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Research article

The Acute Effects of Blood Flow Restriction on Ankle Muscle Reaction Time and Proprioception in Healthy Individuals

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Abstract
Blood flow restriction (BFR) induces hypoxic and metabolic stress, which may alter afferent feedback and neuromuscular control. However, its acute effects on ankle sensorimotor function remain unclear. The aim of the study was to investigate the acute effects of lower-limb BFR on multidimensional ankle sensorimotor function in healthy adults. Twenty-four participants (12 females, 12 males) completed two conditions in randomized order and a crossover design: BFR at 60% arterial occlusion pressure (AOP) and a control condition (20 mmHg). All measurements were performed during occlusion. Outcomes included joint position sense (active and passive), kinesthesia, static and dynamic balance, lower-limb muscle activation (surface electromyography), and muscle reaction time during sudden ankle inversion. BFR impaired active joint position sense at 20 degrees of inversion ($p = 0.011$), with no changes at other angles or in kinesthesia. Static balance deteriorated, with increases in sway area ($p = 0.017$), sway distance ($p = 0.029$), and sway velocity ($p < 0.001$), particularly under eyes-closed single-leg stance. Posterolateral reach distance decreased ($p = 0.023$), accompanied by reduced lower-limb muscle activation. Tibialis anterior muscle reaction time during 30 degrees of inversion in the ankle neutral position was shortened ($p < 0.001$), whereas peroneus longus muscle responses were unchanged. Acute lower-limb BFR impairs ankle sensorimotor control by reducing proprioceptive accuracy, balance performance, and muscle activation, while shortening reaction time. These findings suggest caution when applying BFR during tasks that require high postural demands or end-range control. Registration number and date: NCT07307339, 12/26/2025

Key words: Blood flow restriction, ankle, electromyography, balance, reaction time.

Introduction

Proprioception refers to the perception of joint position and movement mediated by afferent input from mechanoreceptors located in muscles, ligaments, joint capsules, bones, and skin (Lephart et al., 1998). Through neuromuscular feedback mechanisms, proprioception plays a key role in joint stability, coordination, and injury prevention. (Riemann and Lephart, 2002). As fundamental components of the somatosensory system, kinesthesia and joint position sense (JPS) are commonly used to evaluate proprioceptive function (Deshpande et al., 2003). Kinesthesia mediates the perception of movement speed and direction, whereas JPS reflects the ability to perceive and reproduce static joint positions. Together, these processes operate within a continuous sensorimotor feedback loop, providing rapid afferent information that enables precise motor planning, execution, and adjustment. Impairments in proprioceptive function, reflected by deficits in kinesthesia, JPS, and muscle reaction time, have been associated with impaired neuromuscular control and an increased risk of joint and soft-tissue injuries (Xue et al., 2021; Zazulak et al., 2007).

Blood flow restriction (BFR) involves applying a tourniquet cuff to the proximal portion of a limb to restrict venous outflow while partially maintaining arterial inflow, creating a hypoxic metabolic environment. This condition promotes fatigue and increases motor unit recruitment, and low-load BFR produces patterns similar to high-load resistance training (Hwang and Willoughby, 2019; Takarada et al., 2002). Fatigue can alter afferent feedback and motor output, potentially impairing lower-limb position sense and increasing the risk of injury (Hiemstra et al., 2001; Karabulut et al., 2010).

Evidence regarding BFR effects on proprioception remains limited. Previous studies reported no impairment in knee proprioception (Yamada et al., 2021), increased fatigue without balance deterioration (Bielitzki et al., 2024), and impaired joint position sense in the upper limb (Królikowska et al., 2023), indicating that BFR effects may be joint-specific.

As BFR is increasingly incorporated into exercise and rehabilitation programs, understanding its effects on ankle sensorimotor function during occlusion is clinically important. Since ankle stability depends on accurate proprioceptive input and rapid neuromuscular responses, any acute alterations occurring during BFR may have implications for exercise safety and injury risk. Therefore, evaluating ankle sensorimotor function during occlusion may provide clinically relevant information regarding the safe application of BFR.

Therefore, the present study aimed to investigate the acute effects of BFR on ankle sensorimotor control. Measurements were performed during occlusion at 60% AOP. We hypothesized that BFR-induced fatigue would reduce muscle activation and impair joint position sense, kinesthesia, and static and dynamic balance.

Methods

Participants

A priori sample size calculation (G*Power 3.1.9.7, Heinrich Heine University Düsseldorf, Germany) based on between-condition differences in quadriceps muscle activation reported by Bielitzki et al. (2024) indicated that 22

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participants were required ($\eta p2 = 0.63$, $\alpha = 0.05$, power = 0.80). To account for potential dropout, 24 healthy participants (12 females, 12 males; aged 18 - 40 years) were included. Descriptive data are presented as mean ± standard deviation. Mean age was 23.6 ± 2.5 years, height 173.6 ± 9.4 cm, weight 73.9 ± 18.6 kg, and BMI 24.5 ± 4.4 kg/m^2. Mean systolic and diastolic blood pressures were 117.3 ± 9.0 and 79.4 ± 7.3 mmHg, respectively. Mean arterial occlusion pressure was 196.4 ± 16.5 mmHg, with 60% AOP corresponding to 117.8 ± 9.9 mmHg.

