International Journal of Strength and Conditioning

Montoye, A. H. K., McFate, D. G., Nordbeck, J. T., Bigham, E. A., Cox, B. A., Rider, B. C., & Vranish, J. R. (2024). Variability in Limb Occlusion Pressures Across Visits and Between Limbs in Collegiate Soccer and Cross Country Athletes. International Journal of Strength and Conditioning
https://doi.org/10.47206/ijsc.v4i1.293

Variability in Limb Occlusion Pressures Across Visits and Between Limbs in Collegiate Soccer and Cross Country Athletes

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ABSTRACT

Our study assessed limb occlusion pressure (LOP) variability over time and between limbs. Collegiate athletes (n=42; Sample 1 = 15 soccer players, Sample 2 = 13 cross country runners, Sample 3 = 14 cross country runners) attended five visits separated by ≥48 hours (Sample 1), three visits separated by ~3 weeks each (Sample 2), or four visits separated by ~3 weeks each (Sample 3). For all samples, supine LOP was assessed in each leg (and also in each arm for Sample 3) using an automated system. Paired samples t-tests or RMANOVA were used to compare LOP between limbs and across trials, respectively. Additionally, agreement and variability across measures were assessed using intraclass correlations and mean absolute percent differences (MAPD). There were no significant differences in LOP across visits for any of the samples, with primarily moderate or good agreement (intraclass correlations r=0.29-0.88) and low variability (MAPD 4.3-9.0%). There were no significant differences in LOP between left and right limbs, with moderate to good agreement (r=0.74-0.93) and low variability (MAPD 3.2-7.2%). The demonstrated stability in LOP over time and between sides of the body suggests that LOP may not always need to be measured daily or bilaterally, adding feasibility to field-based implementation.

Keywords: limb occlusion pressure; arterial occlusion pressure; ischemic preconditioning; blood flow restriction; ergogenic aid.

INTRODUCTION

In recent years, there has been keen interest in using blood pressure cuffs, tourniquets, or bands (hereafter collectively referred to as cuffs) placed on the proximal portion of a limb before or during exercise in order to elicit favorable acute responses and/or chronic adaptations to exercise. When employed prior to exercise, use of occlusive cuffs is called ischemic preconditioning (IPC) and is used in order to trigger brief ischemia (low oxygen) followed by acute physiologic responses such as increased systemic hormone release or increased resistance to ischemia and vasodilation at the downstream tissue. Recent reviews have shown IPC to be efficacious in improving certain types of acute exercise performance (Caru et al., 2019; Incognito et al., 2016; Salvador et al., 2016). For IPC, cuffs are typically inflated to pressures at or above an individual's limb occlusion pressure (LOP), which is defined as the minimum pressure to occlude arterial inflow and venous outflow of blood through the occluded limb (O'Brien & Jacobs, 2021). Due to the acute ergogenic effects of IPC, it is appealing for athletes looking to maximize competition

performance (Kilduff et al., 2013).

Cuffs are also used to occlude blood flow during exercise in blood flow restriction (BFR) training. Occluded tissues fatigue quickly and at low absolute workloads with BFR training, and past research has shown that BFR training elicits large neuromuscular and strength/power adaptations to exercise, comparable or possibly superior to non-occlusive training especially when used in rehabilitation settings (Bobes Álvarez et al., 2020; Heitkamp, 2015; Hughes et al., 2017; Patterson et al., 2019). For BFR training, cuffs are most often inflated to sub-occlusive pressures that occlude venous outflow but only partially occlude arterial inflow of blood (Patterson et al., 2019; Pignanelli et al., 2021). BFR training has become a popular modality in rehabilitation settings because it allows individuals to perform exercises with lower strain on joints and ligaments, thereby reducing injury risk while potentially enhancing rehabilitation effectiveness (Wilkinson et al., 2019).

While IPC and BFR differ markedly in their purpose and in the settings and populations in which they are employed, they share a common characteristic in that cuffs need to be inflated to specific pressures relative to LOP to optimally achieve exercise goals (Rider et al., 2022). Therefore, it is important to be able to measure or predict LOP accurately to most effectively utilize IPC and BFR modalities. It is possible to measure LOP using ultrasound techniques (Brekke et al., 2020; Laurentino et al., 2020) or through automated LOP detection programs available with certain cuff brands (Hughes & McEwen, 2021), but such techniques are time-consuming and require expensive equipment. Alternatively, past research demonstrates that LOP can be estimated using regression equations which require variables including limb circumference, blood pressure, and body composition as inputs (Hunt et al., 2016; Loenneke et al., 2015; Montoye et al., 2023; Tafuna'i et al., 2021). Such equations are more feasible but still require physiologic measurements that take time and access to specific equipment and therefore may not be viable options in field-based settings.

