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ORIGINAL ARTICLE

Effects of cuff width on arterial occlusion: implications for blood flow restricted exercise

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Abstract The purpose of this study was to determine the difference in cuff pressure which occludes arterial blood flow for two different types of cuffs which are commonly used in blood flow restriction (BFR) research. Another purpose of the study was to determine what factors (i.e., leg size, blood pressure, and limb composition) should be accounted for when prescribing the restriction cuff pressure for this technique. One hundred and sixteen (53 males, 63 females) subjects visited the laboratory for one session of testing. Mid-thigh muscle (mCSA) and fat (fCSA) cross-sectional area of the right thigh were assessed using peripheral quantitative computed tomography. Following the mid-thigh scan, measurements of leg circumference, ankle brachial index, and brachial blood pressure were obtained. Finally, in a randomized order, arterial occlusion pressure was determined using both narrow and wide restriction cuffs applied to the most proximal portion of each leg. Significant differences were observed between cuff type and arterial occlusion (narrow: 235 (42) mmHg vs. wide: 144 (17) mmHg; $p = 0.001$, Cohen's $D = 2.52$). Thigh circumference or mCSA/fCSA with ankle blood pressure, and diastolic blood pressure, explained the most variance in the cuff pressure required to occlude arterial flow. Wide BFR cuffs restrict arterial blood flow at a lower pressure than narrow BFR cuffs, suggesting that future studies account for the width of the cuff used. In addition, we have outlined models which indicate that restrictive cuff pressures should be largely based on thigh circumference and not on pressures previously used in the literature.

Keywords Kaatsu · Hypertrophy · Strength · Vascular occlusion training

Introduction

High load (70% 1-RM) resistance exercise provides a means of increasing skeletal muscle size, strength, and endurance (ACSM 2009). Despite the positive effects, some populations (e.g., elderly, rehabilitating patients, etc.) are contraindicated to performing high-load resistance training and are limited to performance of low-load resistance exercise. Training with low loads in combination with venous blood flow occlusion from the working muscle and arterial blood flow restriction to the working muscle (BFR) may be beneficial for such populations. This type of training has been shown to result in similar muscular adaptations as higher load exercise (for reviews please see (Loenneke and Pujol 2009, 2011; Loenneke et al. 2010b) through a variety of proposed mechanisms (Loenneke et al. 2011b, c).

Despite the observed benefits from this novel mode of exercise, results have been variable from different laboratories, which may be attributed to the different techniques

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used to restrict blood flow. A variety of devices have been used to restrict blood flow during exercise, including elastic knee wraps (Loenneke et al. 2010a, 2011a, b, d), elastic belts with a pneumatic bag inside (Fahs et al. 2011; Rossow et al. 2011), nylon pneumatic cuffs (Cook et al. 2007; Manini et al. 2011), or a traditional nylon blood pressure cuff (Laurentino et al. 2008; Teramoto and Golding 2006). In addition, a range of restrictive cuff pressures have been used for restricting blood flow, generally ranging from approximately 1.3 times greater than systolic blood pressure (SBP; ~160 mmHg) to over 200 mmHg. Many pressures are not set relative to the individual (e.g., 1.3× SBP), but are instead set to a universal pressure for every individual in the study. Some previous BFR exercise studies have based the restriction cuff pressure on a study (Iida et al. 2007) which only measured blood flow during blood flow restriction on nine young men using two different-sized elastic narrow cuffs (3 and 6 cm wide) interchangeably in the supine position. This same pressure may not necessarily restrict the same amount of blood flow on all individuals or under conditions in which a different blood flow restriction device is used, since the amount of tissue surrounding the blood vessels influences the pressure exerted on the vasculature and therefore, the degree of blood flow restriction. Furthermore, in many published reports, the width of the belt used to restrict blood flow is not reported. This is an important point to consider, since wider cuffs transmit pressure through soft tissue differently than narrow cuffs (Crenshaw et al. 1988) and therefore may impact changes in muscle hypertrophy (Kacin and Strazar 2011). Crenshaw et al. (1988) demonstrated that wider cuffs (18 cm) occlude arterial blood flow at a lower overall pressure than a narrow belt (4.5 cm). Kacin and Strazar (2011) found that the application of a wider cuff (13 cm) during knee extension exercise had a deleterious impact on muscle hypertrophy at the site at which the wider cuff was applied. The authors hypothesized that this may have occurred due to the high restrictive pressure (230 mmHg) used coupled with a wide cuff, which likely resulted in high levels of compression and shear stress under the cuff. Thus, for the purposes of low-load BFR exercise, applying 200 mmHg using a 5 cm wide cuff will likely produce a different stimulus than 200 mmHg applied using a 13.5 cm wide cuff. In addition, Shaw and Murray (1982) demonstrated using four hip-disarticulation specimens that limb circumference is also a determining factor in the level of blood flow restriction from a given pressure, especially with a narrow cuff. Using an 8 cm wide cuff, they observed a consistent decrease in the mean maximal tissue-fluid pressure as the circumference of the limb increased. Table 1 includes recent research (2011) highlighting the wide range of cuff pressures and cuff widths used in the literature.

