OPEN ACCESS

Journal of Advances in Sports and Physical Education
Abbreviated Key Title: J Adv Sport Phys Edu
ISSN 2616-8642 (Print) | ISSN 2617-3905 (Online)
Scholars Middle East Publishers, Dubai, United Arab Emirates
Journal homepage: https://saudijournals.com

Original Research Article

The Effects of Blood Flow Restriction on Lower Extremity EMG Amplitude While Performing a Resisted Sled Push in Healthy Subjects

Luciano Garcia (PT ScD OCS COMT)[1], Wayne Brewer (PT PhD OCS)[1], Meghan Skevington (SPT)[1], Lydia Smith (SPT)[1], Haley Waters (SPT)[1], Martin Rosario (PT PhD CSFI ATRIC)[2*]

[1]Texas Woman's University, Physical Therapy Program, Houston Campus, Texas
[2]Texas Woman's University, Physical Therapy Program, Dallas Campus, Texas

DOI: 10.36348/jaspe.2024.v07i03.001 | **Received:** 27.01.2024 | **Accepted:** 02.03.2024 | **Published:** 09.03.2024

***Corresponding author:** Martin Rosario
Texas Woman's University, Physical Therapy Program, Dallas Campus, Texas

Abstract

Introduction: Studies have demonstrated that resistance training and blood flow restriction (BFR) has notable advantages, including enhancing muscle growth, boosting muscle activation, and improving function. In the field of neuromuscular research, muscle electromyography (EMG) is a widely utilized method for understanding and analyzing neuromuscular recruitment patterns and identifying any adaptive changes that may occur. Purpose: The objective of this study was to examine the impact of blood flow restriction (BFR) on the amplitude pattern of six lower extremity (LE) muscles during resisted sled pushing activity at two different walking speeds: 80 bpm and 140 bpm. Methods: A convenience sample of 32 healthy individuals, an average of 23.8 years old (±1.42 SD). Surface electromyography was used on subjects' tibialis anterior (TA), gastrocnemius (GA), vastus medialis (VM), biceps femoris (BF), gluteus maximus (GMa), and gluteus medius (GMe) on their dominant LE. The subjects then pushed a resistive sled with 40 feet for three trials at 80 and 140 bpm. After adding BFR at 80% limb occlusion pressure, all the trials were repeated. Statistical Analysis: A 2 × 6 (BFR group and muscle) repeated measures analysis of variance (ANOVA) test was used for significant interactions and main effects during each speed and BFR condition. The minimum (MIN), average (AVG), and maximum (MAX) electromyography (EMG) values are presented for each muscle. Results: ANOVA revealed a significant interaction between the BFR group and muscles with AVG F (1.92, 59. 39)=4.23,p=.021, and MAX F(2.53,78.56)=3.751, p=.019 at 80 bpm. The main effects between muscle groups were found with MIN at 80 bpm and AVG and MAX at 140 bpm. The main effects for the BFR group were AVG and MAX at 80 bpm and AVG and MAX at 140 bpm. When comparing AVG BFR 80 to 140 bpm, the main effects were found for both speeds and increased activation of all six muscles, most notably the GA and VM. Conclusion: At 80 bpm, BFR affected the GA, VM, and GMa. At 140 bpm, all six muscles showed increased AVG and MAX activation. When comparing 80 to 140 bpm, all six muscles showed increased activation at the BFR faster pace, most notably the GA and VM.

Keywords: EMG, Blood Flow Restriction, Sled Pushing, Amplitude, Neuromuscular Activation.

INTRODUCTION

As the population of the United States continues to grow, it is becoming increasingly crucial for individuals to actively engage and participate in their communities and society. According to a study conducted by Krysztofid M *et al.*, in 2019, individuals with low levels of strength are at higher risk for cardiovascular disease, cardiac and metabolic diseases in their adolescent years, and type 2 diabetes in their adult years. Decreased physical activity has also been shown to cause premature mortality in older Americans, making weaker older adults >50% more likely to die earlier than the non-weak (Kate Duchowny, 2018) and exhibit depression symptoms (Marques A. *et al.*, 2020). Exercise has been utilized in various ways to help combat and manage various health conditions, such as obesity, diabetes mellitus, cardiovascular disease, and hypertension (Celik, 2021). Regular exercise in your daily routine is crucial for maintaining overall health and can effectively combat and prevent musculoskeletal disorders that may arise.

Citation: Luciano Garcia, Wayne Brewer, Meghan Skevington, Lydia Smith, Haley Waters, Martin Rosario (2024). The Effects of Blood Flow Restriction on Lower Extremity EMG Amplitude While Performing a Resisted Sled Push in Healthy Subjects. *J Adv Sport Phys Edu*, *7*(3): 35-46.

