Title: Beneath the Cuff: Often Overlooked and Under-Reported Blood Flow Restriction Device Characteristics and their Potential Impact on Practice

Short title: Cuff Design Variables Impacting BFR

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Abstract

Exercise with blood flow restriction (BFR) has been shown to be a useful technique to improve muscle mass, muscle strength and a host of other physiological benefits in both healthy and injured populations using low intensities (20-30% 1-repetition maximum or $< 50\%$ VO_{2max}). However, as BFR is gaining popularity in both practice and research, there is a lack of awareness for potentially important design characteristics and features associated with BFR cuff application that may impact the acute and longitudinal responses to training as well as the safety profile of BFR exercise. While cuff width and cuff material have been somewhat addressed in the literature, other cuff design and features have received less attention. This manuscript highlights additional cuff design and features and hypothesizes on their potential to impact the response and safety profile of BFR. Features including the presence of autoregulation during exercise, the type of bladder system used, the shape of the cuff, the set pressure versus the interface pressure, the ratio of bladder to cuff width, and the bladder length will be addressed as these variables have the potential to alter the responses to BFR training. As more devices enter the marketplace for consumer purchase, investigations specifically looking at their impact is warranted. We propose numerous avenues for future research to help shape the practice of BFR that may ultimately enhance efficacy and safety using a variety of BFR technologies.

Key words: BFR training, safety, autoregulation, bladder, kaatsu, occlusion training

Introduction

Interest in blood flow restriction (BFR) training has led to its increased adoption in fitness and rehabilitation settings (1–3) due to the numerous musculoskeletal, cardiovascular and performance benefits observed following chronic use. However, varied methodologies (e.g., applied pressures, repetition schemes, and cuffs and their various design feaures used to provide the BFR stimulus) reported in the literature increase uncertainty interpreting the magnitude of the effects of BFR exercise due largely to use of non-personalized pressures (4) and minimal reporting of rationales for the applied pressure (5). Similar issues exist within the exercise science and rehabilitation literature from insignificant reporting (6–9), although interpretation of BFR interventions are exacerbated by the heterogeneity of BFR cuff prescription factors. A recent article attempted to provide BFR application guidance based upon a consensus of researchers and clinicians (10), recommending that personalized pressures be implemented across research and clinical practice because it accounts for many of the variables (e.g., cuff width, blood pressure and limb circumference) that have been associated with impacting arterial occlusion pressure (AOP), the minimum pressure needed to occlude both arterial and venous return. Use of personalized pressures allows for a better determination of the relative intensity of BFR because when standardized to a relative %AOP, blood flow is similar at rest despite differences in cuff width (11) indicating a similar restrictive stimulus. While cuff width and material have been reported in the literature, there are other cuff design and features that may impact the restrictive stimulus and/or the cardiovascular and perceptual experiences of the exerciser, hindering extrapolation to practice. This is especially relevant considering the numerous reported devices used in administration of BFR (3) that have varied capabilities to produce a personalized BFR stimulus. Without consideration and reporting of these cuff-specific designs/features, it may lead to poorly designed research studies with limited utility as practitioners are guiding their BFR prescriptions from the literature.

For example, a recent publication attempted to compare two commercially available BFR devices (B-Strong™ and Delfi Personalized Tourniquet device) against a heavy load strength training control group on muscle excitation and training-related perceptual factors (rate of perceived exertion and muscle pain) in a fixed repetition design (12). However, the research design was poorly constructed due to a failure to consider the differences in occlusive capabilities of the devices, resulting in a disparate comparison as one condition was likely exercising significantly closer to failure than the other, augmenting the perceptual experience of the exerciser in the Delfi Personalized Tourniquet device condition (13). The researchers did not consider that the B-Strong™ cuff is designed to be very difficult to achieve full occlusion (width – 5 cm; multi-chambered bladder system) (14) whereas the Delfi Personalized Tourniquet device is designed to produce full limb occlusion (width - 11.5 cm; single-bladder system) (15). The authors did not report this important design characteristic of the B-Strong™ cuff (multi-chambered bladder) and as such, the study's conclusions stated that it was more tolerable than the Delfi Personalized Tourniquet device while providing similar electromyographic activation of the quadriceps. Nonetheless, oversights like this impact application of BFR because practitioners may assume the B-Strong™ cuff is just as effective as the Delfi Personalized Tourniquet device with better participant tolerability and similar myoelectric activity. As accelerated muscle fatigue is likely the primary way BFR induces its beneficial effect on muscle (16), the design of Bordessa et al. (2021) gives limited guidance to the potential efficacy of the B-Strong™ cuff compared to the Delfi Personalized Tourniquet device as both exercised in a work-matched fashion, limiting our understanding of the proximity to failure between conditions and related perceptual factors.

To date, there have been no effort-matched studies that can provide insight as to the degree of fatiguability (e.g., repetitions to failure) experienced between different pneumatic cuff types (e.g., nylon vs. elastic; single vs. multi-chambered bladder systems) set at different pressure schemes (e.g., %AOP vs. arbitrary pressure application based on limb circumference). In part, this oversight is due to the rapid growth of BFR in the literature and a lack of awareness of potentially important cuff designs and features that may impact the BFR prescription and participant experience. Thus, the purpose of this manuscript is to discuss and hypothesize on the potential impact of these BFR cuff designs and features to allow for better translation of research to practice and propose numerous avenues for future research.