We have previously hypothesized that the pressures used to restrict blood flow during exercise should to some degree be determined by the width of the cuffs and limb circumference, and not necessarily by pressures previously used in the literature (Loenneke et al. 2011e), while others believe that the pressure should be dependent on SBP (Cook et al. 2007). Thus, the purpose of this study was to determine the difference in cuff pressure which occludes arterial blood flow for two different types of cuffs which are both commonly used in BFR research. Another purpose of the study was to determine what factors (i.e., leg size, blood pressure, and limb composition) should be accounted for when prescribing the restriction cuff pressure for this training technique.

Table 1 Summary of lower body BFR studies from 2011

Citation	Body position	Restrictive cuff pressure	Restrictive cuff width
(Fahs et al. 2011)	Upright	200 mmHg	5 cm
(Inagaki et al. 2011)	Upright	150 mmHg	20.5 cm
(Kacin and Strazar 2011)	Upright	230 mmHg	13 cm
(Karabulut et al. 2011a)	Upright	160–240 mmHg[a]	5 cm
(Karabulut et al. 2011b)	Upright	120, 140, 160, 180, 200, 220 mmHg	Not Reported
(Kubota et al. 2011)	Supine	50 mmHg	Not Reported
(Laurentino et al. 2011)	Upright	50% of arterial occlusion pressure	17.5 cm
(Loenneke et al. 2011a)	Upright	N/a	7.6 cm
(Loenneke et al. 2011d)	Standing	N/a	7.6 cm
(Loenneke et al. 2011f)	Standing	N/a	7.6 cm
(Patterson and Ferguson 2011)	Upright	110 mmHg	Not reported
(Rossow et al. 2011)	Upright	200 mmHg	5 cm
(Sakamaki et al. 2011)	Standing	160–230 mmHg[a]	5 cm
(Sugaya et al. 2011)	Supine	180/230 mmHg	5 cm
(Takada et al. 2011)	Supine	1.3× SBP	18.5 cm

[a] Progressive increase in restrictive cuff pressure during training

Methods

Subjects

One hundred and sixteen (53 males, 63 females) subjects with no known cardiovascular or metabolic diseases visited the laboratory for one session of testing. All the subjects were tested at least 2 h post-prandial and were instructed to avoid caffeine, medications, and exercise on the day of their visit. The study received approval from the university's Institutional Review Board, and each subject gave a written informed consent before participation. This study was performed according to the Declaration of Helsinki.

Study design

Upon arriving at the laboratory, subjects' height and body mass were measured using a standard stadiometer and an electronic scale. Mid-thigh muscle (mCSA) and fat (fCSA) cross sectional area of the right thigh were assessed using peripheral quantitative computed tomography (pQCT). Following the mid-thigh scan, subjects quietly remained in a supine position on an examination table with their arms kept at their sides for 10 min. Following 10 min of rest, measurements of leg circumference, ankle brachial index (ABI), and brachial blood pressure were obtained (in order). Finally, in a randomized order, arterial occlusion pressure was determined using both narrow and wide restriction cuffs applied to the most proximal portion of each leg.

