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Case Reports

Utilization of Blood Flow Restriction Therapy with a Former Triathlete After Total Knee Arthroplasty: A Case Report

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Introduction and Purpose

Knee osteoarthritis (OA) is a common condition that limits function and reduces quality of life. Total knee arthroplasty (TKA) is a surgical procedure that replaces the joint surfaces to address anatomical changes due to knee OA. While TKA improves symptoms and function, postoperative impairments are common, including reduced quadriceps strength. Blood flow restriction (BFR) may be a viable option for patients following TKA, as it can improve strength with a minimal amount of joint loading compared to traditional strength training. The purpose of this case report is to describe the impact of BFR use in an individual after TKA, employing pain measurements, quantitative sensory testing, patient-reported outcome measures, physical performance tests, and muscle strength and power testing to explore potential treatment effects and identify potential predictors of response for future studies.

Case Description

A 49-year-old former female triathlete with a history of knee injury and arthroscopic surgery underwent a right TKA and sought physical therapy (PT) due to pain, limited range of motion (ROM), and knee instability during weight bearing activity. PT interventions included manual therapy, gait training, and a home program. Despite participating in supervised PT, she had persistent pain, ROM deficits, and muscle weakness 16 weeks following TKA. BFR was incorporated into her home program, 16-weeks postoperatively. The Short Form McGill Pain Questionnaire-2 (SF-MPQ-2) and Numeric Pain Rating Scale (NPRS) were used to measure pain. Quantitative sensory testing included pressure pain threshold (PPT) and two-point discrimination (TPD) to measure change in sensory perception. Patient-reported outcome measures to assess perceived physical function were the Knee injury and Osteoarthritis Outcome Score (KOOS) and the KOOS- Joint Replacement (KOOS-JR). Physical performance was measured through the 30-second fast walk test (30SFW), timed stair climb test (SCT), 30-second chair standing test (CST), and the timed up and go (TUG). Knee ROM was assessed through standard goniometry. Knee extensor and flexor muscle strength and power were measured with an instrumented dynamometer for isokinetic and isometric testing, generating a limb symmetry index (LSI).

Outcomes

Pain and quantitative sensory testing achieved clinically meaningful improvement suggesting reduced sensitivity during and after BFR utilization. Perceived physical function and symptoms significantly improved, particularly in sports and recreation activities, and were best captured in the KOOS, not the KOOS-JR. Physical performance

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reached clinically meaningful improvement in walking speed, chair stand repetitions, and timed stair climb tests after BFR. Isokinetic and isometric strength and power in knee extensors and flexors increased significantly after BFR compared to the uninvolved leg as determined by LSI.

Discussion

In this case, BFR appeared to be a safe and well-tolerated intervention. The results suggest potential benefits in terms of increased function, strength, power, and reduced pain in this specific person after TKA. Comprehensive pain and sensory assessments alongside clinical measures may help identify suitable patients for BFR after TKA. The KOOS-Sport & Recreation subscale may be more responsive to monitor functional recovery compared to the KOOS-JR, possibly due to the subject's athletic background.

Level of Evidence

4

INTRODUCTION

Knee osteoarthritis (OA) is a common musculoskeletal condition that can significantly limit an individual's functional status and reduce their quality of life.[1] One treatment for persons with end-stage knee OA is total knee arthroplasty (TKA). This is a surgical procedure in which the articulating surfaces of the femur, tibia, and sometimes the patella are removed and replaced to form a prosthetic joint.[2] Utilization of TKA for surgical management of symptomatic knee OA has increased in the United States, with 480,958 completed in 2019 compared to 394,259 in 2015.[3] This number is projected to increase annually by 4.44%, leading to 1,222,988 procedures by 2040.[3] Although TKA is intended to improve a person's symptoms and function, some postoperative impairments are common. Quadriceps femoris strength was reported to be reduced by an average of 60% one month postoperatively compared to preoperative levels, with some patients demonstrating as great as 85% quadriceps strength loss.[4] Quadriceps strength deficits often persist for years after TKA.[5] Improvement of quadriceps strength is one primary goal of rehabilitation and is recommended by the American Physical Therapy Association (APTA) clinical practice guidelines (CPG) for management of patients following TKA.[6] However, many people who have undergone a TKA cannot tolerate the level of exercise intensity needed to generate muscle hypertrophy due to increased postoperative pain.

