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Does Blood Flow Restriction Cause Neuromuscular Adaptability in Lower Limb Musculature While Pushing Low-Load Resistance?

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Abstract

Introduction: Blood flow restriction (BFR) combined with resistance training can promote hypertrophy, enhance muscle activation, and improve function. Muscle electromyography (EMG) is commonly used to elucidate neuromuscular recruitment and highlight adaptive changes in recruitment due to BFR. ***Purpose***: This study used electromyography (EMG) to determine the influence of BFR on lower-extremity (LE) neuromuscular activation timing during resistive sled training. ***Methods***: Sixty-two participants were recruited (eight males and 54 females; mean age, 23 years). EMG) electrodes were placed on the belly of selected muscles of the dominant LE to record muscle activation. Participants pushed an XPO sled trainer at slow (60 bpm) and fast (140 bpm) walking speed protocols (three trials each) with and without the application of BFR to the LE for a total of 12 trials. The EMG variables assessed were time to peak, decay, and duration of muscle activation. ***Results***: The outcomes revealed several adaptations in EMG variables for functionally activated muscles above and below the cuff when pushing a sled while using BFR. ***Conclusions & Clinical Relevance***: Several tendencies have been identified in the gastrocnemius, tibialis anterior, and hip extensors depending on walking speed, which may be foundational to future research and should be explored further. Our results suggest that low-load BFR can benefit patients with leg musculature weakness, extensor musculature fatigue, and proximal thigh musculature rehabilitation.

Keywords: Blood flow restriction (BFR), enhance muscle activation, electromyography (EMG).

INTRODUCTION

According to the literature, blood flow restriction (BFR) training promotes hypertrophy, enhances muscle activation, and improves function in diverse young and old populations (Patterson *et al.*, 2019). Most BFR interventions are implemented while performing resistance exercises with various sets and repetitions (Patterson *et al.*, 2019). Resistance training (RT) is the most frequently employed training modality (Giallauria *et al.*, 2016). This training modality (i.e., body weight, implements, vibration, and kettlebells) may integrate variables such as sequence, velocity, frequency, and rest intervals (Fragala *et al.*, 2019). BFR can be recommended when heavy load resistance exercise is not tolerated or advised, such as during recovery from musculoskeletal injuries such as surgery (Patterson *et al.*, 2019; Ladlow *et al.*, 2018; Trofa *et al.*, 2020). Although reasonable evidence supports using BFR with RT, the literature is limited to determining similarities between BFR and RT programs. Additionally, to the best of our knowledge, the characterization and benefits of BFR on neuromuscular recruitment are limited, if not nonexistent. To the above utterance, two detailed reviews of BFR literature stated limitations in concluding best-practice recommendations based on the scarcity of investigations assessing the effectiveness of BFR (Patterson *et al.*, 2019; Ladlow *et al.*, 2018; Trofa *et al.*, 2020). More specifically, other researchers have concluded that evidence using BFR to improve the functional performance of daily activities in different populations, such as older adults, is scarce (Kim *et al.*, 2016; Abe *et al.*, 2010).

Although systematic reviews and meta-analyses have demonstrated an increase in muscular strength via low-load blood flow restriction (LL BFR) training (Patterson *et al.*, 2019; Ladlow P *et al.*, 2018; Trofa *et al.*, 2020), variability among studies include differences in exercise regimens, patient populations,

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and outcome measure utilization. Patterson *et al*., (2019) noted variations in research protocols due to factors such as the wide range of cuff widths used in the BFR literature. This width variation causes the amount of pressure required to occlude blood flow to a limb to be highly inconsistent, as this is primarily determined by cuff width. In agreement with the aforementioned, Trofa *et al*., (2020) highlighted the variability of BFR application owing to the use of elastic wraps or inflatable cuffs and differences in pressure calibration, which, according to the authors, some studies still need to report. Trofa *et al*., (2020) also spotlighted divergences in the methods used for recording outcome measures, such as muscle hypertrophy, which have further obscured the effects of BFR. Some studies have used proxy measurements, such as limb girth (Trofa *et al*., 2020), whereas others have used cross-sectional muscle areas (Ladlow *et al*., 2019). Some researchers underlined that associated findings related to increases in strength parameters with LL-BFR training are often limited to pooled data linked to specific, selected, and inclusive study criteria (Patterson *et al*., 2019; Ladlow *et al*., 2018; Trofa *et al*., 2020).

Furthermore, the comparative variability noted in cellular alterations (Ladlow *et al*., 2018; Abe *et al*., 2010), blood flow (capillarization (Trofa *et al*., 2020; Kim *et al*., 2016)), and subject population variation often mitigate the determinants of BFR study validity and generalizability. A possible solution for the above, recommended by the current study, is surface electromyography (sEMG) with BFR. sEMG is a valuable clinical tool, as Medved *et al*., (2020) pointed out in their study. The authors stated that sEMG provides information about muscle performance during functional activities such as gait, therefore enhancing the ability of clinicians to diagnose and treat different abnormalities.