Peripheral quantitative computed tomography

The mCSA and fCSA of the right mid-thigh of all subjects were measured by a pQCT scanner (XCT 3000) with software version 6.00 (Stratec Medizintechnik GmbH, Pforzheim, Germany). All pQCT scans were measured by a trained pQCT technician whose coefficient of variation for repeat measurements was 1.59% for mCSA, and 1.52% for fCSA. The length of the femur was measured from the greater trochanter to the femoral condyle with a tape measure. With the subject seated, the right leg of each participant was positioned in the center of the scanning area and the leg was secured to minimize movement. A scout view was used to find the end of the femur, and then the gantry moved proximally from the femoral condyle area to 50% of the femoral length. Scans were performed using a 0.4 mm voxel and a scan speed of 20 mm/sec. A region of interest was drawn around the total CSA scan and analyzed for mCSA and fCSA using the Stratec threshold driven software along with a median smoothing filter F01F06U01. Specifically, mCSA and fCSA were determined by two sequential analyses. In the first analysis, fat and marrow were separated from muscle and bone within the total cross-sectional slice. In the second analysis, the bone and marrow areas were subtracted from the muscle + bone area and fat + marrow area, respectively, leaving mCSA and fCSA.

Thigh circumference

The distance from the inguinal crease to the top of the patella was measured using a tape measure and a mark was made on the leg 33% distal to the inguinal crease. Thigh circumference (33% circ.) was measured at this mark to capture an accurate representation of the site at which the cuffs would be applied.

Ankle brachial index (ABI)

The ankle brachial index (ABI) is a ratio of the blood pressure in the lower legs to the blood pressure in the arms and was used to detect peripheral vascular disease. With the subjects supine, the brachial SBP was obtained in each arm using a hand-held bidirectional Doppler (MD4, Hokanson, Bellevue, WA) probe placed on the artery at an angle of 45–60°. A MV10 segmental cuff attached to a manual hand-held cuff inflator (Hokanson, Bellevue, WA) was placed proximal to the Doppler probe and inflated on the limb to a supra-systolic pressure and then slowly deflated until a pulse (arterial flow) was detected. Ankle blood pressure (ABP) was measured at the posterior tibial artery using the same procedure. The ABI was calculated by dividing ABP by the higher of two brachial pressures. Peripheral vascular disease is indicated by an ABI of <0.9. All subjects had an ABI ≥ 0.9.

Systolic and diastolic blood pressure

Systolic blood pressure and diastolic brachial blood pressure (DBP) were measured using an appropriate-sized automatic blood pressure cuff (Omron, Model HEM-773). Blood pressure was taken in duplicate and if SBP values were not within 5 mmHg, a third measurement was taken. The closest two values were averaged for analysis.

Determination of arterial occlusion pressure

With the subjects supine, in a randomized order, either the wide (Hokanson, SC12, Bellevue, WA; 13.5 cm × 83 cm) or narrow (Kaatsu Master, Sato Sports Plaza, Tokyo Japan; 5 cm × 135 cm) cuffs were applied to the most proximal portion of each leg. The pulse at the ankle (arterial blood flow) was detected using a hand-held bidirectional Doppler probe placed on the posterior tibial artery. This site was chosen because femoral artery blood flow is difficult to measure with cuffs applied. Both auditory and visual signals from the Doppler probe indicated if the pulse was present.

The narrow cuffs were applied with an initial compressive force between 40 and 60 mmHg (Karabulut et al. 2011b). The wide cuffs were applied tightly around the upper thigh; however, the device which inflates the wide cuffs does not allow an initial compressive force to be set. The narrow cuffs were connected to a Kaatsu Master Cuff inflator (Sato Sports Plaza, Tokyo, Japan); the wide cuffs were connected to an E 20 Rapid Cuff Inflator (Hokanson, Bellevue, WA). Both devices adjust cuff pressure automatically and actual cuff pressures were confirmed on the machines' digital window. The same inflation protocol was used for both types of cuffs. The cuffs were first inflated to 50 mmHg for 30 s and then deflated for 10 s. Cuffs were then inflated to the subject's SBP for 30 s and then deflated for 10 s. Cuff pressure was then increased incrementally by 40 mmHg (30 s inflation followed by a 10 s deflation) until the arterial flow was no longer detected during inflation. When arterial flow was no longer detected, cuff pressure was decreased in 10 mmHg units until arterial flow was present. Arterial occlusion pressure was recorded to the nearest 10 mmHg as the lowest cuff pressure at which a pulse was not present. This process was repeated with both the wide and narrow cuff devices with 5 min rest allotted between the procedures. Cuff pressures were increased up to but not over 300 mmHg. If subjects still had a detectable pulse at 300 mmHg cuff pressure, arterial occlusion pressure was recorded as "300 + mmHg." Subjects in which arterial occlusion did not occur with the narrow cuffs were not included in the regression analysis (explained below).