Blood flow restriction (BFR) creates a hypoxic environment like that of a high-intensity exercise program using a tourniquet to restrict blood flow to the extremity. The goal of BFR is to allow a person to experience the benefits of high-intensity strength training while performing low-intensity resistance exercise by creating an anaerobic environment for the working muscles.[7] BFR involves partially restricting arterial blood flow in and venous blood flow out of a region of the body, creating an anaerobic training environment within muscles even though the training intensity is low.[8] The proposed metabolic effect during BFR involves a decrease in local oxygen availability, which increases nitric oxide and stimulates muscle hypertrophy by the activity of satellite cells.[8] BFR during exercise improves isometric strength, sprint speed, power output, and muscular and aerobic endurance in healthy individuals.[9-13] Research supports BFR following anterior cruciate ligament (ACL) reconstruction in the acute phase of tissue healing when the patient is unable to tolerate high-load resistance training.[14] Patients treated with low-load training BFR following ACL reconstruction had significantly less pain and swelling than patients treated with traditional high-load resistance training.[14] However, muscle hypertrophy and strength were similar in both groups.[14]

BFR may be able to address the two key impairments, increased pain and decreased strength, in individuals following TKA. Endogenous pain modulation is a method by which the central nervous system can modulate the pain experience.[15] Conditioned pain modulation (CPM) is a method of stimulating the endogenous pain modulation mechanism through a noxious stimulus, by the use of a tourniquet in a remote area, thus creating a change in sensory processing systemically.[16,17] Tourniquet use in both BFR and CPM generate a noxious stimulus for an extended period for improved strength and pain, respectively. The literature to date is limited regarding the use of BFR for patients during postoperative TKA rehabilitation. To the authors' knowledge, only a randomized pilot study, case report, and retrospective study are currently available.[18-20] These studies utilized physical performance measures (6-minute walk test, 30-second chair stand test, stair climb test); muscle strength and hypertrophy outcome measures (isokinetic strength testing, muscle hypertrophy, and manual muscle testing); and assessment of pain (numeric pain rating scale). These studies are devoid of comprehensive pain measurement (phenotypes and quantitative sensory testing (QST)), physical performance tests, or patient-reported outcome measures. This case report addresses these gaps by reporting pain phenotypes (affective, nociceptive, and neuropathic pain), QST, perceived function measures, physical performance, isokinetic and isometric tests. The purpose of this case report is to describe the impact of BFR use in an individual after TKA, employing pain measurements, QST, patient-reported outcome measures, physical performance tests, and muscle strength and power testing to explore potential treatment effects and identify potential predictors of response for future studies.

CASE DESCRIPTION

SUBJECT INFORMATION AND TIMELINE

A 49-year-old female had chief complaints of pain, loss of range of motion (ROM), and instability of the knee when completing activities of daily living, affecting her QOL and progressively worsening over the previous 10 years. The subject reported previous high levels of recreational activity, including rowing, hiking, and long-distance triathlon participation, before significantly reducing activity levels due to pain and instability of the right knee. The subject's past medical history included hypothyroidism, right knee ACL reconstruction (1995 and 2001), multiple right knee arthroscopic debridement, and partial meniscectomy, with the most recent medial and lateral partial meniscectomy with loose body removal seven years prior. Medications included levothyroxine and NSAIDS as needed to manage knee pain. Three cortisone injections were received only when the subject could not bear weight due to acute episodes of pain and swelling. Tricompartmental TKA was elected after multiple courses of conservative physical therapy and five years of bi-annual hyaluronic acid injections.

The subject presented to outpatient physical therapy two-weeks following TKA with goals to resume swimming, biking, hiking and general recreational activities with her family. Pain ratings postoperatively fluctuated from 1-5/10 pain depending on activity level, requiring 400 mg of Ibuprofen every six to eight hours for pain.