Why Personalizing Pressure Application is Likely the Best Approach to BFR Prescription

BFR exercise repetitions to failure (17), neuromuscular responses (e.g., torque and myoelectric activity) (18), and the perceptual experience during exercise have been shown to be impacted by the pressure applied to the exercising limb and the type of BFR cuff used. For example, one study compared the acute muscular and perceptual response to a bout of 4 sets of biceps curl exercise performed with either a 3-cm wide Kaatsu® elastic cuff inflated to an arbitrary 160 mm Hg applied pressure or a 5-cm wide Hokanson nylon cuff inflated to 40% AOP (19). Despite similar cellular swelling, electromyographic amplitudes and post-exercise torque production, the nylon cuff condition reported greater number of repetitions performed during sets 2 and 3, lower rate of perceived exertion during set one and lower rate of perceived discomfort during all sets compared to the elastic cuff condition. This is particularly important as both device selection and perceptual responses have been identified as major barriers to successful BFR training implementation (20). The discrepancy between conditions in perceptual responses and repetitions to failure may be explained by the higher relative applied pressure of the elastic cuff (~65 ± 19% AOP) compared to the nylon cuff (40% AOP). As higher applied pressures have been shown to reduce repetitions to failure, increase cardiovascular responses (21), and elevate perceptual experiences compared to lesser applied pressures (22), personalizing the pressure may reduce the excessive physiologic and perceptual responses associated with higher pressures, increasing compliance in a long-term periodized program (20). Moreover, at 30% 1RM, lower relative applied pressures have been shown to be equally as effective in producing muscle hypertrophy as higher applied pressures (23) with decreased perceptual demands (24,25). In addition, when cuffs of different widths and materials are standardized to a %AOP, the physiologic and perceptual responses are largely equivocal (26–28) indicating that much of the differences observed following arbitrary pressure application protocols are due to varied degrees of relative personalized pressures. Last, there is also a potential safety concern when using non-personalized pressures as different prescriptions of pressures do not provide similar levels of relative restriction and may predispose the exerciser to full occlusion (23) or an ineffective pressure (17). Further, the assessment of AOP via handheld doppler has been shown to be a surrogate for systolic blood pressure (29). As clinicians do not often perform blood pressure screenings in outpatient settings (30), routinely assessing AOP potentially may identify important hemodynamic status changes in patients/clients that could warrant referral; further increasing the contribution of BFR to the medical community on the whole. Given the aforementioned, it is prudent for practitioners to implement BFR prescriptions using personalized pressures to account for differences in anthropometry of the participants as well as some differences in cuff design. As lower applied pressures may be equally as effective as higher pressures given a minimum threshold of load (31), cuff characteristics that may reduce the amount of applied pressure needed to achieve AOP should gain more recognition and be specifically outlined in research designs moving forward.

The Impact of Lesser-Known Cuff Characteristics & Features on Personalized Pressure Application

Cuff width and cuff material's impact on AOP has been described elsewhere (28,32) and is more commonly reported in the recent literature. Generally, wider cuffs reduce total AOP with greater effectiveness of transmission to the limb and broader pressure plateaus (e.g., more distributed applied pressure) compared to narrower cuffs. This aspect becomes relevant for prescribing BFR exercise because when the same pressure (% brachial systolic pressure) is applied, resistance exercise performed with wider (non-elastic) cuffs can promote higher cardiovascular and perceptual responses (33). Lesser applied pressures with wider cuffs may provide a safer restrictive stimulus to the neurovasculature (34,35) that may enhance the safety profile of BFR exercise. Cuff material (e.g., nylon vs. elastic) appears to not matter in altering the acute BFR exercise response as long as AOP can be determined (28), although only one study exists in this area. Below we address additional cuff designs and features that may play a role in further enhancing the safety profile of BFR exercise that are rarely (if ever) reported.

Autoregulation of Applied Pressure

Autoregulation refers to the capability of a device to maintain a consistent applied pressure on an exercising limb (Figure 1). Conversely, manual pneumatic cuffs (e.g., non-autoregulated) do not adjust for the phase of muscular contraction and may increase the hemodynamic and perceptual responses to BFR exercise, potentially impacting safety profile (36). Therefore, whether a BFR device is autoregulated may be an important variable to report as it may impact perceptual experience and hemodynamic response to exercise. To date, no published study has directly compared BFR exercise performed with- and without autoregulation using a cuff of similar width. A study currently *in review* from the lead author attempted to answer that question. We showed that autoregulation reduced risk of minor adverse events (e.g., feeling faint, numbness in the leg, excessive pain) ~7x compared to the same exercise performed without autoregulation and was associated with lower delayed onset muscle soreness and reduced perceptual experiences. The results of this study appear to provide preliminary support for the use of autoregulation to enhance the safety profile of BFR exercise, but more research is needed to make firmer conclusions. In addition, commercially available BFR devices vary in their capacity to provide quick adjustments to applied pressure during exercise, limiting conclusions about autoregulation to a particular device and not the feature itself. Future BFR research should specifically report the presence or absence of autoregulation.

INSERT FIGURE 1 HERE

Multi- vs. Single-Chambered Bladder System

A tourniquet – by definition – is designed to occlude arterial flow (37) and this concept forms the basis for the majority of BFR cuffs on the marketplace and in research because it allows a personalization of applied pressure (10). The bladder is the portion of the tourniquet that encircles and applies circumferential pressure to the limb to eliminate arterial inflow and venous return. Typically, most BFR cuffs are single-chambered and apply circumferential pressure around the limb that increase cardiovascular and perceptual responses at a given workload (38) and may reduce hypertrophy of the muscles underneath the cuff in longitudinal regimens (39,40). Nonetheless, despite these potential limitations, the use of a single-chambered bladder is commonplace in the BFR literature and is the most implemented bladder type in the BFR training literature as its able to determine AOP as long as it is wide enough (15).