Another option when using IPC or BFR training would be to measure an individual's LOP once during a routine laboratory or clinical assessment, ideally in only one limb, and then have the individual use this same LOP in each limb during all ensuing exercise sessions. Such a protocol would dramatically reduce the burden of determining LOP daily, but for it to be useful LOP would have to be stable over time and between limbs. Between-day consistency would allow a single LOP measure to be used across multiple days in a field setting, and between-limb consistency would allow measures in only one side of the body to be taken, lessening subject burden for administering IPC and BFR modalities.

We are aware of only a few studies which have directly evaluated the variability in LOP. When assessing between-leg variability, a study by Tafuna'i et al. (2021) found significantly higher LOP in the dominant leg than the non-dominant leg by an average of 13-21 mmHg, whereas a study by Evin et al. (2021) reported no difference in LOP between the left and right legs (mean differences between legs of 0.4 mmHg on one day and 0.7 mmHg on a second day). There is also a dearth of research evaluating variability in LOP across days. Evin et al. (2021) found no differences in leg LOP between two days spaced approximately 3-10 days apart (mean difference for left leg was 0.2 mmHg, mean difference for right leg was 0.3 mmHg) but referred to this as "small but non-negligible" since, at the individual level, 17% of variation in LOP was explained by the day of testing in their analysis. In another study which evaluated LOP variability in two days spaced a week apart, Hughes et al. (2018) found high between-day consistency in LOP assessment in the dominant leg (intraclass correlations of >0.95, coefficient of variation <3%) across three body positions. In a final study on the topic, Bezerra de Morais et al. (2017) found an intraclass correlation of 0.795 and a coefficient of variation of 5.6% for variability in dominant arm LOP across three days each separated by at least 48 hours. Given the sparse and inconsistent findings of the few studies that have evaluated LOP variability, our study examined variability of LOP across visits and between sides of the body in three distinct collegiate athlete samples.

METHODS

Subjects

Data from these samples were collected as part of three separate IPC interventions, and their use for the purposes of determining LOP variability constitutes a secondary analysis. The initial three studies were designed with sample sizes sufficient to determine statistically significant intervention changes if the effect size of the change was medium or large. Participants in all three studies were recruited via word of mouth and in-person visits by research staff to team practices.

Subjects in Sample 1 were males (n=15) on the roster of a collegiate soccer team. Subjects self-reported being apparently healthy (i.e., no known chronic cardiovascular, respiratory, metabolic, renal disease), were aged 20.5±1.1 years (mean ± standard deviation), 177.8±6.3 cm tall, and weighed 72.3±6.1 kg. Sample 2 subjects were apparently healthy male (n=5) and female (n=8) subjects on the roster of a collegiate cross country team. Sample 2 subjects were aged 19.5±1.1 years, 168.7±12.7 cm tall, and weighed 63.7±8.3 kg. Sample 3 subjects were apparently healthy male (n=3) and female (n=11) subjects on the roster of a second collegiate cross country team. Sample 3 subjects were aged 19.6±1.2 years, were 165.8±8.3 cm tall, and weighed 59.6±6.9 kg. For all three studies, participants had to be current members on their respective teams, could not have a current injury which affected their ability to practice or complete the required elements of the study, and could not have increased risk for injury or blood clotting with the application of blood flow restriction cuffs. Prior to subject recruitment, all study methods were approved by the Alma College Institutional Review Board (Sample 1: IRB# R_2TtaSTU4NaUEYd2; Sample 2: IRB# R_2VrKwENd78z7MHQ; Sample 3: IRB# R_s5ct3y2eYrvkU6Z), and all subjects provided written informed consent to participate.

Procedures

Sample 1 completed five identical visits each performed at least 48 hours apart and conducted within one hour of the same time of day (e.g., 1:00-2:00pm) to minimize potential circadian effects (Millar-Craig et al., 1978). Additionally, subjects refrained from exercise, stimulants (e.g., caffeine), and Calorie-containing food or beverage consumption at least three hours prior to arriving at the laboratory. For each visit, subjects had height and weight taken using a stadiometer (Seca GmbH, Hamburg, Germany) and electronic scale (Tanita, Tokyo, Japan), respectively, in light clothing and without shoes. Then, subjects laid supine on a yoga mat, and their right thigh was fitted with an 11.5 cm contoured cuff connected to a Delfi Personalized Tourniquet System (Delfi Medical Innovations, Inc., Vancouver, BC, Canada). Following 3-5 minutes of supine rest, the "Personalized Tourniquet Pressure" procedure was initiated on the Delfi system, increasing the cuff pressure in 10 mmHg increments every 2-3 seconds while the system automatically checked for blood flow cessation (Masri et al., 2016). The Delfi then reported the LOP for that limb, which was recorded by the research staff. This process was repeated on the left thigh.