Accordingly, based on the above, sEMG could be utilized to examine direct muscle activation associated with therapeutic resistive exercises. This proposed research intends to incorporate sEMG to combat the variability associated with BFR training and allow for a reasonable understanding of muscle activation adaptation. Likewise, this examination could furnish a valuable understanding of motor recruitment, muscle performance, endurance, and strength. This information could assist clinicians in determining the optimal adjunct for BFR training. Therefore, the distinct objective of this study is to characterize lower-extremity neuromuscular activation during BFR while pushing a low load resistance (sled).

METHODS

This study recruited 62 participants, 8 males, and 54 females, with an average age of 23 (23.0 +/- 2.98). Participants were screened for eligibility and signed an informed consent form before participation. Following signed consent, the primary investigators collected baseline information before placing the sling. Data included age, sex, height, weight, leg dominance, heart rate, oxygen saturation, and blood pressure. Surface Electromyography (sEMG) electrodes were placed in six areas to monitor muscle activity after cleaning or shaving when applicable. Electromyographic electrode placement was performed using the protocol described by Rosario *et al*., (2021 & 2022). sEMG electrodes were placed on the belly of the dominant leg of the anterior tibialis medial gastrocnemius, vastus medialis oblique, biceps femoris, gluteus maximus, and gluteus medius.

Sled protocol: An XPO trainer sled was used for the sled push protocol. The XPO trainer was a 60-lb sled measuring 43" H x 43.5" L x 35" W and fitted with a 25-lb rubber plate to provide traction to the wheels. This sled trainer is a rolling sled attached to a motor that provides constant resistance with sustained speed, which reflects the difficulty of pushing it. The sled protocol was based on a study by Rosario *et al*., (2022). The protocol mentioned above consisted of two walking components: Slow Walk (SW), in which the participants walked at a pace of 80 bpm, and Fast Walk (FW), in which they walked at a pace of 140 bpm. Participants completed three trials in each protocol, pushing the sled 40 feet in each trial and using a metronome to maintain the assigned pace.

Participants were assigned to groups using consecutive allocation based on the order in which they were enrolled in the study: odd-numbered participants were assigned to one group, and even-numbered participants were assigned to the other. Both groups completed the SW and FW protocols but in different orders. The odd-numbered group completed FW first, followed by SW, whereas the even-numbered group completed the opposite.

The participants were instructed to push the sled at a designated pace with straight arms, given a visual demonstration, and one attempt to practice pushing alongside the metronome (80 or 140 beats per minute). Participants completed each protocol in the order of their assigned groups.

Participants then had Blood Flow Restriction (BFR). Delfi's Personalized Tourniquet System for Blood Flow Restriction was used in this study, alongside Delfi's Easi-Fit BFR Tourniquet Cuffs and limb protection sleeves. A tourniquet cuff was worn on the proximal thigh of the patient's dominant leg. Delfi's Personalized Tourniquet System for Blood Flow Restriction calculated the total occlusion pressure before sustaining 80% of the total occlusion. The participants then completed the same sled protocols, resting in a seated position for 3 min with 0% occlusion between the protocols. Data were recorded for all trials using the Delsys Trigno Research+System and Delsys EMGworks Ⓡ Software.

DATA ANALYSIS

The EMG activity of the hip (gluteus maximus and medius), knee (hamstring and quadriceps), and leg (tibialis anterior and gastrocnemius) musculature was collected at 1,000 Hz for all tasks pre/post-BFR. The neuromuscular timing (in seconds) for the studied muscles included the threshold at maximal peak activation (time to peak TP), after the activity ended (decay), and the period of muscle activation (duration). Data compilation averaged three successive activation points for each muscle under all the conditions at the midpoint of the walking trace to ensure the stability or consistency of the lower limb musculature. The present study used SPSS (version 28) with MANOVA to draw a parallel between neuromuscular time data points for slow walking at 80 bpm pre-/post-BFR and fast walking at 140 bpm pre-/post-BFR while pushing the sled. The current study considered a p-value of < 0.05.

RESULTS

Table 1 presents all participants' baseline demographics, including age, sex, and BMI. Our participant pool (n = 62) comprised 8 males and 54 females with a mean age of 23.60 +/- 2.98 years. The following tables show the EMG timing results for the six muscles. The results were found using MANOVA, with a significance value set at p≤0.01.

Tables 2a and 2b compare BFR and non-BFR for the tibialis anterior and gastrocnemius at 80 and 140 bpm, respectively. These data revealed a pattern of higher activation of the gastrocnemius at slower walking speeds, as shown by EMG timing. Another pattern shown is that the muscle activation of the tibialis anterior is higher at faster walking speeds.

Tables 3a and 3b compare BFR and non-BFR for the hamstring and quadriceps at 80 and 140 bpm, respectively. Tables 4a and 4b also compare BFR and non-BFR for the gluteus maximus and gluteus medius. Higher activation patterns were observed in the hip extensor musculature at lower walking speeds than higher ones.