Statistical analyses

Data were analyzed using PASW Statistics 18 with all variability, unless stated otherwise, represented using standard deviation (SD). Two different models of hierarchal linear regression were used to determine which variables predicted the pressure at which arterial occlusion occurred, for both the narrow and the wide restriction cuffs (four models total). As 33% circumference would logically be highly related to mCSA and fCSA, two separate models were employed to examine whether the leg size (thigh circumference) or composition (mCSA and fCSA) would serve as a better predictor of arterial occlusion pressure.

All four models consisted of four individual blocks to determine changes in the Pearson correlation, adjusted R^2, standard error of the estimate (SEE), and the change in the F value when each individual variable was added into the overall model. The first model consisted of 33% circumference, and then, ABP, DBP, and SBP were subsequently added into the model with each block based on our theoretical model and the variables hypothesized previously in the literature. The second model consisted of mCSA and fCSA in the first block, and then, ABP, DBP, and SBP were subsequently added into the model with each block based on our theoretical model and variables hypothesized previously in the literature. The variance inflation factor (VIF) and Pearson correlations were used to determine the degree of multi-collinearity of the ith independent variable with other independent variables for all hierarchal regression models (O'Brien 2007). Multi-collinearity between variables was defined as a VIF $\geq$10 and/or Pearson correlations of 0.85 or greater.

Paired sample t-tests were used to determine differences in arterial occlusion between the narrow and wide cuffs. The subjects were divided into two groups: those in which arterial occlusion occurred at a pressure <300 mmHg (arterial occlusion) or +300 mmHg (no arterial occlusion) with the narrow cuffs. Independent sample t-tests were used to determine the differences between those groups for age, height, body mass, BMI, 33% circ., mCSA, fCSA, SBP, DBP, ABP, wide cuff arterial occlusion, and narrow cuff arterial occlusion. The effect sizes for the independent sample t-test and paired sample t-test were determined with Cohen's D. Statistical significance was set at $p \leq 0.05$.

Results

Subject characteristics for the entire data set are presented in Table 2 ($n = 116$). For mCSA and fCSA analysis one subject was excluded because his thigh diameter exceeded

Table 2 Subject characteristics (n = 116)

Variable	Mean (SD)	Minimum	Maximum
Age (years)	22 (3)	18	32
Height (m)	1.71 (0.08)	1.52	1.91
Body mass (kg)	73.0 (16.5)	47.4	137.7
BMI (kg/m^2)	24.7 (4.4)	17.2	45.4
33% Circ (cm)	58.1 (6.0)	48.0	77.5
mCSA (mm^2)[a]	14,630 (3,740)	7,863	24,769
fCSA (mm^2)[a]	7,120 (2,991)	1,428	16,141
SBP (mmHg)	112 (12)	81	155
DBP (mmHg)	69 (8)	49	110
ABP (mmHg)	122 (13)	84	162
Wide cuff arterial occlusion pressure (mmHg)	156 (26)	100	250

BMI body mass index, *33% Circ* 33% thigh circumference, *mCSA* muscle cross-sectional area, *fCSA* fat cross-sectional area, *SBP* systolic blood pressure, *DBP* diastolic blood pressure, *ABP* ankle blood pressure

[a] $n = 115$

Table 3 Subject characteristics comparing those with (n = 73) and without (n = 43) arterial occlusion using the narrow cuffs