Exclusion criteria included cardiovascular, neurological, or musculoskeletal disorders, medication affecting neuromuscular or cardiovascular function, pregnancy, hypertension (> 140/90 mmHg), and lower-limb wounds. All participants provided written informed consent, and the study was conducted in accordance with the Declaration of Helsinki. Ethical approval was obtained from the Bursa Uludağ University Clinical Research Ethics Committee (No: 2025 - 15/31).

Experimental procedure

Participants attended a familiarization session including anthropometric measurements and arterial occlusion pressure (AOP) determination. They avoided alcohol, caffeine, and strenuous exercise for 48 hours before testing. The protocol consisted of eight laboratory visits within a randomized, counterbalanced crossover design, including two conditions (60% AOP BFR and control 20 mmHg). Condition order was computer-randomized (Microsoft Excel 365, USA), and sessions were conducted 24 hours apart at the same time of day. Assessments were distributed across four test days: (1) plantarflexion joint position sense and kinesthesia, (2) inversion joint position sense and kinesthesia, (3) static balance tests, and (4) muscle reaction time evaluation using an inversion simulation platform and the Y-Balance Test. Blood flow restriction was applied using a pneumatic cuff device (Fit Cuffs Complete V3.1, Fit Cuffs LLC, USA), which included an adjustable lower-extremity cuff (10 cm width, 51 - 76 cm length) and a precision inflation pump with a manual pressure gauge capable of reaching pressures up to 300 mmHg with an accuracy of ± 3 mmHg. All measurements were performed on the dominant leg, defined as the leg naturally used to kick a ball (Knight and Weimar, 2011). The cuff was positioned at the most proximal region of the tested limb and inflated to 60% of each participant's AOP in the experimental condition and to 20 mmHg in the control condition. After placement, participants rested for 4 minutes, and sessions were limited to 20 minutes (Patterson et al., 2019). Balance was assessed under eyes-open and eyes-closed conditions. Muscle activation and reaction parameters were recorded using surface electromyography (EMG). Participant blinding could not be fully achieved due to the perceptible difference in cuff pressure between conditions. However, participants were not informed of the study hypotheses or expected outcomes. Cuff application and outcome assessments were performed by the same investigator (Figure 1).

Arterial occlusion pressure measurements

Participants were seated with hip, knee, and ankle at 90 degrees. After 10 minutes of rest, a cuff was applied to the proximal thigh. Arterial flow was detected using a handheld bidirectional Doppler probe over the posterior tibial artery, and AOP was determined according to established protocols (Loenneke et al., 2012). Pressure was set at 60% AOP and verified before each test.

An occlusion pressure of 60% arterial occlusion pressure (AOP) was selected because pressures above 40% AOP are required to induce sufficient metabolic stress during low-load exercise (Patterson et al., 2019).

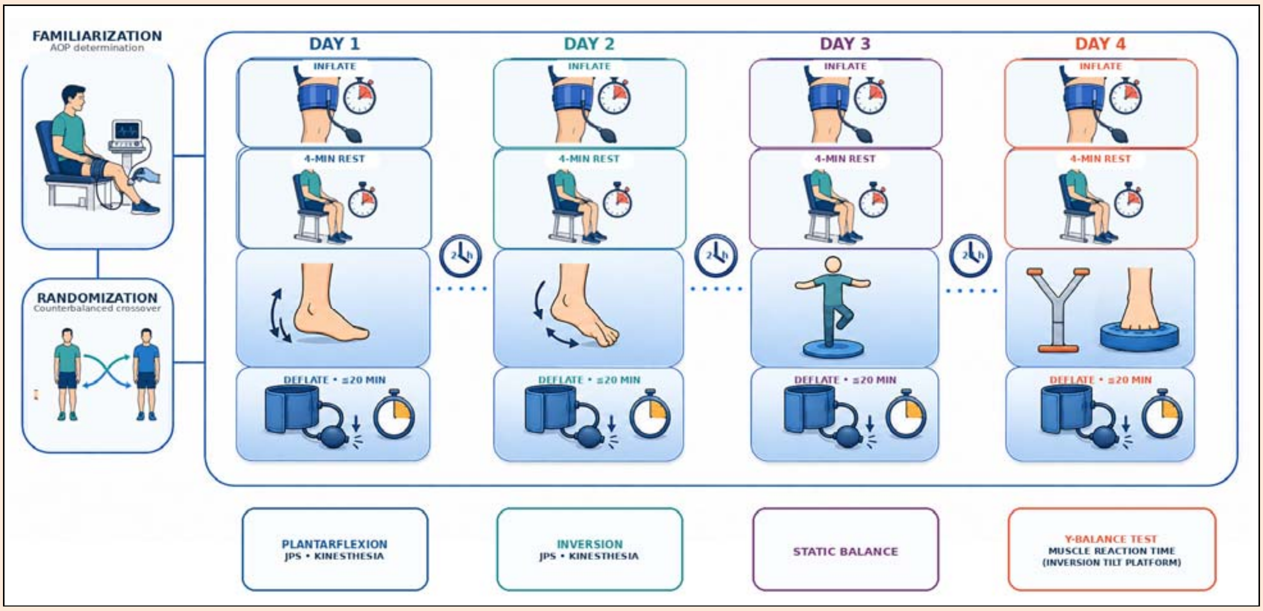

Figure 1. Experimental protocol and occlusion timeline. Participants first attended a familiarization visit that included an anthropometric assessment and determination of arterial occlusion pressure (AOP). They subsequently completed both experimental conditions (60% AOP and 20 mmHg) in a randomized counterbalanced crossover design across eight laboratory visits (four test days per condition). At each visit, the cuff was inflated to the target pressure and maintained for a 4-minute resting period before testing. All outcome assessments were completed under uninterrupted occlusion, and the cuff was deflated only after completion of the final assessment. The total occlusion time did not exceed 20 minutes.