INSERT FIGURE 2 HERE

Recently, commercially available devices have entered the marketplace that consist of numerous sequential bladders that according to the manufacturer are designed to reduce the potential for arterial occlusion and result in a non-uniform circumferential pressure during exercise (Figure 2) (41). As the multi-chambered bladder system is not designed to occlude, AOP is largely unfeasible and arbitrary pressures by the manufacturer have been recommended for use in practice (250 mm Hg for the upper body and 350 mm Hg for the lower body) (41) limiting generalizability. To the authors' knowledge, only one training study utilizing the B-Strong™ cuff has been published and it does not help in answering the potential efficacy of the bladder type given that exercise was conducted to failure, no low-load comparison group was included, and no volume load was reported (41). This is important because low-load exercise with- and without BFR has been shown to improve muscle mass and strength to a similar degree (42,43). To date, no study has investigated longitudinal musculoskeletal outcomes and volume load when exercise is performed to failure between low-loads with and without different BFR bladder designs and heavy loads (> 70% 1-repetition maximum).

Within the current BFR body of literature, there are three published studies comparing the acute responses of a multi-chambered bladder system to a single-bladder system (12,14,44). All studies have similar methodological issues due to the multi-chambered cuff construction preventing researchers from making pressures relative to that induced by the single chamber systems. Presumably, this results in a greater magnitude of AOP achieved by the single chambered systems, affecting acute measures and leading to potentially faulty conclusions on safety risk and/or longitudinal outcomes. For example, one walking study compared the acute perceptual and hemodynamic responses between the B-Strong™ cuff (5-cm cuff width) and Hokanson rapid-inflator research device (18-cm cuff width) inflated to 300 mm Hg and 160 mm Hg, respectively (44). The results appear to support the use of the B-Strong™ cuff for BFR aerobic exercise as the Hokanson device promoted greater increases in heart rate, blood pressure, and double product during exercise with elevated perceptual demands. Lactate levels were observed to be significantly greater in the Hokanson condition indicating that metabolic stress was greater for this condition than the B-Strong™ condition. This likely resulted in a larger stimulation of the afferents governing the muscle metaboreflex response, increasing cardiovascular and perceptual responses (45). Considering the width of the Hokanson cuff (18cm), the magnitude of pressure used (160 mm Hg), and the demographics of the participants, the authors of this manuscript conjecture that most were exercising very near 100% AOP. For comparison, Hughes et al. (36) used a narrower Hokanson cuff (13 cm v 18 cm width) and reported full arterial occlusion in 18 subjects at 163.33 +/- 17.06 mm Hg (36). The Hughes et al. cohort likely had higher AOP values than the Stray-Gunderson cohort given the subject pool was entirely male, had higher BMI values (23 +/-3 versus 28.94+/-3.28), and higher resting systolic blood pressure (116+/-11mm Hg versus 129+/-9 mm Hg), all factors that have been shown via direct or indirect evidence to influence AOP. Extrapolating safety and potential longitudinal outcomes given the current dearth of longitudinal research on multi-chambered bladder systems warrants caution given the likely minimal amount of pressure needed to induce beneficial adaptations and the uncertainty regarding that pressure threshold without standardization to a personalized pressure (17). Nonetheless, BFR appears to be safe across a variety of cuffs, pressure applications, and protocols (46).

Because the multi-chambered bladder system is very difficult to achieve arterial occlusion (12,14,41), studies investigating the potential relevancy of a multi-chambered bladder system have accounted for the lack of restriction capability by increasing volume performed (e.g., 3 sets of 30 repetitions compared to commonly recommended 4 sets totaling 75 repetitions in single-bladder systems) (41). To reduce flaws in comparisons between devices with different bladders, future studies should investigate the magnitude of post-exercise muscle fatigue (e.g., isometric/dynamic torque loss) following various application parameters. Of most value to practice are acute studies that compare repetitions to failure between different bladder types applied at recommended application settings (e.g., 250/350 mm Hg in multi-chambered bladder systems and 40-80% AOP in single-bladder systems) and longitudinal studies that track volume load, relevant outcomes, and occurrence of adverse events in non-failure and failure repetition schemes. These experimental designs will greatly increase practical relevancy, thus helping practitioners make informed decisions regarding the device they choose to use with their clients and patients.

Contour vs. Straight Cuff

Cuff shape has been shown to impact the amount of applied pressure needed to determine AOP (Figure 3) (47). Contour cuff shapes are longer at the top and shorter at the bottom, creating a closer fit on the limb due to differences in diameter. Contoured cuffs also can be manufactured with variable contour shape, a design feature that allows for an even more secure fit to the limb as the device fastener apparatus can account for small differences in extremity size and shape (48). Nonetheless, the difference in proximal to distal diameter of a contoured cuff reduces AOP slightly (~5.9 mm Hg) compared to a straight cuff (e.g., cuff that is similar length on the top and the bottom) (49). Further, the occlusive stimulus may be different as straight cuffs are more likely to apply asymmetric pressures to the limb given the change in limb circumference proximally to distally in the extremities (37). In at risk populations where pressures during BFR exercise may want to be minimized to theoretically enhance safety, the use of a contoured cuff may be preferred to accommodate for the conical limb shape. To date, no study has directly compared the acute and longitudinal responses to a BFR exercise regimen using cuffs of similar widths but varying in cuff shape, so this area of research is largely unknown.