In recent years, there has been a notable rise in physical activity and research surrounding exercise training, indicating its growing importance and relevance in society. In addition to low-load endurance and high-load strength training (Hughes *et al*., 2018), newer approaches can include high-intensity interval training (Gialluria *et al*., 2018), as well as low-load resistance training (Karanasios *et al*., 2022). According to a study conducted by Yang *et al*., in 2012, incorporating resistance exercise into one's routine has been shown to improve physical health and increase sleep quality in older adults. Various forms and methods of exercise are studied and utilized in the treatment of numerous conditions, one of which is non-specific low back pain, as reported by Owen *et al*., (2020).

One example of a resistance training task is the pushing exercises, such as pushing a resistive sled. The XPO trainer (Armored Fitness Equipment, LLC: Plano TX) is a push-weight sled that provides consistent resistance (at constant speed) to walking or running. Previous studies have used this type of sled for resistance training. Rosario *et al*., (2020) found modified lower extremity muscle activation, mainly in the gastrocnemius, while pushing the sled at self-selected speeds. Comparing walking to running while pushing, Mathis and Rosario (2021) analyzed the significance of muscle amplitude or amount of muscle activation. The researchers concluded that pushing the sled increased quadriceps muscle activation (comparable to strengthening) over the gastrocnemius, hamstring, and tibialis anterior muscles.

Blood Flow Resistance (BFR) training is a treatment method that has recently increased in popularity and has similar muscle benefits to resistance training. Blood flow resistance training involves placing a pneumatic tourniquet system in the proximal thigh to occlude the femoral artery and supply the rest of the lower extremity. Blood flow resistance training occludes venous outflow and reduces arterial inflow during low-load resistance exercise (Cognetti DJ *et al*., 2022). This results in controlled oxygen deprivation of the muscle, shifting skeletal muscle activation from slow oxidative fibers to fast oxidative glycolytic fibers, resembling the effects of exercising with heavy resistance (Karabulut & Perez, 2013). In a shorter time frame, BFR training programs can slightly improve muscle strength and activation through neuromuscular adaptations (May A. *et al*., 2022). In contrast, longer-range training programs can enhance muscle strength through hypertrophy and increased cross-sectional area (May AK *et al*., 2022).

Electromyography (EMG) has been extensively used during resistive exercise, as evidenced by numerous studies conducted, such as Barnes *et al*., (2018), Freitas *et al*., (2020), and Rosario *et al*., (2022). Maximum voluntary isometric contraction (MVIC) is an evaluation approach extensively used with EMG in various studies (Mason *et al*., 2018; Owens *et al*., 2020; Rosario *et al*., 2021). Researchers often use EMG to capture muscle activation during functional activities to better understand muscle patterns and propose treatment or rehabilitation approaches (Barnes *et al*., 2018; Freitas *et al*., 2020; Rosario *et al*., 2022). A relevant example of this concept can be seen in the study conducted by Rosario *et al*., (2020), where they demonstrated that incorporating a resistance sled into training at varying speeds led to greater activation of distal muscles in the lower extremities, with recruitment increasing as the task speed increased. Fatela *et al*., (2019) incorporated low-load resistance training of unilateral knee extension for resistance exercises in 20% of subjects with a maximum of one repetition. Researchers found that, although training was at a lower load, BFR training resulted in a higher EMG amplitude than non-BFR subjects.

In situations where heavy load resistance exercise is not feasible or allowed, it is suggested that BFR training may be viable, as supported by various studies, such as those conducted by Patterson *et al*., (2019), Ladlow *et al*., (2018), and Trofa *et al*., (2020). For instance, studies have shown that individuals with post-exercise soreness could benefit from BFR (Barnes *et al*., 2018). BFR combined with resistance training enhances post-activation performance (Sun & Yang, 2023), with female football players demonstrating improved vertical jump height. When BFR is coupled with low-load resistance exercises, it has been shown that BFR improves quadriceps strength after anterior cruciate ligament reconstruction (Roman *et al*., 2023). The literature supports the use of BFR with resistance training, however, the greatest problem is that the information available has some constraints to determine similarities between BFR and RT programs. Two reviews of BFR literature noted limitations in making best-practice recommendations due to a lack of investigations on its effectiveness (Patterson *et al*., 2019; Ladlow *et al*., 2018; Trofa *et al*., 2020). Despite systematic reviews and meta-analyses showing a correlation between low-load BFR (LL BFR) training and an increase in muscular strength (Patterson *et al*., 2019; Ladlow P *et al*., 2018; Trofa *et al*., 2020), there is still variability among studies due to variations in exercise regimens, patient populations, and outcome measures being utilized.

Our study attempted to analyze how adding BFR affects the activation firing pattern of six LE muscles during sled-resistant walking activity. Based on the work of Rosario *et al*., (2021), our first hypothesis was that adding BFR would increase the minimal, average, and maximal EMG amplitudes at walking speeds of 80 and 140 bpm. Our second approach was to analyze the effect of the BFR when comparing two different walking speeds. Based on the work of Rosario *et al*., (2020), our second hypothesis is that gastrocnemius activation increases as the speed of resisted walking increases. Based on the specific criteria outlined above, our main goal was to investigate and analyze the potential impacts of walking at two distinct speeds (80 and 140 beats per minute) and implementing BFR on the firing patterns of the lower extremity muscles in a group of healthy young adults.

