Technical Note

Blood Flow Restriction Therapy After Knee Surgery: Indications, Safety Considerations, and Postoperative Protocol

Nicholas N. DePhillipo, A.T.C., O.T.C., C.S.C.S., Mitchell I. Kennedy, B.S., Zachary S. Aman, B.A., Andrew S. Bernhardson, M.D., Luke O'Brien, P.T., M.Phty (Sports), S.C.S., and Robert F. LaPrade, M.D., Ph.D.

Abstract: Blood flow restriction (BFR) training involves occluding venous outflow while maintaining arterial inflow by the application of an extremity tourniquet after surgery. BFR ultimately reduces oxygen delivery to muscle cells, similar to an anaerobic environment, and allows patients to exercise with low resistance and stimulates muscle hypertrophy and strength using heavy resistance. Thus orthopaedic surgeons and physical therapists are incorporating this type of training into their postoperative rehabilitation protocols, particularly after injuries or surgical procedures about the knee joint. The purpose of this Technical Note is to describe a BFR clinical application technique and to report on the indications, safety considerations, and postoperative knee surgery rehabilitation protocols for BFR.

Blood flow restriction (BFR) therapy occludes venous outflow while restricting arterial inflow[1] by the application of an extremity tourniquet. This ultimately reduces oxygen delivery to muscle cells during low-resistance exercises. The induced anaerobic environment has been reported to promote muscle hypertrophy by initiating cell signaling[2] and hormonal changes[1,3] that stimulate protein synthesis,[2,4] proliferation of myogenic satellite cells,[5] and preferential activation and mobilization of type II muscle fibers.[3,6,7] When BFR is used as an adjunct to postoperative rehabilitation, it has been suggested that exercises performed at lower loads (20%-50% of 1 repetition maximum) can promote muscle hypertrophy similar to traditional strengthening protocols while reducing pain and adverse joint loading.[7,8]

Currently, the data regarding the efficacy of BFR as part of a rehabilitation protocol after knee surgery have been inconclusive. This may be largely attributed to the paucity of BFR studies after knee surgery, as well as the inconsistencies regarding the technical application of BFR. Furthermore, clinicians may be unaware of the recommended parameters of BFR that may improve patient safety and decrease postoperative complications after knee surgery. Therefore, the purpose of this Technical Note is to describe a clinical application technique for BFR and to report on the indications, safety considerations, and postoperative knee surgery rehabilitation protocols for BFR.

Clinical Application

Indications and Contraindications

BFR therapy is indicated after knee surgery in patients with protected weight-bearing status or muscular inhibition or those who have significant postoperative pain to resist muscular disuse atrophy. Furthermore, it is useful for patients who are attempting to restore preinjury levels of muscular strength (Fig 1). Nonetheless, there are inherent risks with BFR, and thus all patients should be assessed for the risks and contraindications to tourniquet use before BFR application. Patients possibly at risk of adverse reactions are those

From The Steadman Clinic (N.N.D., A.S.B., R.F.L.), Vail; Steadman Philippon Research Institute (M.I.K., Z.S.A., R.F.L.), Vail; and Howard Head Sports Medicine (L.O.), Vail, Colorado, U.S.A.

The authors report the following potential conflict of interest or source of funding: R.F.L. receives support from Smith & Nephew, Ossur, Arthrex. Full ICMJE author disclosure forms are available for this article online, as supplementary material.

Received April 30, 2018; accepted June 20, 2018.