Sample 2 completed three identical visits each performed ~3 weeks apart and conducted on a weekday within one hour of the same time of day. Pre-test procedures were the same as for Sample 1. In each visit, subjects first had height and weight taken using the same procedures and equipment as for Sample 1. Then, subjects laid in a supine position on an athletic training table, and their right thigh was fitted with an 11.5 cm contoured cuff connected to a Delfi Personalized Tourniquet System. Following ~5 minutes of supine rest, the "Personalized Tourniquet Pressure" procedure was initiated on the Delfi system, like with Sample 1, to determine LOP. This process was repeated on the left thigh.

Sample 3 completed four identical visits each performed ~3 weeks apart and conducted on a weekday within one hour of the same time of day. Pre-test procedures were the same as for Sample 1. In each visit, subjects first had height and weight taken using the same procedures and equipment as for Sample 1. Next, subjects laid in a supine position on an athletic training table and had blood pressure assessed in the left arm using a Welch Allyn ProBP 3400 (Hillrom, Skaneateles Falls, New York, USA). Then, circumferences were assessed (using a soft tape measure) for each arm at the widest part of the upper arm, followed by thigh circumferences assessed for each limb at the widest part of the thigh. Next, subjects' right thigh was fitted with an 11.5 cm contoured thigh cuff connected to the Delfi Personalized Tourniquet System. Following ~5 minutes of supine rest, the "Personalized Tourniquet Pressure" procedure was initiated on the Delfi system, like with Sample 1, to determine LOP. This process was repeated on the left thigh. Then, a 11.5 cm contoured arm cuff was wrapped proximally around the right arm and connected the Delfi Personalized Tourniquet System, and the same "Personalized Tourniquet Pressure" procedure was conducted to determine LOP. This was then repeated for the left arm, all while the subjects were supine.

Statistical analysis

Statistical analyses were conducted separately for Sample 1, Sample 2, and Sample 3. Due to inherent limitations present when using any single statistical test (for example, sample distribution affecting correlations (Mehta et al., 2018)), we used several statistical methods for interpreting our data. For the between-visit variability of LOP, the average

LOP from the two limbs was compared overall using repeated-measures analysis of variance (RMANOVA; with significance denoted as $p<0.05$) and in pairwise fashion between all pairs of testing days using intraclass correlation coefficients (one-way random, consistency, average options selected) mean absolute differences, and mean absolute percent differences (absolute difference between measures divided by the average of measures). For the between-limb comparison, data from all testing days were averaged for each limb, and pairedsamples t-tests, intraclass correlation coefficients (one-way random, consistency, average options selected), mean absolute differences, and mean absolute percent differences were used to compare LOP in the left and right limbs. Intraclass correlations were interpreted as follows: <0.50 = poor; 0.50-0.75 = moderate; 0.76-0.90 = good; and >0.90 = excellent (Koo & Li, 2016), and mean absolute percent differences were arbitrarily considered low if they were <10% (Nelson et al., 2016). All analyses were performed in SPSS version 28.0 (IBM Corp., Armonk, NY, USA) and Microsoft Excel 2016 (Microsoft Corp, Redmond, WA, USA).

RESULTS

Between-visit variability

For Sample 1, mean LOP was within 7.9 mmHg for the left lower limb and within 6.9 mmHg for the right lower limb across the five visits (Table 1a), and the RMANOVA ($F(4,70) = 0.447$, $p=0.774$) demonstrated no significant differences in LOP across visits (Figure 1a; left portion). Sample 1 had moderate to good intraclass correlations ($r=0.68$-0.86) and low mean absolute percent differences (5.4-7.7%) for all pairwise comparisons across visits (Table 2a). Maximum differences in LOP measures across visits ranged from 32-54 mmHg, but in 50.3% of cases the mean absolute difference in LOP between visits was ≤10 mmHg.

