symptoms on everyday functioning, including self-care, lifting, reading, occupational activities, driving, sleep, recreational participation, and the ability to concentrate. Each section is rated from 0 to 5, and the total score reflects the severity of disability, with higher values representing greater functional limitation (33,38).

Pressure Pain Threshold (PPT) was used to evaluate pain sensitivity using a Commander™ algometer (JTECH Medical, USA) equipped with a 1.0-cm-diameter probe. The PPT was assessed at the suboccipital region, 2 cm lateral to the spinous process of the axis; the levator scapulae muscle at the superior medial border of the scapula; the upper trapezius muscle at the midpoint between the cervical midline and the lateral border of the acromion (36), and a reference site on an unrelated muscle located at the upper third of the tibialis anterior muscle belly (3). The algometer probe was applied perpendicularly to each measurement site. Participants were instructed to say "yes" when the sensation of pressure first changed to pain (9). Two measurements were obtained at each site (10) with a 30-second resting period between assessments. The average of the 2 measurements was used for statistical analysis. Lower PPT values indicate greater pain sensitivity (13).

Statistical Analyses

Data normality was examined with the Shapiro–Wilk Test. Baseline demographic variables were compared between the 2 Groups using an Independent-Samples *t*-Test when the data met the assumption of normality; whereas, the Mann–Whitney *U* Test was applied for variables that were not normally distributed. To investigate treatment effects, normally distributed outcome measures were analyzed using a two-way mixed-design Analysis of Variance (ANOVA), allowing assessment of both group and time effects. For outcome variables that violated the normality assumption, between-group comparisons were performed with the Mann–Whitney *U* Test, and pre- to post-intervention changes within each Group were assessed using the Wilcoxon Signed-Rank Test. Statistical significance was defined as $p < 0.05$. All analyses were performed using SPSS for Windows, version 17.0.

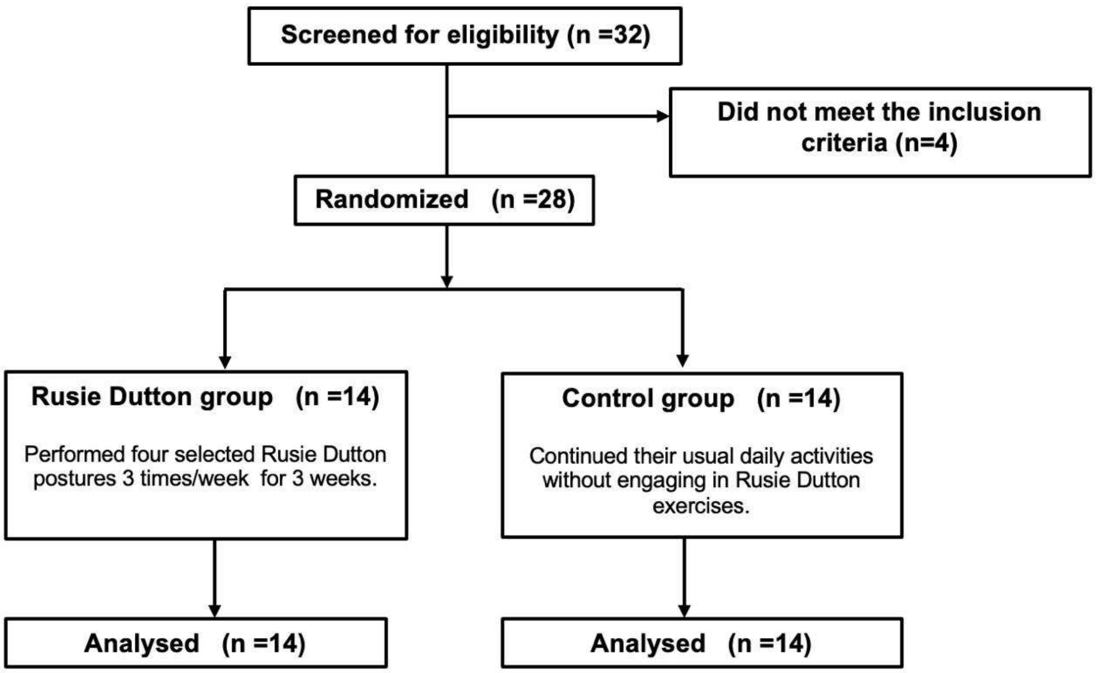

Figure 1. Flow Chart of Study Progress.

RESULTS

The duration of neck pain in the Rusie Dutton Group was 8.57 ±3.93 months while the Control Group was 9.71 ± 6.68 months. There were no statistically significant differences in baseline characteristics between the 2 Groups (P < 0.05) (Table 1). All the participants in the Rusie Dutton Group (i.e., the exercise group) were very strong adherence with 100% with no adverse effects reported.

After completion of the exercise program, the Rusie Dutton Group demonstrated significant reductions in Pain and NDI compared with the baseline, and these values were significantly lower than those observed in the Control Group (P < 0.05) (Table 2).

Table 1. Basic Characteristics.