DIAGNOSTIC ASSESSMENT

PAIN

The Short Form McGill Pain Questionnaire-2 (SF-MPQ-2) is a PROM designed to assess four pain phenotypes: continuous, intermittent, affective, and neuropathic. Individuals rate 22 descriptors on a 0-10 scale and their numeric pain rating (NPRS) on an 11-point scale. The SF-MPQ-2's strengths include high reliability, validity, and responsiveness to change in persons with persistent pain.[21-23]

QUANTITATIVE SENSORY TESTING

Pressure pain threshold (PPT) is a test that helps clinicians and researchers understand how sensitive the body is to mechanical pressure.[24] By applying increasing pressure and asking when an individual feels pain, the test can assess the activity of Aδ mechanonociceptors, which are nerve fibers involved in pain signaling.[24] PPT levels can help identify whether the pain is mainly in the injured area (primary hyperalgesia) or if it is spreading to other areas (secondary hyperalgesia). Central sensitization (secondary sensitization) refers to pain that starts at very light pressures, which may suggest that the nervous system is overly sensitive to pain signals (nociceptive input). PPT has been shown to be a reliable and consistent measure of pain sensitivity.[25,26] The Commander Echo Algometer (JTECHMedical, Midvale, Utah, USA) was used to assess PPT on both medial femoral condyles and the right lateral humeral epicondyle three times with a one-minute rest between tests and a trial mean reported.

Two-point discrimination (TPD) measures how precisely someone can feel light touch.[27] TPD helps assess the function of Aβ mechanoreceptors, which are responsible for our sense of delicate touch. TPD can identify areas with primary hyperalgesia. TPD can be reflected in the central processing of sensory information and how the brain interprets touch sensations, potentially indicating any changes or impairments in perception. TPD has been shown to be a reliable and valid measure of touch sensitivity.[27,28] The subject was tested in both medial femoral condyles with a one-minute rest between tests, reporting the distance where she correctly identified two points.

PATIENT-REPORTED OUTCOME MEASURES

The Knee injury and Osteoarthritis Outcome Score (KOOS) was used as a pathology-specific patient-reported outcome measure (PROM) to measure the subject's perceived impact of her knee condition on pain, function, and QOL.[29,30] The KOOS is reliable, valid, and responsive to change for patients with knee injuries including OA and sports injuries.[30] The KOOS includes 42 items with five subscales for ratings of pain, symptoms, activities of daily living (ADL), sport/recreation, and QOL; all subscales are scored from 0-100% with 100% indicating best function/lowest pain. The KOOS has good-excellent test-retest reliability and responsiveness for patients following TKA for knee OA. Standard error of measurement (SEM) and minimal important change (MIC) for each KOOS subscale for patients who have had TKA were reported to be the following: pain (1.22, 16.7%), symptoms (0.76, 10.7%), ADL (1.11, 18.4%), sport/recreation (0.90, 12.5%), and quality of life (1.13, 15.6%).[31,32] A 7-item short version of the KOOS designed for use with patients following TKA, the KOOS-JR, was also used as a PROM, since the subject was in the rehab phase following TKA.[32] The KOOS-JR is recommended by the American Academy of Hip and Knee Surgeons for assessment of perceived symptoms and function following TKA.[33] The KOOS-JR was found to have satisfactory validity and responsiveness and good-excellent reliability in patients following TKA.[34] The minimum detectable change 95% confidence interval (MDC_{95}) at three months follow-up from TKA is 29.1%, and MDC_{95} is 24.8% at six-month follow-up.[35] The MIC for the KOOS-JR is reported to be 14-15.1%.[35,36]

PHYSICAL PERFORMANCE

Walking ability was measured using the 30-second-fast-walk test (30SFW), which has been shown to be a reliable and valid measure of fast-paced walking in patients with knee OA.[37] The 30SFW is a measure of the distance walked at a fast pace in 30 seconds. The intrarater test-retest SEM for the 30SFW for patients with knee OA is 2.05 meters (MDC_{95} = 5.67 meters).[37] Stair climbing ability was measured using a timed 10-step stair climb test (SCT) as recommended by the Osteoarthritis Research Society International (OARSI), as a reliable, valid, and responsive measure for patients with knee OA.[38] It is a measure of the time

taken to ascend and descend a set number of steps. OARSI recommends a SCT but not the specific number of steps, in this assessment, 10 steps were used due to clinic limitation.[38] The SEM for an 11-step SCT was reported to be 1.00 seconds, and MDC_{90} was reported to be 2.33 seconds.[38] Chair rising ability was measured with the 30" chair stand test (CST), a reliable, valid, and responsive measure of change also recommended by OARSI. The CST is a measure of the number of chair stands a person can perform in 30 seconds. The SEM is reported to be 0.9 chair stands and MDC_{90} of 2.0 chair stands.[38]