In addition, 60% AOP maintains tissue deoxygenation without the excessive deoxygenation observed at higher pressures, such as 80% AOP (Reis et al., 2019). Since the intervention lasted 20 min, which is at the upper limit of durations commonly reported in the literature, participant comfort and tolerability were also considered to avoid unnecessary discomfort associated with prolonged exposure to higher pressures. Therefore, 60% AOP was chosen as an effective and well-tolerated pressure that balances physiological adaptations with minimizing excessive vascular restriction.

Tests

Proprioceptive ability of the ankle joint

Ankle proprioception was evaluated through measurements of active and passive joint position sense and kinesthesia.

Ankle joint position sense

Joint position sense was assessed using a computerized isokinetic dynamometer (Cybex NORM, CSMI, USA) in active and passive conditions. Passive trials were performed at an angular speed of 0.5 degrees/sec. Test angles were 10- and 20-degree inversion and 15- and 30-degree plantarflexion (Gross, 1987; Willems et al., 2002). Participants were blindfolded, and testing was conducted in a quiet environment. Participant positioning and testing procedures followed the protocol previously described by Hanci et al. (2016). Absolute error between reference and reproduced angles was calculated as the mean of three trials.

Kinesthesia

Kinesthesia was assessed as the threshold for detection of passive motion at 0.1 degrees/sec, following the protocol described by Hanci et al. (2016). The mean time of the three trials was used for analysis.

Balance tests

Static balance test

Postural balance was assessed using a platform (HUR SmartBalance BTG4, Finland). Participants were positioned according to the manufacturer's guidelines (Blosch et al., 2019). Single-leg stance was performed on the restricted leg, and tandem stance with the restricted leg posterior (30 sec each, eyes open and closed). Sway area (mm^2), distance (mm), and velocity (mm/s) were recorded.

Y balance test

Maximum reach distance in the anterior (A), posterolateral (PL), and posteromedial (PM) directions was measured using a Y-shaped setup. Tape strips (140 cm) were arranged at 90 ° and 135 ° angles. The dominant foot was positioned at the center of the apparatus, and participants kept their hands on their waist during testing. Three trials were performed in each direction. Trials were repeated if balance was lost or positioning criteria were not met. The maximal reach was maintained for 1 second, and the distance was recorded (cm). Surface EMG activity of the muscles in the cuff-applied limb was simultaneously recorded.

Electromyografic measurements

Preparation

Muscles reaction properties of the peroneus longus (PL) and tibialis anterior (TA) muscles was recorded during the ankle inversion platform assessment, and muscle EMG activity of the lower-limb muscles [peroneus longus (PL), tibialis anterior (TA), gastrocnemius medialis (GM), gastrocnemius lateralis (GL), soleus (S), vastus lateralis (VL), vastus medialis (VM), rectus femoris (RF), biceps femoris (BF), and semitendinosus (ST)] were recorded during the Y Balance Test using a wireless EMG system (Ultium EMG, Noraxon, Scottsdale, AZ, USA).

Bipolar Ag/AgCl surface electrodes were placed according to SENIAM guidelines (Figure 2). Signals were band-pass filtered (20-400 Hz), sampled at 1000 Hz, rectified, and smoothed (100 ms) to obtain RMS amplitudes (μV). Data were processed using Noraxon software (version MR 3.20.84; Noraxon Inc., USA) and synchronized with video recordings through an auxiliary camera system (A4 Tech PK-635G, New Taipei, Taiwan).

Muscle reaction time measurements and ankle inversion tilting platform

A detailed description of the protocol used to measure muscle reaction time, reaction duration, and reaction magnitude during sudden ankle inversion has been previously reported (Keles et al., 2014; Sekir et al., 2019).

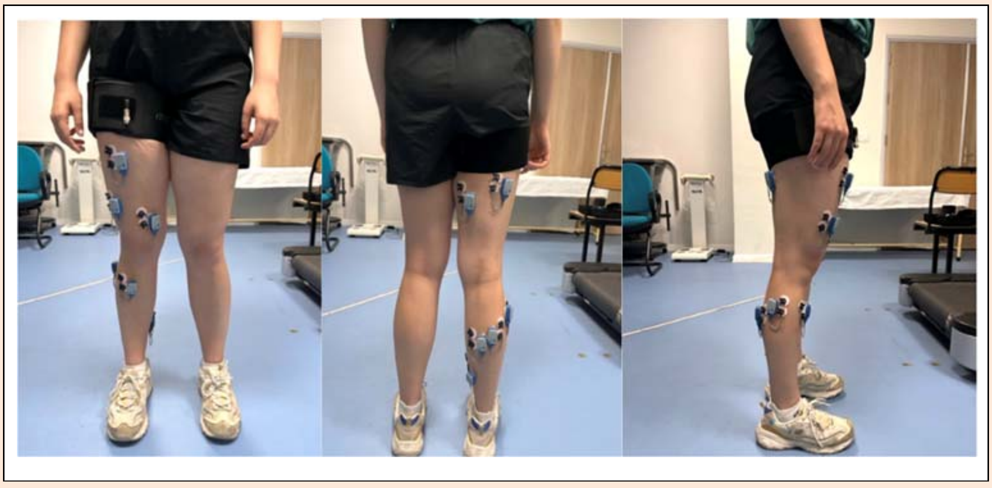

Figure 2. Electrode placements for the EMG recording.

