Biomechanical Effects of Blood Flow Restriction Training after ACL Reconstruction

SCOTT TELFER, JOHN CALHOUN, JOSEPH J. BIGHAM, SIMRAN MAND, JOSHUA M. GELLERT, MIA S. HAGEN, CHRISTOPHER Y. KWEON, and ALBERT O. GEE

Department of Orthopaedics and Sports Medicine, University of Washington Medical Center, Seattle, WA

ABSTRACT

TELFER, S., J. CALHOUN, J. J. BIGHAM, S. MAND, J. M. GELLERT, M. S. HAGEN, C. Y. KWEON, and A. O. GEE. Biomechanical Effects of Blood Flow Restriction Training after ACL Reconstruction. *Med. Sci. Sports Exerc.*, Vol. 53, No. 1, pp. 115–123, 2021. **Introduction:** After anterior cruciate ligament reconstruction surgery, returning the knee to previous levels of strength and function is challenging, with the failure to do so associated with an increased risk of reinjury and long-term degenerative problems. Blood flow restriction (BFR) is gaining popularity as a rehabilitation technique; however, its effects on the mechanics of these exercises have not been fully explored. In this study, we aimed to determine the acute effects of BFR on the performance of a step-up exercise protocol and to assess the acceptability of the technique. **Methods:** Twenty individuals (12 female/8 male; mean age, 30.6 yr) who had recently undergone anterior cruciate ligament reconstruction and 20 controls (11 female/9 male, mean age 28.0 yr) performed a step-up exercise protocol with and without BFR. Lower limb kinematics and kinetics were measured and compared between groups and conditions. Testing was completed in June 2019. **Results:** Participants in both groups had increased external rotation of the tibia of 2° ($P < 0.001$) and reductions in knee flexion and rotation torques around the joint of around 50% ($P < 0.001$) when using BFR compared with nonrestricted step-up exercise. The intervention was found to increase the difficulty of the exercise and induce moderate levels of discomfort ($P < 0.001$). **Conclusion:** The present study provides cautious support for the use of BFR, showing that there are minimal changes in knee joint mechanics when performing the same exercise without BFR, and that the changes do not increase joint torques at the knee. From an acute biomechanical perspective, the intervention appears safe to use under qualified supervision; however, effects of repetitive use and long-term outcomes should be monitored. **Key Words:** BLOOD FLOW RESTRICTION, ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION, REHABILITATION, BIOMECHANICS

Anterior cruciate ligament reconstruction (ACLR) is one of the most common surgical procedures performed on the knee. Returning the joint to full strength and function after surgery is challenging, with muscle weakness, even 12 months postoperatively, often present in these individuals (1,2). This weakness may be associated with an increased risk of reinjury (3), and also the long-term development of knee osteoarthritis, with 50% of patients developing this condition after ACLR injury (4), an approximately sixfold increase compared with the general population (5).

To elicit significant muscle hypertrophy and increases in strength, it is widely accepted that heavy load (~70% of one repetition maximum) resistance exercises are necessary (6). In the context of individuals recovering from injury, or people with reduced neuromuscular control, exercises using these high loads are considered unsafe and may increase the risk of reinjury (7). Blood flow restriction (BFR) is an established training technique where the blood supply to and from the muscles being targeted by the exercise is limited using an external device (8). This technique has received increased attention from the rehabilitation community in recent years, with results suggesting that atrophy can be limited and strength ultimately increased while performing exercises that use considerably lower weights than heavy load resistance training, therefore reducing the stresses on the joint (8). Although the exact mechanism of action is yet to be fully elucidated, it is thought that the combined effects of mechanical tension from the exercise and the metabolic stress induced by the restriction in blood flow combine to activate cellular mechanisms that produce muscle growth (9,10). Modern BFR systems are able to regulate the level of restriction, measured in terms of limb occlusion pressure, in a highly controlled manner, allowing complete venous and partial arterial occlusion (11).

A recent systematic review and meta-analysis concluded that low-load BFR-augmented training was more effective than standard low-load training and was tolerable for patients, making it a potential tool to aid in clinical rehabilitation after ACLR (8). However, the nature of the intervention means that it has the potential to affect how the exercise is performed,

Address for correspondence: Scott Telfer, Eng.D., Department of Orthopaedics and Sports Medicine, University of Washington Medical Center, 1959 NE Pacific Street, Seattle, WA 98195; E-mail: telfers@uw.edu.
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either through movement control or excessive fatigue, and this may place abnormal loads on the recovering joint. Previous studies have suggested that performing exercises in a fatigued state may result in movements that increase the risk of knee injury (12,13). For ACL injuries, it has been proposed that fatigue leads to suboptimal muscle activation and, therefore, inadequate joint stabilization (14,15).

