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Proximal and Distal Muscle Responses to Blood Flow Restriction: Increases in Inter-Peak Muscle Activation Time During Sled-Pushing Tasks

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Abstract

Blood flow restriction (BFR) training is increasingly applied in rehabilitation and performance settings as a low-load alternative to traditional resistance exercise. BFR neuromuscular activation during dynamic, functional activities is less understood, particularly in an acute scenario. ***Purpose:*** To investigate how inter-peak muscle activation time (IPMAT) of lower limb muscles (proximal and distal to the cuff) adapted to blood flow restriction while pushing a sled (constant resistance acquired with continuous speed) at two consistent walking speeds. ***Methods:*** Sixty-two healthy adults (8 men, 54 women; mean age = 23.0 ± 3.0 years) participated. Anthropometrics, vital signs, and limb dominance were documented. Surface electromyography (EMG; Delsys Trigno system) recorded activity of the gluteus maximus, medial gastrocnemius, and tibialis anterior of the dominant leg. Participants pushed an XPO Trainer sled (85 lb total load) over 40 ft at a slow walk (80 bpm) and a fast walk (140 bpm). Three randomized trials were performed under unrestricted and BFR conditions. BFR was applied with Delfi's Personalized Tourniquet System at 80% limb occlusion pressure. The primary outcome was BFR versus non-BFR IPMAT for all muscles, analyzed using multivariate analysis of variance (MANOVA). ***Results:*** BFR significantly increased IPMAT in the gluteus maximus (slow walk: 1.0672 ± 0.1086 s vs. non-BFR 0.9524 ± 0.1228 s, $p < .001$; fast walk: 1.1061 ± 0.0955 s vs. non-BFR 0.9428 ± 0.1150 s, $p < .001$) and medial gastrocnemius (slow walk: 1.1076 ± 0.0798 s vs. 0.8040 ± 0.0969 s, $p < .001$; fast walk: 1.1435 ± 0.1064 s vs. 1.0719 ± 0.1292 s, $p = .008$). No significant differences were observed in the tibialis anterior ($p > .05$). ***Conclusions:*** During the blood-constriction settings, IPMAT adapts the primary pushing muscles (gastrocnemius and gluteus muscles), regardless of occlusion cuff location (proximal versus distal), suggesting delayed recovery between activation bursts due to increased neuromuscular demand under restricted blood flow. This adaptation may represent compensatory strategies to sustain task performance under fatigue or metabolic stress. ***Clinical Relevance:*** BFR sled pushing provides a low-load alternative that increases neuromuscular variation, increases fatigue and compensatory demands, and supports endurance. Clinicians should consider these timing adaptations when prescribing BFR to individuals with lower extremity weakness, balance deficits, or gait impairments.

Keyword: Blood Flow Restriction Inter-Peak Muscle Sled-Pushing Tasks Anthropometrics

INTRODUCTION

Physical activity and exercise are essential for maintaining healthy cardiovascular and musculoskeletal systems (Palazzuoli *et al.*, 2023). However, certain conditions make it challenging for some individuals to engage in high-load exercise, underscoring the need for lower-load training alternatives. One promising approach to addressing this problem is blood flow restriction (BFR) training (Karabulut & Perez, 2013; May *et al.*, 2022). BFR mechanism involves applying external pressure to partially occlude arterial blood flow, thereby inducing muscular adaptations comparable to those achieved through high-load training with lower loads (Karabulut & Perez, 2013; May *et al.*, 2022).

Research on BFR has demonstrated improvements in muscle strength and hypertrophy (Fatela *et al.*, 2019; May *et al.*, 2022), as well as adaptations in neuromuscular recruitment patterns (Rosario *et al.*, 2024; Garcia *et al.*, 2024, 2025). To the best of our knowledge limited evidence exists regarding the influence of BFR on the temporal components of neuromuscular activation during acute functional dynamic tasks, such as normal or resisted walking. An important component of muscle activity and neuromuscular timing is the distance between consecutive peaks of activation, inter-peak muscle activation time (IPMAT). Amplitude data shows the magnitude of muscle contraction (Rosario *et al.,* 2022), while the IPMAT is a metric that quantifies the interval between successive muscle peak activations during gait or other dynamic motor tasks. IPMAT could provide insight into the underlying neuromuscular efficiency and the motor system's capacity to adapt to variable environments, such as ramps, stairs, or uneven walkways. Furthermore, IPMAT has shown promise as a sensitive measure of neuroplasticity, motor learning, and fatigue-related modulation in both healthy and clinical populations. As such, IPMAT not only enhances the quality of gait analysis but also supports early detection of motor control adaptations and deficits, and guides targeted therapeutic interventions (Rinaldi, 2020; Huber *et al.,* 2011; Srivastava, Patten, & Kautz, 2019).

