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ORIGINAL RESEARCH ARTICLE

The Influence of Cuff Width, Sex, and Race on Arterial Occlusion: Implications for Blood Flow Restriction Research

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Abstract

Purpose The main aim of this study was to examine differences in upper arm arterial occlusion pressure (AOP) between three different cuff widths and how individual characteristics influence this. Additional aims of the study were to investigate differences in AOP due to sex and race and to create regression equations that estimate AOP for each cuff width.

Methods Two hundred and forty nine participants (males $n = 102$; females $n = 147$) visited the laboratory once for measurement of arm length, arm circumference, and resting brachial systolic (bSBP) and diastolic blood pressure (bDBP). Next, each cuff was applied to the upper arm and inflated until a Doppler probe placed at the radial artery no longer detected blood flow. The minimum inflation pressure that caused cessation of blood flow was determined to be the AOP.

Results Differences in AOP were observed between cuff widths ($p < 0.001$). The 5-cm-wide cuff required the greatest inflation pressure [145 (19) mmHg], followed by the 10 cm [123 (13) mmHg], and 12-cm-wide cuff [120 (12) mmHg]. A model encompassing arm circumference, bSBP, arm length, bDBP, and sex explained the most variance in AOP for each cuff (5 cm, $R^2 = 0.651$; 10 cm, $R^2 = 0.570$; 12 cm, $R^2 = 0.557$). However, arm circumference explained the most unique variance for each cuff. When separated by sex, males required greater pressures. Additionally, after controlling for sex, it was found that non-Hispanic Blacks required greater pressures compared with Whites. The regression equations for each cuff width are as follows: 5 cm (mmHg) = 2.926 (arm circumference) + 1.002 (bSBP) − 0.428 (arm length) + 0.213 (bDBP) + 12.668 (sex) − 68.493; 10 cm (mmHg) = 1.545 (arm circumference) + 0.722 (bSBP) − 0.235 (arm length) + 0.205 (bDBP) + 6.378 (sex) − 15.918; 12 cm (mmHg) = 1.393 (arm circumference) + 0.710 (bSBP) − 0.294 (arm length) + 0.164 (bDBP) + 6.419 (sex) − 8.752.

Conclusions The AOP is dependent upon cuff width, highlighting the need for authors to report cuff width and consider the impact it has on restriction. Participant characteristics, especially arm circumference, should be considered when applying this blood flow restriction pressure. Lastly, both sex and race have an impact on AOP, although it is not presently known how meaningful this difference is.

Key Points

An inverse relationship exists between cuff width and arterial occlusion pressure in the upper body.

Limb circumference explains the most unique variance in arterial occlusion pressure for each cuff width.

Restriction pressures should be made relative to the cuff being used and to the individual.

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1 Introduction

Blood flow restriction (BFR) in combination with low-load resistance exercise increases muscle mass and strength similar to that observed following high-load resistance training [1–3]. Thus, for populations contraindicated to high-load training, exercise in combination with BFR may provide a safe [4, 5] alternative stimulus to improve strength and muscle mass. Currently, no optimal cuff width/pressure combination has been established for BFR; therefore, no standard exists regarding the application of BFR. As such, potential issues arise in finding an optimal restriction pressure due to the numerous different cuff widths and pressures used (Table 1) for training the upper body. In order to ensure participants are receiving a similar stimulus, it has been suggested that BFR be applied as a relative percentage of arterial occlusion pressure (AOP). Thus, it is important to examine the determinants of AOP for BFR.

Applying a wide cuff to the lower body results in a lower AOP compared with a narrow cuff [6]. This relationship between cuff width and AOP has also been investigated in the upper body; however, these were with small (average $n = 11$) sample sizes [7, 8]. In addition to cuff width, individual differences should be accounted for to make the BFR pressure as relative as possible. Brachial systolic (bSBP) and diastolic blood pressure (bDBP) explain some unique variance in AOP, albeit a small portion in comparison with arm circumference, which is the largest predictor of AOP when applying a 5-cm-wide cuff [9]. Previous studies that have used multiple cuffs in the upper body to investigate individual differences were done with small samples and potentially had too many predictors for the sample size used [8]; therefore, it is not yet known how predictors change across cuff widths. Additionally, no study has been designed to investigate differences in AOP due to race or sex (although potential sex differences have been investigated retrospectively by Loenneke et al. [9]). There is a need to study potential racial differences given the prevalence of hypertension in non-Hispanic Blacks [10] and previous relationships established between blood pressure and AOP [9]. Furthermore, previous studies were conducted with participants in the supine position, which is not reflective of many studies completed with upper body BFR exercise [11]; therefore, there is a need to examine AOP in the standing position.