METHODS

Thirty-two subjects were recruited from the local Institute of Health Sciences. Inclusion criteria were age from 18 to 45 years, ability to walk and push a sled, and ability to follow commands. The exclusion criteria included standard BFR contraindications, history of vascular or clotting disorders, recent muscle trauma, skin issues, sickle cell disease, peripheral nerve injury, and any painful lower limb condition.

A quick posteriorly directed perturbation was applied to the subject's torso to determine the subject's dominant leg, while the subject was unaware of it. Whichever lower extremity was used for the stepping strategy was deemed the dominant leg (Bowman & Rosario *et al*., 2021). The subject was then prepped for the trials by cleaning the skin where the electrodes were to be placed with an alcohol wipe, weighing it, and measuring it for height, initial blood pressure, and circumference of the proximal thigh region.

The equipment used for this study included an XPO Trainer Sled and a Delphi Personal Tourniquet System unit (Delphi Medical USA). The electromyography system consisted of a Delsys Trigno Wireless EMG System (Delsys Inc., USA) equipped with Avanti surface electrodes.

After placing the appropriate EMG electrodes (Rosario & Orozco, 2022; Orozco *et al*., 2022), maximal voluntary isometric contractions (MVIC) were performed as follows. For the tibialis anterior, the subject performed the maximum unilateral dorsiflexion contraction. For the gastrocnemius muscle, the subject performed a unilateral heel raise. For the vastus medialis, the subject performed a belt-resisted quad contraction in a neutral position. In contrast, a belt-resisted hamstring contraction was performed in a neutral position for the hamstrings. For the gluteus maximus, the standing subject performed belt-resisted hip extension isometric contractions and isometric hip abduction contractions in the gluteus medius.

The protocol involved the subjects performing three repetitions of 40-foot walking while pushing the XPO sled at 140 beats per minute (BPM), followed by three repetitions at 80 bpm. A metronome was used to keep the subjects on the same pace. Randomization was included for alternating subjects to perform either slow or fast walk repetitions. Our verbal cueing to subjects was, "Walk while pushing the sled to the pace of one step for each beat of the metronome." After the initial six repetitions were performed, the subjects were allowed a 5-minute rest break that also included configuring their BFR personal tourniquet pressure (PTP). For the subject’s BFR pressure, 80% occlusion pressure was applied during the BFR trials. Once the pressure was applied, the subjects performed six trials as before, and this time with BFR added.

The Delfi Personalized Tourniquet System utilizes a nylon cuff (24" or 34") placed around the proximal thigh over a matching limb protective sleeve. The airtight hose tubing was connected to a rechargeable battery pneumatic pump. A researcher placed the tourniquet to ensure proper maximal occlusion of the femoral artery and vein. In the relaxed supine position, the limb occlusion pressure (LOP) and personalized tourniquet pressure (PTP: 80% of LOP) for the subject per Abbas (2022) were calculated and recorded. The cuff was inflated to 80% PTP for the BFR trials when ready. This protocol included three trials at either the slow or fast pace, then a 3-minute seated rest break, and the last three trials. The BFR cuff was then deflated and removed.

Fig. 1

Data Analysis

All EMG data analyses were performed using Delsys EMGworks software (Delsys Inc., USA) version 1.0.0.0. Raw EMG signals of the tibialis anterior (1), gastrocnemius (2), vastus medialis (3), bicep femoris (4), gluteus maximus (5), and gluteus medius (6) were collected, quantified using root mean square values, and normalized to MVIC to compare BFR conditions and speed (Cleary *et al*., 2020: Rosario *et al*., 2020). More specifically, the EMG data was meticulously run through a specialized filter and then rectified to accurately normalize the maximal voluntary contraction (MVC) data to the muscle activations within the various tasks for each participant. After the data was collected and analyzed, it was transferred and downloaded into spreadsheets for further review and organization. In order to measure the duration of each gait task accurately, the time (in seconds) was normalized and converted to a percentage of the total task time (ranging from 0-100%). Following the initial trials, investigators meticulously analyzed and pinpointed the peak activation points for each muscle, considering the precise timing percentage within the gait cycle. After estimating the average of each data point, the mean maximal activation and timing of the corresponding task were calculated for a more comprehensive analysis. After completing all necessary preparations, the means were entered into the SPSS Data Analysis 28 system for a thorough repeated-measures ANOVA analysis. In this particular study, the minimum (MIN), average (AVG), and maximum (MAX) EMG values are presented concerning the maximal voluntary isometric contraction (MVIC). A p-value of 0.05 or less was considered statistically significant.

RESULTS

Subject demographics with standard deviations were as follows: the average age of the 32 subjects was 23.8 (±1.42 SD) years old, 17 female and 15 male, 155 pounds (±29.89 SD), and 66 inches (±3.61 SD) in height.