Table 1: Demographic data of all participants

Characteristics	**Participant Data**
Age	23.60 +/- 2.98
Gender	Male = 8 Female = 54
Height (in)	64.66 +/- 2.89
Weight (lb)	151.8 +/- 32.99
BMI (kg/m^2)	21.95 +/- 3.21
Heart Rate (bpm)	81.08 +/- 16.00
Systolic BP (mmHg)	117.38 +/- 11.10
Diastolic BP (mmHg)	79.55 +/- 10.01
Sat O2 (%)	98.37 +/- 0.89
Leg Dominance	R = 31 L = 31

Table 2a: Comparisons of EMG timing for TA and GA among tasks. Results of a MANOVA were performed comparing Non-BFR and BFR @ 80bpm. The significance level was set at p≤0.01.

Tibialis Anterior	**Non-BFR @80bpm**	**SD +/-**	**BFR @80bpm**	**SD +/-**	P-value
Time to peak	1.7	+/- 0.676	1.8	+/- 0.753	0.25
Decay	0.6	+/- 0.345	0.6	+/- 0.290	0.60
Duration	1.3	+/- 0.421	1.4	+/- 0.442	0.21
Inter-Peak	2.2	+/- 0.540	2.2	+/- 0.657	0.84
GA	Means and SD	SD +/-	Means and SD	SD +/-	P-Value
Time to peak	1.5	+/- 0.600	1.5	+/- 0.539	0.94
Decay	0.44	+/- 0.281	0.51	+/- 0.260	0.05
Duration	1.10	+/- 0.400	1.16	+/- 0.32	0.14
Inter-Peak	2.23	+/- 0.193	2.22	+/- 0.235	0.85
GA=gastrocnemius, bpm=beat per minute, S.D.=Standard Deviation					

Table 2b: Comparisons of EMG timing for TA and GA among tasks. Results of a MANOVA were performed comparing Non-BFR and BFR @ 140bpm. The significance level was set at p≤0.01.

Tibialis Anterior	**Non-BFR @140bpm**	**SD +/-**	**BFR @140bpm avg**	**SD +/-**	P-value
Time to peak	1.20	+/- 0.431	1.22	+/- 0.551	0.40
Decay	0.40	+/- 0.221	0.41	+/- 0.183	0.77
Duration	0.91	+/- 0.269	0.94	+/- 0.277	0.37
Inter-Peak	1.43	+/- 0.403	1.48	+/- 0.446	0.27
GA	Means and SD	**SD +/-**	Means and SD	**SD +/-**	P-Value
Time to peak	1.1	+/- 0.384	1.1	+/- 0.286	0.22
Decay	0.4	+/- 0.176	0.3	+/- 0.105	0.23
Duration	0.8	+/- 0.263	0.8	+/- 0.155	0.14
Inter-Peak	1.4	+/- 0.388	1.4	+/- 0.158	0.26
GA=gastrocnemius, bpm=beat per minute, S.D.=Standard Deviation					

Table 3a: Comparisons of EMG timing for HAM and QUAD among tasks. Results of a MANOVA were performed comparing Non-BFR and BFR @ 80bpm. The significance level was set at p≤0.01.

Hamstring	**Non-BFR @80bpm**	**SD +/-**	**BFR @80bpm avg**	**SD +/-**	P-value
Time to peak	1.4	+/- 0.584	1.3	+/- 0.550	0.64
Decay	0.6	+/- 0.872	0.7	+/- 0.574	0.21
Duration	1.2	+/- 0.835	1.3	+/- 0.611	0.22
Inter-Peak	2.2	+/- 0.337	2.2	+/- 0.467	0.50
Quadriceps	Means and SD	**SD +/-**	Means and SD	**SD +/-**	P-value
Time to peak	1.7	+/- 0.794	1.2	+/- 0.472	0.87
Decay	0.8	+/ 0-.216	0.8	+/- 0.338	0.31
Duration	1.3	+/- 0.353	1.3	+/- 0.380	0.41
Inter-Peak	2.2	+/- 0.450	2.2	+/- 0.393	0.87
bpm=beat per minute, S.D.=Standard Deviation					

Table 3b: Comparisons of EMG timing for HAM and QUAD among tasks. Results of a MANOVA were performed comparing Non-BFR and BFR @ 140bpm. The significance level was set at p≤0.01.

Hamstring	**Non-BFR @140bpm**	**SD +/-**	**BFR @140bpm avg**	**SD +/-**	P-value
Time to peak	0.97	+/- 0.356	1.08	+/- 0.405	0.005
Decay	0.49	+/- 0.211	0.46	+/- 0.149	0.05
Duration	0.9	+/- 0.251	0.9	+/- 0.204	0.70
Inter-Peak	1.4	+/- 0.332	1.4	+/- 0.326	0.91
Quadriceps	Means and SD	SD +/-	Means and SD	SD +/-	P-Value
Time to peak	0.8	+/- 0.371	0.7	+/- 0.236	0.20
Decay	0.5	+/- 0.139	0.5	+/- 0.126	0.09
Duration	0.8	+/- 0.217	0.8	+/- 0.170	0.74
Inter-Peak	1.4	+/- 0.303	1.4	+/- 0.223	0.83
bpm=beat per minute, S.D.=Standard Deviation					

Table 4a: compares EMG timing for GLUT MAX and GLUT MED among tasks. Results of a MANOVA were performed comparing Non-BFR and BFR @ 80bpm. The significance level was set at p≤0.01.