For Sample 2, mean LOP was within 6.5 mmHg for the left lower limb and within 8.9 mmHg for the right lower limb across the three visits (Table 1b), and the RMANOVA ($F(2,36)=1.347$, $p=0.275$) revealed no significant differences in LOP across visits (Figure 1b; left portion). Intraclass correlations were moderate ($r=0.51$-0.65) in two comparisons but poor in one ($r=0.29$); however, mean absolute percent differences were low (7.4-8.8%) in all comparisons (Table 2b). Maximum differences in LOP measures across visits ranged from 28-46 mmHg, but in 43.6% of cases the mean absolute difference in LOP between visits was ≤10 mmHg.

For the Sample 3 lower limb comparison, mean LOP was within 7.8mmHg for the left lower limb and within 5.0 mmHg for the right lower limb across the four visits (Table 1c), and the RMANOVA ($F(3,52)=0.653$, $p=0.586$) revealed no significant differences in LOP across visits (Figure 1c; left portion). Intraclass correlations were moderate to good ($r=0.50$-0.88), and mean absolute percent differences were low (5.3-9.0%) in all comparisons (Table 3). Maximum differences in LOP measures across visits ranged from 35-68 mmHg, but in 54.2% of cases the mean absolute difference in LOP between visits was ≤10 mmHg. Thigh circumferences were not significantly different across the four visits ($F(3,52) = 2.171$, $p=0.107$), with average circumferences ranging from 48.1-50.0 cm for the left thigh and 48.4-49.9 cm for the right thigh.

For the Sample 3 upper limb comparison, mean LOP was within 9.8 mmHg for the left upper limb and within 4.5 mmHg for the right upper limb across visits (Table 1c), and the RMANOVA ($F(3,52)=2.339$, $p=0.088$) revealed no significant differences in LOP across visits (Figure 1d; left portion). Intraclass correlations were good ($r=0.81$-0.88), and mean absolute percent differences were low (4.3-6.9%) in all comparisons (Table 2b). Maximum differences in LOP measures across visits ranged from 23-30 mmHg, but in 60.1% of cases the mean absolute difference in LOP between visits was ≤10 mmHg. Arm circumferences were not significantly different across time points ($F(3,52) = 1.473$, $p=0.237$), with average circumferences ranging from 24.5-25.6 cm for the left arm and 25.0-25.5 cm for the right arm. Moreover, neither systolic nor diastolic blood pressures were significantly different across visits ($F(3,52) = 0.158$, $p=0.924$ for systolic; $F(3,52) = 0.394$, $p=0.758$) diastolic) with systolic blood pressures ranging from 112.6-114.6 mmHg and diastolic blood pressures ranging from 67.7-70.3 mmHg.

Between-limb variability

For Sample 1, mean LOP was within 6.0 mmHg (Table 1a) between limbs; additionally, there were no significant differences in LOP between limbs ($p=0.700$), with mean differences of only 0.4 mmHg (Figure 1a; right portion). Furthermore, there was an excellent intraclass correlation ($r=0.93$) and low mean absolute percent difference (3.2%) when comparing average LOP between the left and right

limbs (Table 2a). The maximum difference between limbs was 32 mmHg, but in 73.3% of measures the mean absolute difference between limbs was ≤10 mmHg.

For Sample 2, mean LOP was within 2.8 mmHg between (Table 1b); additionally, there were no significant difference in mean LOP between limbs (p=0.328), with mean differences of only 1.6 mmHg (Figure 1b; right portion). Furthermore, there was a good intraclass correlation (r=0.89) and low mean absolute percent difference (4.4%) when comparing LOP between the left and right limbs (Table 2b). The maximum difference between limbs was 29 mmHg, but in 66.7% of measures the mean absolute difference between limbs was ≤10 mmHg.

For the Sample 3 lower limb comparison, mean LOP was within 6.0 mmHg between lower limbs (Table 1c); additionally, there were no significant differences in mean LOP between limbs (p=0.318), with mean differences of only 2.1 mmHg (Figure 1c; right portion). Furthermore, there was a moderate intraclass correlation (r=0.74) and low mean absolute percent difference (7.2%) when comparing limbs (Table 2c). The maximum difference between limbs was 46 mmHg, but in 48.2% of measures the mean absolute difference was ≤10 mmHg. Average circumferences for the left (49.4 cm) and right (49.3 cm) thighs were not significantly different from each other (p=0.648).

For the Sample 3 upper limb comparison, mean LOP was within 5.2 mmHg between limbs (Table 1c); additionally, there were no significant differences in mean LOP between limbs (p=0.816), with mean differences of only 0.3 mmHg (Figure 1d; right portion). Furthermore, there was a good intraclass correlation (r=0.87) and low mean absolute difference (5.9%) when comparing limbs (Table 2c). The maximum difference between limbs was 39 mmHg, but in 69.6% of measures the mean absolute difference was ≤10 mmHg. Average circumferences for the left and right arms were significantly different from each other (p=0.035), but with a mean difference of only 0.2 cm (25.1 cm for left arm, 25.3 cm for right arm).