The MIN EMG data at 80 bpm were compared using × 2x6 (BFR group and muscle) ANOVA. There was no significant interaction or main effect in the BFR group (*p*.893 and *p*=.417, respectively. There was a significant main effect of muscle type, F (2.64,81.853)=32.23, *p*<.001. Pairwise comparisons (Bonferroni corrected) for the main effect of muscle showed significant differences (TABLE 1).

Table 1

MUSCLE- MIN at 80 bpm	***MEAN***	***Std Error***	***p values***
Muscle 1 vs. 3	5.160	.864	*p*<.001
Muscle 1 vs 5	9.655	1.148	*p*<.001
Muscle 1 vs 6	4.725	1.108	*p*=.003
Muscle 2 vs 3	4.907	.824	*p*<.001
Muscle 3 vs. 5	4.495	1.364	*p*=.037
Muscle 4 vs 3	6.001	.786	*p*<.001
Muscle 4 vs. 6	5.566	1.200	*p*<.001
Muscle 5 vs 2	9.402	1.196	*p*<.001
Muscle 5 vs. 4	10.496	1.220	*p*<.001
Muscle 6 vs 2	4.472	1.172	*p*=.009
Muscle 6 vs. 5	4.390	1.110	*p*=.002

The AVG EMG data at 80 bpm was compared using a 2x6 (BFR group and Muscle) ANOVA. There was a significant main effect of the BFR group and muscle at *p*=.019 and *p*<.001. However, there was also a significant interaction of group and time at F (1.92,59.39)=4.23, *p*=.021. Simple effect comparisons within muscle and BFR groups are presented below in Table 2.

Table 2

AVG 80 bpm: Simple effect	**p-value**
Muscle 1 (group 0 vs group 1):	*p=.562*
Muscle 2 (group 0 vs. group 1):	*p=.002**
Muscle 3 (group 0 vs group 1):	*p=.032**
Muscle 4 (group 0 vs group 1):	*p=.214*
Muscle 5 (group 0 vs group 1):	*p=.031**
Muscle 6 (group 0 vs group 1):	*p=.106*

***Significance**

Pairwise comparisons at 80 bpm (Bonferroni-corrected) for the main effect of the muscle revealed significant differences between the following:

Table 3

MUSCLE- AVG at 80 bpm	***MEAN***	***Std Error***	***p values***
Muscle 1 vs 2	8.421	1.598	*p*<.001
Muscle 1 vs 3	15.940	2.963	*p*<.001
Muscle 1 vs 5	23.171	3.494	*p*<.001
Muscle 2 vs 4	10.954	2.416	*p*=.001
Muscle 2 vs 5	14.750	3.604	*p*=.004
Muscle 3 vs 4	18.473	3.076	*p*<.001
Muscle 4 vs. 5	25.704	3.436	*p*<.001
Muscle 4 vs. 6	12.959	3.455	*p*=.011
Muscle 5 vs. 6	12.744	3.584	*p*=.019
Muscle 6 vs 1	10.427	3.141	*p*=.035

The MAX EMG data at 80 bpm was compared using a 2x6 (BFR group and muscle) ANOVA. There was a significant main effect of the BFR group and muscle at *p*=.007 and <.001. However, there was also a significant interaction between the BFR group and muscle at F (2.53,78.56)=3.751, *p*=.019. Simple effect comparisons within time and group are presented below.

Table 4

Simple Effect: MAX 80 bpm	***p* values**
Muscle 1 (group 0 vs group 1):	*p=.300*
Muscle 2 (group 0 vs. group 1):	*p<.001**
Muscle 3 (group 0 vs group 1):	*p=.003**
Muscle 4 (group 0 vs group 1):	*p=.275*
Muscle 5 (group 0 vs group 1):	*p=.036**
Muscle 6 (group 0 vs group 1):	*p=.305*

***Significance**

Table 5

MUSCLE- MAX at 80 bpm	***MEAN***	***STD. ERROR***	***p values***
Muscle 1 vs. 2	*44.303*	*5.223*	*<.001*
Muscle 1 vs 3	*31.832*	*5.731*	*<.001*
Muscle 2 vs. 1	*44.303*	*5.223*	*<.001*
Muscle 2 vs 4	*48.211*	*7.152*	*<.001*
Muscle 2 vs 6	*37.350*	*5.345*	*p<.001*
Muscle 3 vs 1	*31.832*	*5.731*	*<.001*
Muscle 3 vs 4	*35.740*	*7.115*	*p<.001*
Muscle 3 vs 6	*37.350*	*7.221*	*p=.025*
Muscle 4 vs 2	*48.211*	*7.152*	*p<.001*
Muscle 4 vs 3	*35.740*	*7.115*	*p<.001*
Muscle 4 vs. 5	*33.679*	*9.553*	*p=.020*
Muscle 5 vs. 4	*33.679*	*9.553*	*p=.020*
Muscle 6 vs 2	*37.350*	*5.345*	*p<.001*
Muscle 6 vs. 3	*37.350*	*7.221*	*p=.025*