Glut Max	**Non-BFR @80bpm**	**SD +/-**	**BFR @80bpm avg**	**SD +/-**	P-value
Time to peak	1.1	+/- 0.516	1.3	+/- 0.611	0.05
Decay	0.7	+/- 0.364	0.8	+/- 0.292	0.28
Duration	1.2	+/- 0.454	1.3	+/- 0.437	0.05
Inter-Peak	2.2	+/- 0.447	2.2	+/- 0.548	0.34
Glut Med	Means and SD	SD +/-	Means and SD	SD +/-	P-Value

Glut Max	**Non-BFR @80bpm**	**SD +/-**	**BFR @80bpm avg**	**SD +/-**	P-value
Time to peak	1.1	+/- 0.605	1.3	+/- 0.679	0.06
Decay	0.8	+/- 0.263	0.7	+/- 0.512	0.26
Duration	1.3	+/- 0.337	1.3	+/- 0.577	0.80
Inter-Peak	2.2	+/- 0.368	2.2	+/- 0.724	0.52
bpm=beat per minute, S.D.=Standard Deviation					

Table 4b: Comparisons of EMG timing for GLUT MAX and GLUT MED among tasks. Results of a MANOVA were performed comparing Non-BFR and BFR @ 140bpm. The significance level was set at $p \leq 0.01$.

Glut Max	**Non-BFR @140bpm**	**SD +/-**	**BFR @140bpm avg**	**SD +/-**	P-value
Time to peak	0.9	+/- 0.428	0.9	+/- 0.354	0.56
Decay	0.5	+/- 0.215	0.5	+/- 0.164	0.05
Duration	0.9	+/- 0.286	0.85	+/- 0.212	0.93
Inter-Peak	1.5	+/- 0.483	1.4	+/- 0.298	0.05
Glut Med	Means and SD	SD +/-	Means and SD	SD +/-	P-Value
Time to peak	0.9	+/- 0.433	0.9	+/- 0.466	0.91
Decay	0.5	+/- 0.188	0.5	+/- 0.237	0.97
Duration	0.9	+/- 0.255	0.9	+/- 0.316	0.99
Inter-Peak	1.5	+/- 0.401	1.4	+/- 0.470	0.32
bpm=beat per minute, S.D.=Standard Deviation					

DISCUSSION

This study explored the impact of blood flow restriction on lower extremity muscle activation while pushing a low-load resistance sled in healthy young adults. This study selected these specific muscles because of their role and importance in gait (Shumway-Cook *et al.*, 2007; Hogsholt., 2022) and pushing a sled (Rosario & Mathis, 2021). This investigation tried to answer the following: Does *blood flow restriction cause neuromuscular adaptability in lower limb musculature while pushing low-load resistance? Yes.* The current study identified several tendencies that may be foundational to future research.

First, our main finding suggests that cross-sectional smaller muscles, distal to the cuff, such as TA, benefit the most from BFR. Primarily, at the ankle, there was more notable variation in tibialis anterior activation at higher walking speeds (Tables 2a and 2b). At a slower pace, there was a recognized increase in the TA time to peak and duration compared to non-BFR. In contrast, at 140bpm, TA had an increased time to peak, decay, duration, and inter-peak. The greater modification observed in TA activation at higher speeds through BFR highlights that BFR substantially influences this muscle group. Lung *et al*., (2021) supported this assumption by observing greater TA activation at higher walking speeds. Lung *et al*., reviewed the TA versus GA activity without BFR at various walking speeds. The authors utilized sEMG activities of the TA and GA to quantify muscle fatigue and activation. The study highlighted that during walking and running speeds, there was increased muscle fatigue in the TA compared to slow and regular walking. The TA showed greater recruitment at these walking speeds due to increased fatigue or activation in the TA. However, Rosario (2020) found that, while pushing the same type of sled, the prevalent muscle recruited was the GA over the TA at self-selected speeds. The above statement implies that BFR promotes TA recruitment over GA during pushing tasks.

Rosario *et al*., (2021, 2022) observed a similar TA activation pattern, pushing a sled at a controlled gait speed. These remarks indicate that BFR promotes TA activation while pushing a slow load resistance. Previous studies indicated the usefulness (increased strength and muscle size) of BFR for specific muscles, such as the quadriceps and hamstrings (Barber-Westin & Noyes, 2019). Nevertheless, the outcome of this work suggests an added benefit (increased muscle recruitment) of BFR, acutely (during the first treatment) while pushing a sled on lower limb musculature such as the TA. The previously mentioned changes in TA time-to-peak with BFR at 80 bpm imply a possibility of preferential stimulation of TA recruitment speed. Therefore, when targeting faster TA recruitment, our recommended interventions will involve pushing the sled while using the BFR at 80 bpm, whereas targeting TA endurance will benefit more from pushing the sled while using the BFR at 140 bpm.