KNEE RANGE OF MOTION, STRENGTH, AND POWER

Knee joint passive and active ROM was measured using a standard 12" universal goniometer, shown to have excellent interrater and intrarater reliability in patients with knee ROM restrictions following TKA.[6] Quadriceps and hamstrings strength were measured using a Biodex System 4 Pro™ instrumented dynamometer (Biodex Medical Systems, Inc., Shirley, NY) using the anti-shear attachment to provide both proximal and distal contact with the lower extremity (LE). The subject was positioned on the dynamometer chair according to manufacturer instructions, with the back fully upright and the subject stabilized in position using rigid fabric straps across the torso, waist, and non-tested thigh. The dynamometer lever arm axis of rotation was positioned opposite the lateral femoral epicondyle of the tested knee. Isometric knee extensor and flexor testing was performed with the knee positioned at 60° flexion for two repetitions in both LE and muscle groups.[39] Isokinetic testing of knee extensors and flexors was performed at 180°/second in the concentric mode for both LEs. The subject performed two sets of 10 repetitions for each LE. The subject's non-operative LE was tested first for all strength tests, and practice trials were performed prior to testing. The subject rested for one minute between trials. The greatest peak torque for knee extensors and knee flexors, for both isometric and isokinetic tests, was used for outcomes.[40] The subject's body weight was collected to calculate power normalized to body weight.[40] This type of dynamometry has excellent test-retest reliability for knee extensors and flexors in both isometric and isokinetic modes.[41-44] Isometric and isokinetic testing of the knee extensors in patients following TKA has demonstrated excellent test-retest reliability and responsiveness to change (SEM for isometrics = 6.2% and isokinetic peak torque = 7.3%).[39,45] Both LEs were tested in isometric and isokinetic muscle groups to allow for comparison using a limb symmetry index (LSI) where a percentage is calculated with the operative score divided by the non-operative score.

CLINICAL FINDINGS

The subject's chief complaints at the initial examination were pain, loss of function, leg weakness, and abnormal gait (Table 1). Her pain and weakness were the most significant body structure impairments, limiting her functional mobility and ability to participate in social, family, and recreational activities. The subject was diagnosed with significant weakness and pain after unilateral postoperative TKA. Her prognosis was fair given her surgical history, functional limitations, and levels of pain. This case report utilized multiple outcome assessments to measure change in various aspects of pain, function, strength, and power after the initiation of BFR to her HEP to explore potential treatment effects and identify potential predictors of response for future studies.

THERAPEUTIC INTERVENTIONS

The course of physical therapy following TKA spanned 20 visits, over five months. Sessions followed the APTA clinical practice guidelines for TKA and included manual therapy to improve ROM, gait training, and neuromuscular reeducation with a home exercise program (HEP) that focused on improving cardiovascular endurance, functional strengthening, and ROM.[6] The subject cycled five days per week x 30 minutes, incorporating a combination of steady state and high intensity interval training (HIIT). A ROM HEP was performed twice daily and included low-load prolonged knee flexion stretch and Grade 2 and 3 Maitland self-mobilization into terminal knee extension.[46] Strengthening exercises included single leg heel raises, squats using TRX straps, seated leg extension and hamstring curls, and single leg press. The subject also underwent weekly acupuncture sessions performed by a Doctor of Chinese Medicine as an adjunct therapy for symptom modulation from weeks 8 - 16 post operatively.

At 16-weeks postoperatively, the subject had continued mild to moderate pain, knee flexion ROM deficits, and significant strength deficits in the right quadriceps (40% deficit) and hamstrings (29.4% deficit) compared to the uninvolved leg through isokinetic testing. These impairments resulted in general dissatisfaction with postoperative function. At this time, the subject was returning to work and no longer had time to attend PT sessions regularly. To accommodate the subject's schedule, a home BFR unit was provided to her to continue her rehabilitation. Assessments of the subject were taken at weeks 20, 25, and 42 postoperatively to track HEP progress.