Variable	Group	
	Rusie Dutton (n = 14)	Control (n = 14)
Age (yr)	25.93 ± 993	24.71 ± 8.88
Gender (male/female)	2/12	1/13
Weight (kg)	60.86 ± 1.11	60.57 ± 13.14
Height (cm)	159.43 ± 8.32	160.71 ± 6.01
BMI (kg/m^2)	24.25 ± 5.66	23.33 ± 4.02
Neck Pain Duration (month)	8.57 ± 3.93	9.71 ± 6.68

The data are represented as mean ± SD. **BMI** = Body Mass Index

Table 2. Pain Numeric Rating Scale and Neck Disability Index.

Variable	Group	Pre-Test	Post-Test	P-value
NRS (score)	**Rusie Dutton**	6.00 (4.75 - 6.00)	1.50 (1.00 - 2.00)	0.001*
	Control	5.14 (4.00 - 6.25)	4.57 (3.75 - 5.25)	0.057
	P-value	0.344	<0.001	
NDI (score)	**Rusie Dutton**	9.50 (7.00-14.00)	4.5 (2.00-8.00)	0.001*
	Control	10.64 (7.75-14.25)	11.64 (7.75-17.00)	0.502
	P-value	0.963	0.001*	

The data are represented as median and interquartile range (IQR). *Statistically significant ($P < 0.05$).
NRS = Numeric Rating Scale, **NDI** = Neck Disability Index

Local pressure pain thresholds, comprising suboccipital, trapezius, and levator scapulae, increases were observed in trapezius and in left levator scapulae relative to pre-exercise values; however, these changes were not statistically significant compared with the control group. In contrast, for peripheral pressure pain thresholds (tibialis anterior), no changes were observed following completion of the exercise program, and no statistically significant differences were found between the 2 Groups (Table 3).

Table 3. Pressure Pain Threshold.

Variable	Group	Pre-Test	Post-Test	P-value
Lt. Suboccipital Site	Exercise	1.98 (1.34-2.74)	2.18 (1.58-2.83)	0.074
(kg/cm^2)	Control	2.21 (1.45-2.76)	1.87 (1.48-2.34)	0.132
	P-value	0.490	0.250	
Rt. Suboccipital Site	Exercise	2.03 (1.11-2.25)	1.95 (1.73-2.78)	0.22
(kg/cm^2)	Control	2.18 (1.55-2.91)	2.13 (1.61-2.60)	0.851
	P-value	0.370	0.836	
Lt. Trapezius	Exercise	1.75 (1.03-2.50)	2.03 (1.64-2.84)	0.025*
(kg/cm^2)	Control	1.95 (1.28-2.56)	2.04 (1.29-2.65)	0.600
	P-value	0.490	0.800	
Rt. Trapezius	Exercise	1.40 (1.01-2.18)	2.25 (1.63-2.69)	0.003*
(kg/cm^2)	Control	1.88 (1.23-2.30)	2.15 (1.31-2.78)	0.208
	P-value	0.301	0.872	
Lt. Levator Scapulae	Exercise	2.48 (1.78-3.23)	2.80 (2.14-3.79)	0.033*
(kg/cm^2)	Control	2.95 (2.44-3.35)	3.01 (2.33-3.67)	0.826
	P-value	0.290	0.713	
Rt. Levator Scapulae	Exercise	2.3 (1.80-3.59)	3.00 (2.41-3.53)	0.079
(kg/cm^2)	Control	3.02 (2.30-3.50)	3.19 (2.20-4.35)	0.683
	P-value	0.223	0.818	
Lt. Tibialis Anterior	Exercise	4.10 (2.96-5.45)	4.40 (3.51-5.00)	0.149
(kg/cm^2)	Control	4.23 (3.61-4.91)	4.78 (3.18-6.26)	0.158
	P-value	0.613	0.260	
Rt. Tibialis Anterior	Exercise	3.87 (3.19-5.44)	4.75 (3.81-5.25)	0.096
(kg/cm^2)	Control	4.29 (3.80-5.08)	4.53 (3.94-5.19)	0.331
	P-value	0.581	0.566	

The data were represented as median and interquartile range (IQR). *Statistically significant ($P < .05$).
kg/cm^2 = Kilogram/Square Centimeter

DISCUSSION

This study demonstrated that the subjects who completed a 3-week program that consisted of 4 Rusie Dutton postures, performed 3 times weekly, experienced a significantly greater reduction in pain intensity than those in the Control Group. In addition, the observed improvement exceeded the minimal clinically important difference (MCID), with a reduction greater than 2.76 points (29,39). These findings are partially consistent with the findings of a previous study by Thanasilungkoon et al. (32), which reported that a 12-posture Rusie Dutton exercise program significantly reduced pain among office workers. Similarly, the results align with those of Maenpuen et al. (21) who found that Rusie Dutton exercise led to significant improvements in both pain and Neck Disability Index in individuals with text neck syndrome.