INSERT FIGURE 3 HERE

Set Pressure Versus Pressure Applied to the Limb

The pressure that is set for BFR (i.e., "the set pressure") may not be the same pressure that is applied to the limb, known as the "interface pressure" (Figure 4) (36). Hughes et al. (2018) showed that when the Delfi Personalized Tourniquet device (automatic autoregulated; cuff width = 11.5 cm; contoured cuff shape) was inflated to 40% and 80% AOP, the interface pressure was 8 ± 4 mm Hg and 9 ± 4 mm Hg lower than the set pressure. Conversely, when the manual cuff (Occlusion Cuff, cuff width = 8 cm; straight cuff shape) was inflated to similar relative pressures, the interface pressure was 20 ± 10 mm Hg and 37 ± 13 mm Hg lower than the set pressure. Thus, despite personalizing the pressure to %AOP, the amount of applied pressure to the limb varied significantly between devices and may influence both acute (e.g., repetitions to failure, cardiovascular and/or perceptual experience) and longitudinal (e.g., muscle hypertrophy, muscle strength and/or vascular adaptations) outcomes. Preliminary results from Hughes et al. (2018) also indicated that cardiovascular and perceptual experiences were heightened in the manual cuff compared to the automatic autoregulated cuff when the same exercise was performed. This is likely due to a much greater interface pressure (> 37 mm Hg) compared to the set pressure during the four exercise sets, indicating that the manual cuff was applying a greater pressure to the limb during exercise than during resting conditions. In contrast, the Delfi Personalized Tourniquet device maintained the set and interface pressure during exercise that did not exceed +15 mm Hg in any of the four sets measured. However, despite setting AOP to a similar percentage based on the cuff, the comparison wasn't direct as cuff widths varied between devices, the Delfi Personalized Tourniquet device is autoregulated, and their cuff shapes varied. Insomuch as what's currently known from the devices in the consumer market, the Delfi Personalized Tourniquet device has been shown to apply a pressure within measurement error (±15 mm Hg) to the underlying limb, ensuring a stimulus that is like the set pressure during resting and exercise conditions. If possible, future studies should integrate measurements for determining interface pressures, particularly when novel devices are being investigated. Special attention should be paid to studies using lower (40-50% AOP) pressures in their lower body interventions as this may impact the clinical relevance given lower pressures in this range have been shown to be ineffective at accelerating fatigue accumulation in BFR exercise (17). If a cuff used in a lower pressure intervention was shown to be ineffective, researchers should determine if it was ineffective due to the parameters set (e.g., lower pressure) or inadequate cuff restrictive capabilities.

INSERT FIGURE 4 HERE

Presence/Absence of an Internal Stiffener

A stiffener is a feature of a tourniquet that directs the pressure from the bladder onto the limb and helps maintain the cuff's position when inflated (48). The presence of an internal stiffener may impact the degree of AOP and/or the exerciser's perceptual experiences during exercise as its presence increases the resistance to cuff deformation with muscular contraction. With respect to BFR exercise, no study has investigated the impact of an internal stiffener on cuffs with similar widths to determine its effect on acute- and longitudinal training outcomes. Future studies should determine its relevance with BFR exercise as more devices are being purchased and used in practice (3).

Bladder to Cuff Width Ratio

A cuff characteristic that is rarely reported is the bladder to cuff width ratio (Figure 5). This ratio is the percent of the cuff that the bladder makes up. The ratio is important because irrespective of cuff width, if the bladder width is significantly narrower, it may increase the amount of applied pressure needed to achieve AOP and predispose a similar stimulus as narrow cuffs. Future research studies should specify the cuff width and bladder width as cuffs with the same width may have different size bladders, impacting the transmissibility of the pressure to the exercising limb as well as related cardiovascular and perceptual responses.

INSERT FIGURE 5 HERE

Bladder Length - Circumferential vs. Partial Circumferential

The last cuff characteristic that can impact BFR exercise is the length of the bladder (Figure 6). In traditional tourniquets, the bladder circumferentially envelopes the limb. In partial circumferential bladders, the bladder does not extend the length of the cuff, leaving areas without pneumatic pressure application that instead relies on compression from the sleeve of the device. In the only published study investigating the influence of bladder location on AOP during resting blood flow restriction, Spitz et al. (2020) showed that positioning the bladder on the outside of the thigh required greater applied pressures than when the bladder was positioned on the inside of the thigh (50). As the femoral artery is located anteromedially (e.g., "inside" position) and not anterolaterally (e.g., "outside" position), a lower pressure was required to occlude the limb in the inside position. As most, but not all (e.g., Airbands/SAGA Fitness Cuffs) BFR devices on the marketplace have circumferential bladders, little is known about the acute responses associated with differences in bladder length. If bladder positioning impacts AOP in cuffs with partial circumferential bladders, this may have relevancy for clinical populations where limited applied pressure may enhance acute safety and/or longitudinal training responses. Future studies should specify positioning of the bladder when utilizing partial circumferential BFR cuffs and determine the potential relevancy of this cuff feature to BFR exercise.