The subject was instructed to apply the BFR tourniquet (KAATSU NANO (Model Number KN-100), KAATSU Global, Huntington Beach, CA) to her thigh and increase pressure to her maximum tolerance of pressure without measuring for arterial occlusion. The subject was then instructed to perform daily seated leg extension, hamstring curls, and straight leg raises in 3 sets (30, 30, 15), with 60 second breaks between sets.[47] During the first week of BFR training (Baseline 2), the three exercises were performed without weight. She performed these exercises without weight due to the fatigue in completing all three sets. The protocol was completed for leg extensions, but failure was reached at the end of the second set of 15 for heel raises and at repetition 10 of the third set of 15 for hamstring curls. Resistance was added to each exercise in five-pound increments once the 75-repetition protocol could be completed, with ease, two sessions in a row. BFR training continued through postoperative weeks 20 (BFR 1) and 25 (BFR 2) where she reached

Table 1. Examination Data

Outcome Measure	
Numeric Pain Rating Scale (0-10, 10 = worst pain)	5
30s Chair Stand Test, reps	5
Stair Climb Test (10 steps)	30.6 (step to pattern)
Timed Up and Go (TUG)	23.67 seconds
Knee Flexion AROM (pre manual therapy)	60 degrees
Knee Extension AROM	10 degrees from neutral
Quadricep MMT	3- /5
Hamstring MMT	3- /5

Abbreviations: (reps = repetitions, AROM = Active Range of Motion, MMT = Manual Muscle Test)

10 pounds in each exercise completing the 75-repetition protocol.

OUTCOMES

PAIN

The subject had similar SF-MPQ-2 total pain scores in the first two time points. Her pain decreased with the start of BFR (week 16) and continued to decrease until the long-term follow-up (Table 2). She had pain classified in the constant and affective domain based on the SF-MPQ-2 subscale scores. The only subscale change pre-BFR was in the affective domain, as the other domains did not decrease until the addition of BFR (week 16). The constant pain domain decreased from 19 to 11 between Baseline 2 and BFR 1.

QUANTITATIVE SENSORY TESTING

PPT scores on the involved knee in the first two time points were greater than 50% lower compared to the uninvolved knee. Once BFR was introduced, PPT scores began to normalize within a normal range between all three testing sites. Initially, the scores before adding BFR suggested primary hyperalgesia that may have been mitigated by adding BFR. The subject had no hyperalgesia in the last two time points. TPD scores were highly sensitive to light touch. Her scores were significantly below normative values.[27] After the addition of BFR, her scores normalized and remained similar, only to return to more sensitive levels after the discharge of BFR (week 25).

PATIENT-REPORTED OUTCOME MEASURES

Physical function and symptoms were improved between the two baseline time points (Table 2), but only the change in the KOOS-Symptom subscale was greater than the MIC. That change may have been due to her improved knee joint ROM. Using Baseline 2 as a comparison, nine weeks of BFR resulted in further improved perceived function and symptoms, but only the KOOS-Sport & Recreation subscale achieved the MIC. At the long-term follow-up, 42 weeks postoperatively, the subject's perceived function and symptoms improved in all five KOOS subscales, with only the KOOS-ADL score not achieving MIC (18.4%) compared to Baseline 2 since her score at Baseline 1 was already 85%. Although the subject's scores on the KOOS-JR improved over time, the change did not reach the MIC level.

PHYSICAL PERFORMANCE

Walking ability improved greater than the MDC between baseline 2 and BFR 1 after four weeks of using BFR (Table 2). Her walking pace at BFR 1 was 2.21 meters/second. SCT improvement approached the MDC between Baseline 1 and Baseline 2 and between Baseline 2 and BFR 1. The change between Baseline 1 and BFR 1 was greater than the MDC (Table 2). CST improved greater than the MDC between Baseline 2 and BFR 1 and between BFR 2 and long-term follow-up.

KNEE RANGE OF MOTION, STRENGTH, AND POWER

Knee extensor isometric and isokinetic strength of the involved LE improved in all time points. The improvement in knee extensor peak isokinetic torque was greater than the SEM for all time points except for long-term follow-up compared to BFR 2 (Table 3). In contrast, the uninvolved knee extensor isokinetic peak torque did not achieve change greater than the SEM.