Our aim in this study was to assess the acute effects of BFR on knee and hip kinematics and kinetics during a standardized, step-up exercise procedure common in ACLR rehabilitation protocols. We hypothesized that BFR would significantly affect knee and hip kinematics and kinetics as compared with a nonrestricted state, and that kinematics and kinetics in each state would differ significantly between healthy individuals and those who have undergone recent ACLR. We also report on the acceptability of BFR use during exercise in terms of difficulty and discomfort and willingness of ACLR patients to use BFR in their postoperative rehabilitation.

METHODS

Study design. This was a cross-sectional motion analysis study where repeated measures were taken within a test single session. The institutional review board at the University of Washington approved all recruitment and testing procedures (reference no. STUDY00004543), and participants provided written, informed consent upon enrollment.

Population. Participants in the ACLR group were recruited from the Sports Medicine Clinic at the University of Washington Medical Center between July 2018 and March 2019. These individuals were eligible to participate if they were 12–15 wk post-ACLR surgery and had approval from their attending physician that their rehabilitation was progressing satisfactorily. At this stage after surgery, the risk of reinjury when performing the exercise was considered extremely low. All participants were following a progressive rehabilitation program aimed at restoring strength and neuromuscular control to the repaired limb. Potential participants were not eligible for the study if they had any other orthopedic or neurological condition(s) that may have affected the standard ACLR rehabilitation protocol, including multiligamentous injury, meniscal transplant, osteotomy, cartilage transfer surgery, or fracture. Those undergoing simultaneous meniscal repair with the ACLR were considered eligible if they had approval from their attending physician, who agreed that they would be able to safely complete the required test protocol. Patellar tendon autograft, hamstring autograft, and allograft ACLR were included. Participants for the control group were recruited from the staff and student bodies at the University of Washington, had no recent orthopedic or neurological condition affecting their lower extremity, no history of lower extremity surgery, and considered themselves able to complete the exercise procedure.

Data collection. Testing consisted of a single visit to a motion analysis laboratory. Before testing, demographic details were collected, and the IKDC questionnaire (16), a validated tool for determining patient-reported knee function after injury (17), was completed by the test subject. For the ACLR group, the operative knee was the test limb; for the control group, a coin toss was used to randomly select the leg to be tested.

The BFR pressure cuff was positioned around the upper thigh of the test leg and secured in place, following the instructions provided by the system manufacturer (Owens Recovery Science, Inc., San Antonio, TX). With the participant lying supine and instructed to remain quiet and motionless, the cuff pressure was calibrated to the individual, and 80% limb occlusion pressure was determined. This level of pressure has evidence to support its efficiency at improving muscle strength (11).

Retroreflective markers were placed on the body to track trunk, pelvis, thigh, shank, and foot segments following the Plug in Gait model (18). An eight-camera Vicon system (Vicon Ltd., Oxford, UK) recording at 100 Hz was used to record the spatial positions of these markers during the exercise procedures. This system has been shown to be suitable for these types of measurements (19).

Two adjacent force plates (Type 9287BA; Kistler Instrument Corp., Amherst, NY) in the center of the motion capture area were used to measure ground reaction forces at a frequency of 1000 Hz during the data collection. A 200-mm-high box was fixed securely on one of the force plates, and during the exercise, the participant stepped from one force plate on to the other.

The tested exercise was a step-up onto the 200-mm box, where participants stepped up leading with the test leg, then stepped back down leading with the contralateral leg (see Video, Supplemental Digital Content 1, step-up exercise, http://links.lww.com/MSS/C43). The step-up is a widely used exercise in ACLR rehabilitation and is intended to increase muscle strength, endurance, and joint control in the repaired limb (20). The exercise was performed at a speed of approximately one full stepping cycle every 4 s. Pacing was maintained via a metronome set at 2-s intervals. The test procedure, commonly recommended for BFR training protocols (11), consisted of 30 step-up exercises, a 30-s break (while standing), then 3 sets of 15 step-ups, each separated by a 30-s standing break. No additional weights were used during the exercise. The full procedure took approximately 7 min to complete.

The test procedure was repeated twice by each participant. Preliminary testing found that the BFR-augmented procedure was likely to bring the muscles in the test leg to a fatigue state. Therefore, to avoid this potentially confounding factor, each participant carried out the procedure in the no-restriction condition first, followed by a 5-min seated break, then they repeated the procedure while BFR was applied. The contralateral leg was not tested to minimize the burden on the participants.

TABLE 1. Participant demographics.

	Group	
	ACLR (n = 20)	Control (n = 20)
Age (yr)	30.6 (range 21–50)	28.0 (range 19–48)
Sex	12F/8M	11F/9M
Mass (kg)	70.4 (range 55.3–90.4)	71.0 (range 55.8–106.0)
Height (m)	1.70 (range 1.52–1.82)	1.71 (range 1.52–1.96)
Body mass index (kg·m^{-2})	23.5 (range 18.5–30.1)	24.5 (range 20.5–30.4)
IKDC score	56 (range 50–66)	99 (range 92–100)
80% limb occlusion pressure (mm Hg)	137 (range 117–147)	139 (range 108–163)

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Immediately after completing the test protocol for each condition (no-restriction and BFR), participants were asked to rate both the discomfort and the difficulty of the exercise on a 0–10 numerical analog scale, with 0 being not at all uncomfortable/difficult, and 10 being the most uncomfortable/difficult imaginable. In addition, after all testing was complete, participants in the patient group were given a lay description of a potential randomized controlled trial design of BFR versus standard care after ACLR and asked if, having experienced the intervention, they would have been willing to volunteer for such a trial had it been offered before beginning their rehabilitation.