Address correspondence to Robert F. LaPrade, M.D., Ph.D., The Steadman Clinic, 181 W Meadow Dr, Ste 400, Vail, CO 81657, U.S.A. E-mail: drlaprade@sprivail.org

2212-6287/18525

https://doi.org/10.1016/j.eats.2018.06.010

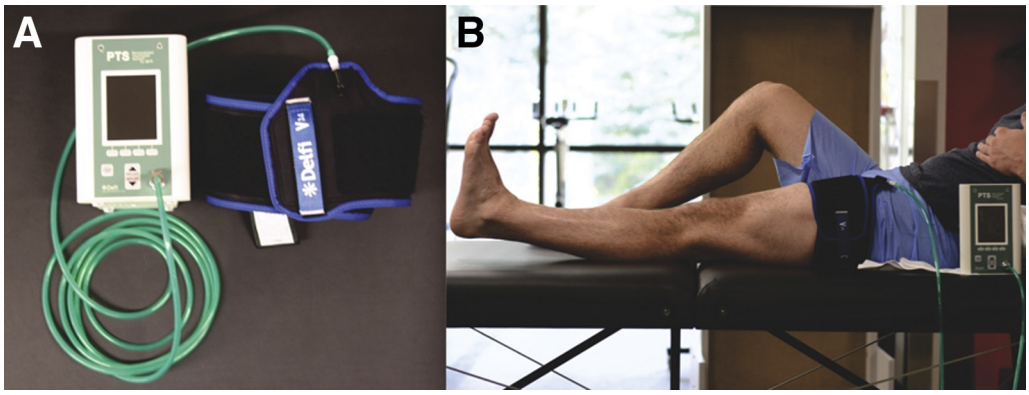

Fig 1. Blood flow restriction (BFR) therapy application. (A) Delfi Personalized Tourniquet System for BFR with pneumatic cuff (third-generation tourniquet). (B) Application of BFR during quadriceps activation exercise after arthroscopic knee surgery.

with poor circulatory systems, obesity, diabetes, arterial calcification, sickle cell trait, severe hypertension, or renal compromise.[9] Potential contraindications to consider are venous thromboembolism, peripheral vascular compromise, sickle cell anemia, extremity infection, lymphadenectomy, cancer or tumor, or medications known to increase clotting risk.[9] However, this is not an exhaustive list of patients at an increased risk of complications during BFR use, and it is recommended that all patients be prescreened before application of BFR.

Safety Considerations

It is estimated that modern pneumatic tourniquets (i.e., third-generation systems) are used in more than 1 million surgical cases per year.[10] More recent advancements in tourniquet systems allow for patient personalization and thus improve patient safety with tourniquet use (Fig 1). By using third-generation pneumatic tourniquets, the risk of tourniquet complications is very low, ranging from 0.04% to 0.8%.[11,12] However, tourniquet use has inherent risks, which include nerve injury, skin injury, increased pain, chemical burns, temperature changes, prolonged postoperative swelling, prolonged ischemia, and arterial injury.[9,10] The underlying causes of these complications include high cuff pressures, narrow cuff widths, high pressure gradients under the tourniquet, and long durations of tourniquet use.[10,13] Features such as automatically measuring the minimum pressure required for limb occlusion and recommendations of a personalized minimum pressure needed for limb occlusion allow for the reduction of the aforementioned risks.[10,13] Crenshaw et al.[14] showed that the wider the cuff, the lower the pressure required for occluding circulation (e.g., for an 18-cm-wide cuff, approximately 140 mm Hg was needed to occlude blood flow, whereas a 4.5-cm-wide cuff required >360 mm Hg of pressure). In comparison, Estebe et al.[15] found that a narrow cuff (7 cm) caused significantly more pain after reaching arterial occlusion compared with a wide cuff (14 cm). Therefore, selective use of pneumatic, wide, and contoured tourniquet cuffs can reduce tourniquet pressure levels and the applied pressure gradients.

Despite the increased risk of a postoperative deep venous thrombosis (DVT) in orthopaedic extremity surgery, use of a pneumatic tourniquet does not appear to be an independent risk factor and tourniquet deflation is instead associated with antithrombolytic factors.[10] In fact, it is well established that acute bouts of tourniquet use have fibrinolytic potential.[16-18] Furthermore, resistance exercise has been shown to stimulate the fibrinolytic system.[19] To date, BFR studies have not found potential markers of thrombus formation when specifically evaluated. Madarame et al.[20] found no increase in markers of thrombin generation or intravascular clot formation after BFR with exercise. Likewise, Clark et al.[21] did not show any changes in the fibrinogen, D-dimer, or C-reactive protein level acutely after 1 bout or after 4 weeks of BFR and high-intensity interval training. In addition, they found that the level of tissue plasminogen activator (a fibrinolytic protein) was significantly increased after BFR and high-intensity interval training. Therefore, these previous findings indicated that BFR therapy may have the potential to actually help prevent a blood clot or decrease the risk of DVT by activating proteins that are involved in the breakdown of blood clots.

