Blood Flow Restriction Does Not Impair Ankle Proprioception in Healthy Male Adults

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Blood Flow Restriction Does Not Impair Ankle Proprioception in Healthy Male Adults

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Abstract

Blood Flow Restriction (BFR) training has been widely used to enhance muscle strength and hypertrophy at low loads, yet its impact on proprioception, particularly ankle Joint Position Sense (JPS), is not fully understood. This study assessed the effect of BFR on ankle proprioception in 30 healthy male participants, who were randomly assigned to control (n=10), sham (n=10), and BFR (n=10) groups. JPS was evaluated using Constant Error (CE) and Variable Error (VE) during passive ankle plantarflexion before, during, and after the intervention. The BFR group underwent 80% arterial occlusion pressure, while the sham group received minimal pressure. Results indicated a significant effect of the group on CE ($p = 0.016$), with participants in the control group overshooting the target angle more than those in the BFR group. However, no significant differences in CE were found between the BFR and sham groups ($p > 0.05$). VE showed a significant effect of time point ($p = 0.048$), but no interaction effect with the group was observed. These findings suggest that BFR does not impair ankle JPS accuracy or consistency in healthy males. These results provide evidence that BFR can be safely incorporated into rehabilitation or training contexts without compromising proprioception, making it a valuable option for populations that cannot engage in high-load resistance training. Future studies should expand on these findings by exploring varied populations and refining BFR protocols for optimal proprioceptive function.

Key Words: Proprioception; Blood Flow Restriction; Joint Position Sense; Ankle Joint

INTRODUCTION

Blood Flow Restriction (BFR) training involves placing a restrictive device on the proximal section of a limb to reduce arterial blood flow and occlude venous return (11). This technique is popular for enhancing muscle strength and hypertrophy at low-intensity levels (typically 20-40% of one-repetition maximum [1RM]) (21,23). Compared to traditional high-intensity training, BFR reduces joint mechanical stress, offering a safer alternative for populations where high-intensity exercise is contraindicated, such as in early rehabilitation or among older adults (7). Recent meta-analyses have shown that muscle strength gains from low-load BFR are comparable to those from high-load resistance training (7). Additionally, BFR training has advantages over standard isometric exercises in reducing disuse atrophy (14). BFR training has also been associated with positive short-term vascular adaptations such as exercise-induced angiogenesis, driven by the increased expression of vascular endothelial growth factor (VEGF) (15). However, the long-term vascular effects of BFR are still unclear and require further investigation (2).

Despite extensive research on the safety and efficacy of BFR in training and rehabilitation, its impact on proprioception, particularly Joint Position Sense (JPS), remains to be established. Proprioception is important for balance, movement coordination, and injury prevention (20,22). The potential impact of BFR on proprioception is significant, particularly because BFR alters blood flow dynamics, creating a hypoxic environment within the muscle. This hypoxia can disrupt nutrient delivery and impair the clearance of metabolic byproducts, potentially compromising the function of proprioceptors (19,29), which depend on these processes to maintain their sensitivity and response accuracy (29). The post-occlusion phase, characterized by reactive hyperemia, is critical for muscle recovery, restoring the metabolic environment, and promoting repair processes, as evidenced by increased expression of angiogenic factors like VEGF post-exercise (30).

Conflicting findings exist regarding the effects of BFR on Joint Position Sense (JPS), though inconsistencies may partially reflect differences in testing protocols. For example, one study assessing knee proprioception used a passive-to-active joint position reproduction method, where the investigator passively moved the participant's dominant leg to one of four target angles (30°, 45°, 60°, or 90°) before asking the participant to actively reproduce the angle (26). No significant impairment in knee JPS was observed following BFR in that study, suggesting its potential safety in lower-limb applications. In contrast, another study using an active-to-active joint position reproduction test during wrist flexion and extension (30° flexion, 45° extension) on an isokinetic dynamometer found significantly increased proprioceptive error under BFR, particularly at lower flexion angles (10). These differing outcomes, along with variations in the joint, test modality, and range of motion, highlight the need for further investigation into how BFR affects proprioception under different mechanical and methodological conditions.