Studies have also suggested that TA demonstrates increased activation with single-limb weight-bearing exercises that induce either a posterior (Cordova *et al*., 1999) or lateral shift in the body's center of gravity, causing a shift in the center of pressure on the foot in a similar direction to maintain balance (Harput *et al*., 2013). Movements that match this description include a single-leg stance on a flexed knee and a single-leg stance with contralateral leg kicks in an anterior or medial-angled direction against resistance. This shift in the center of pressure may explain the heightened TA activity, as the ankle is actively dorsiflexed or inverted to maintain the joint position and stability. Hahn (2011) too suggested that TA exhibits greater recruitment at longer muscle lengths, as is evident from the TA MVC peaking at 90° of knee flexion in their multi-joint leg extension machine, corresponding to increased degrees of dorsiflexion or tasks with balance board activities with a fixed middle fulcrum (Rosario *et al*., 2021). It is essential to point out that various studies examined provoking a distinct activation of TA over GA (for instance) during various tasks such as increasing treadmill inclination (Orozco *et al*., 2022), balance activities during dual motor (Rosario *et al*., 2020; Rosario *et al*., 2022) and cognitive tasks (Rosario & Jose, 2021) and gait dual motor tasks (Rosario *et al*., 2021) unsuccessfully. Based on the above-mentioned and evidence of other potential exercises that may benefit the TA with optimal electrical activation, the current examination provided sled push with BFR as an alternative for populations unable to execute these exercises. The adaptation of TA activity with BFR at 140 bpm suggests prolonged activation of TA, which places a higher muscle endurance demand on TA. Therefore, BFR while pushing the sled could aid people with hip and knee pain or impaired single-leg balance, to name a few.

Our second finding was that hip extensors (hamstrings, gluteus maximus, and gluteus medius) adapted more at slower speeds (80 bpm) than at faster speeds (140 bpm). This previous outcome indicates that BFR with lower speed makes muscles more engaged, which is required for stability during the activity (Wang *et al*., 2023). This principle of hip extensor activity is similar to Liu *et al*., (2008), who found that hip extensors (gluteus maximus, gluteus medius, vastus, hamstrings, gastrocnemius, and soleus) are the main muscles that aid stability and forward progression during walking at any speed. Linden *et al*., (2002) also found that the gluteus medius regularly contributes to gait, which is comparable to our previously reported findings. These muscles are important for forward progression at various walking speeds and stability throughout the gait cycle. Interventions to target this specific musculature could include extension-focused protocols while utilizing BFR.

Other studies have reported similar results for specific exercise protocols encompassing slow- and endurance-focused interventions. De Melo *et al*., 2022 included leg press exercises and hamstring curls in flexor chairs. The dosage of the studies followed a protocol of 30 repetitions, 15 repetitions, 15 repetitions, and 15 repetitions for a total of four sets for each exercise. These repetitions followed a 2-second concentric contraction and a 2-second eccentric contraction. The above is a low-load intensity design that looks toward endurance. Outcomes were favorable for both the hamstrings and quadriceps. This finding is consistent with our second finding on extensor muscle activation. However, our study did not yield significant results for activation at low loads when using a BFR. This above statement represents a potential direction for future research.

Regarding functional activities, walking during the sled-push protocol yielded outcomes similar to those reported by Ozaki *et al*., (2010). They compared BFR versus non-BFR during a 20-minute submaximal treadmill walking exercise program, with intensity measured at 45% of the participant's heart rate reserve. This program was conducted four days a week for ten weeks. The results showed that the maximum knee joint strength and thigh cross-sectional area increased when using BFR compared to the control. Like the current study, Ozaki *et al*., targeted slower speeds and more moderate intensities, which are effective interventions in the elderly population when combined with BFR. Future studies should examine similar effects in healthy individuals using the same protocol. BFR with slower submaximal exercise may be recommended to rehabilitate the lower extremity extensor musculature.

Third, this study supports previous findings that BFR changes muscle activity both distal and proximal to the cuff placement. This notion was evident in the trends observed in the ankle, knee, and hip muscle groups when a sled was pushed. The current literature shows mixed evidence regarding the effects of BFR on proximal musculature. However, similar to this study, Bowman *et al*., (2019) found that BFR on the lower extremities affects the proximal and distal musculature and the contralateral leg (Bowman *et al*., 2019). The current study supports that low-load BFR protocols may benefit various orthopedic conditions by reducing tissue stress.

Additionally, through its displayed effects on the proximal and distal musculature, this study supports the findings of Burton and McCormack and Charles *et al*., respectively, suggesting the use of BFR for various nonoperative conditions, such as tendinopathy and postoperative conditions, such as ACL reconstruction (Burton & McCormack, 2022) (Charles *et al*., 2020). Research supports using BFR to promote muscular changes and reduce pain (Ferraz *et al*., 2018). Ferraz *et al*., compared low-intensity resistance training with and without BFR and found that muscle strength, quadriceps muscle mass, and functionality increased and were similar across all groups. However, in the low-intensity BFR group, pain significantly decreased compared with the non-BFR group (Ferraz *et al*., 2018). Therefore, pairing BFR with commonly used exercises for the gluteal muscle group may provide an increased positive effect on this muscle group without increasing tissue stress or perceived pain, which may benefit patients with various musculoskeletal conditions. Beyond the sled pushed observed in this study, exercises such as step-up, hex bar deadlift, barbell hip thrust, squat, lunge, single-leg squat, and band hip thrust coupled with BFR may show positive effects in patients seeking to maximize proximal lower-extremity musculature adaptations (Neto *et al.*, 2020). Previous researchers completed a feasibility study using BFR for gluteal tendinopathy (Hogsholt *et al.*, 2022). This study included an exercise program for static abduction, side-stepping, glute bridges, and squats. Thus, because of the displayed response of the proximal musculature during sled push with BFR, a combination of proximal musculature-specific programs from the studies above may have the best potential for proximal muscle adaptation using BFR.