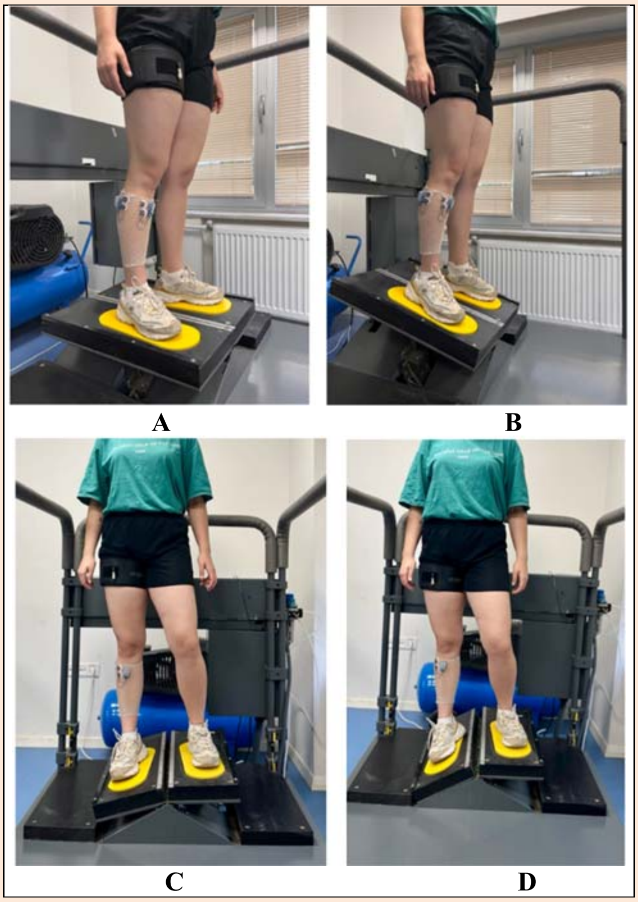

Figure 3. Inversion simulation platform with neutral (A) and 20 degrees of plantar flexion (B) starting positions. Supination positions on the platform included a fall from neutral to 15 degrees of inversion (C) and to 30 degrees of inversion (D). Electrode placement for reaction time measurement is shown in the figure.

Briefly, the reaction time of the peroneus longus and tibialis anterior muscles was measured using surface EMG during sudden ankle supination induced by a tilting platform (Figure 3). The reliability of the tilting platform was previously evaluated in a pilot study conducted in our laboratory (Keles et al., 2010). Four inversion conditions were applied: 15 degrees of inversion in neutral ankle position (N15) and at 20 degrees of plantarflexion (PF15), and 30 degrees of inversion in neutral (N30) and at 20 degrees of plantarflexion (PF30). Reaction time was defined as the interval between inversion onset and the first EMG response exceeding twice the baseline noise level. Reaction duration was defined as the interval from this point to the time at which the signal returned below the same threshold. Finally, the magnitude of the muscle reaction was obtained from the EMG activity amplitude during the reaction duration. This value was normalized against the maximal voluntary contraction trial. The mean of the two trials was used for analysis.

Normalization

EMG signals were normalized to maximal voluntary isometric contraction (MVIC). MVIC values were obtained for the knee flexors (BF, ST), knee extensors (VM, VL, RF), ankle dorsiflexors (TA), plantar flexors (S, GM, GL), and evertor (PL) muscles. Before testing, participants performed a standardized 5-min warm-up on a cycle ergometer at 90 rpm and 100 W for males and 80 W for females. MVICs were performed in a seated position with the hip flexed at 90 degrees. Knee flexion angles were set at 60 degrees for knee extensors and 30 degrees for knee flexors. The soleus muscle was assessed with the knee flexed at 90 degrees and the ankle in neutral position, whereas the gastrocnemius and peroneus longus muscles were assessed with the knee fully extended and the ankle in neutral. The mean EMG amplitude from the middle 2 sec of a 5-sec MVIC was used.

Video-synchronized analyses were used to assess muscle activity. EMG recordings were obtained from the PL and TA muscles during the inversion-tilting platform test, and from the BF, ST, VL, VM, RF, GM, GL, S, TA, and PL muscles during the eccentric phase of the Y Balance Test. EMG amplitudes were expressed as %MVIC.