Data processing. Kinematic and kinetic data were processed in Visual 3D (V6; C-Motion Inc., Germantown, MA). Hip and knee joints were defined based on functional methods (21). Joint angles and moments were presented relative to the proximal segment, and an X-Y-Z angle sequence was used to calculate movement in the relevant anatomical planes. Kinematic waveforms were determined for the stepping phase of the exercise. This was defined as starting at the initial contact of the test limb on the 200-mm step until the time when the test leg was no longer in contact with the step. Kinetic waveforms were determined for the concentric and eccentric phases of the exercise cycle, i.e., when only the test foot was in contact with the step. Specifically, the concentric phase was defined from contact of the test limb on the step, until the contralateral foot made contact with the step, and the eccentric phase as the point

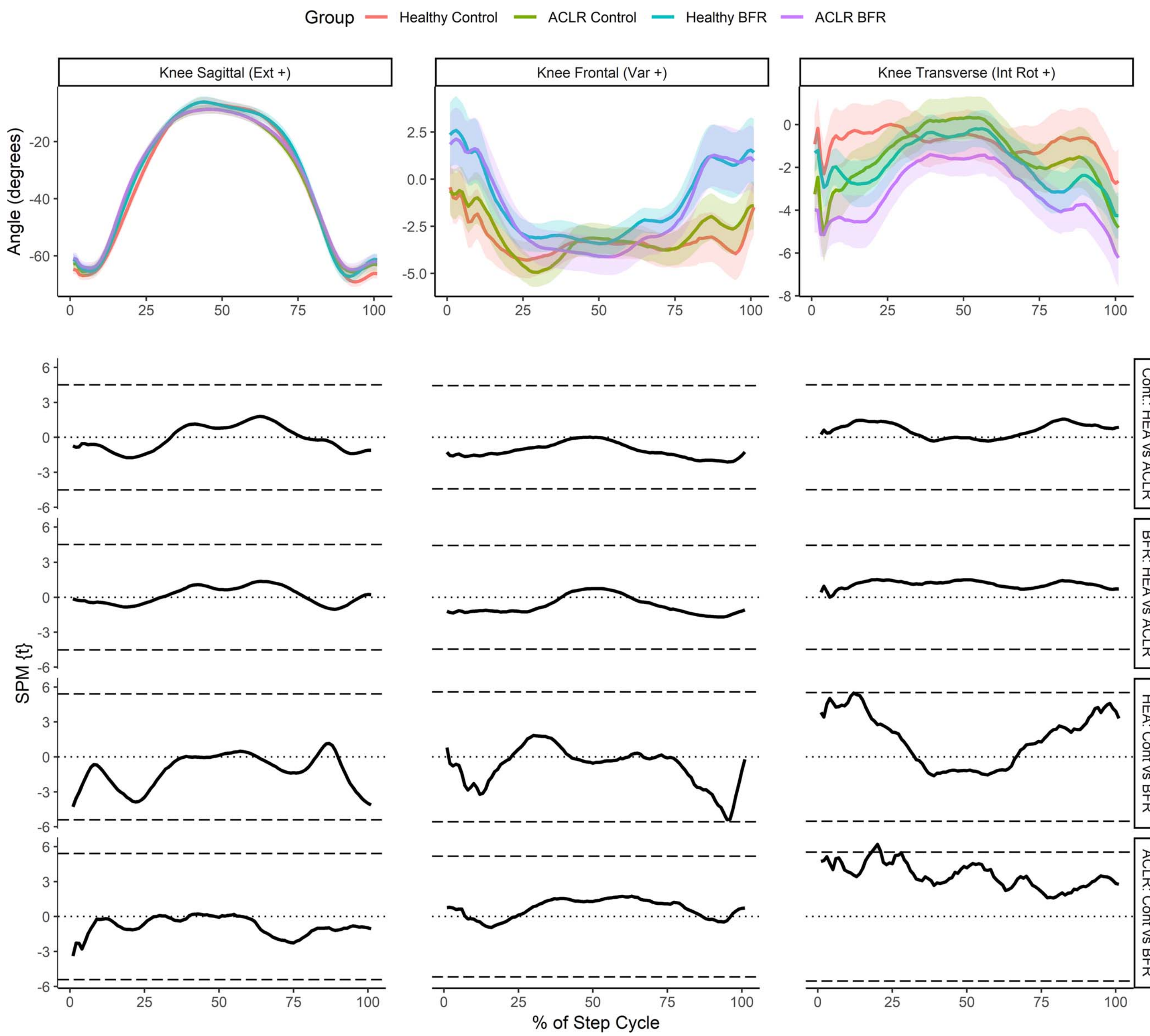

FIGURE 1—Results for knee kinematics. Columns represent the three anatomical planes of motion. Top row: mean motion curves for groups/conditions. Rows 2–5: results from statistical parametric mapping analysis (SPM{t}) with comparisons between groups/conditions described on the right side. Significance levels are indicated by the *large dashed lines*. HEA, healthy group; ACLR, anterior cruciate ligament reconstruction group; Cont., control exercise; BFR, blood flow restriction exercise; Ext, extension; Var, varus; Int Rot, internal rotation.

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when the contralateral foot left the step until the test foot was no longer in contact with the step. Data were temporally normalized across participants.

Kinematic and kinetic variables were calculated in the three anatomic planes of motion at the knee and hip joints for the test leg. There is evidence in the literature for a number of these variables being altered in stepping after ACL injury and subsequent repair (22–25). For each participant, the mean waveforms of these variables were determined for the last 12 step cycles of the final 15-step stage of the procedure. The final set of step-ups was used as this is the stage of the exercise procedure when the subject is most tired and differences in movements are most likely to be apparent. Moments were normalized to the participant's body mass.

Data analysis. For the biomechanical variables, two primary sets of statistical comparisons were performed. First, the healthy and ACLR group were compared with each other for the final set of step-ups during both the control and the BFR exercise conditions. Then, both groups were compared between the control and the BFR conditions for the same time point (repeated measures). Statistical parametric mapping (26), a technique that allows the temporal data such as that collected during this type of biomechanical study to be compared, was used to test for statistically significant differences between the kinematic and the kinetic waveforms. This approach allowed the full data set to be compared, rather than looking at discrete values such as the peak range of motion. The significance level was adjusted to $\alpha = 0.001$ to account for multiple comparisons.