Table 1 Summary of recently published blood flow restriction (BFR) studies in the upper body

Study	Cuff width (cm)	Final pressure (mmHg)
Acute studies		
Barnett et al. (2015) [21]	5	40 % AOP
Brandner et al. (2014) [24]	10.5	80 % SBP/130 % SBP
Counts et al. (2015) [11]	5	40–90 % AOP
Dorneles et al. (2015) [25]	14.5	SBP − 20
Garten et al. (2015) [26]	Unreported	SBP − 20
Maior et al. (2015) [27]	14	SBP − 20
Neto et al. (2015) [28]	6	80 % AOP
Thiebaud et al. (2014) [29]	3.3	120
Vieira et al. (2014) [30]	Unreported	110
Yasuda et al. (2014) [31]	3	160
Chronic studies		
Counts et al. (2015) [11]	5	40–90 % AOP
Farup et al. (2015) [32]	8	100
Luebbers et al. (2014) [33]	7.6	Unknown
Lowery et al. (2014) [34]	Unreported	Unknown
Yasuda et al. (2015) [35]	3	160–270

No study investigating AOP in the upper body has been done using multiple cuff widths applied to a large sample of men and women in the standing position. In addition, it has not been shown how race or sex affect AOP, or how the unique variance due to individual differences changes across cuff widths. Thus, the purposes of this study were as follows: (1) to examine differences in AOP of a large sample when applying three common cuff widths to the upper body while standing; (2) to determine the individual differences explaining the most unique variance in AOP for each cuff width; (3) to examine the effect sex and race differences have on AOP; and (4) to create regression equations for arterial occlusion using each cuff width. Based upon previous relationships found in the lower body, we hypothesized that wider cuffs would result in a lower AOP. Additionally, we hypothesized that limb circumference would explain the most unique variance in AOP regardless of the cuff width applied.

2 Methods

2.1 Participants

A total of 249 participants (males $n = 102$; females $n = 147$) took part in a study designed to determine AOP for cuffs varying in width. Participants were excluded if they were outside the age range of 18–35 years old, were currently taking medication for hypertension, had ingested food within 2 h, or had taken caffeine within 8 h of testing. Participants were also informed of all procedures and any potential risks of the study before giving informed consent. The University's Institutional Review Board approved the protocol and the procedures followed were in accordance with the Helsinki Declaration of 1975, as revised in 2013.

2.2 Experimental Design

Upon arriving at the laboratory, participants filled out paperwork then had their height and body mass measured. Upper arm length and limb circumference were then measured. Participants were asked to rest quietly in the seated position for 10 min. Blood pressure was measured at least twice on the right arm using the cuff size recommended by the manufacturer. After resting for 5 min in the seated position, participants were asked to stand slowly; a cuff was placed on the upper arm (in the relaxed position at the participants side), and inflated until the pulse at the radial artery was no longer detected (using a Doppler probe). This inflation pressure was determined to be the arterial occlusion pressure (AOP) and the cuff was deflated and removed. This process was repeated for each cuff width with 5 min of rest between each of the three cuff widths.

2.3 Height and Body Mass

Participants were instructed to remove any bulky clothing, hats, shoes, and heavy items from pockets in order to obtain an accurate measure of height and body mass. Participants were asked to stand up straight while standing height was measured to the nearest 0.1 cm using a stadiometer. Body mass was measured to the nearest 0.1 kg using a digital scale.

2.4 Blood Pressure

Brachial systolic and diastolic blood pressures were measured using an automated blood pressure machine (Omron #HEM-907XL) by applying the appropriate, manufacturer-recommended cuff size (based upon limb circumference) to the right arm while participants were in the seated position. At least two measurements were taken. If the measurements differed by more than 5 mmHg (systolic or diastolic), subsequent measures were taken. The first two measurements within 5 mmHg were averaged and recorded as average blood pressure.