Statistical analysis

Statistical analyses were performed using SPSS Statistics Version 29.0 (IBM Corp., Armonk, NY, USA). No missing data were observed, and all participants were included in the analysis. All variables were described using mean ± standard deviation. The Shapiro-Wilk test was first applied to assess normality. When both conditions demonstrated a normal distribution, a parametric paired t-test was conducted. Conversely, if at least one of the conditions did not meet the assumption of normality, a non-parametric alternative, the Wilcoxon signed-rank test, was used. The statistical significance was set at $p < 0.05$. In addition, the effect size Cohen's d was calculated and interpreted using the following thresholds: d = 0.2 as a small, d = 0.5 as a medium, and d = 0.8 as a large effect (Cohen, 1992).

Results

No participants were lost after randomization. All 24 participants successfully completed 4 sessions for each condition (control and BFR). No adverse events were reported.

Joint position sense and kinesthesia

A significant condition effect was observed only for active joint position sense at 20 degrees of inversion, where the BFR condition resulted in a higher absolute repositioning error than the control condition (p = 0.011, d = 0.523). No other joint position sense or kinesthesia measures differed between conditions (p > 0.05; Table 1).

Static balance

BFR significantly increased sway area during the single-leg eyes closed (SLEC) condition (p = 0.017, d = 0.459).

For sway distance, significant increases were observed in SLEC (p = 0.029, d = 0.472), tandem eyes open (TEO) (p = 0.042, d = 0.438), and tandem eyes closed (TEC) (p = 0.008, d = 0.586).

For sway velocity, BFR significantly increased values in SLEO (p < 0.001, d = -1.174), SLEC (p < 0.001, d = 1.229), and TEC (p = 0.033, d = 0.328).

All other balance parameters showed no significant condition effects (p > 0.05; Table 2).

Y-Balance test performance

Posterolateral reach distance was significantly lower under the BFR condition (p = 0.023, d = -0.498; Table 3). No significant differences were observed in the anterior or posteromedial directions.

Muscle activation during the Y-Balance Test

BFR altered lower-limb muscle activation patterns during the Y-Balance Test.

In the posterolateral direction, activation of the peroneus longus (PL) (p = 0.022, d = -0.502), gastrocnemius lateralis (GL) (p = 0.037, d = -0.553), gastrocnemius medialis (GM) (p = 0.014, d = -0.548) and soleus (S) (p = 0.002, d = -0.503) muscles decreased significantly.

In the anterior direction, significant reductions were observed in the biceps femoris (BF) (p < 0.001, d = -0.884), semitendinosus (ST) (p < 0.001, d = -1.013), GL (p = 0.037, d = -0.501), and gastrocnemius medialis muscles (GM) (p = 0.001, d = -0.736).

During the posteromedial reach, activation of the rectus femoris (RF) (p = 0.015, d = -0.672), vastus lateralis (VL) (p = 0.023, d = -0.707), vastus medialis (VM) (p = 0.037, d = -0.606), BF (p = 0.015, d = -0.567), tibialis anterior (TA) (p = 0.005, d = -0.620), and gastrocnemius medialis (GM) muscles (p = 0.013, d = -0.548) decreased significantly.

All remaining muscles showed no significant effects of condition (Table 3).

Reaction time and EMG responses during inversion stimulation

For the tibialis anterior reaction time was shorter during 30 degrees of inversion from the neutral ankle position under BFR (p = 0.006, d = -0.640), whereas reaction duration and EMG amplitude did not differ between conditions. For the peroneus longus, reaction time, reaction duration, and EMG activation amplitude showed no significant differences between conditions at any inversion angle (Table 4).

Discussion

The present study investigated the acute sensorimotor consequences of lower-limb BFR at the ankle joint. Overall, the findings indicate that BFR impairs multiple components of ankle sensorimotor function. Results partially supported our hypothesis and provide insight into the sensorimotor consequences of applying BFR at the ankle joint, which plays a fundamental role in postural stability and injury prevention.

Effects on joint position sense and kinesthesia

Among eight joint-position sense conditions, only active 20 degrees of inversion exhibited significant deterioration under BFR. This selective impairment aligns with findings by Królikowska et al. (2023), who demonstrated that upper-limb BFR impaired wrist joint-position sense at specific angles but not across the entire range of motion. However, Krolikowska's et al. (2023) study had methodological limitations, including the lack of venous congestion and the use of the same test sequence in both conditions. In contrast, our crossover design and the inclusion of a 4-minute congestion period prior to testing were implemented to overcome these constraints. On the other hand, type III mechanoreceptors increase sensitivity at extreme joint positions (Freeman and Wyke, 1967). Angle-dependent

Table 1. Active and passive joint position sense in four different ankle joint positions. Data are means ± SD.

		Control	BFR	*p value and ES*
Plantar flexion (PF)	Active PF 15 degrees	2.9 ± 1.4	3.4 ± 2.3	0.335; d = 0.200
	Active PF 30 degrees	3.2 ± 1.8	3.1 ± 2.7	0.635; d = -0.023
	Passive PF 15 degrees	5.6 ± 2.0	5.5 ± 2.1	0.718; d = -0.074
	Passive PF 30 degrees	7.9 ± 4.8	7.0 ± 3.5	0.438; d = -0.161
	Kinesthesia PF	2.0 ± 1.0	2.0 ± 0.8	0.904; d = -0.024
Inversion (INV)	Active INV 10 degrees	1.9 ± 1.1	2.0 ± 1.3	0.348; d = 0.108
	Active INV 20 degrees	1.3 ± 0.8	2.4 ± 2.2	***0.011; d = 0.523**
	Passive INV 10 degrees	2.2 ± 1.0	2.2 ± 1.1	0.778; d = -0.0131
	Passive INV 20 degrees	3.9 ± 1.7	3.8 ± 2.3	0.765; d = -0.0349
	Kinesthesia INV	2.0 ± 1.0	2.0 ± 0.8	0.895; d = -0.027

SD: Standard deviation. ES: Effect Size. *: p <0.05.