Table 1. Limb occlusion pressure comparison across days and between limbs.

	Day 1	Day 2	Day 3	Day 4	Day 5
a. Sample 1					
Mean LOP in left thigh	181.7 (16.1)	183.7 (18.3)	186.2 (19.4)	184.3 (18.1)	178.3 (15.8)
Range of LOP in left thigh	147-208	143-218	144-219	149-222	150-207
Mean LOP in right thigh	187.7 (19.8)	185.9 (18.1)	183.8 (17.8)	180.8 (16.3)	182.9 (16.2)
Range of LOP in right thigh	144-212	143-215	147-214	144-211	157-215
b. Sample 2					
Mean LOP in left thigh	182.5 (15.6)	176.0 (15.0)	179.5 (14.7)	N/A	N/A
Range of LOP in left thigh	162-207	152-195	148-203	N/A	N/A
Mean LOP in right thigh	185.3 (17.2)	176.2 (14.2)	181.2 (17.3)	N/A	N/A
Range of LOP in right thigh	154-207	158-205	153-208	N/A	N/A
c. Sample 3					
Mean LOP in left thigh	169.2 (17.8)	161.4 (16.9)	161.9 (11.2)	168.2 (10.0)	N/A
Range of LOP in left thigh	137-192	135-189	140-175	151-184	N/A
Mean LOP in right thigh	165.4 (14.8)	167.4 (23.7)	166.9 (19.1)	169.4 (17.7)	N/A
Range of LOP in right thigh	144-190	134-212	144-220	132-189	N/A
Mean LOP in left arm	139.6 (16.0)	133.1 (13.8)	136.0 (15.5)	129.8 (11.2)	N/A
Range of LOP in left arm	117-165	102-151	114-157	113-150	N/A
Mean LOP in right arm	134.4 (18.5)	134.3 (15.1)	136.6 (11.9)	132.1 (12.2)	N/A
Range of LOP in right arm	109-165	115-163	118-155	114-151	N/A

Ranges are shown as minimum-maximum. Other data are shown as mean (standard deviation).
Units for all data are mmHg.
N/A: Not applicable.
LOP: Limb occlusion pressure.

Table 2. Between-day and between-limb variability in limb occlusion pressure.

	Intraclass correlation coefficient	Mean absolute difference (mmHg)	Mean absolute percent difference (%)
a. Sample 1			
Between-day variability			
1 vs. 2	0.81	10.6 (9.3)	5.8 (5.1)
1 vs. 3	0.74	12.8 (10.0)	6.9 (5.5)
1 vs. 4	0.75	11.5 (10.3)	6.4 (5.9)
1 vs. 5	0.69	12.2 (10.6)	6.7 (5.7)
2 vs. 3	0.86	10.5 (7.4)	5.6 (3.9)
2 vs. 4	0.74	14.2 (8.9)	7.7 (4.8)
2 vs. 5	0.68	13.8 (8.2)	7.7 (4.6)
3 vs. 4	0.79	9.9 (9.5)	5.4 (5.2)
3 vs. 5	0.76	11.8 (9.4)	6.5 (5.2)
4 vs. 5	0.78	10.8 (8.8)	6.1 (5.1)
Between-thigh variability			
Left vs. right	0.93	5.9 (6.3)	3.2 (3.3)
b. Sample 2			
Between-day variability			
1 vs. 2	0.65	13.3 (9.0)	7.4 (5.0)
1 vs. 3	0.51	13.5 (11.2)	7.5 (6.3)
2 vs. 3	0.29	15.6 (10.7	8.8 (6.1)
Between-thigh variability			
Left vs. right	0.89	7.7 (5.9)	4.4 (3.4)
c. Sample 3			
Between-day variability			
1 vs. 2 legs	0.60	14.0 (11.6)	8.4 (6.7)
1 vs. 3 legs	0.77	10.8 (6.8)	6.5 (4.0)
1 vs. 4 legs	0.82	9.3 (5.2)	5.6 (3.2)
2 vs. 3 legs	0.88	8.9 (6.4)	5.3 (3.6)
2 vs. 4 legs	0.50	15.1 (9.8)	9.0 (5.8)
3 vs. 4 legs	0.63	10.0 (9.4)	5.9 (5.5)
1 vs. 2 arms	0.88	8.5 (5.5)	6.3 (4.0)
1 vs. 3 arms	0.88	8.0 (5.8)	5.8 (4.4)
1 vs. 4 arms	0.81	9.5 (7.3)	6.9 (5.0)
2 vs. 3 arms	0.86	6.3 (6.3)	5.1 (4.8)
2 vs. 4 arms	0.81	7.8 (6.4)	5.8 (4.6)
3 vs. 4 arms	0.87	5.8 (6.5)	4.3 (4.6)
Between-thigh variability			
Left vs. right	0.74	12.2 (9.3)	7.2 (5.2)
Between-arm variability			
Left vs. right	0.87	7.9 (5.6)	5.9 (4.3)