2.5 Limb Anthropometry

Using a body tape measure, upper limb length was measured on the right arm by recording the distance from the acromion process to the lateral epicondyle of the humerus. Arm circumference was measured at 50 % of the upper arm length because this is the approximate location of cuff application, and the specific site has been used in previous research regarding AOP [9].

2.6 Arterial Occlusion Pressure

Arterial occlusion pressure for each cuff size was determined in the standing position. A cuff was secured on the proximal portion of the right arm and connected to a rapid cuff inflator (E20, Hokanson Bellevue, WA, USA). A bidirectional Doppler probe (Hokanson, Bellevue, WA, USA) was held in place at the radial artery of the right wrist to detect blood flow. Once the Doppler probe was able to clearly detect a pulse, the cuff was inflated to 50 mmHg. The inflation pressure was slowly increased until there was no detectable pulse. This inflation pressure was then recorded to the nearest mmHg and determined to be the AOP for the particular cuff in question. Immediately following the determination of AOP, the cuff was deflated and removed. The participant was then instructed to sit back down and rest quietly for 5 min. Following the same protocol as for the first cuff width, AOP was determined for cuff widths 2 and 3 with 5 min of seated rest in between measurements. The 5-cm (SC-5; Hokanson, Bellevue, WA, USA), 10-cm (SC-10; Hokanson, Bellevue, WA, USA), and 12-cm (SC-12; Hokanson, Bellevue, WA, USA) cuffs were applied in a counterbalanced manner in an attempt to eliminate any procedural bias. The 5-cm- [11], 10-cm- [12], and 12-cm-wide cuffs [13] have all been used previously in the BFR literature.

2.7 Statistical Analyses

A one-way repeated measures ANOVA was used to determine differences in AOP between cuff widths. A post-hoc test was used to determine where the differences were amongst cuffs. Hierarchical linear regression was used to determine which variables best predicted AOP for each cuff. Predictors were entered into the model in blocks starting with Block 1, which consisted of arm circumference and bSBP. Block 2 added in arm length and bDBP. The final block, Block 3, added in sex. Changes in Pearson correlation, part correlation coefficient, R^2, standard error of the estimate (SEE), and the change in F value were determined for each block. Variance inflation factor and Pearson correlations were used to determine the degree of multi-collinearity of the ith independent variable with other independent variables for all hierarchical regression models. Multi-collinearity between variables was defined as a VIF $\geq$10 and/or Pearson correlations of 0.85 or greater. To determine the predictive accuracy of our formulas, we randomly split 66 % of our sample and created new formulas. We then applied the new formula to the cross-validation group and determined differences between the actual and predicted using a paired sample t test. In addition, the average deviation of individual scores from the line of identity was calculated to determine the total of error for each comparison.

To further determine sex differences in AOP across cuff widths, a repeated measures ANOVA with a between-subject factor of sex was used. If there was an interaction, a one-way ANOVA was used to identify differences between cuff widths within each sex and independent sample *t* tests were used to identify differences for sex within each cuff width. To identify if differences existed between non-Hispanic Blacks and Whites, a repeated measures ANOVA with a between-subject factor of race was used, co-varying out the influence of sex. If there was an interaction, a one-way ANOVA was used to identify differences between cuff widths within each race co-varying out the influence of sex. To identify differences for race within each cuff width, an ANOVA was used with a fixed factor of race, co-varying out the influence of sex. Cohen's d was used to determine the magnitude of any difference found. Data was analyzed using SPSS statistical software package version 19.0 (SPSS Inc., Chicago, IL, USA). Significance was set at $p \leq 0.05$ for all statistical tests.