Postoperative Rehabilitation Protocols

In our clinical experience, BFR is used after knee surgery for 2 primary reasons: (1) resisting muscle atrophy and (2) building muscle strength. Patients in whom BFR is prescribed for purposes of resisting atrophy include those with restrictive weight-bearing considerations and are usually in the acute and subacute healing phases after knee surgery. Patients in whom BFR is prescribed for building muscle strength include those who are fully weight bearing and

Table 1. Summary of Current Reported Postoperative Rehabilitation Protocols After Knee Surgery for BFR Therapy

Authors (Year)	Start of BFR Training Postoperatively	No. of Exercises	Exercises	Intensity (Sets × Repetitions)	Frequency	Occlusion Time	Occlusion Pressure	Cuff Width	Duration of BFR Treatment
Iversen et al.[22] (2016)	2 d	3	Isometric quadriceps contractions, terminal knee extensions, straight-leg raises	5 × 20	2× per day, consecutive	5 min of occlusion, followed by 3 min of reperfusion	130-180 mm Hg	14 cm	2 wk
Ohta et al.[23] (2003)	2 wk	7	Straight-leg raises, hip abduction, hip adduction, half squats, step-ups, knee flexion with elastic tubing, knee-bending walking	1-3 × 20-60	1× per day, 6 d/wk	NR	180 mm Hg	NR	16 wk
Takarada et al.[1] (2000)	0 d	NA	NA	5 × 5 min	2× per day, consecutive	5 min of occlusion, followed by 3 min of reperfusion	200-260 mm Hg	9 cm	2 wk
Tennent et al.[24] (2017)	2 wk	3	Leg presses, leg extensions, reverse presses	4 × 30, 15, 15, and 15	1× per day, 4 d/wk	5-min occlusion period and 1 min of reperfusion	80% of total LOP	Same width used for all patients	3 wk

BFR, blood flow restriction; LOP, limb occlusion pressure; NA, not applicable; NR, not reported.

Fig 2. The components of blood flow restriction (BFR) consist of a personalized tourniquet system (A), which tailors the personalized tourniquet pressure to each patient after determination of the limb occlusion pressure, and a contoured tourniquet cuff (B), which is available in 3 different lengths (length use is dependent on patient thigh size). These components are then connected by a hose assembly. * indicates the contoured strap of the personalized tourniquet.

are usually in the remodeling phase of healing postoperatively. Table 1 provides a summary of the current reported postoperative rehabilitation protocols after knee surgery for BFR therapy.

BFR components consist of a personalized tourniquet system and a tourniquet cuff, which are connected by a hose assembly (Fig 2, Video 1). Before use, the BFR system should be inspected to verify cleanliness and examine for defects such as cracks or holes in the tubing that can cause leakage or malfunctioning. Next, one should test the tourniquet instrumentation including the BFR cuff and connecting tubing to ensure it is working properly. The tourniquet cuff should be

Table 2. BFR Training Postoperative Protocols

Protocol	Frequency	Duration	Pressure	Intensity	Rest Period	Volume	Exercise Progression
Resisting muscle atrophy	3-6 d/wk	6-12 wk	Personalized, 80% of total LOP	Body weight with minimal to no resistance	15-30 s with cuff inflated	4 sets of 30, 15, 15, and 15 repetitions	Resisted weight-bearing exercise when treatment focus is muscle strength
Building muscle strength	3-6 d/wk	6-12 wk	Personalized, 80% of total LOP	≤30% of 1 RM	30-45 s with cuff inflated	4 sets of 30, 15, 15, and 15 repetitions	Discontinue BFR when treatment focus is muscle power