CONCLUSION

The current study ushers in scrutinizing lower limb neuromuscular adaptation using BFR while pushing a low-load sled. Results highlighted the activity modifications of specific musculature, such as TA with BFR. In the current study, data were collected acutely at one point, providing researchers with more detailed information about the subjects. Although this can be perceived as a limitation, collecting data at a given time was to gather baseline data from healthy adults. Another aspect to mention is the use of a short walkway. Although a more extended walkway may be beneficial for data collection, studies have indicated that this is a significant length for appropriately targeting the studied musculature in the current examination while pushing a sled (Rosario *et al.*, 2022). Future endeavors should focus on longitudinal studies under the same protocol and more extended walkways with a more challenging surface. Lastly, studies should examine the timing of the amplitude of muscle activation, male versus female variations, acceleration and deceleration sections of EMG trace, and exercise changes, such as pushing a sled up a ramp, to make the activity more strenuous.

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Consent to Participate: The participant gave signed consent for this study

Authors' Contributions: All authors contributed to the study’s conception and design.

REFERENCES

- Abe, T., Fujita, S., Nakajima, T., Sakamaki, M., Ozaki, H., Ogasawara, R., ... & Ishii, N. (2010). Effects of low-intensity cycle training with restricted leg blood flow on thigh muscle volume and VO2max in young men. *Journal of sports science & medicine*, *9*(3), 452.
- Barber-Westin, S., & Noyes, F. R. (2019). Blood flow–restricted training for lower extremity muscle weakness due to knee pathology: a systematic review. *Sports Health*, *11*(1), 69-83. https://doi.org/10.1177/1941738118811337.
- Betz, M. W., Aussieker, T., Kruger, C. Q., Gorissen, S. H. M., van Loon, L. J. C., & Snijders, T. (2021). Muscle fiber capillarization is associated with various indices of skeletal muscle mass in healthy, older men. *Experimental Gerontology*, *143*, 111161. doi: 10.1016/j.exger.2020.111161.
- Bowman, E. N., Elshaar, R., Milligan, H., Jue, G., Mohr, K., Brown, P., ... & Limpisvasti, O. (2019). Proximal, distal, and contralateral effects of blood flow restriction training on the lower extremities: a randomized controlled trial. *Sports Health*, *11*(2), 149-156. https://doi.org/10.1177/1941738118821929.
- Brooks, S. V., & Faulkner, J. A. (1994). Skeletal muscle weakness in old age: underlying mechanisms. *Medicine and science in sports and exercise*, *26*(4), 432-439.
- Burton, I., & McCormack, A. (2022). Blood Flow Restriction Resistance Training in Tendon Rehabilitation: A scoping review on intervention parameters, physiological effects, and outcomes. *Frontiers in Sports and Active Living*, *4*, 879860. https://doi.org/10.3389/fspor.2022.879860.
- Centner, C., Wiegel, P., Gollhofer, A., & König, D. (2019). Effects of blood flow restriction training on muscular strength and hypertrophy in older individuals: a systematic review and meta-analysis. *Sports Medicine*, *49*, 95-108. doi: 10.1007/s40279-018-0994-1.
- Charles, D., White, R., Reyes, C., & Palmer, D. (2020). A systematic review of the effects of blood flow restriction training on quadriceps muscle atrophy and circumference post ACL reconstruction. *International journal of sports physical therapy*, *15*(6), 882. https://doi.org/10.26603/ijspt20200882.
- Cordova, M. L., Jutte, L. S., & Hopkins, J. T. (1999). EMG comparison of selected ankle rehabilitation exercises. *Journal of Sport Rehabilitation*, *8*(3), 209-218. https://doi.org/10.1123/jsr.8.3.209
- De Melo, R. F. V., Komatsu, W. R., De Freitas, M. S., De Melo, M. E. V., & Cohen, M. (2022). Comparison of quadriceps and hamstring muscle strength after exercises with and without blood flow restriction following anterior cruciate ligament surgery: a randomized controlled trial. *Journal of Rehabilitation Medicine*, *54*. https://doi.org/10.2340/jrm.v54.2550
- Evans, W. J., & Lexell, J. (1995). Human aging, muscle mass, and fiber type composition. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, *50*(Special_Issue), 11-16. Doi: 10.1093/gerona/50a.special_issue.11.
- Ferraz, R. B., Gualano, B. R. U. N. O., Rodrigues, R. E. Y. N. A. L. D. O., Kurimori, C. O., Fuller, R.,

Lima, F. R., ... & Roschel, H. (2018). Benefits of resistance training with blood flow restriction in knee osteoarthritis. *Med Sci Sports Exerc*, *50*(5), 897-905. https://doi.org/10.1249/MSS.0000000000001530.