The MIN EMG data at 140 bpm was compared using a 2x6 (BFR group and muscle) ANOVA. There was no significant interaction or primary effect of the BFR group at p=.341 and p=.051, respectively. There was a significant main effect of muscle at F (3.34,103.59)=16.56, *p*<.001. Pairwise comparisons (Bonferroni corrected) for the main effect of muscle found significant differences between:

Table 6: Minimal EMG Activation

MUSCLE- MIN at 140 bpm	***MEAN***	***STD. ERROR***	***p values***
Muscle 1 vs 3	*5.395*	*1.037*	*<.001*
Muscle 1 vs 5	*9.137*	*1.364*	*<.001*
Muscle 1 vs 6	*4.747*	*1.245*	*.009*
Muscle 2 vs 3	*4.612*	*.918*	*<.001*
Muscle 2 vs 5	*8.354*	*1.206*	*<.001*
Muscle 2 vs 6	*3.964*	*1.227*	*.044*

MUSCLE- MIN at 140 bpm	*MEAN*	*STD. ERROR*	*p values*
Muscle 3 vs 4	*4.917*	*1.422*	*.024*
Muscle 4 vs. 5	*8.660*	*1.248*	*<.001*
Muscle 5 vs. 6	*4.390*	*1.210*	*.015*

The AVG EMG data at 140 bpm were compared using × 2x6 (BFR group and muscle) ANOVA. No significant interaction was observed (*p*=.506. There was a significant main effect of the BFR group at F(1, 31)=5.836, *p*=.022. The muscle also had a significant main effect at F(2.92,90.44)=5.55, *p*=.002. Pairwise comparisons (Bonferroni corrected) for the main effect of muscle revealed significant differences between the following:

Table 7

MUSCLE- AVG at 140	*MEAN*	*Std Error*	*p values*
Muscle 1 vs 2	11.779	2.282	*p*<.001
Muscle 1 vs 3	19.184	4.278	*p*=.001
Muscle 1 vs 5	24.447	6.276	*p*=.007
Muscle 2 vs 1	11.779	2.282	*p*<.001
Muscle 2 vs 4	11.508	3.470	*p=.035*
Muscle 3 vs 1	19.184	4.278	*p*=.001
Muscle 3 vs 4	18.913	4.733	*p*=.006
Muscle 4 vs 2	11.508	3.470	*p=.035*
Muscle 4 vs 3	18.913	4.733	*p*=.006
Muscle 4 vs. 5	24.176	6.233	*p*=.008
Muscle 5 vs 1	24.447	6.276	*p*=.007
Muscle 5 vs. 4	24.176	6.233	*p*=.008

The MAX EMG data at 140 bpm was compared using a 2x6 (BFR group and muscle) ANOVA. There was no significant interaction at *p*=.435. There was a significant main effect of the BFR group at F(1, 31)=29.84 *p*<.001. Also, muscle had a significant main effect at F(5,155)=29.11, *p*<.001. Pairwise comparisons (Bonferroni corrected) for the main effect of muscle found significant differences between:

Table 8: Maximum EMG at 140 bpm

MUSCLE- MAX at 140 bpm	*MEAN*	*Std Error*	*p values*
Muscle 1 vs 2	43.412	5.061	*p*<.001
Muscle 1 vs 3	32.050	5.069	*p*<.001
Muscle 1 vs 5	19.037	4.704	*p*=.005
Muscle 2 vs 1	43.412	5.061	*p*<.001
Muscle 2 vs 4	48.078	6.345	*p*<.001
Muscle 2 vs 5	24.375	4.927	*p*<.001
Muscle 2 vs 6	32.038	4.282	*p*<.001
Muscle 3 vs 1	32.050	5.069	*p*<.001
Muscle 3 vs 4	36.716	5.000	*p*<.001
Muscle 3 vs. 5	13.013	3.230	*p*=.005
Muscle 3 vs 6	20.676	4.201	*p*<.001
Muscle 4 vs 2	48.078	6.345	*p*<.001
Muscle 4 vs 3	36.716	5.000	*p*<.001
Muscle 4 vs. 5	23.703	5.524	*p*=.002
Muscle 5 vs 1	19.037	4.704	*p*=.005
Muscle 5 vs 2	24.375	4.927	*p*<.001
Muscle 5 vs 3	13.013	3.230	*p*=.005
Muscle 5 vs. 4	23.703	5.524	*p*=.002
Muscle 6 vs 2	32.038	4.282	*p*<.001
Muscle 6 vs 3	20.676	4.201	*p*<.001

To determine the effect of speed (80 bpm vs. 140 bpm) played on the AVG EMG activation between each muscle, a separate 2×6 fully repeated ANOVA was performed for the no BFR and BFR trials. In the no-BFR analysis, no significant interaction at *p*=.856. Speed had a significant main effect, F (1, 31)=*p*<.001. In addition, there was a significant main effect among the muscles, F(2.93, 90.88)=7.899, *p*<.001.