Table 2. Static balance tests results. Data are means ± SD.

		SLEO	SLEC	TEO	TEC
Sway area (mm^2)	**CONTROL**	200.5 ± 97.9	1924.1 ±1302.7	144.0 ± 84.5	1145.2 ± 613.8
	BFR	173.8 ± 83.4	2793.5 ± 2228.3	235 ± 212.7	1282.5 ± 1212.7
	***p* value and ES**	0.550 d=-0.2002	***0.017; d=0.459**	0.063; d=0.399	0.567; d=0.119
Sway distance (mm)	**CONTROL**	375.3 ± 102.9	1262.4 ± 414.4	297.1 ± 63.2	781.8 ± 182.3
	BFR	365.0± 81.2	1428.0 ± 535.8	332.8 ± 89.7	897.7 ± 290.4
	***p* value and ES**	0.5516; d=-0.1233	***0.029; d=0.472**	***0.042; d=0.438**	***0.008; d=0.586**
Sway velocity (mm/s)	**CONTROL**	8.0 ±2.2	33.1 ±21.0	6.7 ±1.7	19.3 ±7.3
	BFR	8.0 ±1.7	43.9 ±31.5	7.7 ±2.3	24.0 ±14.9
	***p* value and ES**	***<0.001; d=-1.174**	***<0.001; d=1.229**	0.126; d=0.4466	***0.033; d= 0.328**

SD: Standard deviation, ES: Effect Size, *: $p<0.05$, SLEO: Single Leg Eyes Open, SLEC: Single Leg Eyes Close, TEO: Tandem Eyes Open, TEC: Tandem Eyes Close, mm: millimeter, mm^2: square millimeters, mm/s: millimeters per second.

effects may reflect increased sensitivity of type III mechanoreceptors at end-range positions, potentially enhanced by venous pooling. Furthermore, joint-specific nature of joint position sense limits the ability to generalize findings across different extremities (Han et al., 2013). Considering the mechanism of ankle sprain, the loss of joint-position sense at more extreme inversion angles reinforces safety concerns.

Contrary to Yamada et al.'s (2021) findings, who reported no impairment in knee proprioception following practical BFR walking with an elastic cuff, our study assessed proprioception during occlusion rather than after cuff removal. This distinction is crucial because hypoxic and hemodynamic changes occurring during BFR likely exert acute effects on peripheral afferent feedback that may not persist once normal perfusion resumes.

Effects on static and dynamic postural control

In this study, BFR significantly increased sway distance, sway velocity, and sway area in most static balance conditions, and this deterioration was accompanied by reductions in lower-limb muscle activation during dynamic balance tasks. These findings contrast with those reported by Bielitzki et al. (2024), who observed no impairments in postural control despite reduced muscle oxygenation and increased fatigue, interpreted as compensatory neuromuscular responses. In the same study, increased quadriceps activation was reported alongside reduced tibialis anterior and triceps surae activity during dynamic balance tasks. Similarly, no significant changes in static or dynamic balance have been observed under full occlusion, despite marked deoxygenation and reduced time to exhaustion (Willberg et al., 2021). In contrast, Burkhardt et al. (2021) reported increased activation of the vastus lateralis and soleus muscles during the Y-Balance test in individuals with chronic ankle instability. Unlike these previous studies, the present study demonstrated an overall reduction in lower-limb muscle activation during dynamic balance performance, suggesting that compensatory neuromuscular strategies may have been insufficient to maintain postural stability under the applied BFR protocol. Although a statistically significant reduction was observed in the posterolateral reach direction during BFR application, the magnitude of change remained below the previously reported minimal detectable change (MDC) threshold, suggesting limited clinical relevance despite statistical significance (Powden et al., 2019). One possible explanation for these discrepant findings may be the longer duration of blood flow restriction applied in the present study. A careful examination of previous methodologies revealed that blood flow restriction was generally applied for relatively short periods, averaging 5-10 minutes. In contrast, the present protocol employed a longer occlusion duration, approaching the upper limit commonly reported in the literature. Prolonged restriction may increase metabolite accumulation and activate group III-IV afferents, producing an inhibitory influence on the motor neuron pool, initially promoting greater motor unit recruitment, but subsequently leading to reductions in muscle activation as fatigue accumulates (Loenneke et al., 2011).