In the current study, the assumption is that prolonged inter-peak intervals indicate more efficient contraction and slower fatigue. This neuromuscular adaptation could be related with fatigue-resistant type I fibers, which is linked to improved endurance and sustained low-threshold motor unit recruitment. On the other hand, shorter inter-peak intervals suggest recruitment of type II fibers, which are commonly associated with faster fatigue (Machado, Alves, & Hendler, 2017). Accordingly, examining IPMAT under blood occlusion conditions may reveal neuromuscular patterns that could be translated into potential benefits during BFR intervention (Pearson & Hussain, 2015; Scott *et al.,* 2015; Yasuda *et al.,* 2010) regardless of cuff location.

In this study, as in the protocols of Rosario *et al.,* (2024) and Garcia *et al.,* (2024), researchers utilized a sled that provides constant resistance at a constant speed, combined with BFR. Muscle activity during resisted gait tasks, such as sled pushing, echoes the required force for lower-extremity muscle activation, thus at lower speeds increases proximal muscle engagement and shifting toward more distal recruitment at higher speeds (Garcia *et al.,* 2024; Mathis *et al.,* 2020; Rosario *et al.,* 2020, 2022). Furthermore, Rosario *et al.,* (2020, 2022) emphasized that load and speed modifications substantially influence muscle activation patterns while pushing a resistance sled. The force–length and force–velocity relationships of muscles such as the gastrocnemius may also affect activation timing as speed increases, potentially necessitating the recruitment of additional muscle groups (Monte *et al.,* 2022). On a related study, Alcaraz *et al.,* (2018) highlighted the role that speed plays in enhancing sprint performance, noting that sled-pushing dynamics, specifically the force exerted and movement speed, are critical for improving athletic speed and explosive power.

Based on the above, the present study examined how BFR affects the timing of lower-limb muscle activity during a -pushing task performed at two different walking speeds. Delineating on earlier work by Rosario *et al.,* (2024) and Garcia *et al.,* (2024; 2025), we hypothesized that regardless of the cuff location (gluteal muscles are proximal to the cuff, whereas gastrocnemius is distal) BFR would modify muscle recruitment by reducing muscle activity in the primary pushing muscles compared with non-BFR tasks.

METHODS

Study Design and Participants

A cross-sectional experimental study was conducted, and 62 healthy adults (8 men, 54 women; mean age = 23.0 ± 3.0 years) were included through convenience sampling from a university setting. Eligible participants were between 18 and 35 years of age and able to perform moderate physical activity without limitations. Individuals were excluded if they had reported a lower extremity injury within the previous six months, had cardiovascular or neurological conditions, or presented contraindications to blood flow restriction (BFR) use. All participants provided written informed consent before enrollment. After signing the informed consent, anthropometric measurements, vital signs, and leg dominance were recorded for each subject.

Instrumentation and Muscle Selection

Muscle activity was measured using surface electromyography (EMG) with a Delsys Trigno wireless system (Delsys Inc., Natick, MA). Similar to the studies of Rosario *et al.,* (2024) and Garcia *et al.,* (2024;2025), proximal to occlusion, electrodes were placed on the gluteus maximus and distal to the occlusion site on medial gastrocnemius and tibialis anterior of the dominant lower extremity. Skin preparation was performed according to previously published guidelines by Rosario *et al.,* (2020).

Experimental Protocol

Sled-pushing trials were completed using an XPO Trainer sled (Armored Fitness Equipment, LLC, Plano, TX) with a base weight of 60 lb plus an additional 25-lb plate (total resistance = 85 lb), following the protocol described by Rosario *et al.,* (2023, 2024). The sled was pushed over a 40-ft distance at two predetermined walking speeds: a slow walk (80 beats per minute) and a fast walk (140 beats per minute). Three trials were performed at each speed under unrestricted (non-BFR) and BFR sled pushing. The order of conditions was randomized to minimize order effects. BFR was applied using Delfi’s Personalized Tourniquet System (Delfi Medical Innovations Inc., Vancouver, BC, Canada) at 80% limb occlusion pressure. A 3-minute seated rest period was provided between conditions.