In the ankle joint, proprioception plays a critical role in supporting body weight and enabling complex movements such as walking and jumping. Impaired ankle proprioception significantly increases the risk of injuries, such as sprains, by up to 2.3 times, particularly in athletes where ankle injuries are common (9). Given the high prevalence of ankle injuries in sports and rehabilitation settings, this study aimed to evaluate the influence of BFR on passive ankle JPS error, using metrics such as Constant Error (CE) and Variable Error (VE) (10,28). By focusing on ankle JPS, the study seeks to address the gap in the literature concerning the effects of BFR on proprioceptive functions. From a strength and conditioning perspective, BFR is increasingly used to maintain or build strength when high mechanical loads are undesirable, for example, during early to mid rehabilitation and load-managed training phases. If BFR were to impair ankle joint position sense, this would have direct implications for exercise selection, return-to-play progressions, and on-field readiness. We therefore examined whether lower-limb BFR, dosed by individual arterial occlusion pressure, alters passive ankle joint position sense across pre, during, and post occlusion assessments. It was hypothesized that BFR would negatively impact ankle JPS, particularly during and immediately following the application of the restriction, compared to a control group.

METHODS

Experimental Approach to the Problem

This study was designed to evaluate the effects of BFR on JPS using a randomized, parallel-group, single-blind, sham-controlled approach. To test this, participants were randomly assigned to one of three groups: BFR, sham, or control. Figure 1 provides a schematic overview of the experimental protocol. The choice of BFR as the independent variable was based on previous research highlighting its influence on proprioception through mechanical and neural pathways (13). The dependent variables, Constant Error (CE) and Variable Error (VE) were selected as standardized measures of proprioceptive performance, providing insight into both accuracy (CE) and consistency (VE) of JPS. These metrics were measured across three-time points; pre-intervention, during intervention, and post-intervention, to assess the temporal effects of BFR on proprioception and to account for any potential carryover or learning effects. To control for variability in cuff application, arterial occlusion pressure (AOP) was standardized for each participant, ensuring a personalized BFR dose for each individual. The sham group served as a placebo, allowing us to isolate the true effects of BFR by mimicking the sensation of occlusion without significant pressure.

INSERT Figure 1

Subjects

A total of 30 healthy male participants aged between 18 and 40 years were recruited for this study. The sample size was determined based on a previous study, which reported a mean difference of 5.6 ± 8° in Joint Position Sense (JPS) under Blood Flow Restriction (BFR), with an effect size of 0.70 (13). A power analysis (G*Power, University of Kiel, Germany) indicated that 25 participants were required to detect a significant difference with a power of 0.80 and an alpha of 0.05/3 (Bonferroni correction for three tests—pre-intervention, during intervention, and post-intervention). To account for potential dropouts, the sample size was increased to 30.

Participants were screened for eligibility via a Qualtrics survey. Exclusion criteria included a diagnosis of rhabdomyolysis, having more than one risk factor for thromboembolism, a body mass index (BMI) ≥ 30, a diagnosis of Crohn's or other inflammatory bowel diseases, past fractures of the hip, pelvis, or femur, recent major surgery (within the last 6 months), or a family history of deep vein thrombosis or pulmonary embolism, any current pain or injury affecting the lower limbs, or prior experience using blood flow restriction. Participants were required to refrain from physical exercise within 48 hours before data collection and to have a systolic blood pressure <140 mmHg and diastolic pressure <90 mmHg upon arrival. Ethical approval was obtained from the [redacted] Research Ethics Committee (ETH2324-0259). All participants were informed of the potential risks and benefits of the study before enrolment and provided written informed consent in accordance with institutional guidelines.

All 30 participants included in the study exhibited comparable baseline characteristics, with no significant differences observed in age, body mass, height, or BMI (Table 1).

Table 1: Participant demographics and between-group comparisons.

