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**Subject factors influencing blood flow restriction in the arm at low cuff pressures**

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Running Head: FACTORS INFLUENCING BFR  
**ABSTRACT**

**BACKGROUND:** Limb circumference predicts the pressure needed for complete occlusion. However, that relationship is inconsistent at moderate pressures typical of effective blood flow restriction (BFR) training. The purpose of this study was to investigate the influence of subject factors on BFR at low restriction pressures in the arm.

**METHODS:** Fifty subjects had arm anthropometrics assessed by peripheral quantitative computed tomography (pQCT), skin folds (sumSKF) and Gulick tape (GulCirc) at cuff level. Blood flow was measured with ultrasound at baseline and five

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restrictive pressures (20,30,40,50, and 60mmHg). Relationships between subject characteristics and BFR were assessed using Pearson correlations and hierarchical regression.

RESULTS: Blood flow decreased ( $p < 0.05$ ) at each incremental pressure. Regression models including muscle composition (%Muscle), pQCT circumference, and systolic blood pressure (SBP), were significant at all 5 pressures ( $R^2 = 0.18$  to  $0.49$ ). %Muscle explained the most variance at each pressure. Regression models including sumSKF, Gul circ, and SBP, were significant at 30–60mmHg ( $R^2 = 0.28$  to  $0.49$ ). SumSKF explained the most variance at each pressure.

CONCLUSIONS: At low pressures (20–60mmHg), there is considerable variability in the magnitude of BFR across individuals. Arm composition factors (muscle, fat) explained the greatest variance at each cuff pressure, and may be the most important consideration when using BFR protocols.

KEYWORDS: anthropometrics, limb circumference, composition

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## Introduction

Low-load exercise with blood flow restriction (BFR), where proximal limb compression reduces arterial inflow and occludes venous outflow, can produce training responses comparable to those of traditional heavy-load exercise, such as increased muscle mass and strength (Yasuda et al. 2012). The hypoxia and metabolic stress caused by BFR accelerates recruitment of larger motor units and creates a localized environment conducive to muscle growth (Fatela et al. 2019; Moore et al. 2004; Moritani et al. 1992; Takarada et al. 2000). However, individual responses to BFR training can vary widely (Hunt et al. 2016), and one potential explanation for the

variability is that many early studies used the same absolute pressure for each subject. This is problematic considering anthropometrical (e.g. limb circumference, muscle and fat thickness) and physiological factors (e.g. systolic and diastolic pressures, and mean arterial pressure) directly influence the local muscle environment a given restriction pressure causes, and using the same pressures for every subject leads to individuals experiencing different degrees of BFR (%BFR).

More recently, the use of relative arterial occlusion pressure (%AOP) has been widespread as a way to individualize pressures for training (Fatela et al. 2016; Jessee et al. 2016; Loenneke et al. 2015; Mouser et al. 2018). However, when the pressure is reduced to a level used during training, substantial variability in the actual %BFR persists across individuals despite being individualized to subjects' AOP. In the first study that presented brachial blood flow measured during restriction at pressures set relative to AOP, the standard deviations in BFR (percent of baseline) for relative pressures from 10%AOP to 90%AOP had standard deviations ranging from  $\pm 27\%$  to  $\pm 47\%$  (Mouser et al. 2018). This suggests there may be other factors besides circumference that, if identified and accounted for, could further enhance the precision of that approach at the lower training pressures.

Several studies have tried to determine what factors influence BFR by assessing the relationship between anthropometric and physiological variables and the AOP. Limb circumference is consistently listed as the principal factor, with larger limbs requiring greater AOPs (Barnett et al. 2016; Loenneke et al. 2015; Loenneke et al. 2012). Based on these results, it has been suggested that cuff pressures used for BFR training should be selected according to an individual's limb circumference (Jessee et al. 2016; Loenneke et al. 2015; Loenneke et al. 2012). However, total occlusion is not used during effective BFR training, rather moderate pressures are

used to partially restrict blood flow (i.e. occlude venous flow and reduce [not occlude] arterial flow) (Cook et al. 2007; Fahs et al. 2012; Hunt et al. 2016; Kacin and Strazar 2011; Manini and Clark 2009; Takarada et al. 2000; Yasuda et al. 2009). When partial restriction is used instead of total occlusion, the relationship between limb circumference and BFR is inconsistent (Hunt et al. 2016; Karabulut et al. 2014; Karabulut et al. 2011), suggesting the relationships between blood flow and anthropometric and physiological variables at AOPs do not consistently generalize to lower pressures.