Table 2 Total participant characteristics ($N = 249$)

Variable	Mean (SD)	Minimum	Maximum
Age (years)	21 (2)	18	34
Height (cm)	170.5 (9.8)	146	200
Body mass (kg)	74.4 (16.2)	45	141
Arm circ (cm)	32.7 (4.8)	22	47
Arm length (cm)	33.2 (2.7)	23	41
bSBP (mmHg)	110 (10)	89	148
bDBP (mmHg)	65 (8)	48	105
AOP 5 cm (mmHg)	145 (19)	108	239
AOP 10 cm (mmHg)	123 (13)	95	175
AOP 12 cm (mmHg)	120 (12)	92	166

AOP arterial occlusion pressure, *Arm circ* arm circumference, *bDBP* brachial diastolic blood pressure, *bSBP* brachial systolic blood pressure

3 Results

Participant characteristics ($n = 249$) for the total sample are presented in Table 2. When further separated by sex, the largest differences between males and females, as determined by Cohen's $d > 1.00$, were height, body mass, arm circumference, and arm length (Table 3).

Significant differences were observed between cuff width and AOP (Table 2; $p < 0.001$) with arterial occlusion pressure decreasing as the cuff became wider. This was also true when separated by sex (Table 3). In addition, there were significant differences in AOP between sexes for the 5 cm ($p = 0.003$), 10 cm ($p = 0.002$), and 12 cm ($p = 0.009$) cuff widths, with pressures always being higher in men. Despite this, the magnitude of the sex difference was not large for either the 5-cm- ($d = 0.36$), 10-cm- ($d = 0.46$), or 12-cm-wide ($d = 0.33$) cuff. When separated by race, non-Hispanic Blacks ($n = 59$; 22 males and 37 females) had higher AOP than Whites ($n = 173$; 73 males and 100 females) for the 5 cm [154 (18) vs 142 (18) mmHg, $p < 0.001$], 10 cm [131 (13) vs 121 (13) mmHg, $p < 0.001$], and 12 cm cuffs [126 (12) vs 118 (12) mmHg, $p < 0.001$]. Within each race, there were similar differences between cuff widths, with 5 cm having the highest AOP and 12 cm having the lowest AOP ($p < 0.001$). The magnitude of the race difference was $d = 0.66$, $d = 0.76$, and $d = 0.66$ for the 5-, 10-, and 12-cm-wide cuffs, respectively.

The hierarchical linear regression models for the 5-, 10-, and 12-cm-wide cuffs can be found in Tables 4, 5, and 6. Block 3, which consisted of arm circumference, bSBP, arm length, bDBP, and sex, explained the most variance for each cuff width. According to part correlation coefficients, arm circumference and bSBP always explained the most unique variance in AOP (Tables 4, 5, and 6). None of the variables met the criteria for multi-collinearity. The respective formulas for each cuff width are as follows:

Table 3 Participant characteristics: male ($n = 102$) and female ($n = 147$)

Variable	Male			Female			Cohen's *D*
	Mean (SD)	Min	Max	Mean (SD)	Min	Max	
Age (years)	22 (3)	18	34	21 (2)*	18	34	0.40
Height (cm)	179.4 (7.0)	164	200	164.3 (6.4)*	146	184	2.27
Body mass (kg)	84.9 (14.9)	62	141	67.1 (12.7)*	45	121	1.30
Arm circ (cm)	35.8 (3.9)	28	47	30.5 (4.1)*	22	47	1.31
Arm length (cm)	35.3 (2.1)	30	41	31.8 (2)*	23	36	1.71
bSBP (mmHg)	114 (9)	91	148	107 (9)*	89	136	0.7
bDBP (mmHg)	65 (8)	48	85	66 (9)	48	105	−0.11
AOP 5 cm (mmHg)	149 (19)	113	239	142 (19)*	108	229	0.36
AOP 10 cm (mmHg)	127 (13)	102	175	121 (13)*	95	166	0.46
AOP 12 cm (mmHg)	122 (12)	95	166	118 (12)*	92	155	0.33

Table 4 Model for 5-cm-wide cuff

	Stand. β	p value	Part	Mean square error	Sig. F change
Block 1					
Arm circumference	0.528	<0.001	0.527		
bSBP	0.481	<0.001	0.480		
	R	R^2	*SEE*		
	0.741	0.550	13.3	178.3	<0.001
Block 2					
Arm circumference	0.605	<0.001	0.519		
bSBP	0.390	<0.001	0.297		
Upper arm length	−0.184	<0.001	−0.153		
bDBP	0.216	<0.001	0.169		
	R	R^2	*SEE*		
	0.782	0.611	12.4	155.2	<0.001
Block 3					
Arm circumference	0.715	<0.001	0.554		
bSBP	0.521	<0.001	0.355		
Upper arm length	−0.058	0.259	−0.043		
bDBP	0.096	0.073	0.068		
Sex	0.315	<0.001	0.199		
	R	R^2	*SEE*		
	0.807	0.651	11.8	140.0	<0.001