Characteristics	BFR	Sham	Control	*p*-value
n	10	10	10	-
Age (years)	21 ± 1.79	22 ± 1.2	21 ± 2.5	0.82
Body mass (kg)	81.5 ± 16.0	89.5 ± 14.7	76.9 ± 9.7	0.14
Height (cm)	180.5 ± 7.8	182.0 ± 7.9	178.4 ± 8.0	0.6
BMI (kg/m2)	24.9 ± 3.8	27.0 ± 3.8	24.2 ± 2.6	0.19
AOP (mmHg)	115.3 ± 12.0	120.6 ± 11.2	-	0.82
80% AOP (mmHg)	92.2 ± 9.6	96.5 ± 8.9	-	0.82
Thigh circumference (cm)	55.9 ± 5.2	58.5 ± 4.4	56.4 ± 4.7	0.45
Dominant Leg	R = 8; L = 2	R = 9; L = 1	R = 9; L = 1	-
Constant Error – Pre-Intervention (°)	-0.24 ± 5.44	1.21 ± 4.94	5.28 ± 3.98	0.01*
Variable Error – Pre-Intervention (°)	2.96 ±1.65	3.35 ± 2.44	2.67 ± 1.21	0.71

Values are expressed as mean and standard deviation (±). AOP = Arterial occlusion pressure. * post hoc analysis indicates Control significantly different to BFR and Sham,

Procedures

Participants were randomly allocated into one of three groups: the BFR group, the sham (placebo) group, or the control group, with 10 participants in each group. Randomization was conducted using GraphPad (31) to ensure equal distribution across the groups.

Determination of Arterial Occlusion Pressure (AOP)

For participants in the BFR and sham groups, AOP was determined before JPS testing. Participants were fitted with a 24-cm wide limb occlusion cuff (Hokanson, Bellevue, WA, USA) around the proximal section of the dominant thigh while lying supine (Figure 2). The cuff was connected to a Hokanson rapid cuff inflation device, and a Doppler ultrasound probe (HI.dop, BT-200 Vascular Doppler, Bistos Co. Ltd., Korea) was used to monitor the pulse of the posterior tibial artery. The cuff was incrementally inflated by 20 mmHg every 10 seconds until the pulse became faint, at which point the increments were reduced to 10 mmHg, 5 mmHg, and finally 1 mmHg until the pulse was no longer detectable. This pressure was recorded as the AOP. To confirm accuracy, the cuff was deflated and reinflated to the recorded AOP. If necessary, adjustments were made by increasing the pressure by 1 mmHg increments until the pulse could no longer be detected, confirming the true AOP. For the BFR intervention, 80% of the AOP was calculated and applied during the intervention JPS assessment. In the sham group, the cuff was inflated to a negligible pressure (7-9 mmHg) to mimic the sensation of BFR without inducing significant occlusion.

INSERT Figure 2

Joint Position Sense (JPS) Assessment

JPS of the ankle was assessed using the Biodex 4 isokinetic dynamometer (Biodex Medical Systems Inc., Shirley, NY, USA) following a validated protocol (28). Participants were positioned supine on the Biodex chair, with the calf of the dominant leg resting on a platform parallel to the seat (Figure 3). The barefoot was secured to the footplate, ensuring that the lateral malleolus was aligned with the axis of the dynamometer. The range of motion (ROM) within the sagittal plane was recorded, with the ankle joint initially positioned at 0° plantarflexion. Participants were blindfolded to eliminate visual compensation for proprioceptive impairments. The ankle was moved passively at 2°/sec through a 40° range of motion (ROM), with 20 plantarflexion as the target angle. A passive JPS protocol was selected to isolate the sensory components of proprioception, particularly the contribution of joint and ligamentous mechanoreceptors, while minimizing the influence of voluntary muscle activation or fatigue (4). Given the compressive nature of BFR and its potential influence on subcutaneous and capsular tissues, a passive test offered a controlled approach to detect subtle alterations in afferent feedback. Plantarflexion was selected as the focus of assessment because it is consistently implicated, alongside ankle inversion and internal rotation, as one of the primary joint motions involved in the mechanism of ankle sprain injuries (12). Given this, plantarflexion represents a clinically and functionally relevant target for evaluating the potential impact of BFR on ankle proprioception. During the familiarization phase, the ankle was paused at the target angle, and participants were instructed to memorize this position. Following a 10-second familiarization period, the dynamometer completed the full ROM, returning to the starting position at 5°/sec. During subsequent trials, participants pressed a button to stop the dynamometer when they believed the target angle had been reached. The dynamometer then completed the remaining ROM and returned to the starting position, with an 8-second rest period between repetitions. Each JPS assessment consisted of 10 repetitions, and participants completed three JPS assessments: pre-intervention, during intervention, and post-intervention. The pre-intervention, during-intervention, and post-intervention JPS assessments were conducted consecutively within a single session, with standardized rest intervals of ten minutes between each time point to minimize fatigue and prevent carryover effects. The passive joint position sense protocol employed in this study is supported by previous test-retest reliability data. Using a comparable passive ankle repositioning protocol, an intraclass correlation coefficient of 0.84 for angular error measurements in young adult male athletes was reported, indicating good reliability (6). Between-day variability was less than 3.5%, supporting the reproducibility of proprioceptive error measures derived from passive plantarflexion tasks (6). While their study used a slightly smaller ROM and slower angular velocity, the methodology is consistent in its focus on passive joint repositioning and afferent acuity, supporting the validity of our approach.