XX vs. XX: days being compared. For example, 1 vs. 2 is the limb occlusion pressure measured on Day 1 compared to the limb occlusion pressure measured on Day 2.

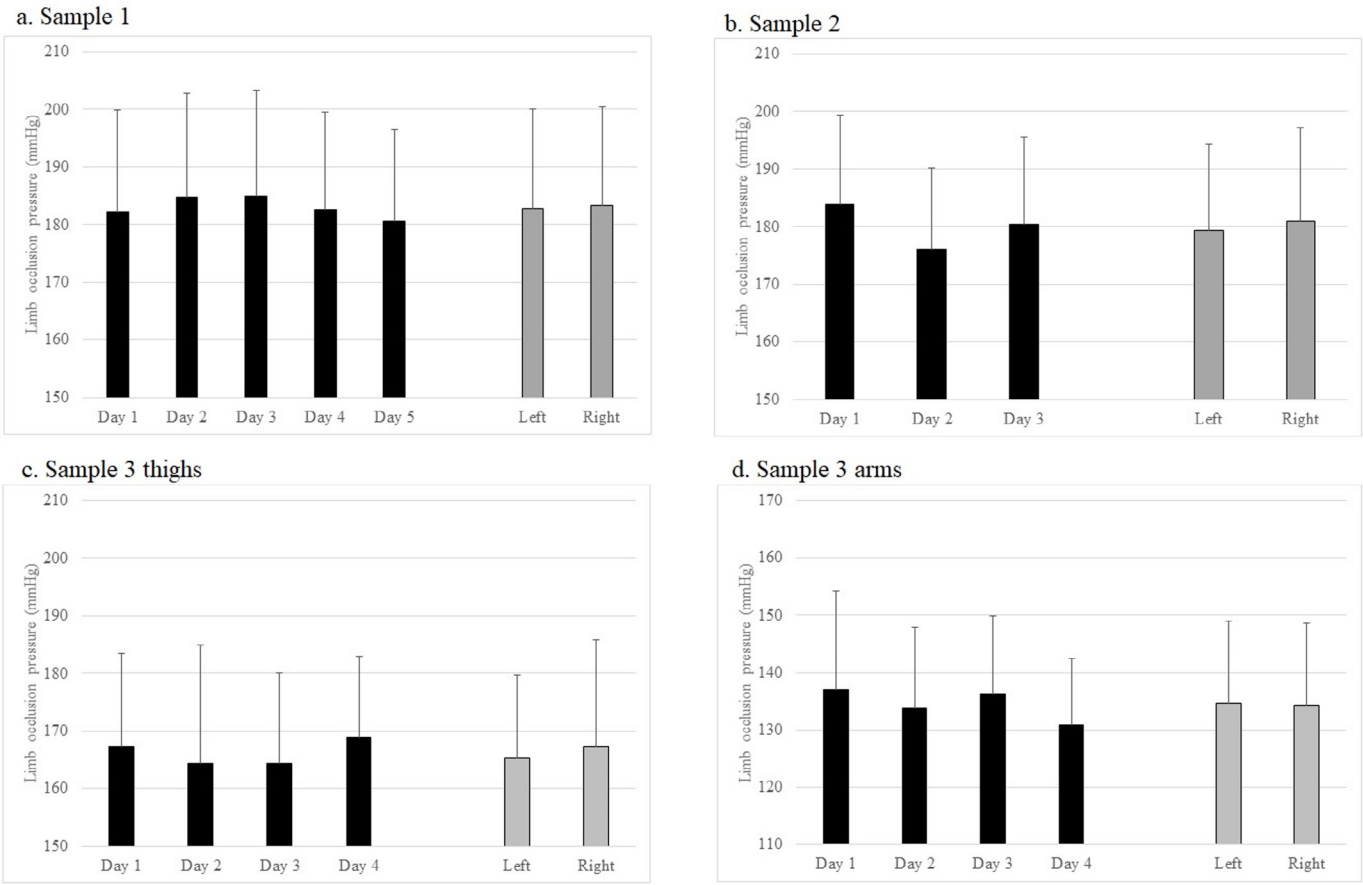

Figure 1. Limb occlusion pressure comparison across days (between-day variability) and between limbs (between-limb variability).