One of the key components of the Rusie Dutton exercise is muscle stretching (19). In the present study, the Rusie Dutton exercise program significantly reduced pain. This may be attributed to the fact that muscle stretching increases range of motion and reduces stiffness, thereby alleviating neural compression and decreasing muscle spindle activity (20). In addition, mechanical tension generated during stretching can stimulate free nerve endings that are sensitive to mechanical stimuli, and these signals are transmitted through faster-conducting afferent pathways than nociceptive fibers. Consequently, these afferent signals may reach the substantia gelatinosa in the dorsal horn earlier, promoting presynaptic inhibition and attenuating pain signal transmission and reducing pain perception (15,18,22,34) and improving Neck Disability Index scores.

In addition, the Rusie Dutton exercise can be categorized as a mind–body exercise that incorporates meditative components with slow, controlled, and graceful movements combined with deep breathing and relaxation techniques. Regular participation in mind–body exercises may contribute to stress reduction and autonomic nervous system modulation, thereby decreasing the secretion of stress-related hormones, including cortisol. Such modulation of the stress response may, in turn, attenuate systemic inflammatory activity and subsequently reduce the perception of pain (11,12). Pressure pain thresholds measured at the painful region indicate localized hyperalgesia; whereas, those measured at remote sites indicate widespread hyperalgesia. Localized hyperalgesia is considered a manifestation of peripheral sensitization involving Aδ and C nociceptive fibers, while widespread hyperalgesia may indicate altered central pain processing resulting from central sensitization (26,31).

Compared with baseline values, the present study demonstrated a significant increase in PPT at the painful regions, including the upper trapezius and the left levator scapulae. These findings partially correspond with those reported by Ylinen et al., who found that PPT values were significantly elevated in both the neck muscle endurance training and neck muscle strength training groups at the 12-month follow-up compared with baseline values in women with chronic non-specific neck pain (37). A 3-week 4-posture Rusie Dutton exercise program significantly improved PPT in the trapezius and the left levator scapulae muscles, while no noteworthy changes were detected in the other muscles evaluated. These findings are consistent with previous research reporting a slight increase in the trapezius muscle stiffness in chronic neck pain, while no significant differences were identified in other muscles between individuals with and without chronic neck pain (28). Chronic neck pain is commonly associated with alterations in muscle properties and increased sensitivity to painful stimuli, particularly in the trapezius muscle. Abnormal mechanical and sensory properties of the upper and middle trapezius have been proposed as contributing factors to chronic neck pain, irrespective of substantial limitations in cervical mobility (4).

However, no statistically significant differences in PPT were observed between the Groups in the present study. These findings align with a previous study reporting significant within-group changes in PPT at the left trapezius muscle after the neck/shoulder training for 20 weeks, while no significant between-Group changes were identified between the exercise and reference groups (23). Several factors may influence the effectiveness of exercise training on pain sensitivity, including exercise frequency, duration, intensity, modality, and participant adherence. A previous review suggested that among individuals with chronic pain, the most substantial benefits are generally observed when exercise interventions are implemented at light-to-moderate intensity, with sessions conducted 2 to 3 times weekly over a minimum duration of 4 weeks (7). Therefore, the 3-week training duration used in the present study may have been insufficient to produce significant between-group effects.

Three weeks of the Rusie Dutton exercise did not alter the pressure pain threshold (PPT) at the remote site (the tibialis anterior). This result is in agreement with O'Leary et al. who reported that specific neck muscle training elicited only localized hypoalgesia without affecting remote pain sensitivity (27). In contrast, Andersen et al. (2) found that 10 weeks of scapular function training increased PPT at the upper trapezius, lower trapezius, and tibialis anterior within the intervention group, although a significant between-group difference was observed only at the lower trapezius (2). The discrepancy between studies may be attributable to the longer intervention duration, which may be necessary to induce widespread hypoalgesic responses.

Limitation in this Study

The relatively short duration of the exercise intervention represents a limitation of this study. While the intervention reduced pain intensity and improved PPT within the exercise group, these changes did not translate into significant between-group differences in pain sensitivity. Hence, it is possible that a longer training period is necessary to elicit more pronounced exercise-induced hypoalgesic effects and to achieve clinically meaningful changes in both local and widespread pain sensitivity.

The effectiveness of exercise interventions in reducing pain may be influenced by several factors, including exercise duration, frequency, and intensity. These variables are likely to determine the magnitude and distribution of exercise-induced hypoalgesia, which may explain the variability in clinical and sensory pain outcomes observed across studies. Therefore, future research should focus on optimizing exercise prescription by systematically investigating dose–response relationships, including intensities, and intervention durations, to enhance both clinical pain relief and objective measures of pain modulation in individuals with neck pain.

Conclusion

A 3-week 4-posture Rusie Dutton exercise program in individuals with chronic non-specific neck pain resulted in a significant reduction in pain intensity and NDI. However, changes in PPT were observed only within the Intervention Group and were not significantly different between the Groups. These findings suggest that while short-term exercise may improve self-reported pain, it may be insufficient to produce between-group differences in pain sensitivity. A longer duration and appropriately dosed progressive exercise prescription should be implemented to achieve clinically relevant improvements in pain modulation and sensory processing.

Conflict of Interest
The authors declare that they have no conflict of interest regarding the publication of this paper.

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