- Fragala, M. S., Cadore, E. L., Dorgo, S., Izquierdo, M., Kraemer, W. J., Peterson, M. D., & Ryan, E. D. (2019). Resistance training for older adults: position statement from the national strength and conditioning association. *The Journal of Strength & Conditioning Research*, *33*(8). doi: 10.1519/JSC.0000000000003230.
- Giallauria, F., Cittadini, A., Smart, N. A., & Vigorito, C. (2015). Resistance training and sarcopenia. *Monaldi Archives for Chest Disease*, *84*(1-2). doi: 10.4081/monaldi.
- Grønfeldt, B. M., Lindberg Nielsen, J., Mieritz, R. M., Lund, H., & Aagaard, P. (2020). Effect of blood-flow restricted vs heavy-load strength training on muscle strength: systematic review and meta-analysis. *Scandinavian journal of medicine & science in sports*, *30*(5), 837-848. doi: 10.1111/sms.13632.
- Hahn, D. (2011). Lower extremity extension force and electromyography properties as a function of knee angle and their relation to joint torques: implications for strength diagnostics. *The Journal of Strength & Conditioning Research*, *25*(6), 1622-1631. https://doi.org/10.1519/jsc.0b013e3181ddfce3.
- Harput, G., Soylu, A. R., Ertan, H., & Ergun, N. (2013). Activation of selected ankle muscles during exercises performed on rigid and compliant balance platforms. *journal of orthopaedic & sports physical therapy*, *43*(8), 555-559. https://doi.org/10.2519/jospt.2013.4456.
- Høgsholt, M., Jørgensen, S. L., Rolving, N., Mechlenburg, I., Tønning, L. U., & Bohn, M. B. (2022). Exercise with low-loads and concurrent partial blood flow restriction combined with patient education in females suffering from gluteal tendinopathy: a feasibility study. *Frontiers in Sports and Active Living*, *4*, 881054. https://doi.org/10.3389/fspor.2022.881054.
- Hughes, L., Paton, B., Rosenblatt, B., Gissane, C., & Patterson, S. D. (2017). Blood flow restriction training in clinical musculoskeletal rehabilitation: a systematic review and meta-analysis. *British journal of sports medicine*, *51*(13), 1003-1011. doi: 10.1136/bjsports-2016-097071.
- Kim, D., Singh, H., Loenneke, J. P., Thiebaud, R. S., Fahs, C. A., Rossow, L. M., ... & Bemben, M. G. (2016). Comparative effects of vigorous-intensity and low-intensity blood flow restricted cycle training and detraining on muscle mass, strength, and aerobic capacity. *The Journal of Strength & Conditioning Research*, *30*(5), 1453-1461. doi:10.1519/JSC.0000000000001218.
- Ladlow, P., Coppack, R. J., Dharm-Datta, S., Conway, D., Sellon, E., Patterson, S. D., & Bennett, A. N. (2018). Low-load resistance training with blood flow restriction improves clinical outcomes in musculoskeletal rehabilitation: a single-blind randomized controlled trial. *Frontiers in physiology*, *9*, 1269. doi:10.3389/fphys.2018.01269.
- Liu, M. Q., Anderson, F. C., Schwartz, M. H., & Delp, S. L. (2008). Muscle contributions to support and progression over a range of walking speeds. *Journal of biomechanics*, *41*(15), 3243-3252. https://doi.org/10.1016/j.jbiomech.2008.07.031
- Lung, C. W., Liau, B. Y., Peters, J. A., He, L., Townsend, R., & Jan, Y. K. (2021). Effects of various walking intensities on leg muscle fatigue and plantar pressure distributions. *BMC Musculoskeletal Disorders*, *22*(1), 1-9. https://doi.org/10.1186/s12891-021-04705-8
- Martín, G., Rosario, D., Heistand, C., Lewis, N., Valdez, M., & Nevarez, M. W. (2021). Lower Limb Muscle Activity Adjustment and Lactate Variation in Response to Increased Speed with Proportional Resistance in Young Adults. *International Journal of Sports Medicine and Rehabilitation*, *4*, 18. DOI: 10.28933/ijsmr-201-02-1005
- Metter, E. J., Conwit, R., Tobin, J., & Fozard, J. L. (1997). Age-associated loss of power and strength in the upper extremities in women and men. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, *52*(5), B267-B276. doi: 10.1093/gerona/52a.5.b267.
- Moro, T., Brightwell, C. R., Phalen, D. E., McKenna, C. F., Lane, S. J., Porter, C., ... & Fry, C. S. (2019). Low skeletal muscle capillarization limits muscle adaptation to resistance exercise training in older adults. *Experimental gerontology*, *127*, 110723. doi: 10.1016/j.exger.2019.110723.
- Neto, W. K., Soares, E. G., Vieira, T. L., Aguiar, R., Chola, T. A., de Lima Sampaio, V., & Gama, E. F. (2020). Gluteus maximus activation during common strength and hypertrophy exercises: A systematic review. *Journal of sports science & medicine*, *19*(1), 195.
- Orozco, E., Joslin, H., Blumenthal, K., & Rosario, M. (2022). Characteristics of lower extremity muscle activation in response to change in inclination while walking on a treadmill. https://doi.org/10.24018/ejsport.2022.1.4.24.
- Ozaki, H., Miyachi, M., Nakajima, T., & Abe, T. (2011). Effects of 10 weeks walk training with leg blood flow reduction on carotid arterial compliance and muscle size in the elderly adults. *Angiology*, *62*(1), 81-86. doi:10.1177/0003319710375942.
- Ozaki, H., Miyachi, M., Nakajima, T., & Abe, T. (2011). Effects of 10 weeks walk training with leg blood flow reduction on carotid arterial compliance and muscle size in the elderly