Effects on muscle reaction time

To our knowledge, ankle muscle reaction time during BFR has not previously been investigated. Rivera et al. (2021) examined rectus femoris muscle reaction time following submaximal leg extension and reported no differences between conditions. In the present study, tibialis anterior muscle reaction time was significantly shortened during sudden inversion at 30 degrees in the neutral ankle position, whereas reaction duration and amplitude remained unchanged. No alterations were observed in peroneus longus reaction metrics. This selective reduction in tibialis anterior muscle latency may reflect an adaptive neural response to BFR induced instability, whereby the nervous system increases reliance on rapid dorsiflexor-mediated corrective strategies. Local hypoxia and metabolite accumulation may also increase motoneuron excitability, as suggested in previous BFR research (Bielitzki et al., 2024; Fahs et al., 2015). However, because the peroneus longus is considered the primary dynamic restraint against sudden ankle inversion (Konradsen and Bohsen Ravn, 1991; Löfvenberg et al., 1995; Mitchell et al., 2008), the isolated shortening of tibialis anterior reaction time should be interpreted cautiously. The absence of changes in peroneus longus latency, together with the concomitant impairments in joint position sense, balance, and muscle activation, suggests that this response is more likely to represent a localized compensatory adaptation than a generalized improvement in ankle sensorimotor function. An additional question concerns the temporal persistence of these alterations, monitoring neuromuscular recovery immediately and at 1, 2, 4, and 8 minutes following reperfusion, demonstrating that despite greater reductions in maximal voluntary torque and contractile function during BFR exercise, most impairments recovered substantially within the first two minutes after cuff release (Husmann et al., 2018). However, these findings were limited to neuromuscular fatigue and contractile function, and whether ankle sensorimotor impairments-including proprioception, muscle reaction time, postural balance, and muscle activation-follow a similar recovery profile remains unknown. Furthermore, the effects of repeated BFR exposure on ankle sensorimotor function have yet to be established. Future studies should therefore investigate both the temporal recovery of these sensorimotor alterations and the cumulative effects of repeated BFR applications. Future studies are needed to determine whether this adaptation is ultimately protective or maladaptive during functional activities. The present findings may also have potential clinical implications. Blood flow restriction is increasingly incorporated into rehabilitation and athletic conditioning programs. Because proprioception and neuromuscular control are fundamental to dynamic joint stability, the acute sensorimotor alterations observed during cuff inflation should be considered when BFR is combined with balance exercises, functional training, or sport-specific activities. Although the present study was conducted in healthy individuals, these findings may be particularly relevant for populations with impaired sensorimotor function, such as patients with acute ankle injuries, chronic ankle instability, or those undergoing postoperative rehabilitation. Nevertheless, direct extrapolation to these clinical populations should be made with caution, and future studies are warranted to determine whether similar sensorimotor responses occur in these populations and influence rehabilitation outcomes or return-to-sport decision-making.

Table 3. **Y Balance test distances and muscle activations. Data are means ± SD.**

	ANTERIOR			POST-MEDIAL			POST-LATERAL		
	CONTROL	BFR	p value and ES	CONTROL	BFR	p value and ES	CONTROL	BFR	p value and ES
DISTANCE (cm)	69.5 ± 7.0	68.6 ± 8.7	0.450; d = -0.156	83.5 ± 12.8	80.8 ± 13.5	0.060; d = -0.402	95.0 ± 12.7	92.8 ± 12.1	*0.023; d = -0.498
RF	15.4 ± 10.9	14.4 ± 10.7	0.797; d = -0.149	18.3 ± 11.8	12.3 ± 10.8	*0.015; d = -0.672	25.3 ± 13.3	22.4 ± 14.4	0.068; d = -0.265
VL	33.8 ± 22.5	31.3 ± 22.1	0.424; d = -0.245	35.2 ± 18.5	28.1 ± 19.7	*0.023; d = -0.707	39.7 ± 23.1	36.2 ± 21.1	0.179; d = -0.267
VM	39.9 ± 26.1	34.9 ± 23.4	0.149; d = -0.418	32.1 ± 15.6	26.2 ± 16.6	*0.037; d = -0.606	41.9 ± 22.1	38.4 ± 21.7	0.179; d = -0.225
BF	6.4 ± 2.6	4.8 ± 1.8	*<0.001; d = -0.884	7.9 ± 3.3	5.9 ± 3.5	*0.015; d = -0.567	6.2 ± 2.8	5.0 ± 1.8	0.076; d = -0.379
ST	11.8 ± 5.7	7.5 ± 3.4	*<0.001; d = -1.013	6.5 ± 3.4	5.0 ± 2.9	0.204; d = -0.554	8.2 ± 4.8	6.0 ± 3.1	0.079; d = -0.606
TA	24.8 ± 12.3	20.8 ± 8.7	0.103; d = -0.432	41.3 ± 16.3	32.7 ± 16.2	*0.005; d = -0.620	35.5 ± 15.6	30.9 ± 13.3	0.103; d = -0.326
PL	34.4 ± 13.3	28.8 ± 11.5	0.063; d = -0.473	27.6 ± 12.8	23.8 ± 10.2	0.07; d = -0.439	32.4 ± 13.2	26.4 ± 10.0	*0.022; d = -0.502
GL	29.5 ± 16.6	25.6 ± 14.9	*0.037; d = -0.501	19.0 ± 14.6	16.6 ± 13.7	0.061; d = -0.339	21.5 ± 15.2	17.7 ± 12.5	*0.037; d = -0.553
GM	16.7 ± 9.4	12.0 ± 6.1	*0.001; d = -0.736	16.1 ± 8.4	12.4 ± 7.3	*0.013; d = -0.548	12.7 ± 8.6	9.3 ± 5.0	*0.014; d = -0.548
S	42.5 ± 32.8	34.4 ± 20.7	0.092; d = -0.367	40.1 ± 31.4	31.4 ± 17.7	0.123; d = -0.406	28.9 ± 18.2	22.6 ± 11.2	*0.002; d = -0.503

ES: Effect Size. cm: centimeter. *: p <0.05. RF: rectus femoris muscle. VL: vastus lateralis muscle. VM: vastus medialis muscle. BF: biceps femoris muscle. ST: semitendinosus muscle. TA: tibialis anterior muscle. PL: peroneus longus muscle. GL: gastrocnemius lateralis muscle. GM: gastrocnemius medialis muscle. S: soleus muscle.