NOTE. Resisting muscle atrophy is desired for patients who have weight-bearing restrictions and are in the acute or subacute phase of healing. Building muscle strength involves patients who are fully weight bearing and are usually in the remodeling phase of healing postoperatively.
BFR, blood flow restriction; LOP, limb occlusion pressure; RM, repetition maximum.

applied to the most proximal portion of the upper thigh and secured tightly; one should avoid placing the cuff too close to the knee joint, which can be associated with a potentially increased risk of direct nerve compression and injury.[25] A protective sleeve should be used between the cuff and skin to protect against wrinkling, pinching, or shearing of the skin and soft tissues. The cuff port connector should always be placed on the lateral aspect of the limb to avoid hose kinking or undue pressure on the superficial nerves. Last, when using a third-generation pneumatic system with built-in Doppler ultrasound (e.g., Delfi Personalized Tourniquet System; Delfi Medical), one should determine the limb occlusion pressure (LOP) before exercise. The recommended percentage of total LOP is 80% and should be calibrated with the patient lying completely supine and being instructed to remain as still as possible during this automatic calculation. Table 2 outlines our prescribed exercise protocols for BFR after knee surgery.

BFR is prescribed after knee surgery for either resisting the effects of disuse atrophy or building strength to restore muscle to preinjury levels (Fig 3). During the early phases of healing, body-weight exercises are prescribed with minimal to no resistance. Because there is minimal tissue damage associated with using low- or no-load strengthening, treatment can focus on the same muscle groups for multiple days in a row. Exercises focus on low-load activities such as quadriceps sets, terminal knee extensions, or spinning on a stationary bike for body weight—restrictive patients. Body-weight closed kinetic chain exercises are prescribed for patients who are ambulating with full weight bearing. The exercise volume, including the number of sets and repetitions, should focus on building muscle endurance, using a high number of repetitions and short rest periods between sets. Rest periods should be altered as needed if the patient is missing his or her target sets and/or repetitions. A 2-second concentric contraction followed by a 2-second eccentric contraction is performed to stimulate a metabolic