Table 5 Model for 10-cm-wide cuff

	Stand. β	p value	Part	Mean square error	Sig. F change
Block 1					
Arm circumference	0.408	<0.001	0.407		
bSBP	0.547	<0.001	0.545		
	R	R^2	*SEE*		
	0.707	0.49	9.8	96.4	<0.001
Block 2					
Arm circumference	0.462	<0.001	0.396		
bSBP	0.443	<0.001	0.338		
Upper arm length	−0.137	0.009	−0.113		
bDBP	0.220	<0.001	0.172		
	R	R^2	*SEE*		
	0.741	0.549	9.3	87.5	<0.001
Block 3					
Arm circumference	0.541	<0.001	0.419		
bSBP	0.537	<0.001	0.366		
Upper arm length	−0.046	0.422	−0.034		
bDBP	0.133	0.026	0.094		
Sex	0.227	0.001	0.144		
	R	R^2	*SEE*		
	0.755	0.570	9.1	83.8	0.001

Table 6 Model for 12-cm-wide cuff

	Stand. β	p value	Part	Mean square error	Sig. F change
Block 1					
Arm circumference	0.373	<0.001	0.372		
bSBP	0.558	<0.001	0.556		
	R	R^2	SEE		
	0.694	0.481	9.3	86.5	<0.001
Block 2					
Arm circumference	0.438	<0.001	0.376		
bSBP	0.466	<0.001	0.355		
Upper arm length	−0.160	0.003	−0.133		
bDBP	0.208	<0.001	0.163		
	R	R^2	SEE		
	0.730	0.533	8.8	78.5	<0.001
Block 3					
Arm circumference	0.524	<0.001	0.406		
bSBP	0.568	<0.001	0.387		
Upper arm length	−0.062	0.288	−0.045		
bDBP	0.114	0.060	0.081		
Sex	0.246	<0.001	0.156		
	R	R^2	SEE		
	0.747	0.557	8.6	74.7	<0.001

$$\begin{aligned}\text{AOP 5cm (mmHg)} = {} & 2.926\,(\text{arm circumference}) \\ & + 1.002\,(\text{bSBP}) - 0.428\,(\text{arm length}) \\ & + 0.213\,(\text{bDBP}) \\ & + 12.668\,(\text{sex}) - 68.493\end{aligned}$$

$$\begin{aligned}\text{AOP 10cm (mmHg)} = {} & 1.545\,(\text{arm circumference}) \\ & + 0.722\,(\text{bSBP}) - 0.235\,(\text{arm length}) \\ & + 0.205\,(\text{bDBP}) \\ & + 6.378\,(\text{sex}) - 15.918\end{aligned}$$

$$\begin{aligned}\text{AOP 12cm (mmHg)} = {} & 1.393\,(\text{arm circumference}) \\ & + 0.710\,(\text{bSBP}) - 0.294\,(\text{arm length}) \\ & + 0.164\,(\text{bDBP}) \\ & + 6.419\,(\text{sex}) - 8.752\end{aligned}$$

Note: Arm circumference and arm length are measured in cm; for sex, a zero should be entered for males and a one should be entered for females.

In order to cross-validate the original equations, we created new formulas using a validation sample ($n = 166$) from the original group of participants ($n = 249$) and then compared them with the remaining participants ($n = 83$). The new formulas for the validation sample appeared similar to the ones for the original total sample ($n = 249$). The respective formulas created from the validation group for each cuff width are as follows:

$$\begin{aligned}\text{AOP 5cm (mmHg)} = {} & 2.790\,(\text{arm circumference}) \\ & + 1.119\,(\text{bSBP}) - 0.439\,(\text{arm length}) \\ & + 0.224\,(\text{bDBP}) \\ & + 12.467\,(\text{sex}) - 77.636\end{aligned}$$