INSERT FIGURE 6 HERE

Conclusion

This manuscript attempted to contextualize the potential importance of infrequently reported BFR cuff characteristics and features and hypothesize their potential impact on BFR training. As BFR continues to expand into practice, researchers should be aware of not only the importance of AOP assessment and its impact on BFR exercise responses, but of the ways that physiological responses may vary between cuffs despite standardization to %AOP. Cuffs that are unable to be standardized to a %AOP (e.g., multi-chambered bladder systems) may have clinical utility, but the current body of evidence on their efficacy is lacking and should be a focal area of future research – particularly if similar beneficial results are obtained with reductions in adverse events.

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Author Contributions

NR wrote the initial draft of the manuscript. KK and VSQ provided critical review and helped edit the manuscript for content and flow. All authors agreed to the final version of the manuscript and the statements made in the article.

Conflict of Interest

NR is the founder of The BFR PROS and teaches BFR training workshops to fitness and rehabilitation practitioners using a variety of BFR training devices. KK is a clinical instructor for Owens Recovery Science, a BFR education company that also distributes the Delfi Personalized Tourniquet Device. VSQ has no actual or potential conflicts to disclose.

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FIGURE LEGEND

Figure 1. Autoregulation of Applied Pressures. Autoregulation is a design feature that accommodates for the changes in limb circumference as a result of muscular contraction. In current available devices, the BFR cuff is attached to a pneumatic air compressor via an air tubing that adjusts according to the pressure sensed at the cuff-limb interface. The speed at which this adjustment occurs varies across devices, making it a cuff-specific feature. Autoregulation may enhance the acute safety of BFR exercise.

Figure 2. Multi-Chambered Versus Single-Chambered Bladder Cuff Design. As opposed to traditional tourniquets whose function is to occlude arterial flow, multi-chambered bladders are composed of sequential bladders that when inflated, leave regions where minimal compression occurs. This cuff feature reduces the ability for the device to occlude arterial flow making it difficult to obtain a personalized pressure. The inability to occlude has been hypothesized to enhance safety during BFR exercise.

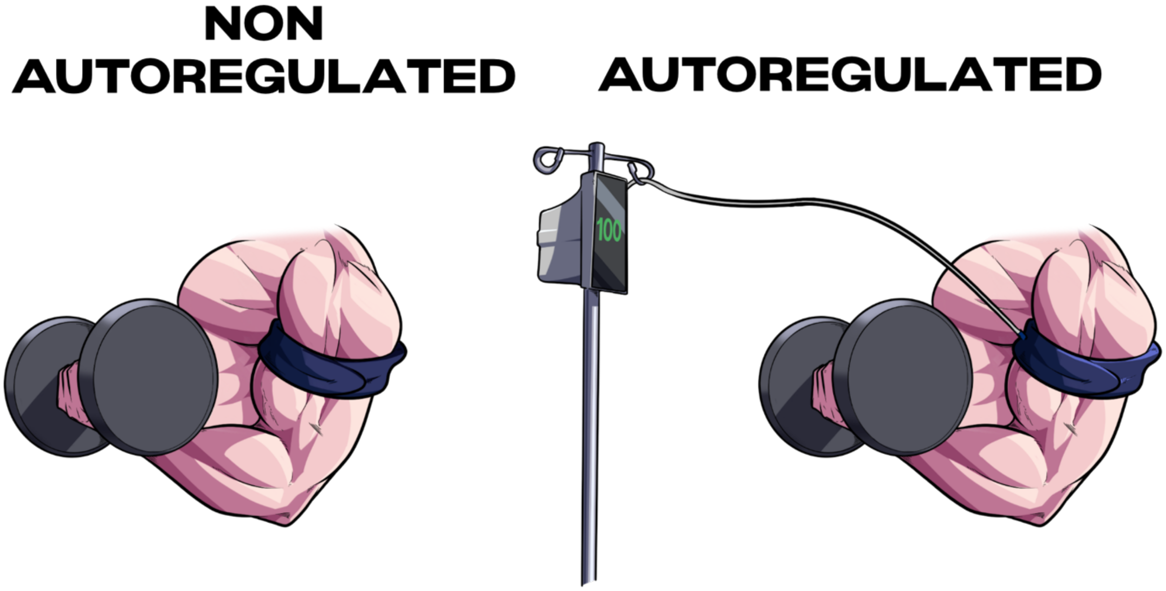
Figure 3. Differences in Limb Fit Between Contoured and Straight BFR Cuffs. Contour cuffs provide a more secure fit due to the conical shape of the limb compared to a straight cuff. This may enhance the safety profile of BFR exercise.

Figure 4. Set Pressure Versus Interface Pressure. The set pressure is the pressure that the pneumatic cuff is inflated to by the clinician/exerciser/researcher whereas the interface pressure is the amount of pressure actually applied to the limb from the cuff. Cuffs that can maintain a similar set and interface pressures may enhance acute safety of BFR exercise.

Figure 5. Bladder to Cuff Width Ratio. The cuff width is the diameter of the cuff whereas the bladder width is the diameter of the bladder. In some cuffs, the cuff width and the bladder width are not identical. As the bladder is the portion of the BFR cuff applying pressure to the limb, if there is a large difference between the cuff width and the bladder width, this may alter the AOP and the applied pressure as a %AOP, influencing the acute safety profile of BFR exercise.

Figure 6. Partial Circumferential Versus Circumferential Bladder Length. In traditional tourniquets, the bladder extends the length of the cuff (Right Image) whereas in some BFR cuffs, the bladder extends partially not covering the entirety of the length of the cuff (Left and Center Illustrations). Studies implementing BFR cuffs with partial circumference bladders should specify the position of the bladder because its placement may impact acute responses to BFR exercise.

Figure 1.