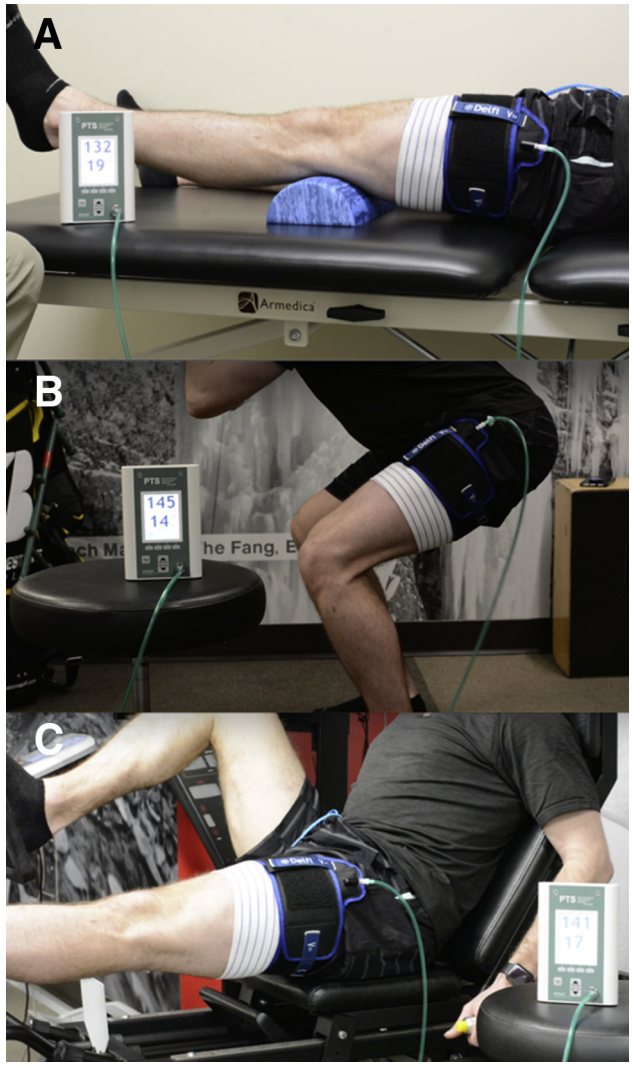

Fig 3. The immediate postoperative condition of non—weight-bearing protocols should be maintained while using blood flow restriction (BFR), having the patient engage in low-load activities (A) strictly consisting of muscle contractions. Patients may later progress to body-weight closed kinetic chain exercises (B) when advanced to weight-bearing protocols and further to low-resistance exercises (C) once postoperative restrictions are reduced.

Table 3. Pearls and Pitfalls

Pearls	Pitfalls
For the sake of limb protection, the tourniquet cuff should be applied to the most proximal portion of the thigh.	An inability to occlude blood flow to the trunk musculature may occur, which may limit proximal gains such as strength to the hip abductors.
Wider tourniquet cuffs should be used to reduce potential complications including increased pain.	Narrow cuffs may increase complications such as increased pain after use.
The tourniquet pressure should be patient specific and based on total limb occlusion pressure, with 80% recommended for lower-extremity tourniquet use.	High pressure gradients may cause complications such as nerve injury and limb ischemia.
Limb occlusion pressure should always be tested supine with the patient as still as possible.	Third-generation tourniquet systems are expensive.
The patient should perform 4 sets of 30, 15, 15, and 15 repetitions with a 30-s rest between sets and a 2-s concentric and 2-s eccentric contraction for a metabolic response.	
The rest period should be manipulated first if the patient is missing his or her target.	

response. The reported key point to achieve a metabolic response is to achieve high volumes with light loads. Exercise progression for patients in this phase should strive for sufficient muscular endurance with no weight-bearing restrictions; when appropriate, patients may progress to resisted weight-bearing exercises and transition to a muscular-strength treatment focus (Table 3).

For patients in the later phases of healing who are fully weight bearing with fewer postoperative restrictions, low-resistance exercises are used, with a volume of 30% of 1 repetition maximum or less. If daily BFR is performed, the muscle groups should be alternated for each daily session (i.e., quadriceps then hamstrings). Low-load weight-bearing or resisted exercises such as leg presses, dead lifts, or lunges are prescribed. The exercise volume, including the number of sets and repetitions, should focus on building muscle strength with moderate to high repetitions and slightly longer rest periods. Once sufficient strength and hypertrophy gains have been made, the clinician can discontinue BFR use for the development of muscular power (Table 4).

Discussion

The most important finding of this report is that BFR after knee surgery may be a viable modality to incorporate into the postoperative rehabilitation protocol for patients who require extra assistance in resisting muscle atrophy or building muscle strength. BFR seems to be safe to incorporate after knee surgery, with no reported increased risk of DVT. However, there is a lack of consistency and standardization regarding BFR protocols for postoperative knee rehabilitation, so definitive programs cannot be determined. Nonetheless, BFR training may be beneficial to incorporate into postoperative rehabilitation plans after arthroscopic knee surgery to help counter the adverse effects associated with muscular atrophy.

We believe that the preferred postoperative knee BFR exercise regimens may be patient specific depending on the surgical procedure and postoperative limitations. Currently, the literature lacks consistency regarding postoperative BFR protocols after knee surgery. Exercise intensity has been described either by a specific repetition range[22-24] or for a prolonged duration.[1] The most consistent exercises reported are knee extensions, leg presses, straight-leg raises, and reverse lunges; however, no evidence exists regarding the preferred exercise regimen. The reported exercise frequency with BFR also varies greatly, with reports of 1 session per day[23,24] to 2 sessions per day,[1,22] anywhere from 4 to 7 days per week.[1,22-24] We theorize that the specific exercise protocol used may be less important than the exercise parameters implemented to bring about a state of anabolic metabolism.