INSERT Figure 3

Data Analysis

Two error metrics were used as dependent variables: Constant Error (CE) and Variable Error (VE) (28). CE measures the average deviation from the target position, indicating a systematic bias in the participant's sensory perception or motor output. It is calculated as the difference between the target angle and the reproduced angle, with positive values indicating overestimation and negative values indicating underestimation.

Constant Error (CE) = $|x - t|$ (Equation 1.)

Where x is the produced angle and t is the target angle.

VE assesses the consistency of the participant's responses, reflecting the variability around their mean performance. It is calculated as the standard deviation of the reproduced angles from the mean reproduced angle (10).

Variable Error (VE) = $\sqrt{(\sum (x - M))}^{2}$ (Equation 2.)

Where x is the produced angle and M is the average constant error in one-time point assessment.

The ten repeated measures per participant were averaged and accumulated per time point and intervention for analysis.

Statistical Analysis

All analyses were performed in R software (v4.3.0). Descriptive data for each participant were collected and categorized by group (BFR, sham, and control). Demographic data were analyzed between groups using paired t-tests and one-way Analysis of Variance (ANOVA). The dependent variables (CE and VE) were analyzed using linear mixed-effects models, with group (Control, sham, BFR), time point (pre-intervention, during-intervention, post-intervention), and their interaction as fixed effects, and a random intercept for subjects to account for repeated measures. Baseline JPS values (pre-intervention) were included as part of the repeated measures structure, allowing the model to account for any initial between-group differences. A Type 3 ANOVA was performed on the mixed model to test the significance of the fixed effects. Pairwise contrasts were applied to determine specific differences between time points at each group level. Statistical significance was set at $p < 0.05$.

RESULTS

There were no instances of missing or excluded data across any participant or protocol group.

Analysis of the CE data showed a significant main effect of group ($F[2,27] = 4.81$, p = 0.016) and time point ($F[2,234] = 13.42$, $p < 0.001$), but no significant interaction effect between group and time point ($F[4,234] = 1.81$, p = 0.117) (Figure 4a). Participants in the Control group overshot the target angle significantly more than those in the BFR group (3.91° [95% CI: 1.30°, 6.51°], p = 0.005). However, the differences in CE between the Control and sham groups (2.41° [95% CI: -0.19°, 5.02°], p = 0.068) and between the Sham and BFR groups (1.49° [95% CI: -1.11°, 4.10°], p = 0.250) were not statistically significant (Figure 4a).

INSERT Figure 4

There was a significant main effect of time point ($F[2,81] = 3.15$, p = 0.048) for VE, indicating that the consistency of participants' responses differed across intervention time points. However, there was no significant main effect of group ($F[2,81] = 1.16$, p = 0.319) or significant interaction effects between group and time point (F[4,81] =

0.81, $p = 0.730$) (Figure 4b). VE was significantly lower in the during-intervention JPS assessment compared to pre-intervention (1.08° [95% CI: 0.17°, 2.00°], $p = 0.021$). No significant differences in VE were observed between the pre-intervention and post-intervention assessments (0.87° [95% CI: -0.05°, 1.79°], $p = 0.062$) or between the during-intervention and post-intervention JPS assessments (-0.21° [95% CI: -1.13°, 0.70°], $p = 0.643$) (Figure 4b).