Variable	No arterial occlusion	Min–Max	Arterial occlusion	Min–Max	*p* value	Cohens *D*
Age (year)	23 (4)	18–31	21 (3)	18–32	0.009	0.59
Height (m)	1.72 (0.09)	1.5–1.91	1.70 (0.07)	1.5–1.8	0.283	0.26
Body mass (kg)	84.4 (17.9)	55–138	66.3 (11.2)	47.4–100.6	0.001	1.29
BMI (kg/m^2)	28.2 (4.8)	20.3–45.4	22.6 (2.5)	17.2–30.2	0.001	1.60
33% Circ. (cm)	63.3 (5.2)	56–78	55.1 (4.2)	48–68	0.001	1.80
mCSA (mm^2)	16,635 (4,039)[a]	9,876–24,769[a]	13,476 (3,027)	7,863–22,497	0.001	0.93
fCSA (mm^2)	9,082 (3,234)[a]	3,573–16,141[a]	5,991 (2,161)	1,428–13,231	0.001	1.19
SBP (mmHg)	118 (11)	103–156	108 (11)	81–141	0.001	0.92
DBP (mmHg)	71 (8)	56–110	67 (7)	49–82	0.008	0.55
ABP (mmHg)	127 (12)	98–160	119 (12)	84–162	0.001	0.67
Wide cuff arterial occlusion pressure (mmHg)	176 (25)	140–250	144 (17)	100–180	0.001	1.58
Narrow cuff arterial occlusion pressure (mmHg)	N/A	N/A	235 (42)	120–300	N/A	N/A

BMI body mass index, *33% Circ* 33% thigh circumference, *mCSA* muscle cross-sectional area, *fCSA* fat cross-sectional area, *SBP* systolic blood pressure, *DBP* diastolic blood pressure, *ABP* ankle blood pressure

[a] indicates $n = 42$

the capability of the machine; however, his data were used in subsequent analyses using 33% circumference as a predictor. Subject characteristics with ($n = 73$) and without ($n = 43$) arterial occlusion with the narrow cuffs are presented in Table 3. The largest differences between groups with and without arterial occlusion from the narrow cuffs determined by Cohen's *D* (>1.00) were body mass, body mass index (BMI), 33% circumference, and fCSA. Significant differences were observed between cuff type and arterial occlusion (Narrow: 235 (42) mmHg vs. Wide: 144 (17) mmHg; $p = 0.001$, Cohen's $D = 2.52$).

The hierarchical regression models for the wide cuffs are found in Table 4. Block 3 of model 1, composed of 33% circumference, ABP, and DBP, explained the most variance; adding SBP in block 4 did not explain any additional variance (Sig. *F* change = 0.971) in the cuff pressure required to occlude arterial flow. Standardized betas and part correlation coefficients indicated that 33% circumference explained the most variance from each individual block. In model 2, block 3, composed of mCSA, fCSA, ABP, and DBP, also explained the most variance; adding SBP in block 4 did not explain any additional variance (Sig. *F* Change = 0.280). The standardized betas and part correlation coefficients indicated that fCSA explained the most variance. None of the variables met the criteria for multicollinearity.

The hierarchical regression models for the narrow cuffs are found in Table 5 ($n = 73$). Block 3 of model 1, composed of 33% circumference, ABP, and DBP, explained the most variance in the cuff pressure required to occlude arterial flow; however, ABP was not a significant predictor of the overall model. The standardized betas and part correlation coefficients indicated that 33% circumference explained the most variance from each individual block. Adding SBP in block 4 did not explain any additional variance (Sig. *F* Change = 0.678). Block 3 of model 2 composed of mCSA, fCSA, ABP, and DBP explained the most variance; however, ABP was not a significant predictor of the overall model. The standardized beta and part correlation coefficients indicated that fCSA explained the most variance in occluding pressure from each individual block.

Discussion

Heretofore restrictive cuff pressures used with low-load BFR exercise were largely based on SBP or pressures used previously in the literature with little correction for differences between individuals or cuff type. The results of this study indicate that differences of arterial occlusion between two commonly used cuffs for low-load BFR exercise exist. Further, this study shows quantitatively for the first time that restrictive cuff pressure should be based on the width of the cuff and confirms that thigh circumference is the largest determinant of arterial occlusion pressures.