Table 9: No BFR AVG 80 bpm vs. 140 bpm

MUSCLE- no BFR: AVG 80 vs. 140 BPM	*MEAN*	*STD Error*	*p VALUE*
Muscle 1 vs 2	*10.230*	*1.854*	*p<.001*
Muscle 1 vs 3	*17.718*	*3.582*	*p<.001*
Muscle 1 vs 5	*25.111*	*5.669*	*p=.002*
Muscle 2 vs 1	*10.230*	*1.854*	*p<.001*
Muscle 2 vs 4	*11.926*	*3.214*	*p=.012*
Muscle 3 vs 1	*17.718*	*3.582*	*p<.001*
Muscle 3 vs 4	*19.414*	*3.935*	*p<.001*
Muscle 4 vs 2	*11.926*	*3.214*	*p=.012*
Muscle 4 vs 3	*19.414*	*3.935*	*p<.001*
Muscle 4 vs. 5	*26.807*	*5.539*	*p<.001*
Muscle 5 vs 1	*25.111*	*5.669*	*p=.002*
Muscle 5 vs. 4	*26.807*	*5.539*	*p<.001*

No significant interaction was observed (*p*=.300. There were significant main effects of speed, F (1,31)=40.07, *p*<.001. There was a significant main effect for the muscle at F (3.42,106.06)=9.75, *p*<.001.

Table 10: EMG with BFR 80 bpm vs. 140 bpm

MUSCLE- with BFR: AVG 80 vs. 140 BPM	*MEAN*	*STD Error*	*p VALUE*
Muscle 1 vs 2	*8.751*	*1.868*	*p<.001*
Muscle 1 vs 3	*16.374*	*3.590*	*p=.001*
Muscle 1 vs 5	*20.297*	*3.597*	*p<.001*
Muscle 2 vs 1	*8.751*	*1.868*	*p<.001*
Muscle 2 vs 4	*9.242*	*2.704*	*p=.027*
Muscle 3 vs 1	*16.374*	*3.590*	*p=.001*
Muscle 3 vs 4	*16.865*	*3.841*	*p=.002*
Muscle 4 vs 2	*9.242*	*2.704*	*p=.027*
Muscle 4 vs 3	*16.865*	*3.841*	*p=.002*
Muscle 4 vs. 5	*20.788*	*4.123*	*p<.001*
Muscle 5 vs 1	*20.297*	*3.597*	*p<.001*
Muscle 5 vs. 4	*20.788*	*4.123*	*p<.001*

DISCUSSION

Our research endeavor aimed to thoroughly examine the impact of incorporating BFR on the activation firing patterns of six lower extremity muscles during sled-resistant walking. Based on the specific criteria outlined above, our main goal was to investigate and analyze the potential impacts of walking at two distinct speeds (80 and 140 beats per minute) and implementing BFR on the firing patterns of the lower extremity muscles in a group of healthy young adults.

Drawing upon the research conducted by Rosario *et al*., (2021 & 2020), we designed two working hypotheses. Our initial assumption was that the incorporation of BFR would result in a noticeable rise in the minimal, average, and maximal EMG amplitudes while walking at both 80 and 140 beats per minute. After thoroughly examining our results and data, we have concluded that our hypothesis is partially accepted. Our findings suggest that at 80 bpm of resisted walking, the minimum level of muscle recruitment was significant. At the same speed, the average and maximum levels were also significant regardless of BFR use. Based on our observations, a higher speed of 140 bpm generally leads to greater muscle activation, regardless of the amplitude level being performed. Furthermore, according to the data gathered at 140 bpm, it can be concluded that both the average and maximum levels have a statistically significant impact on the utilization of BFR training.

As part of our research, we also used an additional method, which involved conducting a comprehensive analysis of the effects and consequences of implementing the BFR technique, specifically when comparing and contrasting two different walking speeds. Based on Rosario *et al*., 's (2020) study, we have developed a secondary hypothesis that proposes a direct relationship between the speed of resisted walking and the degree of gastrocnemius activation, a push-off muscle. After consideration, we have concluded that we can only partially accept the previous assumption. Specifically, at a slower speed of 80 bpm, the average EMG activation increased in the gastrocnemius, vastus medialis, and gluteus maximus muscles. Our results also showed a similar increase in activation of the maximum EMG levels at this speed. This increase suggests that a slower speed of pushing activity allowed for an improved lower leg push-off, as well as the time for the proximal joints to complete full extension. The results of this study suggest that allowing the lower extremity to complete a full range of motion while overcoming resistance may have played a significant role in the observed findings.

In correspondence to the recorded results of 140 bpm, it was consistently noted that each muscle had a significant EMG activation effect, regardless of whether BFR was utilized. When the speed was increased, the analysis of minimum activation shows that the biceps femoris exhibits the most notable increase in muscle activation when BFR is added. At the same time, the other muscles also experience an increase in activation, although at a considerably lower rate. For all three activation levels at 140 bpm, a main effect for the muscle group was found, as well as average and maximal levels for using BFR, but there was no interaction between the two groups. An intriguing observation during the analysis of both average and maximal levels was that all six muscles exhibited a decrease in activation when BFR was introduced at this particular speed.