$$\begin{aligned}\text{AOP 10cm (mmHg)} = {} & 1.521\,(\text{arm circumference}) \\ & + 0.833\,(\text{bSBP}) - 0.296\,(\text{arm length}) \\ & + 0.139\,(\text{bDBP}) \\ & + 6.869\,(\text{sex}) - 21.344\end{aligned}$$

$$\begin{aligned}\text{AOP 12cm (mmHg)} = {} & 1.444\,(\text{arm circumference}) \\ & + 0.736\,(\text{bSBP}) - 0.297\,(\text{arm length}) \\ & + 0.159\,(\text{bDBP}) \\ & + 7.355\,(\text{sex}) - 13.216\end{aligned}$$

For the 5-cm-wide cuff, the new formula explained 65.3 % of the variance with a SEE of 12.379 and a mean square error of 153.25. When we compared the new formula with the remaining sample ($n = 83$), there were no significant differences (actual: 146 (17) vs predicted: 145 (15) mmHg, $p = 0.301$), with a total error of 10 mmHg. For the 10-cm-wide cuff, the new formula explained 58.7 % of the variance with a SEE of 9.352 and a mean square error of 87.461. When we compared the new formula with the remaining sample ($n = 83$), there were no significant differences [actual: 124 (12) vs predicted: 124

(10) mmHg, $p = 0.926$], with a total error of 8 mmHg. For the 12-cm-wide cuff, the new formula explained 58 % of the variance with a SEE of 8.648 and a mean square error of 74.787. When we compared the new formula with the remaining sample ($n = 83$), there were no significant differences [actual: 120 (12) vs predicted: 120 (9) mmHg, $p = 0.489$], with a total error of 8 mmHg.

4 Discussion

Currently there are no standard established procedures for the application of BFR. Throughout the literature there are numerous different cuff widths and inflation pressures used, often times without taking into consideration the impact both cuff width and limb size have on the amount of restriction occurring. This is problematic as the present study revealed significant differences in AOP when comparing the 5-, 10-, and 12-cm-wide cuffs applied to the upper arm. Further, our results suggest that limb circumference explains the most unique variance for all three cuff widths tested. Lastly, both sex and race have an impact on AOP; however, it is not presently known how meaningful this difference is.

The results of our study reveal an inverse relationship between cuff width and AOP in the upper body. The 5-cm-wide cuff required the highest inflation pressure to occlude blood flow, followed by the 10-cm-wide cuff, then the 12-cm-wide cuff. This agrees with previous studies comparing wide and narrow cuffs in the upper [8, 14] and lower [6, 7, 15] body. Applying a wide cuff compared with a narrow cuff increases the distance of pressure being applied to the tissue [7]. Therefore, within the tissue, blood vessels are compressed over a longer distance with a wide cuff versus a narrow cuff, which in turn will create a greater resistance to blood flow. For each of the three cuff widths tested (5, 10, 12 cm), females had a lower AOP compared with males. When examining the magnitude (determined by Cohen's *d*) of these differences (5 cm, $d = 0.36$; 10 cm, $d = 0.46$; 12 cm, $d = 0.33$), they were relatively small, and consequently unlikely to be meaningful when prescribing BFR. Regardless, these differences are accounted for in the equations provided as well as when measuring AOP directly. In addition, considering the prevalence of hypertension among non-Hispanic Blacks in comparison with other races [10] and the relationship previously established between brachial blood pressure and AOP [9], we thought it necessary to retrospectively investigate the effect race might have on AOP. Although racial differences in AOP were present, they appeared relatively small. Thus, correcting for race might not be necessary as differences in inflation pressure may be inappreciable when prescribing a common BFR stimulus (i.e., 40 % of AOP [11]). However, this is the first study to consider potential racial differences in the application of the restriction stimulus; thus, future studies aimed towards answering this question specifically are needed.