Occlusion pressure and cuff width are 2 variables that have been reported to influence patient outcomes during administration of BFR.[24,26] Loenneke et al.[26] reported that wide BFR cuffs restrict arterial blood flow at a lower pressure than narrow BFR cuffs, and restrictive cuff pressures of high magnitude

Table 4. Advantages and Disadvantages

Advantages	Disadvantages
Can increase muscular strength with low resistance after surgically related knee procedures	May yield only short-term improvements (2-16 wk)
Can counteract muscle atrophy after knee surgery	Can cause inadvertent increase in muscular pain
Can begin immediately after knee surgery	May cause prolonged swelling postoperatively

(160-240 mm Hg) may cause complete ischemia in some individuals depending on the limb size. They recommended obtaining an arterial occlusion measurement at rest and using a percentage of that measurement for the prescribed BFR pressure that is patient specific. Only 1 study in the current literature has reported an occlusion pressure based on the patient's specific total LOP when investigating BFR after knee surgery.[24]

The timing of the initiation of BFR postoperatively has been reported to range from immediately after surgery (day 0)[1] to 2 weeks after surgery,[23,24] with no complications or adverse effects (e.g., DVT) reported. Thus BFR appears to be a safe therapy intervention used postoperatively after arthroscopic knee surgery, with no reported increased risk of DVT development, and can begin immediately after knee surgery. However, the duration of BFR treatment postoperatively varies greatly in the literature, with a range of 2 weeks[1,22] to 16 weeks.[23] Ohta et al.[23] conducted a Level I randomized controlled trial and reported significant increases in thigh muscle cross-sectional area after a 16-week BFR intervention. Three other studies that used BFR after knee surgery reported prescribing interventions for 2- or 3-week periods[1,22,24]; however, muscle atrophy still occurred when compared with baseline measurements. Thus BFR training for less than 3 weeks does not seem to completely eliminate muscle atrophy postoperatively. However, 2 of these studies reported significant reductions in the extent of muscle atrophy after knee surgery compared with matched controls,[1,24] whereas 1 study reported no difference in the amount of muscle atrophy.[22]

The current literature indicates that BFR is a safe intervention that may improve muscle strength and atrophy after knee surgery compared with traditional therapy. However, the improvements are shown in the short term (2-16 weeks) only, with a paucity of literature overall. There is also inconsistency regarding postoperative knee rehabilitation protocols that have used BFR. However, there appears to be clinical evidence suggesting that BFR training for less than 2 weeks is not sufficient for increasing muscle strength and/or size. Postoperative knee surgery protocols should incorporate patient-specific pressures and avoid generalized and/or predetermined pressures. Future research is needed to evaluate the efficacy of BFR regarding delayed muscle atrophy, particularly in patients who are non−weight bearing after knee surgery.