Black bars represent the between-day comparison of limb occlusion pressure, using the average limb occlusion pressure from both thighs.
Grey bars represent the between-limb comparison of limb occlusion pressure, using the average of all five days of data (Sample 1), three days of data (Sample 2), or four days of data (Sample 3).

DISCUSSION

Our study's purpose was to evaluate the variability in LOP over time and between sides of the body, and our rationale was to determine the importance of serial testing of LOP for use in IPC or BFR protocols often performed in training and rehabilitation settings. Across three distinct samples, we found acceptably low between-visit and between-limb variability. Several studies have evaluated between-day LOP variability separated by 2-10 days, all finding high correlations and small differences across days (Bezerra de Morais et al., 2017; Evin et al., 2021; Hughes et al., 2018). Our study expands on these findings by increasing the number of test days to 3-5, evaluating lower and upper limbs, and comparing sessions as many as 63 days apart.

Past research has shown that LOP is influenced primarily by blood pressure, limb circumference, and body composition (Hunt et al., 2016; Loenneke et al., 2015; Montoye et al., 2023; Tafuna'i et al., 2021). While limb circumference and body composition would be unlikely to change much across days, blood pressure levels fluctuate both within a day due to circadian and behavioral patterns (Mancia et al., 1983; Parati et al., 2013) as well as day-to-day (Kikuya et al., 2008). Blood pressure variation is less for healthy individuals compared to those with chronic disease (Chadachan et al., 2018; Parati et al., 2018), so the small day-to-day LOP variability in our samples may be partly attributable to our subjects being young, apparently healthy adults. Additionally, in our Sample 3, both blood pressure and limb circumference changed minimally over the 9 weeks of measurement, providing support for why there was high stability in LOP. Our findings are encouraging as they suggest that, at least in populations similar to those we tested, it may not be necessary to measure LOP daily and, rather, could be done periodically (e.g., once per month) for IPC or BFR modalities. Even for Sample 3, LOP varied minimally over the course of ~9 weeks of in-season training, showing its stability despite overall fitness levels which were

likely improving across the season.

Our study also found good comparability of LOP between the left and right sides of the body, with a mean difference of <1 mmHg across visits for Sample 1, <2 mmHg across visits for Sample 2, and <1 mmHg for the upper limbs and <3 mmHg for the lower limbs across visits for Sample 3. This finding is in contrast to a recent study by Tafuna'i et al. (2021), who found a 21 mmHg higher LOP in the dominant leg than the non-dominant leg in males and a trend in females (13 mmHg higher in dominant leg, p=0.053). This finding was counter to their hypothesis, and they did not have a clear explanation for the difference since thigh circumference, their main determinant of LOP, was not significantly different between legs. Yet, similar to our study, Evin et al. (2021) found no differences between legs when assessing LOP on the same day, with mean differences of <1 mmHg on both days of testing. The conflicting findings in these studies might relate to the populations used or to other factors such as time of day of measurement. Nonetheless, potential differences between left and right sides of the body decrease if pressures below LOP are used, which is especially common in BFR protocols. For example, differences in LOP between lower limbs would require a difference in pressure between left and right sides of only ~6-10 mmHg at 50% of LOP in the study by Tafuna'i et al. (2021) and <3 mmHg for our study and the study by Evin et al. (2021). Therefore, potential variability in LOP is less concerning if lower cuff pressures were being utilized during BFR modalities. However, individual differences may be considerably larger, with Tafuna'i et al. (2021) finding between-limb differences as large as 80 mmHg, Evin et al. (2021) finding between-limb differences exceeding 50 mmHg (estimated using a spaghetti plot in their study), and our study which found differences as large as 68 mmHg. Therefore, at an individual level there are participants who would benefit from LOP assessment in both limbs.