adults. *Angiology*, *62*(1), 81-86. doi:10.1177/0003319710375942.

- Patterson, S. D., Hughes, L., Warmington, S., Burr, J., Scott, B. R., Owens, J., ... & Loenneke, J. (2019). Blood flow restriction exercise: considerations of methodology, application, and safety. *Frontiers in physiology*, 533. doi:10.3389/fphys.2019.00533.
- Rosario, M. G. (2020). Neuromuscular timing modification in responses to increased speed and proportional resistance while pushing a sled in young adults. *European Journal of Human Movement*, *44*, 50-66. https://doi.org/10.21134/eurjhm.2020.44.544.
- Rosario, M. G., & Jose, A. (2021). The impact of balance and visual feedback on tibialis anterior/gastrocnemius neuromuscular activation timing in healthy young adults. *Human Movement*, *22*(4), 46-55. doi: https://doi.org/10.5114/hm.2021.103289.
- Rosario, M. G., & Mathis, M. (2021). Lower limb muscle activation and kinematics modifications of young, healthy adults while pushing a variable resistance sled. *Journal of Human Sport and Exercise*, *16*(4), 809–823. https://doi.org/10.14198/jhse.2021.164.06
- Rosario, M. G., Bowman, C., & Jose, A. (2020). Neuromuscular timing activity on ankle musculature in young adults during single and dual-motor tasks accompanied with altered sensory conditions. *J Rehab Pract Res*, *1*(2), 112. https://doi.org/10.33790/jrpr1100112.
- Rosario, M. G., Bowman, C., Versemann, A., & Heistand, D. (2021). The Impact of a High/Low Fulcrum Rotating Balance Platform on Standing Postural Stability in Healthy Young Adults. *Journal of Sports Research*, *8*(1), 8-15. doi: DOI: 10.28933/ijsmr-2021-04-0505.
- Rosario, M. G., Smith, T., & Buckingham, S. (2022). Dual-motor balance tasks prompts slight lower limb neuromuscular adaptations in healthy young adults. doi:doi.org/10.18488/90.v9i2.3019.
- Rosario, M. G., Versemann, A., Bowman, C., & Orozco, E. (2021). Lower Limb Muscle Activation Adaptation During Single and Dual Walking Tasks in Healthy Young Adults. *International Journal of Physiotherapy*, 136-142. https://doi.org/10.15621/ijphy/2021/v8i2/997
- Rosario, M., Kietel, M., Meyer, J., & Weber, M. (2022). Constant resistance at different speeds while pushing a sled prompts different adaptations in neuromuscular timing on back and lower limb muscles. *International Journal of Physical Education, Fitness and Sports*, 66–74. https://doi.org/10.34256/ijpefs2217
- Rosario, M., Pagel, C., Miller, W., & Weber, M. (2022). Pushing A Sled with Constant Resistance and Controlled Cadence Induces Lower Limb Musculature Quicker Activation Response and Prolongs Duration with Faster Speed. *European Journal of Sport Sciences*, *1*(2), 23–28. https://doi.org/10.24018/ejsport.2022.1.2.12
- Shumway-Cook, A., & Woollacott, M. H. (2007). *Motor control: translating research into clinical practice*. Lippincott Williams & Wilkins.
- Trofa, D. P., Obana, K. K., Herndon, C. L., Noticewala, M. S., Parisien, R. L., Popkin, C. A., & Ahmad, C. S. (2020). The evidence for common nonsurgical modalities in sports medicine, Part 2: Cupping and blood flow restriction. *JAAOS Global Research & Reviews*, *4*(1).
- Walston, J. D. (2012). Sarcopenia in older adults. *Current opinion in rheumatology*, *24*(6), 623. Doi: 10.1097/BOR.0b013e328358d59b.
- Wang, Y., Li, Z., Tongtong, C., Zhang, W., & Li, X. (2023). Effect of continuous and intermittent blood flow restriction deep-squat training on thigh muscle activation and fatigue levels in male handball players. *Scientific Reports*, *13*(1), 19152. Doi: 10.1038/s41598-023-44523-7.