DISCUSSION

This study investigated the effect of an acute bout of BFR on ankle JPS in healthy individuals. Results for accuracy (CE) and precision (VE) showed that BFR did not significantly impair JPS, suggesting that when applied correctly, BFR does not negatively affect proprioception at the ankle joint and therefore the hypothesis was rejected.

Results for CE align with previous research, which found no significant impact of BFR on proprioceptive accuracy at the knee (30). In contrast, other studies have reported negative effects on wrist JPS, suggesting potential joint-specific differences in BFR outcomes (13). This discrepancy may be attributed to variations in anatomical sites, occlusive pressures, and cuff sizes. For instance, while our study applied 80% AOP with a 24-cm wide cuff, other studies have either used a narrow 7-cm cuff without reporting AOP values (30) or did not provide details on cuff size or AOP (13,30). Research has demonstrated that cuff width significantly affects AOP, with narrower cuffs requiring higher pressures for effective occlusion (16). Additionally, while our study occluded the thigh, other studies focused on the upper arm, where arterial proximity to the skin surface may influence AOP. The deeper location of the femoral artery compared to the brachial artery necessitates higher pressures for effective occlusion in the thigh (8,16). These variations in methodology and location of interest underscore the need for standardization in BFR research, possibly by basing BFR pressure on individual AOP to ensure both optimal and safe application (17). Such standardization would enhance the comparability of findings across studies.

Previous research on BFR and JPS has employed active JPS tests (13,30) whereas our study utilized passive tests. Active JPS tests engage muscle spindles and Golgi tendon organs (GTOs) more directly, which could amplify the effects of blood flow restriction, leading to more pronounced differences in JPS outcomes (27). In contrast, passive JPS primarily involves joint capsules and ligaments, which may be less affected by changes in blood flow, possibly explaining the lack of significant alterations in CE under BFR conditions in our study.

Our analysis revealed that BFR did not significantly affect VE, indicating that proprioceptive consistency was maintained under BFR conditions. This finding is consistent with earlier studies that reported no significant differences in VE during knee flexion-extension tasks in populations with type 2 diabetes (5). It is important to consider that VE may be influenced by the focus of attention. Evidence suggests that an external focus, such as awareness of a cuff, can enhance JPS accuracy compared to an internal focus (3). In our study, the presence of the cuff in the sham condition may have provided this external focus, potentially contributing to consistent proprioceptive performance. Conversely, the control group, which lacked this external cue, relied more on an internal focus, yet this did not result in increased variability. The stability of VE across conditions suggests that both external and internal foci can maintain consistent proprioceptive feedback, suggesting that the application of BFR, when carefully managed, does not disrupt proprioceptive consistency.

A potential confounding factor in our study is proprioceptive drift, a phenomenon where perceived limb position gradually shifts over time, particularly when the limb is held at a constant position without visual feedback (24). This drift is evident in the progressively lower CE values observed across all groups from the pre-intervention time point to the intervention and post-intervention time points. While this trend indicates a gradual shift in JPS accuracy, it does not suggest a significant underestimation, as some groups recorded CE values above zero, indicating overestimation. This observed reduction in CE over consecutive time points is consistent with the effects of proprioceptive drift reported in previous research, where prolonged tasks without visual feedback led to inaccuracies in position sense over time (1,24).

Despite the trend in CE, variance VE, which reflects the precision of JPS, remained stable across all conditions. This stability implies that, although JPS accuracy (CE) showed a trend of drifting over time, the precision of proprioceptive performance was not compromised. During BFR, the potential for altered blood flow and sensory feedback might have been expected to exacerbate proprioceptive drift. However, our findings indicate that VE was unaffected, suggesting that JPS precision was maintained even under these conditions. To improve the accuracy of future JPS assessments and mitigate the effects of drift, strategies such as incorporating brief visual cues or repeated proprioceptive feedback during assessments could be employed (26).