The influence of limb composition factors on AOP has been noted, but as a function of muscle thickness and fat thickness together reflecting overall limb circumference (Loenneke et al. 2015). In contrast, individual composition factors (i.e. muscle or fat thickness) usually influence BFR more than circumference at moderate compressive pressures (Hunt et al. 2016; Karabulut et al. 2014; Karabulut et al. 2011). Compared to at considerably higher AOPs, the relationship between limb circumference and BFR at moderate pressures is weak or non-existent (Yasuda et al. 2008). Nonetheless, the relationship between BFR and limb composition factors, such as fat thickness (Hunt et al. 2016; Karabulut et al. 2014) or muscle thickness (Karabulut et al. 2011), remains significant. Thus, it may not be the amount of tissue surrounding the vasculature that primarily determines BFR at moderate or low pressures, but rather the relative amount of each tissue type within that circumference.

Initial cuff tightness (ICT) refers to the relatively low pressures (~30 mmHg) used to quantify the initial compression caused by the cuff before inflation to a final training pressure (Karabulut et al. 2010; Karabulut et al. 2011; Weatherholt et al.

2013; Yasuda et al. 2013). Even though ICTs are only quantifiable with some BFR devices (KAATSU devices), the importance of the restriction provided by the ICT has been shown for both continuous and intermittent BFR training. During continuous BFR, higher ICTs exacerbate the responses to exercise at the training pressure, even though the cuff is inflated to an identical training pressure (Karabulut et al. 2014; Karabulut et al. 2011; Karabulut and Perez 2013). Intermittent BFR training, in which compression is reduced between sets, can remain effective if the residual pressure from the initial tightness maintained during rest periods is sufficient to sustain venous occlusion (Fahs et al. 2012; Hiatt et al. 1989) and curtail arterial inflow enough to limit recovery from increased oxygen availability (Yasuda et al. 2013). Despite the evident importance ICTs, no one has looked at the physiological and morphological factors influencing BFR at these low ICT pressures by themselves.

Differences in the degree of BFR between subjects may cause variance in acute and long-term physiological responses to BFR training. It is a common recommendation that cuff pressures for BFR training be adjusted based on AOP, which is predicted largely by limb circumference. However, studies using partial restriction pressures typical of effective BFR training have generally not supported this recommendation. Additionally, even though it has been shown that relatively low restriction pressures used as ICTs in continuous BFR and between sets of intermittent BFR training are integral to the strength of the training stimulus, the influence of subject characteristics on BFR at low restriction pressures has yet to be investigated. Therefore, the purpose of this study was to investigate the influence of anthropometrical and physiological factors on the degree of BFR at low restriction pressures in the arm.

## Methods

### *Subjects*

Fifty non-hypertensive subjects (29 males, age  $23.4 \pm 3.5$  yrs; 21 females, age  $21.2 \pm 2.1$  yrs) participated in the study. Subjects were instructed to avoid exercise and caffeine ingestion prior to visiting the laboratory. Testing lasted approximately 1.5 hours. The Institutional Review Board approved the study procedures, and each individual provided informed consent before participating.

### *Study Design*

Subjects rested 5 minutes before a resting blood pressure was taken. If a hypertensive blood pressure was taken, subjects sat quietly for 5 more minutes and were reassessed. If hypertension persisted, subjects were excluded from the study. The testing arm (i.e., right or left) was randomly assigned. Subject height and weight were measured with an electronic stadiometer and a digital scale. Next, BFR cuffs were positioned on the proximal arm and the distal border was traced. Based on the marking, peripheral quantitative computed tomography (pQCT) scans were performed at the level of the cuff to assess limb composition and circumference where mechanical compression occurs.

After the pQCT scan, anterior and posterior skinfolds and Gulick tape circumference measurements were performed at the marked cuff location. Subjects then had blood flow measured distal to the cuff at the antecubital space via pulse wave Doppler ultrasound at baseline (no pressure) and five low restriction pressures (20, 30, 40, 50, and 60 mmHg).

### *Cuff Placement*

BFR cuffs were placed proximally on the arm, distal to the deltoid insertion but proximal to the bellies of the biceps and triceps muscles. The bottom border of

the cuff was traced and used as a positioning reference for the pQCT scans, skinfolds, and Gulick tape circumferences.