Data Collection and Analysis

EMG signals were sampled and processed to calculate inter-peak muscle activation time (IPMAT), which was defined as the interval, in seconds, between consecutive peaks of muscle activation during the sled-pushing task. A multivariate analysis of variance (MANOVA) was conducted to examine the effects of BFR and walking speed with no BFR on IPMAT across the three muscles. Statistical significance was set at $p < .05$.

RESULTS

Participant Characteristics

As shown in Table 1, 62 participants (8 males and 54 females) were included in the analysis. The current study recruited young healthy adults (mean age of 23.0 ± 3.0 years, height of 64.7 ± 3.0 inches, weight of 152.0 ± 33.0 lb, and BMI of 22.0 ± 3.2 kg/m²). After signing informed consent and data collection, vitals were gathered from all participants (heart rate 81.1 ± 16.0 bpm, systolic blood pressure 117.4 ± 11.10 mmHg, diastolic pressure 79.6 ± 10.01 mmHg, and oxygen saturation 98.37 ± 0.89%) to ensure cardiovascular stability. Interestingly, leg dominance was assessed using EMG electrodes and BFR placement, and, for this study, it was evenly distributed (31 right- and 31 left-dominant participants).

Table 1: Demographic Data of All Participants

Characteristic	Participant Data
Age (years)	23.0 ± 3.0
Gender	Male = 8, Female = 54
Height (in)	64.7 ± 3.0
Weight (lb)	152.0 ± 33.0
BMI (kg/m²)	22.0 ± 3.2
Heart Rate (bpm)	81.1 ± 16.0
Systolic BP (mmHg)	117.4 ± 11.10
Diastolic BP (mmHg)	79.5 ± 10.01
SpO_2 (%)	98.37 ± 0.89
Leg Dominance	Right = 31, Left = 31

Inter-Peak Muscle Activation Time (IPMAT)

A multivariate analysis of variance (MANOVA) revealed significant differences in IPMAT between BFR and Non-BFR conditions for the gluteus maximus and medial gastrocnemius muscles ($p < .001$). Table 2 shows that the gluteus maximus, IPMAT was significantly greater under BFR (1.0672 ± 0.1086 sec) compared to non-BFR (0.9524 ± 0.1228 sec) at 80 bpm, and similarly at 140 bpm (BFR = 1.1061 ± 0.0955 sec; non-BFR = 0.9428 ± 0.1150 sec, $p < .001$). Medial gastrocnemius results showed a similar pattern to gluteus maximus, with increased IPMAT under BFR at both 80 bpm (1.1076 ± 0.0798 sec vs. 0.8040 ± 0.0969 sec, $p < .001$) and 140 bpm (1.1435 ± 0.1064 sec vs. 1.0719 ± 0.1292 sec, $p = .008$). As depicted in Table 3, no significant differences were detected for the tibialis anterior across BFR and non-BFR conditions ($p > .05$).

Table 2: Inter-Peak Muscle Activation Time (IPMAT) for Gluteus Maximus and Medial Gastrocnemius Under BFR and Non-BFR Conditions

Muscle	Speed (bpm)	Non-BFR Mean ± SD (sec)	BFR Mean ± SD (sec)	p-value
Gluteus Maximus	80	0.9524 ± 0.1228	1.0672 ± 0.1086	< .001
	140	0.9428 ± 0.1150	1.1061 ± 0.0955	< .001
Medial Gastrocnemius	80	0.8040 ± 0.0969	1.1076 ± 0.0798	< .001
	140	1.0719 ± 0.1292	1.1435 ± 0.1064	.008

Table 3: Inter-Peak Muscle Activation Time (IPMAT) for Tibialis Anterior Under BFR and Non-BFR Conditions

Speed (bpm)	Non-BFR Mean ± SD (sec)	BFR Mean ± SD (sec)	p-value
80	1.7 ± 0676	1.8 ± 0.753	0.22
140	0.6 ± 0.34	0.6 ± 0.29	0.44

DISCUSSION

The present study investigated the effects of BFR on inter-peak muscle activation time (IPMAT) during sled pushing at two walking speeds. BFR significantly increased IPMAT in the gluteus maximus proximal to the occlusion site and distal to the tourniquet, medial gastrocnemius. In the pushing flexor musculature, tibialis anterior showed no significant effect. These findings indicate that BFR prolongs activation intervals in muscles directly involved in propulsion, consistent with heightened neuromuscular demand during resisted locomotion. Based on the above, we accept our hypothesis.