The primary limitation of this study is the use of a healthy, young male participant base, which restricts the generalizability of the findings to broader populations, including females and older adults. Research has shown that intrinsic differences in proprioception exist across different ages and sexes, attributed in part to variations in subcutaneous tissue and muscle mass. These physiological differences can influence AOP and occlusion depth during BFR, potentially affecting proprioceptive outcomes (8,18). Future studies should aim to include a more diverse participant pool, encompassing various ages, sexes, and health statuses. Additionally, body composition may influence both the effectiveness of BFR and proprioceptive function. Greater subcutaneous fat thickness, for example, can attenuate mechanical pressure transmission during BFR, potentially reducing the degree of arterial or venous occlusion for a given cuff pressure (16). This may alter the physiological stimulus and associated sensory feedback. From a proprioceptive perspective, higher adiposity may impair joint position sense by dampening cutaneous receptor input and distorting somatosensory cues (25). Therefore, incorporating advanced assessment methods such as skinfold thickness measurements or dual-energy X-ray absorptiometry (DEXA) would allow for more accurate characterization of tissue composition and its moderating effect on both BFR application and proprioceptive acuity. Such measures would enhance the interpretability of BFR studies across individuals with varying morphologies. Another limitation was the use of only one target angle for JPS assessment, which may not fully capture variability in proprioceptive accuracy and could allow for a learning effect. Incorporating multiple target angles, particularly those near the extremes of a participant's ROM, would offer a more comprehensive evaluation of JPS and reduce the likelihood of learning biases (13). Future research should also consider using a range of target angles and more dynamic assessment methods to provide a more nuanced understanding of the effect of BFR on JPS across the full ROM.

This study found that BFR did not significantly affect passive ankle JPS accuracy or precision in healthy young males. The findings suggest that BFR, when applied with proper consideration of cuff size and anatomical differences, may be safe for maintaining normal proprioceptive function. However, the influence of BFR on JPS is complex and affected by factors such as cuff width, occlusion site, proprioceptive drift, and the type of proprioceptive test used. These results highlight the need for standardized BFR protocols that use precise tools, such as Doppler ultrasonography for LOP determination, to ensure reliable outcomes across studies.

PRACTICAL APPLICATIONS

This study highlights that BFR training at 80% limb occlusion pressure does not affect JPS accuracy and precision during plantarflexion, a critical aspect in maintaining joint stability and preventing injury. These findings are particularly relevant for patients recovering from musculoskeletal injuries who need muscle strengthening but cannot perform high-load resistance training. Our results suggest that BFR can be a versatile tool throughout different phases of rehabilitation. In the early stages, BFR can aid in pain reduction and ROM improvement without compromising proprioceptive function in patients with acute ankle injuries. As patients progress, BFR training can enhance muscle endurance and stability, thus supporting a smooth transition to more advanced rehabilitation stages. BFR can be a safer alternative to traditional heavy-load exercises, allowing athletes and individuals with joint pain to maintain and improve muscle mass and strength without increasing the risk of injury. The study's findings that BFR does not adversely affect ankle JPS suggest that it can be used to strengthen muscles while preserving joint stability, thus preventing injuries. BFR is adaptable and can be tailored to meet the specific needs of various populations, including older adults and individuals with chronic conditions. These factors make BFR an excellent addition to personalized rehabilitation and training programs, highlighting its broad applicability and potential to improve outcomes across diverse groups.

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List of Figures:

*Footnote: Point estimate with 95% CI as error bars, overlaid by violin plots of a) constant error and b) variable error. * Indicates statistically significant results.*