#### *Peripheral Quantitative Computed Tomography (pQCT)*

Subjects were positioned supine with the shoulder abducted approximately 90° so the pQCT gantry aligned with the cuff location. The arm was supported on either side of the pQCT gantry with the eliminating external compression of the arm near the cuff trace. The distal arm was stabilized with straps to reduce extraneous movement.

pQCT scans were performed using a Stratec XCT 3000 machine (Stratec Medizintechnik GmbH, Pforzheim, Germany) equipped with Stratec software version 6.20 C. A tomographic slice (thickness=2.3mm; voxel size 500 $\mu$ m; scan speed=20mm/s) was taken at the cuff tracing. Tomographic slices were analyzed to determine muscle and fat composition (%Muscle and %Fat), muscle and fat cross-sectional area (mCSA and fCSA, cm<sup>2</sup>), and circumference (pQCT Circ., cm) of the limb. These values were obtained by analyzing the slices using contour mode 1 (threshold= -100 mg/cm<sup>3</sup>) to identify the skin surface and peel mode 2 (threshold= -100 mg/cm<sup>3</sup>) to segregate both fat and muscle/bone, respectively. Bone was subsequently segmented from muscle using cortical mode 1 (threshold = 710 mg/cm<sup>3</sup>). Areas of interest for soft tissue and bone were manually traced by the pQCT technician.

#### *Skinfolds and Gulick tape circumference*

Subjects stood with their arms relaxed at their sides while skinfold measurements were performed with Lange skinfold calipers at the level of the cuff on the anterior and posterior midline surfaces of the arm. Three skin folds were measured at each site (3 anterior and 3 posterior - 6 total for each limb) and averaged.

The average anterior and posterior skinfold measurements were summed for a third skinfold variable. Gulick tape circumference measurements were performed at the same level as the skinfold measurements. All skin folds (anterior skinfold thickness (Ant. SKF), posterior skinfold thickness (Pos. SKF), sum of skinfolds (Sum SKF)) and Gulick circumference (Gulick Circ.) were performed by the same researcher to eliminate inter-rater variability.

#### *Blood Flow Measurement*

Subjects sat upright on a stool, shoulder abducted laterally approximately 45°, forearms rested on a table in front of them at approximately heart level with the limb relaxed. Blood flow (BF) was measured in the brachial artery in the antecubital space with pulse-wave Doppler ultrasound (Esaote MyLab25GOLD; Florence, Italy) at baseline (i.e., no pressure) and at five restriction pressures (i.e., 20, 30, 40, 50, and 60 mmHg). A linear array transducer (LA435; Esaote, Florence, Italy) was used at frequencies between 10–18 MHz. Pulse wave Doppler measurements were taken in the longitudinal view with an angle of correction between  $\pm 60$  degrees. B-mode images of the vessel's diameter (mm) at the end of systole also were captured in longitudinal view.

BF was calculated as diameter flow  $\text{ml} \cdot \text{min}^{-1}$  ( $\text{D-Flow} = \text{Time Average Velocity} * \Pi(\text{D}/2)^2 * 60 \text{ sec}$ ). Doppler waveforms were analyzed to determine time average velocity across 3 heartbeats. Blood vessel diameters were measured from longitudinal view B-mode images of the vessel at the end of systole. All BF analysis (waveform tracing, vessel diameter measurement, and flow calculation) was completed using the proprietary Esaote software (MyLab Desk, Esaote, Florence, Italy). BF test-retest reliability was determined using Shrout-Fleiss reliability method



(Shrout and Fleiss 1979) ( $ICC(3,1) = \text{'\#'}[95\%CI]$ ) at baseline, ICT 20, 30, 40, 50 and 60 mmHg and ranged from 0.97[0.95,0.99] to 0.94[0.90,0.97] for the arm.

### *Blood Flow Restriction*

A 4 cm wide BFR cuff (KAATSU training cuffs, Sato Sports Plaza, Tokyo, Japan) was inflated with a control unit (KAATSU Master), which continuously monitored the cuff pressure. The cuffs were inflated with a small amount of air (i.e. enough to register 10 mmHg in the cuff, uncompressed). The cuff was then placed around the limb and tightened. The cuff pressure displayed on the control unit allowed for quantification of the five pressures.

Before cuff application, baseline BF was measured. The cuff was subsequently positioned on the arm and the restrictive pressures were applied in an increasing ramp fashion. One researcher tightened the BFR cuff until the first restrictive pressure (20 mmHg) registered on the control unit. The pressure was maintained at least 45 seconds before blood flow was measured to allow for stabilization of the blood flow response. Once BF images were captured, the cuff was tightened further until the next pressure was achieved (i.e., 30 mmHg). This was repeated until BFR had been measured at all five restriction pressures.

### *Data Analysis*

Data were analyzed using SPSS 20 for Windows (IBM Corp., Armonk, NY). The degree of blood flow restriction was quantified at each pressure relative to baseline (no cuff). Normal distributions were confirmed with a Shapiro-Wilk test and homogeneity of variance was tested with Mauchley's test of sphericity. Differences in the degree of blood flow restriction at the incremental pressures (20 to 60 mmHg) were determined by a repeated measures ANOVA with Greenhouse-Geisser correction for sphericity violation.