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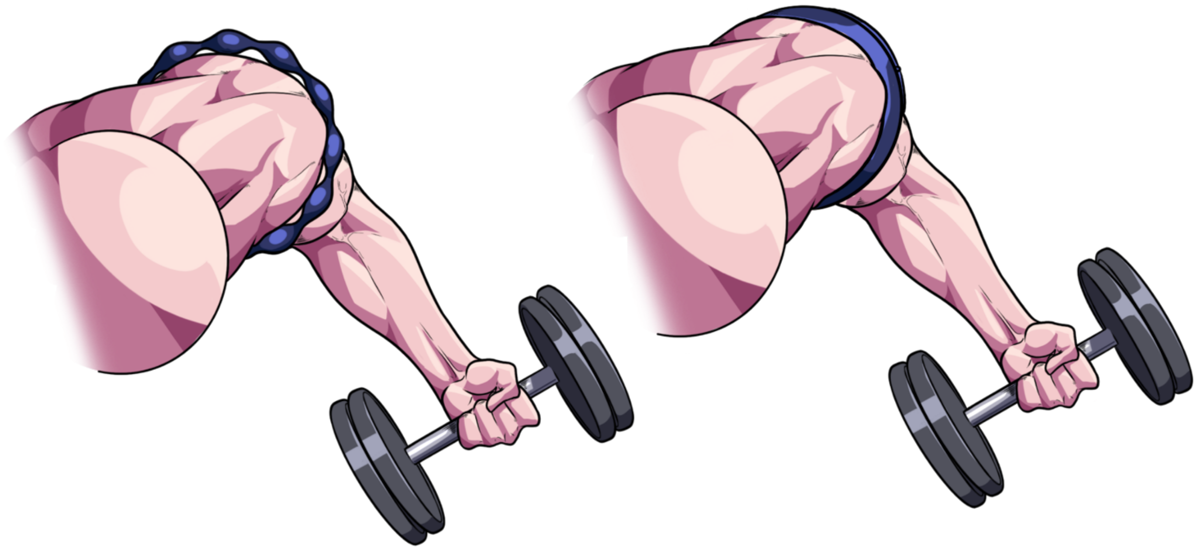

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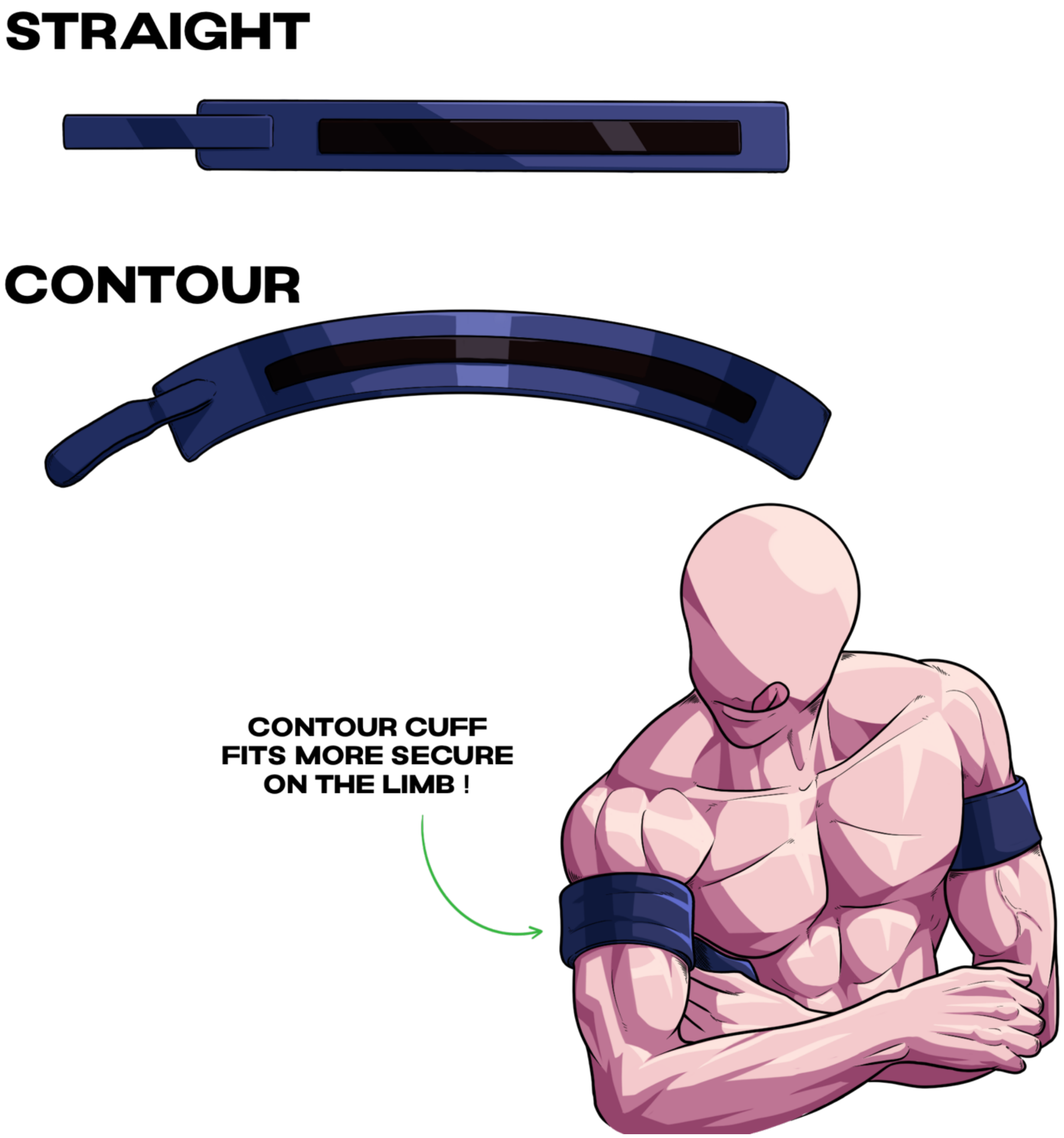