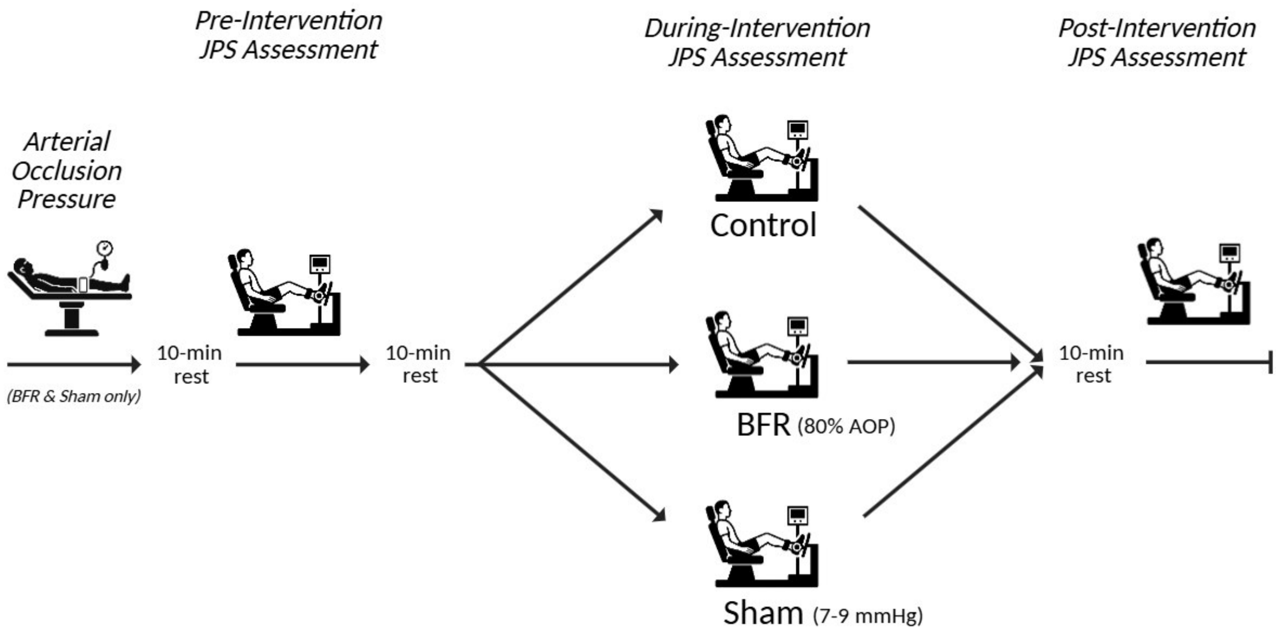
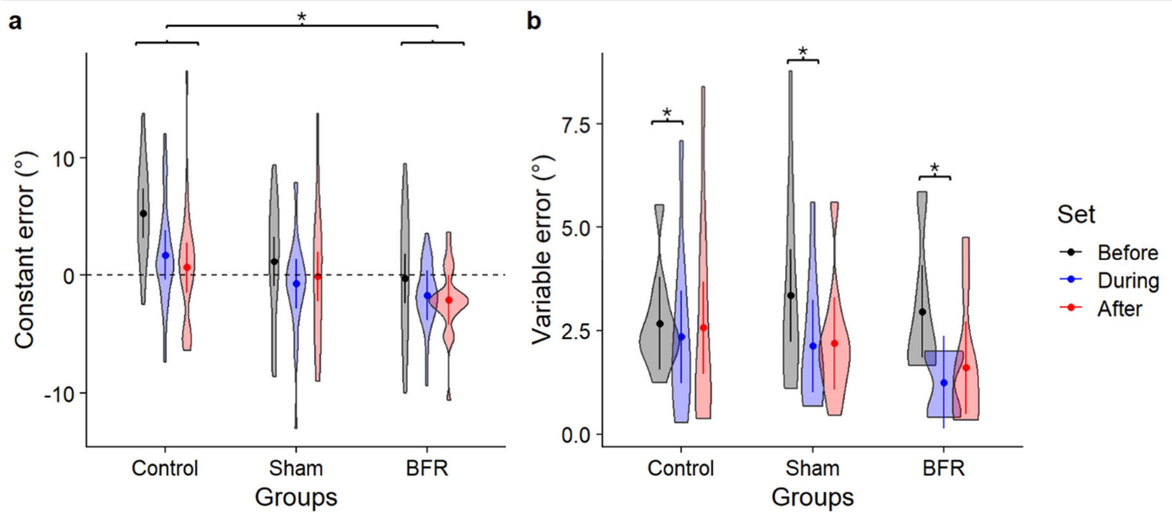


Figure 1. Schematic illustration of the study design.

Figure 2. Pneumatic cuff location during limb occlusion pressure assessment

Figure 3. Isokinetic dynamometer set-up position

Figure 4. Point estimate with 95% CI as error bars, overlaid by violin plots of a) constant error and b) variable error. * Indicates statistically significant results.



*Point estimate with 95% CI as error bars, overlaid by violin plots of a) constant error and b) variable error. * Indicates statistically significant results.*