Table 4. **Muscle reaction time, reaction duration and normalized muscle reaction magnitude datas in the four different ankle inversion positions. Data are means ± SD.**

		Muscle reaction time			Muscle reaction duration			Normalized muscle reaction magnitude		
		CONTROL	BFR	P value and ES	CONTROL	BFR	P value and ES	CONTROL	BFR	P value and ES
Peroneus Longus Muscle	N15	97.1 ± 38.8	85.7 ± 37.0	0.132; d = -0.268	267.6 ± 165.6	225.9 ± 107.0	0.171; d = -0.339	21.7 ± 12.7	25.8 ± 10.6	0.056; d = 0.353
	N30	100.5 ± 47.5	83.7 ± 34.0	0.081; d = -0.362	462.9 ± 221.2	385.5 ± 166.0	0.181; d = -0.247	10.4 ± 6.4	10.0 ± 7.3	0.753; d = 0.014
	PF15	91.0 ± 26.0	94.1 ± 39.7	0.39; d = 0.065	159.7 ± 119.1	196.8 ± 150.9	0.380; d = 0.191	26.9 ± 14.8	26.1 ± 13.1	0.648; d = -0.064
	PF30	94.4 ± 44.1	91.2 ± 41.3	0.53; d = -0.061	410.5 ± 266.2	403.0 ± 248.3	0.907; d = -0.024	30.8 ± 13.2	31.7 ± 12.3	0.732; d = 0.076
Tibialis Anterior Muscle	N15	85.4 ± 30.4	83.4 ± 35.5	0.584; d = -0.045	85.4 ± 30.4	83.4 ± 35.5	0.238; d = -0.258	7.8 ± 10.3	7.4 ± 5.1	0.241; d = -0.049
	N30	92.3 ± 36.3	65.8 ± 24.8	*<0.001; d = -0.640	538.5 ± 290.2	589.0 ± 348.9	0.513; d = 0.135	10.4 ± 6.4	10.0 ± 7.3	0.932; d = -0.054
	PF15	76.7 ± 28.0	80.4 ± 36.4	0.502; d = -0.164	229.7 ± 138.8	217.0 ± 84.1	0.53; d = -0.097	9.0 ± 6.4	7.3 ± 4.9	0.059; d = -0.405
	PF30	84.1 ± 29.8	83.8 ± 37.5	0.974; d = -0.006	370.3 ± 227.8	399.6 ± 224.7	0.637; d = 0.079	13.1 ± 10.6	10.5 ± 5.3	0.689; d = -0.255

SD: Standard deviation, ES: Effect Size, ms: millisecond, *: p <0.05, N15: Ankle neutral, 15° inversion; N30: Ankle neutral, 30° inversion; PF15: Ankle 20° plantarflexion, 15° inversion, PF30: Ankle 20° plantar flexion, 30° inversion, %MVC: Percent maximum voluntary contraction

Strengths and Limitations

This study has several strengths, including individualized AOP calibration, a randomized crossover design, and simultaneous EMG assessment during the Y-Balance test, allowing comprehensive evaluation of ankle sensorimotor function through joint position sense, kinesthesia, reaction time, and static and dynamic balance measures.

Some limitations should also be acknowledged. First, AOP was determined in a seated position, whereas experimental assessments were conducted in standing and supine positions, which may have resulted in deviations from the intended 60% AOP during testing. Second, EMG recordings were not obtained during static balance tasks. Third, although the EMG system included an integrated motion-capture camera, this unit was unavailable in our laboratory; therefore, video signal synchronization was performed using an external camera, which may have introduced minor synchronization errors. Finally, intramuscular oxygenation was not measured and should be considered in future studies using similar protocols.

Conclusion

This study suggests that acute blood flow restriction may influence several components of ankle sensorimotor function during occlusion, including joint position sense, postural balance, muscle activation, and tibialis anterior muscle reaction time. Although these findings indicate that BFR may transiently affect neuromuscular control, the persistence and clinical significance of these alterations remain unclear. Further studies are required to determine the recovery profile of these responses and the effects of repeated BFR exposure before definitive conclusions regarding their implications for injury risk or rehabilitation can be drawn.

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Key points

- BFR at 60% AOP impaired ankle joint position sense and static balance, particularly during eyes-closed single-leg stance.
- BFR reduced lower-limb muscle activation across all three Y-Balance Test directions and shortened tibialis anterior muscle reaction time without altering peroneus longus responses.
- Balance-demanding, perturbation-based, and end-range ankle tasks should be performed cautiously while the cuff remains inflated, even in healthy individuals.

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