Pearson's correlation was used to determine the relationship between the degree of BFR at each of the pressures and the physiological and anthropometrical variables. Hierarchical linear regressions were then used to determine how much of the variation in the % BFR at each cuff pressure (20, 30, 40, 50, and 60 mmHg) was explained by the physiological and anthropometrical variables. The Pearson's correlations provided a rationale for predictor variable selection and the order of entry into the regression models. Multi-collinearity was defined as a Pearson  $r \geq 0.85$  or a VIF  $\geq 10.0$ . Two regression models were developed for degree of BFR at each of the 5 cuff pressures, one using laboratory measures (pQCT anthropometry) and one using field measures (manual anthropometry). All models consisted of 3 blocks. To minimize multicollinearity, only a single variable for limb composition (%Muscle or sumSKF), limb morphology (pQCT circumference or Gulick circumference), and blood pressure (SBP) were included in each model. The Pearson correlation, semi-partial correlation, and change in  $F$  value were assessed at each block as a new variable was entered into the equation. Study-wise alpha level was set at  $p \leq 0.05$ .

## Results

The general characteristics and specific limb anthropometrics of the subjects are described in Table 1 ( $n = 50$ ; 29 males, 21 females). The average baseline blood flow (mean  $\pm$  SD) in the brachial artery was  $135.76 \pm 74.81 \text{ ml} \cdot \text{min}^{-1}$ . For the 5 restriction pressures, 20 mmHg, 30 mmHg, 40 mmHg, 50 mmHg and 60 mmHg, the average blood flow was  $127.36 \pm 72.70$ ,  $118.13 \pm 71.37$ ,  $108.79 \pm 62.69$ ,  $95.32 \pm 54.66$ , and  $83.92 \pm 50.01 \text{ ml} \cdot \text{min}^{-1}$ , respectively. Expressed relative to baseline (% of baseline), the average blood flow at each pressure was  $93.58 \pm 10.13\%$ ,  $85.04 \pm 15.27\%$ ,  $79.88 \pm 16.63\%$ ,  $70.68 \pm 18.13\%$ , and  $62.48 \pm 20.52\%$  of baseline.

**Insert Table 1 about here**

Blood flow decreased relative to baseline (% of baseline) as the restrictive pressure increased (Figure 1). A repeated measures ANOVA with a Greenhouse-Geisser correction determined that each increase in restrictive pressure resulted in a significant decrease in the average degree of BFR ( $F[2.536, 124.261] = 79.467, p < 0.01$ ). However, across subjects there was substantial individual variability in the degree of blood flow restriction at each cuff pressure (Figure 1).

**Insert Figure 1 about here**

Correlation and multiple regression analyses were conducted to examine the relationship between BFR and the potential physiological and anthropometrical predictors for each of the 5 restriction pressures. The correlation coefficients are summarized in Table 2. For the laboratory measures, mCSA and %Muscle, both had a strong to moderate positive correlation with BFR at each restriction pressure ( $r = .34$  to  $.64, p < 0.05$ , Figure 2a). %Fat, being the direct inverse of %Muscle, also significantly correlated with BFR at each pressure with a strong to moderate negative relationship ( $r = -.35$  to  $-.57, p < 0.05$ ). pQCT circumference was significantly correlated with degree of BFR only at 30 mmHg ( $r = .41, p = 0.003$ ). Although significance was not reached, there was a positive trend between pQCT circumference and degree of BFR at 40 mmHg ( $r = .26, p = .07$ ) and 50 mmHg ( $r = .27, p = 0.06$ ) (Figure 2b). For field measures, there was a moderate correlation between sum of skinfolds and degree of BFR at 30, 40, 50, and 60 mmHg ( $r = .45$  to  $.49, p < 0.05$ ). There was a small to moderate positive correlation between Gulick circumferences and degree of BFR at 30, 40, and 50 mmHg ( $r = .28$  to  $.45, p < 0.05$ ).

**Insert Table 2 here**

**Insert Figure 2 here**

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For the lab measures, the full hierarchical regression models, including muscle composition, circumference, and systolic blood pressure were statistically significant at each pressure ( $R^2$  = ranged from 0.18 to 0.49,  $p < 0.05$ ). The standardized betas and semi-partial correlations ( $\Delta R^2$ ) indicated that muscle composition explained the most variance in the degree of BFR at each restriction pressure. Although the addition of limb circumference as a predictor (model 2) led to an increase in the explained variance at each restriction pressure, only at 30 mmHg was the increase in  $R^2$  of 0.11 statistically significant ( $F[1, 47] = 10.055$ ,  $p = 0.003$ ). The addition of systolic blood pressure (model 3) did not lead to a significant increase in the explained variance in BFR at any pressure.