For every subject except one, we observed that the wider cuffs cut off arterial flow at a lower pressure compared to the narrow cuffs, which supports earlier work by Crenshaw et al. (1988). The reason for this one exception is unknown. These findings highlight the importance of reporting the cuff size and type used for a particular study. This is

Table 4 Model 1 (n = 116) and Model 2 (n = 115) for the wide cuffs

Block 1	Stand. β	p value	Part		
33% Circumference	0.707	0.001	0.707		
	R	Adj. R^2	SEE	Mean square error	Sig. F change
	0.707	0.495	18.606	346.169	0.001
Block 2	Stand. β	p value	Part		
33% Circumference	0.570	0.001	0.527		
ABP	0.358	0.001	0.331		
	R	Adj. R^2	SEE	Mean square error	Sig. F change
	0.780	0.602	16.514	272.722	0.001
Block 3	Stand. β	p value	Part		
33% Circumference	0.587	0.001	0.541		
ABP	0.245	0.001	0.198		
DBP	0.217	0.001	0.189		
	R	Adj. R^2	SEE	Mean square error	Sig. F change
	0.803	0.635	15.813	250.294	0.001
Block 4	Stand. β	p value	Part		
33% Circumference	0.587	0.001	0.515		
ABP	0.244	0.002	0.181		
DBP	0.216	0.005	0.162		
SBP	0.003	0.971	0.002		
	R	Adj. R^2	SEE	Mean square error	Sig. F change
	0.803	0.632	15.884	252.294	0.971
Block 1	Stand. β	p value	Part		
mCSA	0.484	0.001	0.483		
fCSA	0.536	0.001	0.534		
	R	Adj. R^2	SEE	Mean square error	Sig. F change
	0.696	0.475	18.557	344.380	0.001
Block 2	Stand. β	p value	Part		
mCSA	0.355	0.001	0.331		
fCSA	0.455	0.001	0.443		
ABP	0.377	0.001	0.347		
	R	Adj. R^2	SEE	Mean square error	Sig. F change
	0.778	0.594	16.323	266.428	0.001
Block 3	Stand. β	p value	Part		
mCSA	0.353	0.001	0.330		
fCSA	0.472	0.001	0.457		
ABP	0.275	0.001	0.223		
DBP	0.204	0.003	0.178		
	R	Adj. R^2	SEE	Mean square error	Sig. F change
	0.798	0.623	15.729	247.417	0.003
Block 4	Stand. β	p Value	Part		
mCSA	0.297	0.001	0.213		
fCSA	0.483	0.001	0.461		
ABP	0.235	0.004	0.170		
DBP	0.156	0.054	0.112		
SBP	0.124	0.280	0.062		
	R	Adj. R^2	SEE	Mean square error	Sig. F change
	0.800	0.623	15.717	247.012	0.280

ABP ankle blood pressure, *DBP* diastolic blood pressure, *SBP* systolic blood pressure, *mCSA* muscle cross-sectional area, *fCSA* fat cross-sectional area

Table 5 Model 1 ($n = 73$) and model 2 ($n = 73$) for the narrow cuffs

Block 1	Stand. β	p value	Part		
33% Circumference	0.400	0.001	0.400		
	R	Adj. R^2	SEE	Mean square error	Sig. F change
	0.400	0.148	39.180	1,535.103	0.001
Block 2	Stand. β	p value	Part		
33% Circumference	0.344	0.002	0.338		
ABP	0.305	0.005	0.300		
	R	Adj. R^2	SEE	Mean square error	Sig. F change
	0.500	0.229	37.290	1,390.556	0.005
Block 3	Stand. β	p value	Part		
33% Circumference	0.384	0.001	0.374		
ABP	0.088	0.479	0.070		
DBP	0.359	0.004	0.290		
	R	Adj. R^2	SEE	Mean square error	Sig. F Change
	0.578	0.305	35.397	1,252.943	0.004
Block 4	Stand. β	p value	Part		
33% Circumference	0.375	0.001	0.357		
ABP	0.064	0.640	0.046		
DBP	0.334	0.017	0.241		
SBP	0.061	0.678	0.041		
	R	Adj. R^2	SEE	Mean square error	Sig. F Change
	0.579	0.297	35.611	1,268.126	0.678
Block 1	Stand. β	p value	Part		
mCSA	0.350	0.006	0.314		
fCSA	0.388	0.002	0.348		
	R	Adj. R^2	SEE	Mean square error	Sig. F Change
	0.392	0.129	39.623	1,570.009	0.003
Block 2	Stand. β	p value	Part		
mCSA	0.285	0.017	0.252		
fCSA	0.378	0.002	0.340		
ABP	0.339	0.351	0.334		
	R	Adj. R^2	SEE	Mean square error	Sig. F Change
	0.515	0.233	37.189	1,383	0.002
Block 3	Stand. β	p value	Part		
mCSA	0.282	0.013	0.250		
fCSA	0.429	0.001	0.380		
ABP	0.133	0.277	0.107		
DBP	0.360	0.004	0.288		
	R	Adj. R^2	SEE	Mean square error	Sig. F change
	0.590	0.309	35.282	1,244.796	0.004
Block 4	Stand. β	p value	Part		
mCSA	0.178	0.163	0.136		
fCSA	0.467	0.001	0.405		
ABP	0.016	0.906	0.011		
DBP	0.265	0.052	0.191		
SBP	0.295	0.102	0.160		
	R	Adj. R^2	SEE	Mean square error	Sig. F change
	0.611	0.327	34.837	1,213.594	0.102