To make BFR relative to each participant, individual differences should be accounted for. The results of this study reveal a model consisting of arm circumference, bSBP, upper arm length, bDBP, and sex explaining the most variance in AOP for the 5-, 10-, and 12-cm-wide cuffs. Coinciding with previous literature on the upper [8, 9] and lower body [6], our data revealed limb circumference always explained the most unique variance in AOP for each cuff width. When examining tissue pressure patterns underneath an inflated cuff, Hargens et al. [16] found subcutaneous tissue experiences a greater percentage of applied pressure compared with deep tissue. This disparity in tissue pressure becomes more pronounced as limb circumference becomes larger. Therefore, if cuff width were the same, a higher inflation pressure would be needed to reach the same deep tissue pressure in a larger limb compared with a small one. It is of note that a similar model in the upper body examining muscle thickness and fat thickness did not explain any more variance than a model measuring limb circumference [9]; therefore, taking into account differences in limb circumference appears to be sufficient. After limb circumference, bSBP was the next largest predictor of AOP for each cuff width, which was in congruence with previous literature on the upper body [9, 17]. This may be due to similarity of measurements between upper body AOP and bSBP, as bSBP is not a significant predictor of AOP in the lower body [6, 15]. Differences in bDBP and sex were significant predictors of AOP, although they were relatively small when compared with limb circumference and bSBP. Upper arm length was also not a significant predictor of AOP when controlling for all other variables. We originally chose to include upper arm length in the model due to the possible role it has in hemodynamics. Blood pressure is dependent upon many variables such as viscosity, as well as the diameter and length of the blood vessel. When all other variables remain unchanged, increasing or decreasing the length of a vessel will change the fluid pressure within that blood vessel [18]. However, when controlling for all other variables, upper arm length did not explain any additional variance in AOP for any cuff width. This may be related to circumference having a much greater impact on resistance/flow than the length of the vessel. For example, resistance is directly related to the vessels length but inversely related to the fourth power of the vessel's radius.

To our knowledge, no previous studies have compared AOP for multiple cuff widths in the upper body while also examining the influences of individual differences and how they change along with cuff width. The inflation pressure needed for arterial occlusion in the upper body is dependent upon width of the cuff applied, emphasizing the importance of authors to carefully consider the cuff used for BFR. Furthermore, cuff width should always be reported in the literature to make methodology truly replicable. To ensure a similar stimulus for all participants undergoing BFR in the upper body, individual differences such as arm circumference and bSBP should be accounted for, as they were responsible for explaining the most unique variance in AOP for each cuff width tested. The equations yielded from our data will allow other researchers the practical ability to determine AOP for three commonly used cuff widths in the upper body with the use of minimal equipment. Further, our cross-validation analysis suggests that the formulas are valid and similar to the formulas created for the entire sample. While this study is primarily focused on improvement of BFR methodology, the results may also have implications into other fields of study involving the use of cuff application, such as clinical blood pressure measurements, and flow mediated dilation. Based on current and previous findings [6, 9], we would recommend against applying a universal pressure for every participant as is commonly done with blood flow measurements in the upper and lower body [19, 20].

Our study is not without limitations. First, we did not measure the effects of cuff width on AOP during exercise. This has been investigated previously in the upper body using a 5-cm cuff and the results showed AOP increased immediately after a bout of exercise [21]. It is of note, however, that BFR elicits favorable muscle adaptation in the absence of exercise [22, 23]. Second, we did not measure the blood flow volume during inflation for each cuff. Therefore, we were not able to determine differences in the amount of blood flow, only whether blood was present or absent at the radial artery. Third, the racial comparisons were limited to non-Hispanic Blacks and Whites due to sample size. Future research could expand on potential race differences in AOP. Lastly, these findings are only specific to the age range of 18–34 years.

5 Conclusions

Our findings highlight the difference in AOP due to the width of the cuff being applied in the upper body. Thus, any investigator or clinician applying BFR should carefully consider the cuff width being used in order to control for differences. Furthermore, it is of utmost importance that researchers report cuff width used for BFR in order to make methodology truly replicable. Additionally, we point out that individual differences (i.e., limb circumference, bSBP) should be accounted for when applying restrictive pressures to ensure a relative stimulus for each participant. Controlling for these differences by making BFR relative to the cuff and to the individual could potentially help avoid any adverse events due to inadvertently applying pressures that result in near or complete arterial occlusion. The equations derived from this study will provide other investigators a quick, practical method to determine AOP for three commonly used cuff widths in the BFR literature.

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