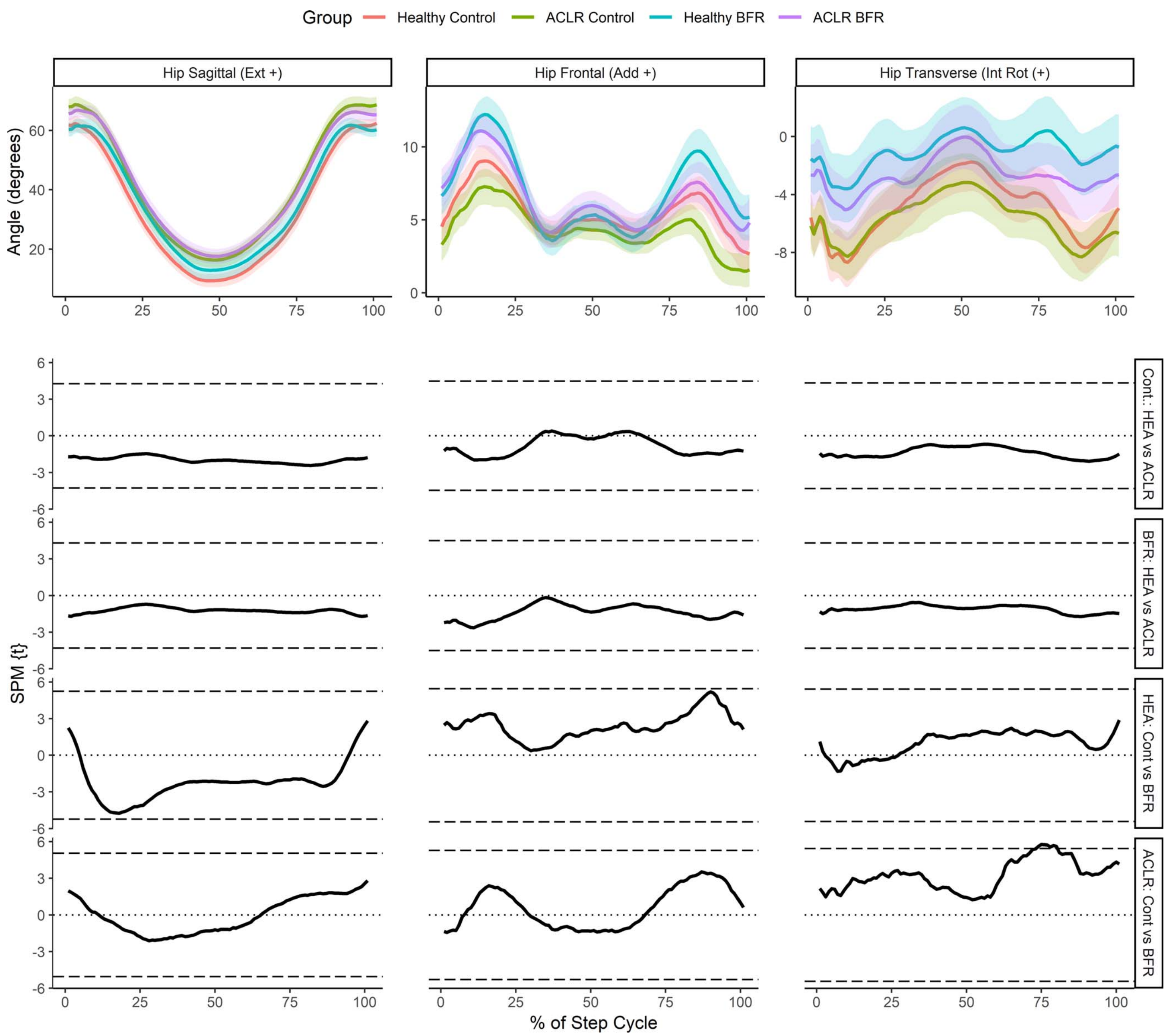

FIGURE 2—Results for hip kinematics. Columns represent the three anatomical planes of motion. Top row: mean motion curves for groups/conditions. Rows 2–5: results from statistical parametric mapping analysis with comparisons between groups/conditions described on the right side. Significance levels are indicated by the *large dashed lines*. HEA, healthy group; ACLR, anterior cruciate ligament reconstruction group; Cont., control exercise; BFR, blood flow restriction exercise; Ext, extension; Add, adduction; Int Rot, internal rotation.

Effect sizes were calculated for time points where significant differences were found. Descriptive statistics were calculated for the demographics and IKDC data. Participant-reported scores for difficulty and discomfort were compared using Wilcoxon signed-rank tests (between exercise conditions) and Wilcoxon rank-sum tests (within exercise conditions). Data were analyzed using R V3.5.2 (27) and Python 2.7. Figures were produced using the ggplot2 package (28).

RESULTS

Twenty individuals who had undergone ACLR and 20 matched controls took part in this study. Demographic details and baseline IKDC score for both test groups are reported in Table 1. All participants were able to complete the test protocol for both conditions.

Kinematic variables. At the knee, there were no differences found between the healthy and the ACLR groups (Fig. 1). A significant increase in external rotation of the tibia was seen for both the healthy and the ACLR groups when using BFR compared with the control condition (effect sizes, 0.37 and 0.33, respectively). This difference occurred during the step-up phase of the exercise in both cases and was equivalent to an increase of around 2° of external rotation in both groups.

At the hip, there were no kinematic differences found between the healthy and the ACLR groups for either of the