For the field measures, the full regression models including sum of skinfolds, circumference, and systolic blood pressure were statistically significant at 30 mmHg, 40 mmHg, 50 mmHg, and 60 mmHg ( $R^2$  = ranged from 0.28 to 0.49,  $p < 0.05$ ). None of the models were statistically significant at 20 mmHg. Based on the standardized betas and partial correlation coefficients ( $\Delta R^2$ ), sum of skinfolds explained the most variance in the degree of BFR at each restriction pressure. The addition of circumference as a predictor (model 2) led to an increase in the variance explained at each pressure; however, the increase in  $R^2$  was only significant at 30 mmHg ( $\Delta R^2 = 0.22$ ,  $F[1, 47] = 19.113$ ,  $p < 0.001$ ), 40 mmHg ( $\Delta R^2 = 0.09$ ,  $F[1, 47] = 6.113$ ,  $p = 0.02$ ), and 50 mmHg ( $\Delta R^2 = 0.09$ ,  $F[1, 47] = 6.118$ ,  $p = 0.02$ ). The addition of systolic blood pressure (model 3) did not lead to a significant increase in the explained variance in BFR at any pressure.

## Discussion

The results of this study demonstrate that physiological and morphological characteristics influence the level of BFR attained at low restriction pressures applied

with a narrow cuff (4 cm). We found that composition factors had the greatest impact on BFR. In particular, relative muscle composition (%Muscle) explained the greatest unique variance in BFR for the lab measures and sum of skinfold thickness (SumSKF) explained the greatest unique variance in BFR for the field measures across the restriction pressures. Adding circumference to the lab measure hierarchical regressions with %Muscle explained an additional 2% to 11% of variance in BFR. Adding circumference to the field measure hierarchical regressions with SumSKF explained an additional 5% to 22%. The addition of systolic blood pressure did not significantly increase the variance explained by any model at any pressure. Altogether, these results suggest that greater muscle mass and arm circumference tend to reduce the amount of BFR at low restriction pressures in the arms.

Compared to the strong positive relationship between arm circumference and AOP (Barnett et al. 2016; Loenneke et al. 2015), the influence of arm circumference at low cuff pressure was relatively minor. Although the relationship was much weaker at low pressures, it was similarly positive (i.e. larger arms developed less restriction). Our results support previous findings that have shown circumference to be less influential at partial restriction pressures (Hunt et al. 2016; Karabulut and Perez 2013). It has been posited that limb circumference may be less influential for partial BFR because of local vascular function potentially having a more significant effect at lower pressures (Hunt et al. 2016). Additionally, the different compression characteristics of muscle and fat tissues may be more influential at lower pressures, whereas at high pressures, the differences in tissue compressibility may be negligible.

Although the current results agree with AOP study findings in that a significant positive relationship was found between arm muscle composition factors and BFR (Loenneke et al. 2015), there is an important distinction in the interpretation

of these results. The relationship between muscle thickness and AOP was explained as a function of muscle thickness and fat thickness together reflecting overall limb circumference, which reinforces that circumference, rather than composition, is the most predictive factor. At low pressures, however, we found that the influence of muscle composition was independent of its relationship to overall arm circumference. Despite a strong relationship between mCSA and arm circumference ( $r = 0.761$ ,  $p < 0.001$ ), mCSA accounted for greater variance in BFR at each pressure compared to circumference. Moreover, relative muscle composition (%Muscle), which is unrelated to circumference ( $r = 0.128$ ,  $p = 0.375$ ), accounted for similar variance as mCSA at each pressure. In contrast to the positive relationship between AOP and fat thickness (Loenneke et al. 2015), a negative relationship between BFR and fCSA was found at low restriction pressures in the current study. These results are consistent with those of Hunt et al (2016) who reported a negative relationship between adipose thickness and the cuff pressure needed to achieve a 60% reduction in arterial flow in the arm.

SBP did not account for additional variance in any of the regression models at any pressure, which concurs with previous partial BFR findings (Hunt et al. 2016). AOP studies often report SBP as a significant factor for BFR (Barnett et al. 2016; Loenneke et al. 2015), however, it appears that other factors are responsible for the variance in blood flow response when lower cuff pressures are applied. For instance, it was reported the DBP as a significant factor for partial BFR in the upper body (Hunt et al. 2016), but no such relationship was found in the present study with low pressures. No other blood pressure variables had a stronger relationship to BFR than SBP and thus no others were entered into the hierarchical regressions. It should be noted that previous studies have reported larger ranges of blood pressure than the current study (Barnett et al. 2016; Loenneke et al. 2015). It is possible that the

narrower blood pressure range truncated the strength of the relationships between BFR and the blood pressure variables.