As mentioned earlier, interactions were found between the muscle and BFR groups, with the average and maximum activation levels occurring at 80 bpm. These interactions suggest that BFR was able to modify each muscle activation pattern more selectively at a slower pushing speed (related to the gastrocnemius, vastus medialis, and gluteus maximus). In comparison to trials without BFR (nonBFR), both average and maximum EMG activation levels decreased when BFR was utilized in these specific muscle groups, which is consistent with the findings of Dankel *et al*., (2017) and Hill *et al*., (2019). Similar to our findings, Gizzi and colleagues (2021) discovered no significant difference in EMG amplitude when comparing the neuromechanical effects of continuous BFR with non-restricted circulation during isometric elbow flexion exercises.

Our research discovered that while walking and pushing at a speed of 140 beats per minute, there is a notable minimal activation of the biceps femoris muscle, which is the most highly activated muscle at this specific pace. These findings provide valuable insight into the muscular responses and demands during walking at various speeds. According to the study conducted by Higashihara *et al*., in 2010, there is a correlation between the activity speed and the heightened activation of the biceps femoris muscle. It is possible that with increased speed, the hamstrings were required to be more actively engaged eccentrically to slow down the knee extension moment.

One possible justification for the outcomes of this study could be the duration of the training session. However, in their study on strength gains, Takarada *et al*., (2002) implemented an eight-week training program completed twice a week, resulting in noteworthy enhancements in isometric and isokinetic strength among male rugby players. Similarly, to assess the immediate effects of BFR training, Freitas *et al*., (2020) and Fatella *et al*., (2019) conducted single sessions as part of their research. Because our study focused on analyzing the changes in muscle activation at an early stage, conducting a single exercise session was deemed suitable. In the future, researchers could conduct related studies to analyze and compare the effects of a single session versus multiple sessions on muscle activation to pinpoint any potential differences.

It is possible that the positioning of the EMG electrode could explain the decreased levels of activity observed in the biceps femoris muscle, as it displayed the lowest maximum voluntary isometric contraction levels among all the muscles studied, except the previously mentioned minimum levels at 140 beats per minute (bpm). As a result of the placement of the BFR tourniquet, it was necessary to relocate the BF electrode to the distal tendon, which could account for the decreased levels of activation observed. According to a study by Yang *et al*., (2023), when an EMG electrode is positioned on the distal tendon, a decrease in signal amplitude and an increase in signal-to-noise ratio are expected. Despite any potential obstacles, the positioning of the electrodes closely adhered to the well-established gait protocol, as outlined by Rosario and Orozco in their 2022 publication and the more recent findings of Orozco *et al*., in the same year. In order to ensure accurate results, it is imperative that future studies carefully consider the placement of electrodes on the distal hamstring. It would also be beneficial to analyze various locations within the same area to better understand whether the data will fluctuate or remain consistent.

When examining the two muscles located proximal to the cuff, gluteus maximus and medius, it was found that they exhibited distinct patterns of activation depending on the speed at which pushing was performed and whether or not BFR was applied. After analyzing the data and comparing the pushing speeds, it was found that all six muscles examined showed a statistically significant relationship, except for the gluteus medius muscle. Despite varying speeds, no discernible change was observed in the performance of the gluteus medius muscle. Therefore, after thorough analysis, we conclude that one of the main factors contributing to the consistent activation of the gluteus medius in EMG readings, regardless of activity speed, is its crucial role as a stabilizer for pelvic lateral movements. Regarding the statement above, a study conducted by Høgsholt *et al*., in 2022 found that female participants with gluteal tendinopathy displayed a notable increase in isometric hip abductor strength. As previously mentioned, the gluteus maximus muscle showed a noticeable decrease in activity at 80 beats per minute, with both average and maximum levels of activation affected by the inclusion of BFR, mirroring the findings of Sun and Yang in their 2023 study. While the results may only be temporary, it is possible that the gluteus maximus muscle could experience improved blood flow through the use of a BFR cuff placed at its distal insertion point.

After analyzing the data, it was discovered that significant differences were observed in both speed and muscle groups when comparing the average beats per minute of 80 bpm to 140 bpm. According to the findings of Rosario *et al*., in 2022, all six muscles examined showed significant increases in activation when subjected to higher speeds. According to the data gathered from the experiment, the two muscles with the highest activation were the gastrocnemius and the VM. When increasing your pace, it is important to note that a faster speed will require a greater push-off event and knee extension moment than a slower speed. Based on research conducted by Kyrölöinen *et al*., (2005), it is predicted that the forward propulsion muscles will experience higher activation when using the XPO resistive sled, as it is designed to be speed-dependent in its resistance. Gait deficiencies have been observed in populations living with HIV, suggesting future studies should consider this group (Rosario MG, 2023). Furthermore, when conducting prospective studies, it is recommended that the pace of the test be adjusted to a more typical cadence and speed chosen by the individual to create a more natural and realistic experience while pushing the sled (Rosario & Mathis *et al*., 2020).