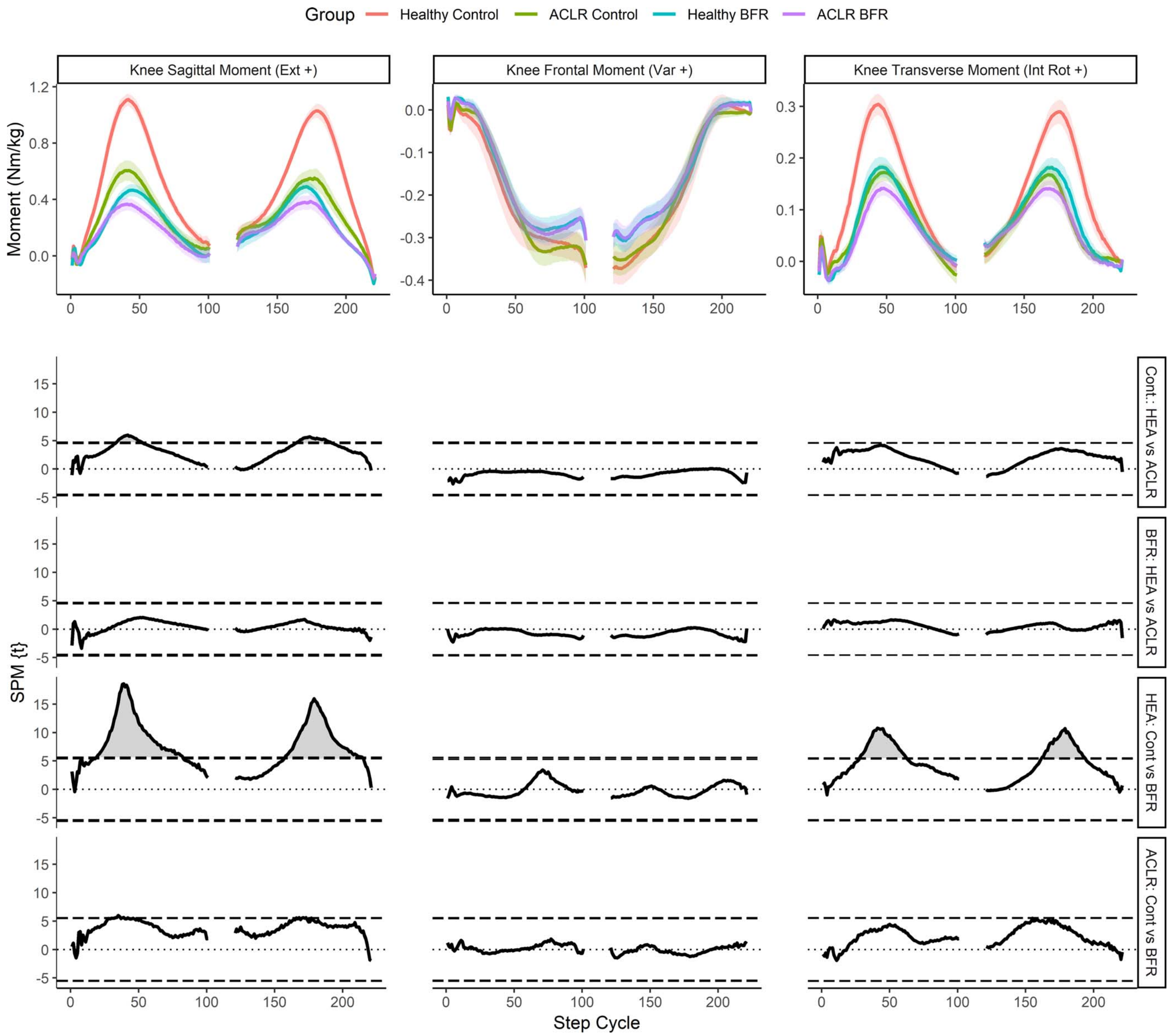

FIGURE 3—Results for knee kinetics. Columns represent the three anatomical planes of motion. Top row: mean motion curves for groups/conditions across all planes. Rows 2–5: results from statistical parametric mapping analysis with comparisons between groups/conditions described on the right side. Significance levels are indicated by the *large dashed lines*. Note that the gap in the moment curves represents the time when the participant is standing on the step (both feet in contact) and is approximate. HEA, healthy group; ACLR, anterior cruciate ligament reconstruction group; Cont., control exercise; BFR, blood flow restriction exercise; Ext, extension; Add, adduction; Int Rot, internal rotation.

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exercise conditions (Fig. 2). An increase of approximately 4° in the internal rotation of the hip was seen during the step-down phase of the exercise for the ACLR group in the BFR condition compared with the control condition (effect size, 0.29).

Kinetics. As shown in Figure 3, healthy subjects had a knee extension moment that was statistically significantly greater compared with the ACLR group during the step-up and step-down phases of the exercise (effect sizes, 1.4 and 1.2, respectively). Both groups were found to have a statistically significant reduction in the extension moment with the BFR condition for both step-up and step-down, around 70% for the healthy group (effect sizes, 1.72 and 1.65, respectively) and 50% for the ACLR participants (effect sizes, 0.84 and 0.60, respectively). The internal rotation moment was also significantly reduced by ~40% for the healthy group when using BFR (effect sizes, 1.26 [up] and 1.27 [down]).

At the hip, for healthy participants, there was a significantly increased flexion moment when stepping up (effect size, 1.15), decreased varus moment when stepping up (effect size, 1.18) and down (effect size, 1.24), and increased internal rotation moment for stepping up (effect size, 0.81) when using BFR (Fig. 4). The flexion moment increased by over 100% for both the step-up and the step-down phases of the exercise in this group. No significant differences were seen between the healthy and the ACLR groups.