Intermittent BFR training reportedly offers the benefits of continuous BFR training with increased tolerability, but not all studies have found intermittent BFR to be similarly effective (Burgomaster et al. 2003; Cook et al. 2007; Loenneke et al. 2010; Suga et al. 2012). However, many investigations of intermittent BFR completely removed compression during the rest periods, thus enabling unrestricted tissue perfusion. It seems that an approximate 30% reduction in arterial flow during intermittent BFR rest periods sufficiently maintains the BFR stimulus, causing fatigue levels similar to continuous BFR (Yasuda et al. 2013). The pressures used in the present study are comparable to those reported for inter-set rest periods of effective intermittent BFR training (i.e. ~30 mmHg). Since the relatively low inter-set pressures are sufficient for venous occlusion (Fahs et al. 2012; Takarada et al. 2000), it is the increased arterial inflow of oxygenated blood that dictates the extent of recovery between sets (Yasuda et al. 2013). Our study has shown that relative limb composition and circumference impact the degree of arterial restriction caused by pressures similar to those employed during intermittent BFR rest periods. Thus, limb composition and circumference should be considered when inter-set pressures are selected.

These findings could have importance for continuous BFR training as well. The ICT with which a restriction cuff is applied can dramatically alter the intensity of the BFR stimulus created by the subsequent inflation pressure. Even with the same final inflation pressure, differences in the ICT before inflation leads to differences in tissue deoxygenation (Karabulut et al. 2014; Karabulut et al. 2011), muscular activity (Karabulut and Perez 2013), and fatigue levels (Karabulut et al. 2014; Karabulut and

Perez 2013). The present study has provided evidence that the pressure from the ICT alone generates a different relative BFR across individuals. Thus, before the cuff is inflated to higher restriction pressures, there are already differences in the relative BFR each individual experiences. If some individuals experience greater BFR than others in response to a particular ICT, it can be expected that the discrepancies at the ICT will persist and potentially be exacerbated with inflation to higher cuff pressures. For instance, Karabulut et al. (2011) found pressures up to 220mmHg on the thigh were tolerated with no complications when cuffs were initially tightened to 30 mmHg or 50 mmHg. However, when initial tightness was 70mmHg, only one out of six individuals could tolerate inflation pressures greater than 180mmHg. If the goal is to ensure an equally potent and tolerable BFR stimulus for individuals with varying limb size and composition, it may be necessary to first apply cuffs with a sufficient ICT that all individuals start with a comparable degree of BFR before inflating the cuffs to even higher restriction pressures.

There were a few individuals with high muscle composition who demonstrated an increase in arterial flow at the low restriction pressures. Even though no contractions were performed, the exercise-pressor reflex may explain this observation. Lactate is believed to play a significant role in evoking the metaboreceptor mediated portion of the pressor response (Kaufman and Hayes 2002) and Takarada et al (2000) have shown that at rest, a cuff pressure of 50mmHg can cause lactate accumulation up to twice normal resting concentrations. Since venous pooling occurs at very low pressures, and was indeed observed in our study while measuring arterial flow, the pressures in our study may have been sufficient to evoke a pressor response while simultaneously providing insufficient compression to reduce arterial flow with the increase in arterial pressure and heart rate from the pressor



reflex. It was noted that the individuals who had increased blood flow across all the pressures were highly strength trained with significant muscle mass. Therefore, they may have had an elevated sensitivity to metabolic stimuli and a more robust metaboreceptor mediated pressor-response compared to those who were less frequently exposed to local muscle ischemia and metabolic stress.

To our knowledge, this is the first investigation of factors that influence BFR at low restriction pressures in the arm. The results of this study demonstrate that there is substantial variability in the degree of blood flow restriction across individuals at low restriction pressures like those used as ICTs for BFR training. The results also suggest that arm composition factors have a greater influence on the degree of blood flow restriction at low pressures compared to arm circumference. Future studies should investigate if limb composition differences explain remaining variance in BFR at %AOPs, particularly for subjects with similar limb circumferences, but disparate composite profiles. These measures were taken at rest, so there could be additional variation due to exercise-mediated effects even at the low pressures. Future studies should investigate how the exercise response influences the BFR achieved with low pressures like those used in rest periods with intermittent BFR training.

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There are no conflicts of Interest

DA statement: The data that support the findings of this study are available from the corresponding author, ZAR, upon reasonable request.