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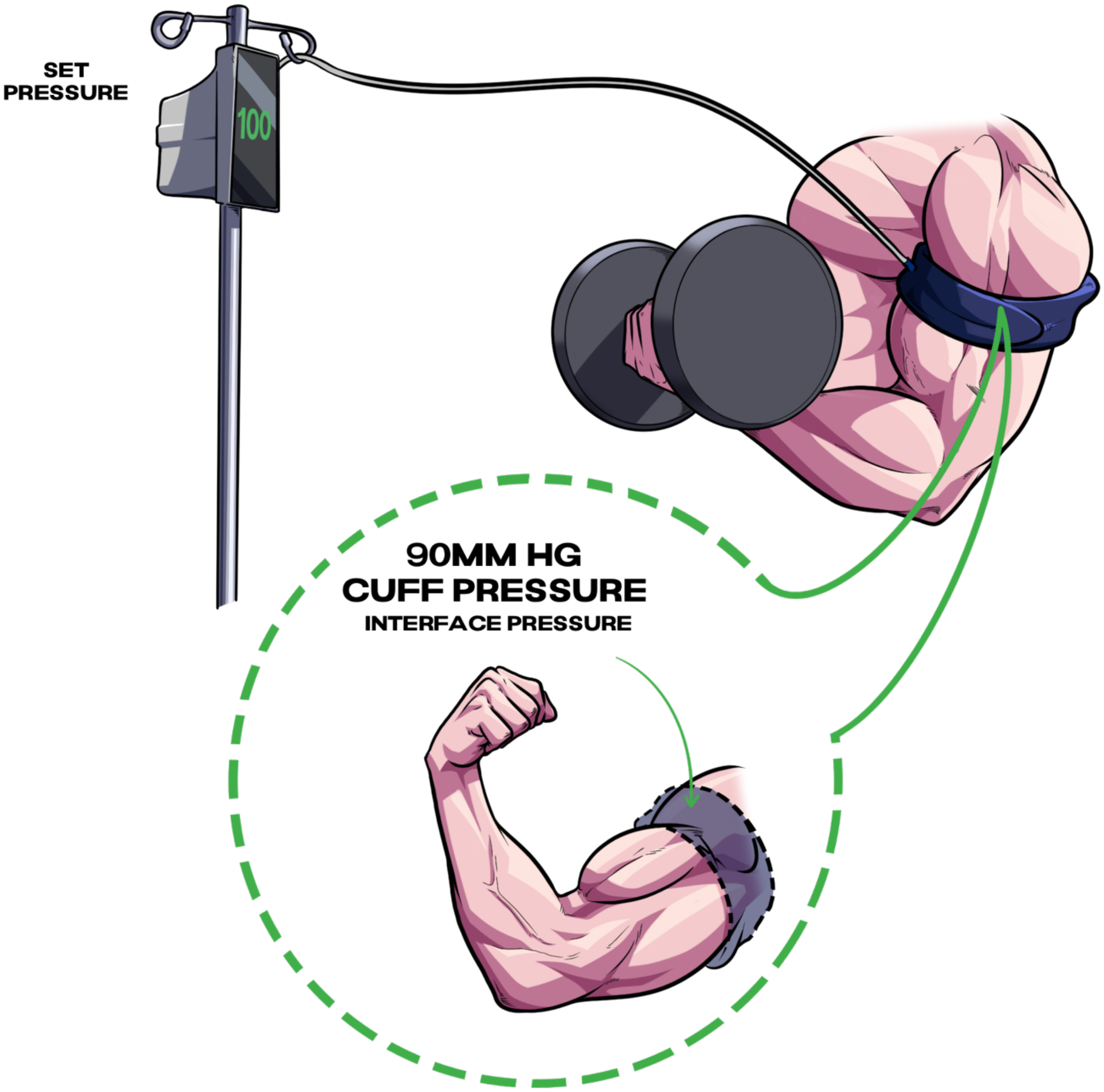
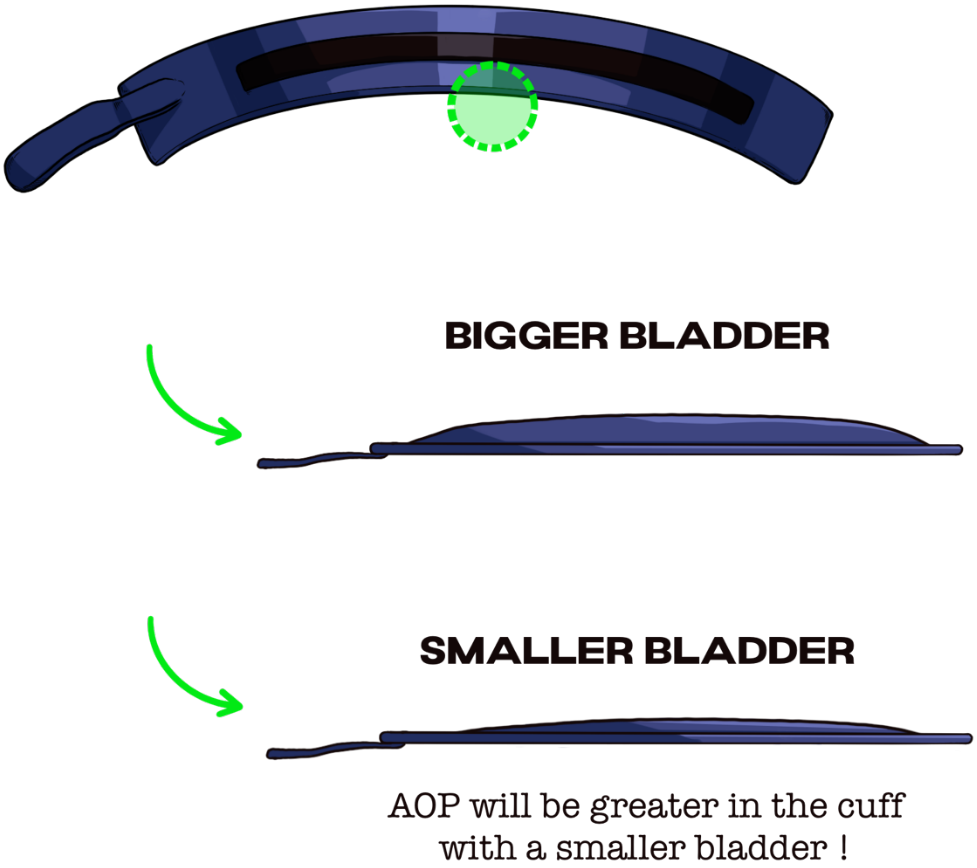
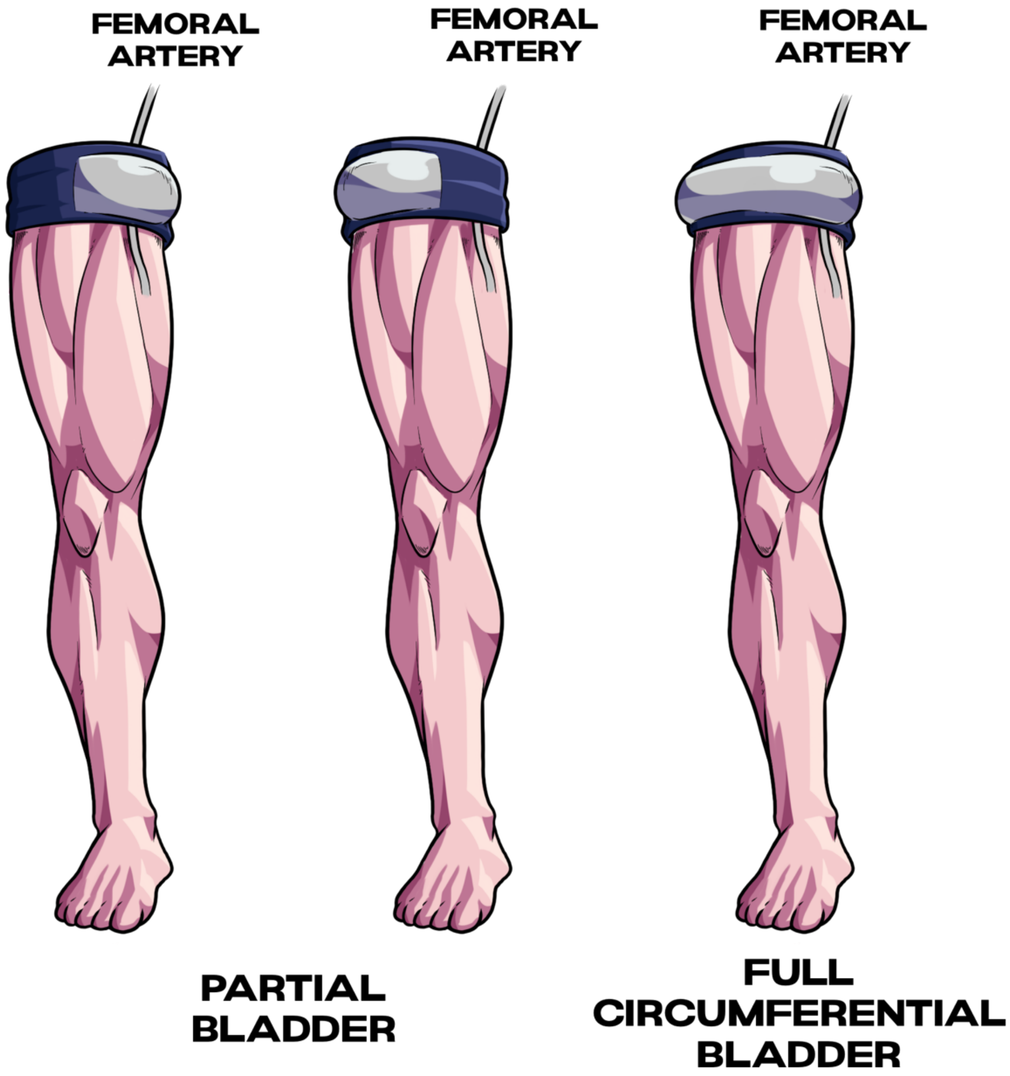


Figure 5.


BIGGER BLADDER
SMALLER BLADDER
AOP will be greater in the cuff with a smaller bladder !

654 Figure 6.



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