References

1. Takarada Y, Takazawa H, Ishii N. Applications of vascular occlusion diminish disuse atrophy of knee extensor muscles. *Med Sci Sports Exerc* 2000;32:2035-2039.
2. Gundermann DM, Walker DK, Reidy PT, et al. Activation of mTORC1 signaling and protein synthesis in human muscle following blood flow restriction exercise is inhibited by rapamycin. *Am J Physiol Endocrinol Metab* 2014;306:E1198-E1204.
3. Loenneke JP, Fahs CA, Wilson JM, Bemben MG. Blood flow restriction: The metabolite/volume threshold theory. *Med Hypotheses* 2011;77:748-752.
4. Fry CS, Rasmussen BB. Skeletal muscle protein balance and metabolism in the elderly. *Curr Aging Sci* 2011;4:260-268.
5. Nielsen JL, Aagaard P, Bech RD, et al. Proliferation of myogenic stem cells in human skeletal muscle in response to low-load resistance training with blood flow restriction. *J Physiol* 2012;590:4351-4361.
6. Moritani T, Sherman WM, Shibata M, Matsumoto T, Shinohara M. Oxygen availability and motor unit activity in humans. *Eur J Appl Physiol Occup Physiol* 1992;64:552-556.
7. Wernbom M, Augustsson J, Raastad T. Ischemic strength training: A low-load alternative to heavy resistance exercise? *Scand J Med Sci Sports* 2008;18:401-416.
8. Yasuda T, Ogasawara R, Sakamaki M, Ozaki H, Sato Y, Abe T. Combined effects of low-intensity blood flow restriction training and high-intensity resistance training on muscle strength and size. *Eur J Appl Physiol* 2011;111:2525-2533.
9. Association of Operating Room Nurses. Recommended practices for use of the pneumatic tourniquet in the preoperative practice setting. In: *Preoperative standards and recommended practices for inpatient and ambulatory settings*. Denver, CO: AORN Inc, 2014;183-208.
10. Noordin S, McEwen JA, Kragh JF Jr, Eisen A, Masri BA. Surgical tourniquets in orthopaedics. *J Bone Joint Surg Am* 2009;91:2958-2967.
11. Odinsson A, Finsen V. Tourniquet use and its complications in Norway. *J Bone Joint Surg Br* 2006;88:1090-1092.
12. Kalla TP, Younger A, McEwen JA, Inkpen K. Survey of tourniquet use in podiatric surgery. *J Foot Ankle Surg* 2003;42:68-76.
13. Loenneke JP, Wilson JM, Wilson GJ, Pujol TJ, Bemben MG. Potential safety issues with blood flow restriction training. *Scand J Med Sci Sports* 2011;21:510-518.
14. Crenshaw AG, Hargens AR, Gershuni DH, Rydevik B. Wide tourniquet cuffs more effective at lower inflation pressures. *Acta Orthop Scand* 1988;59:447-451.
15. Estebe JP, Le Naoures A, Chemaly L, Ecoffey C. Tourniquet pain in a volunteer study: Effect of changes in cuff width and pressure. *Anaesthesia* 2000;55:21-26.
16. Robertson BR, Pandolfi M, Nilsson IM. "Fibrinolytic capacity" in healthy volunteers as estimated from effect of venous occlusion of arms. *Acta Chir Scand* 1972;138:429-436.
17. Shaper AG, Marsh NA, Patel I, Kater F. Response of fibrinolytic activity to venous occlusion. *Br Med J* 1975;3:571-573.
18. Stegnar M, Pentek M. Fibrinolytic response to venous occlusion in healthy subjects: Relationship to age, gender, body weight, blood lipids and insulin. *Thromb Res* 1993;69:81-92.

19. deJong AT, Womack CJ, Perrine JA, Franklin BA. Hemostatic responses to resistance training in patients with coronary artery disease. *J Cardiopulm Rehabil* 2006;26:80-83.
20. Madarame H, Sasaki K, Ishii N. Endocrine responses to upper- and lower-limb resistance exercises with blood flow restriction. *Acta Physiol Hung* 2010;97:192-200.
21. Clark BC, Manini TM, Hoffman RL, et al. Relative safety of 4 weeks of blood flow-restricted resistance exercise in young, healthy adults. *Scand J Med Sci Sports* 2011;21:653-662.
22. Iversen E, Røstad V, Larmo A. Intermittent blood flow restriction does not reduce muscle atrophy following anterior cruciate ligament reconstruction. *J Sport Health Sci* 2016;5:115-118.
23. Ohta H, Kurosawa H, Ikeda H, Iwase Y, Satou N, Nakamura S. Low-load resistance muscular training with moderate restriction of blood flow after anterior cruciate ligament reconstruction. *Acta Orthop Scand* 2003;74:62-68.
24. Tennent DJ, Hylden CM, Johnson AE, Burns TC, Wilken JM, Owens JG. Blood flow restriction training after knee arthroscopy: A randomized controlled pilot study. *Clin J Sport Med* 2017;27:245-252.
25. Sharma JP, Salhotra R. Tourniquets in orthopedic surgery. *Indian J Orthop* 2012;46:377-383.
26. Loenneke JP, Fahs CA, Rossow LM, et al. Effects of cuff width on arterial occlusion: Implications for blood flow restricted exercise. *Eur J Appl Physiol* 2012;112:2903-2912.