ABP ankle blood pressure, *DBP* diastolic blood pressure, *SBP* systolic blood pressure, *mCSA* muscle cross-sectional area, *fCSA* fat cross-sectional area sometimes not reported in the literature making the methods impossible to replicate.

Hierarchical regression models were used to determine what factors (i.e., leg size, blood pressure, and limb composition) should be accounted for when prescribing the restriction cuff pressure for this training technique. It is often speculated in the literature that thigh circumference or composition of the limb may restrict flow differently between individuals which might account for some of the variability in the response to low-load BFR exercise (Karabulut et al. 2011b; Loenneke et al. 2011e). For this analysis we included one model with thigh circumference and another using mCSA/fCSA to determine whether leg size or leg composition independently affected arterial blood flow restriction using either wide or narrow restriction cuffs. An interesting finding was that the leg circumference (field method) models predicted the cuff pressure needed to restrict arterial blood flow equally as well as or better than the limb composition (lab method) models. This suggests that measuring limb circumference rather than limb composition would be adequate for determining restrictive cuff pressure.

Comparing the factors which influence arterial blood flow restriction between the narrow and wide cuffs, our regression models indicate that limb size and composition have a greater influence on the pressure at which arterial blood flow restriction occurs using the wide cuffs compared to the narrow cuffs (63.5% vs. 30.5% variance explained, respectively). Furthermore, brachial SBP which is often used to determine the restrictive cuff pressure used during exercise did not explain additional variance in any model. This confirms previous research from Crenshaw et al. (1988) who also found that SBP did not affect the arterial occlusion pressure. Based on our results, we do not suggest adjusting restrictive cuff pressure based on brachial SBP. Ankle blood pressure was entered into the model after thigh circumference/mCSA, fCSA because we hypothesized that ABP would be a better predictor of arterial occlusion pressure from blood flow restriction of the lower body than DBP or SBP. Ankle blood pressure was a significant predictor of arterial occlusion pressure for the wide cuff models but not for the narrow cuff models, for which brachial DBP along with either thigh composition or thigh circumference was a significant predictor of arterial occlusion pressure. Diastolic brachial blood pressure may be physiologically predictive of arterial occlusion pressure because it is classically linked with peripheral resistance, which may be emulated to a certain degree with blood flow restriction. Based on our results, we suggest that future BFR studies adjust the restrictive cuff pressure based on either thigh circumference or thigh composition, along with ABP and brachial DBP when using wider cuffs. When using more narrow BFR cuffs, it may be appropriate to adjust cuff pressure for either thigh circumference or thigh composition along with brachial DBP.