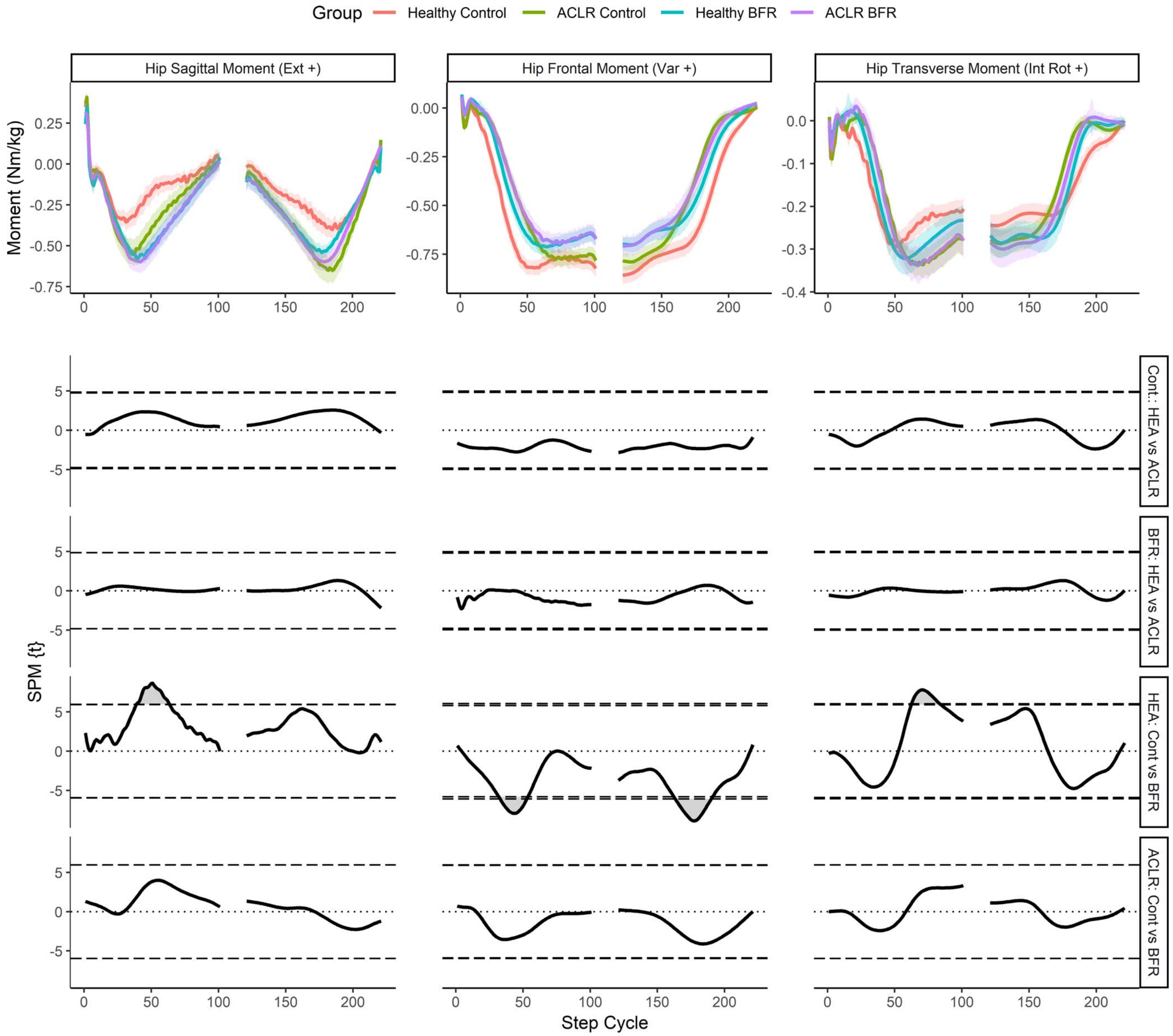

FIGURE 4—Results for hip kinetics. Columns represent the three anatomical planes of motion. Top row: mean motion curves for groups/conditions across all planes. Rows 2–5: results from statistical parametric mapping analysis with comparisons between groups/conditions described on the right side. Significance levels are indicated by the *large dashed lines*, and time periods where the differences were significant are shaded *gray*. HEA, healthy group; ACLR, anterior cruciate ligament reconstruction group; Cont., control exercise; BFR, blood flow restriction exercise; Ext, extension; Add, adduction; Int Rot, internal rotation.

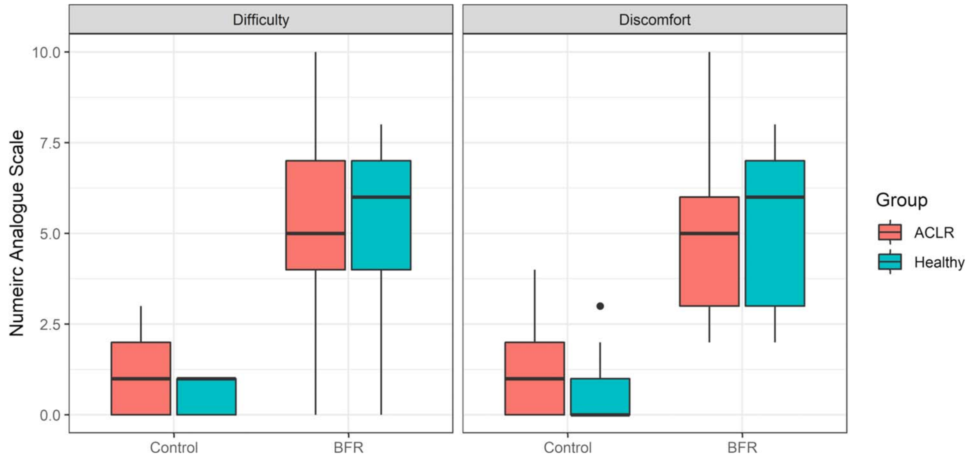

FIGURE 5—Box plots showing participant-reported scores for difficulty and discomfort of the exercise procedure for healthy and ACLR groups under different conditions.