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## TABLES

**Table I.** Participant descriptive statistics

General subject characteristics		
Age (years)	22.5 ± 3.2	(15.0)
Height (cm)	173.5 ± 9.0	(38.3)
Weight (kg)	81.1 ± 19.24	(85.0)
BMI	26.7 ± 4.9	(18.4)
SBP (mmHg)	120.4 ± 7.9	(36.0)
DBP (mmHg)	76.1 ± 8.6	(30.0)
Arm anthropometrics		
Lab Measures		
pQCT Circ (cm)	33.8 ± 5.0	(19.0)
mCSA (cm <sup>2</sup> )	57.9 ± 24.6	(92.1)
fCSA (cm <sup>2</sup> )	29.7 ± 18.4	(86.0)
%Muscle (%)	61.7 ± 16.5	(62.4)
%Fat (%)	32.3 ± 16.8	(64.4)
Field Measures		
antSKF (mm)	10.1 ± 6.0	(26.3)
posSKF (mm)	16.0 ± 7.3	(28.3)
sumSKF (mm)	26.1 ± 12.9	(54.7)
Gul Circ (cm)	33.9 ± 5.3	(19.1)

*Notes:* Values are mean ± SD and (range).

*BMI* body mass index, *SBP* systolic blood pressure, *DBP* diastolic blood pressure, *mCSA* muscle cross-sectional area, *fCSA* fat cross-sectional area, *%Muscle* percent muscle composition, *%Fat* percent fat composition, *pQCT Circ* pQCT circumference, *antSKF* anterior skinfold thickness, *posSKF* posterior skinfold thickness, *sumSKF* sum of skinfold thickness, *Gul Circ* Gulick tape circumference

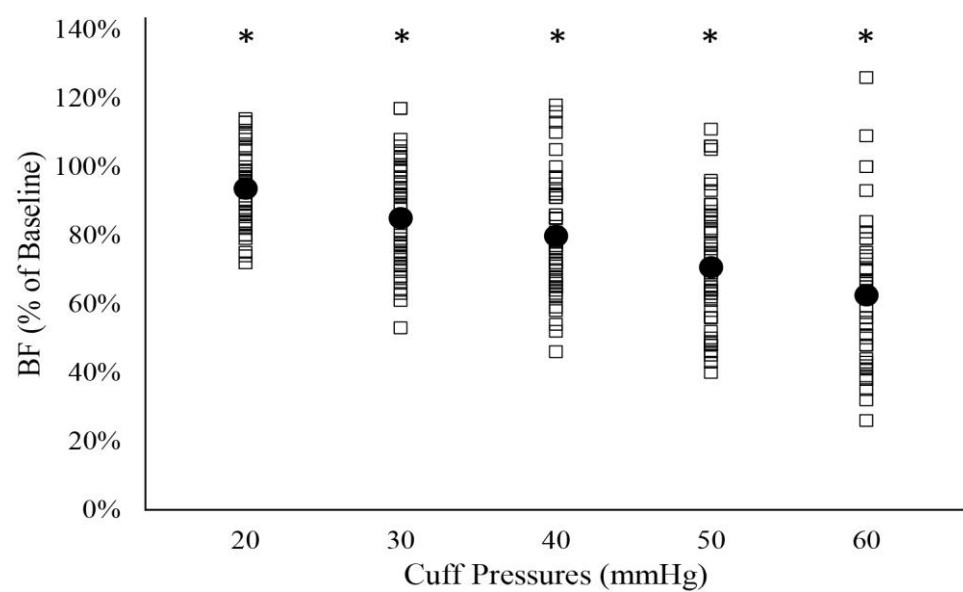
**Table 2.** Pearson correlations between arm anthropometric variables and blood flow restriction at each restriction pressure

	20	30	40	50	60
Variable	mmHg	mmHg	mmHg	mmHg	mmHg
%Muscle	0.37*	0.60*	0.56*	0.52*	0.50*
%Fat	-0.35*	-0.57*	-0.54*	-0.50*	-0.48*
pQCT circ	0.18	0.41*	0.26	0.27	0.22
mCSA	0.34*	0.64*	0.53*	0.52*	0.46*
fCSA	-0.19	-0.29*	-0.36*	-0.33*	-0.33*
sumSKF	-0.24	-0.49*	-0.48*	-0.47*	-0.45*
Gulick circ	.22	0.45*	0.28*	0.28*	0.24
SBP	0.25	0.34*	0.21	0.21	0.22
DBP	-0.18	0.03	0.07	0.12	0.12