Interestingly, as previously mentioned, the variance explained for was much lower for the models involving the narrow cuffs (31%) compared to the models involving wide cuffs (64%). Out of the entire sample, 37% of the subjects in this study still had arterial inflow when 300 mmHg of pressure was applied with the narrow cuffs. This is likely due to several factors, but one might be the nature of the narrow cuffs which are elastic, whereas the wider cuffs are made of a nylon material that does not stretch as easily. Table 3 highlights that the major difference between those with (arterial occlusion pressure <300 mmHg) and without (arterial occlusion pressure 300+ mmHg) arterial occlusion from the narrow cuffs was overall body size (i.e., thigh circumference, BMI, body mass), with thigh circumference specifically having the largest effect. It appears that the elasticity of the cuffs allows a more uniform restriction between subjects (i.e., less dependence on leg size and composition) compared to the wider nylon cuffs. It should be noted that pressures as low as 100 mmHg (wide cuffs) and 120 mmHg (narrow cuffs) were capable of completely restricting arterial flow in some individuals. Based on changes in body position and blood pressure, we would assume that pressures that decrease would not completely restrict arterial flow during exercise. However, it is common to prescribe restrictive cuff pressures much higher than this, ranging from 160 up to 240 mmHg in some cases. Certainly, restrictive cuff pressures of this magnitude may cause complete ischemia in some individuals depending upon limb size and/or composition regardless of restrictive cuff type.

The results of our study may have both clinical and practical importance. One of the criticisms of BFR exercise is that although exercise may be with lower loads, rating of pain and perceived exertion may be very high during exercise, limiting its application to those who are highly motivated (Wernbom et al. 2006, 2009). However, it should be noted that these studies used wider cuffs which may be causing almost complete arterial occlusion, and thus higher ratings of pain and perceived exertion. For BFR to be applied to older or clinical populations, the cuff type and cuff pressure should be of special concern. Secondly, mechanical compression of the arteries with the restrictive cuffs has also been a proposed safety concern with this type of exercise. Although we did not measure soft tissue or arterial compression directly, our results indicate that wider restrictive cuffs cause inherently more tissue compression at any given pressure compared to narrow cuffs.

This study is novel in that it is the first to investigate differences in arterial occlusion between two cuff types commonly used in the BFR exercise literature. Furthermore, although recent manuscripts have postulated thigh circumference (Loenneke et al. 2011e; Manini et al. 2011) and limb composition (Karabulut et al. 2011b) as overall determinants of arterial occlusion, this is the first investigation to date with a substantial subject pool of men and women to quantify the impact of leg size, leg composition, and brachial and ankle BP. Measurements were taken in the supine position, a position that has been used in studies investigating the clinical application of BFR (Kubota et al. 2008, 2011). Thus, these results may not translate directly to a seated position due to possible postural changes in blood flow. While this is a noted limitation in that greater pressures are likely required to restrict arterial flow in an upright position, the impact of each variable is likely to hold constant; however, future studies should seek to investigate as to whether this remains true with different body positions. Thus, our findings that thigh circumference, ABP, and DBP have the greatest impact on arterial occlusion pressure with the wide cuffs, and thigh circumference and DBP have the greatest impact on arterial occlusion pressure with the narrow cuffs are expected to remain regardless of whether the subject is lying down or upright. In addition, these results are only applicable to the lower body and do not necessarily translate to blood flow restriction of the upper body. We chose to perform this investigation on the lower body because the majority of BFR studies have utilized lower body BFR exercise training and because we expected to obtain a greater range of limb circumferences among the legs compared to the arms. We suggest future studies quantify the amount of arterial blood flow restriction using a variety of cuff types and cuff sizes in order to better control the amount of arterial blood flow restriction between individuals with different methodologies. Due to the inherent error built into any prediction equation, we propose that a uniform blood flow restriction stimulus may be able to be applied to each subject by obtaining an arterial occlusion measurement at rest (as done in this study), and using a percentage of that measurement for the BFR pressure (Laurentino et al. 2011). This proposal, while speculative, would hypothetically produce a more reliable BFR stimulus to all.

In conclusion, this study found that different types of cuffs occlude arterial blood flow at much different inflation pressures. In addition, we have outlined models showing the impact of different variables on arterial occlusion pressure and confirm our hypothesis that restrictive cuff pressures should be largely based on thigh circumference and not on pressures previously used in the literature. Furthermore we question the continued use of SBP as a determinant of BFR pressures. This study may help future investigations reach the goal of developing a model producing equal BFR between subjects.

Conflict of interest None of the authors report a conflict of interest.

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