The prolongation of IPMAT under occlusion is in agreement with prior reports of accelerated neuromuscular fatigue with restricted blood flow, even under low external loads (Scott *et al.*, 2014; May *et al.*, 2022). The heightened adaptation of the gluteus maximus aligns with earlier evidence demonstrating increased gluteal activation during incline and load-bearing gait tasks (Sturdy *et al.*, 2024; Hora *et al.*, 2024). Similarly, the gastrocnemius response supports findings that distal muscles exhibit timing adaptations to task demands and speed (Monte *et al.*, 2022; Valencia *et al.*, 2023). By contrast, the tibialis anterior remained largely unaltered, at the set speed, consistent with previous attempts to selectively enhance its activation through functional tasks, which have shown limited efficacy (Rosario *et al.*, 2020; Rosario *et al.*, 2021; Rosario & Jose, 2021; Orozco *et al.*, 2022).

The slowing of neuromuscular rhythm could represent a compensatory adjustment in recruitment strategies to preserve task performance in hypoxic conditions. Of the two muscles distal to the occlusion site, tibialis anterior show constant muscle activation during both conditions, which could be explained in the musculature recruited in sled propulsion, as presented by Rosario *et al.*, (2020 & 2022). Notably, the gluteus maximus located proximal to the cuff site also exhibited significant changes, indicating that BFR can influence muscles beyond the occluded region. The upstream adaptation is important to highlight and further study, especially in populations with hip and pelvic injury. Based on the above, the assumption is that the upstream effect is caused by reduced hemodynamics on the common iliac artery before its division to the external (femoral artery towards the leg) and internal iliac artery (superior gluteal vessels towards the gluteal muscles). The upstream effect seen in this work is consistent with evidence from upper-limb studies showing proximal adaptations despite distal cuff application (Lambert *et al.*, 2021).

Finally, this study suggests that BFR, when combined with sled pushing —a low-load training modality —imposes substantial neuromuscular demands and may accelerate fatigue during functional activities. The characteristics of rehabilitation settings — where a reduction in mechanical loading is required or recommended, yet muscle engagement is preferred — make this modality ideal for some populations. However, clinicians should exercise caution when prescribing BFR for individuals with limited endurance or impaired motor control, as prolonged activation intervals may compromise task efficiency or stability.

The current study focuses on shorter walkways (40 feet), a young, healthy adult population, and acute adaptation (rather than long-term compound effects) to highlight a few restrictions. Related to the walkway, a 40-foot sled-pushing distance perhaps was insufficient to elicit maximal fatigue, particularly in the tibialis anterior. The acute focus in the current research makes it challenging to draw parallels with previous, longer-term occlusion studies. Finally, the sample consisted exclusively of young healthy adults, which could limit generalizability to older or clinical populations. Although the above are potential constraints, the authors believe that, to understand the baseline mechanics of occlusion's impact on the lower limbs combined with a low-load resistance device, the aforesaid starting points were necessary.

CONCLUSION

The novelty of this work highlights the notion that acute BFR increases the inter-peak activation duration of the primary posterior chain muscles (gluteus maximus and gastrocnemius) during slow walking (80 bpm) and faster walking (140 bpm). The present study advances understanding of neuromuscular adaptations to BFR, specifically IPMAT, during sled pushing at different walking speeds. BFR selectively alters activation timing in muscles used for propulsion, both proximal and distal to the occlusion site. Increased IPMAT likely reflects neuromuscular fatigue or compensatory strategies, and this adaptation should be considered in individuals with lower extremity injuries, balance impairments, or conditions requiring low-load exercise interventions. Sled-pushing protocols incorporating BFR may be particularly ideal for targeting key pushing proximal muscles, such as the gluteus maximus, which is critical for conditions like patellofemoral pain and lower back dysfunction.

Future research should evaluate IPMAT as a functional marker of neuromuscular adaptation across different dynamic tasks and loading conditions. Studies incorporating non-dominant extremity (lower limb variability), diverse sled-pushing modalities (e.g., incline surfaces, longer walkways, faster speeds, or backward tasks), and clinical populations (People living with HIV, Autonomic Dysfunction, or peripheral neuropathy) are needed to determine the broader applicability of BFR for enhancing neuromuscular control in both performance and rehabilitation contexts.

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