Upon examination of the activation pattern, it was found that the TA muscle activation was considerably lower than the MVIC. The only analysis that showed increased TA activation was with maximum activation at 80 bpm, where it was the only muscle that showed increased EMG activation at this speed. When comparing the two pushing speeds, all conditions demonstrated increased TA activation at 140 bpm, regardless of the addition of BFR. A faster speed required greater TA activation to achieve foot clearance because a more forward posture was demonstrated at this speed, which was more noticeable at later repetitions. According to the findings of Kjeldsen *et al*.,'s (2019) research, TA contractions showed a noticeable increase during the final 20 repetitions when BFR was utilized in a single training session. In order to gain a deeper understanding of the potential impact of BFR on TA, future prospective studies must be conducted to explore the role of this muscle in toe clearance with BFR, as it plays a crucial role in maintaining proper foot function.

Finally, it is important to note that the occlusion pressure used in the study may have significantly impacted the results and should be considered in interpreting the results. However, the findings presented in the study conducted by Freitas *et al*., in 2020 determined that when training the lower extremities, utilizing an occlusion pressure of 80% resulted in the most optimal and efficient outcomes. In their 2023 research, Sun and Yang concluded that a recommended percentage of 50% arterial occlusion pressure is most effective in warm-up activities. Despite their efforts, Cerqueira and colleagues (2021) could not make a definitive statement about the effectiveness of adjusting cuff pressure to improve patient comfort and safety while achieving comparable physiological outcomes. For future research, it would be beneficial to compare neuromuscular activation in various occlusion scenarios to determine the most suitable occlusion protocol based on the discrepancy above.

A recent investigation by Rosario et al. (2024) showed different adaptations in lower limb musculature while pushing a sled with BFR. The authors pointed out the feasibility of utilizing this procedure in other clinical scenarios. Since the previous review looked into the mid-data point of the EMG trace (the steady portion of the muscle activation), the current examination suggests that future analyses examine a more specialized approach to LE muscle activation patterns. Each stepping pattern acceleration and deceleration portions can be viewed when analyzing individual EMG tracings. From this information from a specific stepping rate, we determine whether a learning effect for the LE can be discovered during the BFR task. Any delays in muscle activation or rapid decay in EMG spikes could explain the impact of BFR during training for a specific sport.

CONCLUSIONS

Through our extensive study, we were able to determine that the BFR method had a notable effect on the muscles of the gastrocnemius, vastus medialis, and gluteus maximus, particularly when the exercise was performed at a slower speed of 80 beats per minute. When the speed of movement increases to 140 beats per minute, a noticeable change in the average and maximum activation patterns of all six muscles analyzed can be observed, suggesting that these changes are related to the body's efforts for self-propulsion. In a comparison between 80 beats per minute and 140 beats per minute, it was observed that all six muscles showed a significant increase in activation at a faster pace. Particularly noteworthy were the minimal activation of the TA muscle with BFR and the maximal activation of the gastrocnemius and vastus medialis muscles with BFR.

As we move forward and embark on future endeavors, it may be worth delving into pulling tasks instead of pushing, as this approach can yield more efficient and effective results. Similar to walking backward, a comprehensive study with pulling exercises could potentially reveal the effects of BFR on muscle activation patterns in the lower extremities and antagonist recruitment. Secondly, over the past few years, there has been a notable increase in the comprehension and recognition of the impacts of BFR on the upper extremity (UE). Using the XPO Trainer, scapular and UE muscle recruitment patterns can be studied while pushing the sled at a controlled speed. Based on the valuable insights and data gathered from these studies, it is highly probable that implementing BFR in a closed-chain training method would prove more beneficial than using isotonic exercises on free limbs.

Furthermore, extensive research on the effects of "upstream" recruitment patterns has revealed a significant and noteworthy increase in outcomes. In order to gain a more thorough understanding of the impact of BFR on functional tasks, further research should be conducted to investigate the potential effects of BFR on marginal trunk regions and their potential influence on timing alterations during pushing activities. In the study conducted by Silfies *et al*., (2009), it was suggested that the feedforward mechanisms of the spine could potentially be enhanced by utilizing a unilateral or bilateral extremity maneuver as part of the approach. By utilizing this method, one can delve into the effects of preemptive abdominal contractions, varying movement speeds, and even subjects dealing with low back pain.

One potential application of the current research findings is the implementation of BFR in functional tasks such as pushing or even in any upper extremity closed-chain environment. One way to achieve resisted forward propulsion is to perform inclined treadmill walking, while another option is to engage in resisted cable walking. Both methods can effectively challenge and strengthen the muscles involved in forward movement. As a concluding remark, to gain a comprehensive understanding of the potential long-term effects and unique benefits for various sports, additional extensive research must be carried out to determine these discoveries' durability and sport-specific advantages.

The Texas Woman's University Institutional Review Board approved this study protocol: IRB-FY2022-24.

Financial Disclosure and Conflict of Interest: I affirm that I have no financial affiliation (including research funding) or involvement with any commercial organization with a direct financial interest in any matter included in this manuscript.

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