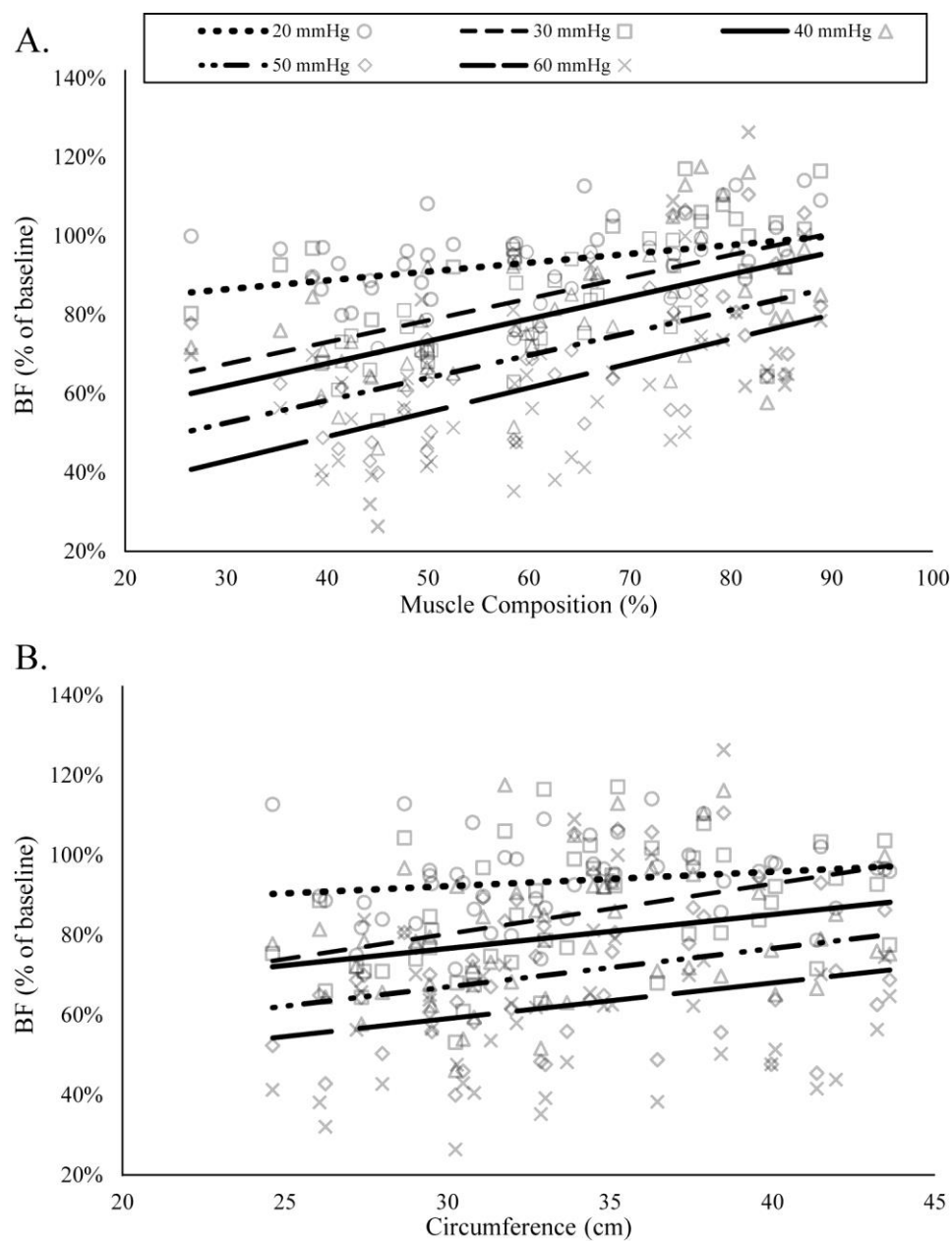
Notes: \*Significant Pearson correlation ( $p < 0.05$ )

%Muscle percent muscle composition, %Fat percent fat composition,  
 pQCT Circ pQCT circumference, mCSA muscle cross-sectional area, fCSA  
 fat cross-sectional area, sumSKF sum of skinfold thickness, Gul Circ  
 Gulick tape circumference, SBP systolic blood pressure, DBP diastolic  
 blood pressure

**Figure 1.**



**Figure 2.**





## FIGURES CAPTIONS

**Figure 1.**— Level of blood flow restriction at each pressure. Blood flow values are expressed as a percent of baseline blood flow. Each white square represents a subject at each pressure. Black circles indicate mean at each pressure.

\* Significant difference from all other pressures ( $p < 0.05$ )

**Figure 2.**— Relationship between blood flow restriction (% baseline) and (A) arm muscle composition and (B) arm pQCT circumference at restriction pressures 20 mmHg, 30 mmHg, 40 mmHg, 50 mmHg, and 60 mmHg.