The findings in our study and in past work tend to support the relative stability of LOP between limbs and across days or weeks at the group level. Therefore, when it is difficult, inaccessible, or expensive to assess LOP, periodic assessments may be sufficient for prescribing BFR or IPC protocols in field settings, at least in groups of healthy, younger, and athletic populations like those tested in past research. However, Tafuna'I et al. (2021), Evin et al. (2021), and the present study all found that individual differences could occasionally be much larger than would be suggested when only looking at group means. Additionally, while participants in this and past work likely did not appreciably change in their anthropometric characteristics throughout the study period, in rehabilitation settings individuals may expect/hope for significant changes in limb circumference and/or body composition throughout a rehabilitation program. Additionally, such individuals may have larger day-to-day blood pressure fluctuations due to higher levels of morbidity in clinical settings (Chadachan et al., 2018; Parati et al., 2018). Finally, while most past work including the present study controlled for time of day, in reality exercise training and rehabilitation sessions may happen at different times of day, and LOP may therefore vary more due to between- and within-day fluctuations in blood pressure (Ferreira & Cunha, 2019), stress (Lin et al., 2020), ambient temperature (Wang et al., 2017), and diet/hydration (Nowson et al., 2004). Therefore, in some populations and in ideal conditions it is still likely to be preferable to assess LOP daily and in both sides of the body and, if large differences are present between limbs, to administer day- and side-specific pressures in order to achieve the desired degree of occlusion. Given the diagnostic and prognostic value of inter-arm or inter-leg blood pressure comparisons when assessing cardiovascular conditions such as peripheral artery disease, it may also be good practice to assess LOP daily in both limbs especially in clinical or rehabilitation settings (Chrysant, 2020; Singh et al., 2015).

One notable strength of our study was the comparison of LOP across 3-5 separate visits, under minimally restrictive conditions, and in three distinct samples including both males and females which would increase study generalizability, at least in these athletic populations. Additionally, the long time-courses (~6-9 weeks) for measurements in Sample 2 and Sample 3 provide an idea of stability of LOP measures across a dedicated training period.

Study limitations should also be considered. We did not assess body composition for any sample and did not assess limb circumference or blood pressures for Sample 1 or Sample 2 as our use of the data was a secondary analysis of data collected for other purposes, so we are unable offer a physiologic rationale for the low variability seen in our study. Second, we purposely scheduled visits for a similar time of day and had standardized pre-test instructions to minimize potential circadian or hydration effects on LOP. However, in practice individuals may use IPC and BFR modalities at different times of day, so further research should examine potential LOP variability throughout a single day. Finally, even though we had distinct populations tested in this study, our sample

size for each sample was relatively small and homogenous; as IPC and BFR modalities are used in both athletes and clinical populations, our findings should be confirmed in different population groups.

CONCLUSION

Our study found good stability of LOP measures, with low variability in LOP measures taken across visits and low variability in LOP when compared between the left and right sides of the body. Such high consistency in LOP may allow such assessments to be performed infrequently in clinical or field-based settings when daily and bilateral measures are not possible or are overly burdensome. Such flexibility in LOP assessment may increase the feasibility of IPC and BFR modalities and thereby further increase their use for improving training and rehabilitation effectiveness. That said, individual-level differences suggest that, when possible, it may be desirable to assess LOP bilateral and each day of use in order to best administer IPC, BFR, and other training modalities which rely on LOP-dependent occlusion pressures.

PRACTICAL APPLICATION

Ischemic preconditioning and blood flow restriction are modalities which rely on using cuffs or bands to reduce blood flow to the limbs prior to or during exercise. Cuff pressures set too low are ineffective, while pressures set too high increase discomfort and risk of injury. Previous studies have employed a "one-size-fits all" strategy of applying a standardized occlusion pressure for all athletes (e.g. 220 mmHg) which lacks precision and, thus, is suboptimal for most athletes. Accordingly, it is important for coaches to assess an individual's limb occlusion pressure (the pressure needed to stop blood flow to the downstream tissue) and set cuff pressures at a percentage of limb occlusion pressure in order to get the desired stimulus while minimizing injury and discomfort. However, strategies to accurately measure limb occlusion pressures are expensive and cumbersome, so having the option to assess limb occlusion pressure less frequently may make it more feasible to use especially in field-based settings. Our study found encouraging evidence that limb occlusion pressures were stable for the upper and lower limbs when measured as many as nine weeks apart and not significantly different between limbs in young, apparently healthy collegiate athletes. These findings support that, at least in some populations such as the ones tested in this study, limb occlusion pressures may be measured infrequently since they seem to vary little on a day-to-day or week-to-week basis, and infrequent measures will increase the feasibility of these modalities across a variety of settings and ultimately improve athlete buy-in and adherence. However, when possible, best practices should still advocate for daily, bilateral LOP assessments to most specifically tailor exercise training or rehabilitation strategies to the individual.

ACKNOWLEDGEMENTS

The authors would like to thank Peyton Erndteman and Joshua Lang for their assistance with data collection, and to the athletes and coaches willing to participate in this study. This study was funded by the Alma College Student Research Support Grant. The authors declare that they have no conflicts of interest to report.

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