Patient-reported scores. Results for patient-reported difficulty and discomfort scores are summarized in Figure 5. Both groups of participants rated the difficulty of performing the exercise to be greater when using BFR than for the control condition ($P < 0.001$, 95% CI [4.5, 6]; $P < 0.001$, 95% CI [3, 5.5] for healthy and ACLR groups respectively). Similarly, there were significant increases in the reported level of discomfort for the BFR condition compared with the control in both groups ($P < 0.001$, 95% CI = 3.5–5.5; $P < 0.001$, 95% CI = 5–3) for healthy and ACLR groups respectively). There were no differences between the groups for any of the conditions. When asked if they would have been willing to take part in a randomized controlled trial of BFR versus standard care, 19 of the participants in the ACLR group (95%) indicated that they would have be willing to enroll.

DISCUSSION

We investigated the effects of BFR on the kinematics and kinetics of the lower limb during step-up rehabilitation exercises in both healthy and ACL reconstructed knees. BFR is a relatively novel technique, and the nature of the intervention leads to some questions regarding its effects on the biomechanics of exercise performance. It has been shown that performing movements in a fatigued state, such as that which appears to be simulated by BFR, can lead to movements and loading that have been associated with injury (12,13).

In this study, we found several changes in the kinematics and kinetics of the exercise associated using BFR. Moments around the knee joint during the step-up and step-down phases were found to be significantly reduced with the BFR condition, suggesting that subjects use compensatory strategy while the intervention is applied that protects the knee from abnormal loads. This may be a combination of increasing the load on the hip joint, and perhaps generating larger forces from the contralateral leg. Given that the tested exercise is considered safe as part of a standard rehabilitation protocol, the reduction in moments around the knee joint with the BFR state (as compared with nonrestricted state) also suggests that BFR is a safe technique to use after ACLR.

There were small increases in the internal rotation of the knee seen in both the ACLR and the control groups. This variable has been suggested to be relevant to ACL injury in biomechanical studies (29). This emphasizes the need for therapists and patients to work to maintain control of out of plane movements during rehabilitation that is augmented with BFR.

Differences in joint mechanics after ACLR surgery have been extensively reported in the literature (22–25). Therefore, it was not surprising to find that moments around the knee joint during the step-up and step-down phases were different between the ACLR and the control groups. Knee extensor and internal rotation moments were larger in the healthy group. This may be as a result of reduced quad strength postoperatively and the patients being naturally more protective of the repaired knee than the healthy controls. No differences in knee kinematics were found, which was not the case in previous studies of stepping or stair climbing in this group (22–24); however, it should be noted that we analyzed data for the subjects toward the end of the protocol when fatigue may affect both groups.

BFR has been shown to produce changes in the muscles of healthy (30) and clinical populations (31). There is good emerging evidence that BFR can produce greater increases in muscle strength than low-load training alone, and a recent trial of BFR compared with high load resistance training found similar increases in muscle hypertrophy and strength, with a reduction in pain and joint effusion (32).

Participants in both groups rated the difficulty and discomfort involved with performing step-up exercises while using BFR to be significantly greater than in the nonrestricted condition, in line with findings from other studies of BFR. However, this did not appear to adversely affect their willingness to use the technique, with all but one of the individuals in the patient group stating that had a randomized controlled trial that included an arm involving the regular use of BFR throughout post-ACLR rehabilitation been available, they would have

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been willing to volunteer for it. Individuals who have undergone ACLR tend to be relatively young and highly motivated to return to previous levels of function, making them a group likely to be willing to endure short-term discomfort as part of their rehabilitation if it could lead to long-term benefits. A previous study of BFR in ACLR patients in the first 16 wk after surgery reported a drop out rate of two participants from an initial group of 24, primarily due to pain and discomfort associated with the technique (31). BFR is a relatively low-risk intervention with few contraindications (circulatory problems, pregnancy) or safety concerns (33), and combined with our survey showing patient willingness to use it, there appear to be few concerns with using it in future clinical trials.

We note several limitations with this study. The individuals in the patient group were around 3 months postsurgery; however, clinically BFR may be introduced earlier in the rehabilitation process. We did not directly measure muscle strength in this study; however, patients at 3 months post-ACLR surgery have been repeatedly shown to have significant muscle weakness and strength asymmetry (34,35). Therefore, we believe testing the effects of BFR at this point is justified and relevant. Further investigation of the biomechanical effects of the intervention at the earlier stages may be warranted. It was not possible to separate any direct effects of the BFR system and the accelerated fatigue caused by the technique. Furthermore, this study looked at one session of BFR training, and a single exercise. It is possible that, over time, individuals may develop compensatory strategies that further alter their biomechanics. It has been recommended that two to three BFR-augmented training sessions per week is sufficient to induce gains in strength (36). The physical nature of BFR meant that it was not possible to blind participants to the exercise condition.

There remains limited prospective long-term data on the efficacy and safety of BFR after ACL reconstruction. The present study demonstrates that BFR leads to small changes in knee joint mechanics compared with a nonrestricted state, thus providing cautious support for the use of BFR from a biomechanical perspective.

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The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. The authors have no declared conflicts of interest. The results of the present study do not constitute endorsement by the American College of Sports Medicine.

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