Isometric strength changes of the involved knee extensors from Baseline 1 to Baseline 2 were greater than the SEM (Table 4). Isometric knee extensor peak torque change of the involved knee was also greater than the SEM from BFR 1 to BFR 2 (Table 4). The uninvolved LE isometric knee extensor peak torque did not show change greater than the SEM between any two time points.

Knee flexor strength for the involved LE improved over all measurements. While no SEM value was available in the literature for knee flexors, the peak isokinetic torque improved more than 140% from Baseline 2 to BFR 2, and the peak isometric torque improved more than 120% from Baseline 2 to long-term follow-up (Table 3, Table 4). The uninvolved LE had knee flexor peak torque that was relatively unchanged.

The subject's ability to forcefully contract her involved knee extensors and flexors rapidly also improved, as demonstrated by the increase in involved knee extensor and

Table 2. Clinical Examination Data

	Baseline 1 (POW 12)	Baseline 2 (POW 16)	BFR 1 (POW 20)	BFR 2 (POW 25)	Long-term follow-up (POW 42)
SF-MPQ-2	20	19	11	10	7
SF-MPQ-2 (continuous)	9	11	7	5	2
SF-MPQ-2 (intermittent)	0	0	0	0	2
SF-MPQ-2 (neuropathic)	4	5	3	3	3
SF-MPQ-2 (affective)	7	3	1	2	0
Present Pain Intensity	2	2	0	0	0
PPT (L Knee, kg^2) mean	5.2	8.5	6.9	6.3	5.9
PPT (R Knee, kg^2) mean	2.2	4.2	5.1	5.8	4.9
PPT (Elbow, kg^2) mean	4.9	4.4	5.5	6.3	4.2
TPD (L Knee, mm)	9	8	42	25	10
TPD (R Knee, mm)	7	4	30	14	10
KOOS (pain), 0-100%	72	69	72	81	92
KOOS (symptom), 0-100%	50	61	64	68	82
KOOS (ADL), 0-100%	85	88	94	94	97
KOOS (sport), 0-100%	40	50	60	70	80
KOOS (QoL), 0-100%	44	56	56	63	81
KOOS-JR, 0-100%	70.704	73.342	76.332	73.342	79.914
Knee Extension AROM (PROM), degrees	2 (2)	0 (0)	0 (0)	0 (0)	0 (0)
Knee Flexion AROM (PROM), degrees	109 (112)	105 (110)	110 (120)	115 (120)	120 (120)
30s Chair Stand Test, reps	13	14	19	19	21
30s Fast-Paced Walk Test, meters	51.69	57.20	66.32	63.09	63.45
Stair Climb Test 10 steps, seconds	10.4	8.14	6.40	6.73	6.24

Abbreviations (ADL = Activities of Daily Living, QoL = Quality of Life, POW = Postoperative Week)

flexor power (Table 3). The uninvolved LE power for knee extensors and flexors remained relatively unchanged.

DISCUSSION

The subject successfully integrated BFR into a HEP to achieve her desired outcomes. She safely utilized home BFR and had no adverse or unanticipated events during the weeks she used BFR. BFR may have contributed to the changes in the measurements of sensory processing, pain, strength, and function.

The SF-MPQ-2 appeared to be more sensitive in the measurement of pain compared to the NPRS. In addition to its greater responsiveness to change, it may be helpful in identifying pain phenotypes to assist in patient-specific treatment based on classification in future research studies.[48] Future research on the use of BFR in the TKA population should continue to use these QST measures to determine whether they are predictors of positive outcomes when using BFR during a strengthening program to improve the pain.

Changes in QST measures (PPT and TPD) during the integration of BFR into the HEP suggest that CPM, because of the tourniquet, affected the subject's endogenous pain modulation mechanism.[49] The changes in QST along with the decrease in constant pain subscore in the SF-MPQ-2 after the introduction of BFR, support QST as possible predictors for those with TKA who could benefit from BFR. However, the presence of central sensitization may limit BFR use in this population due to the known lack of CPM in those with central sensitization, as up to 10% of those after TKA have this adaptation.[50,51] The subject did not have signs and symptoms of central sensitization, and further research is needed to determine whether BFR may only be helpful in persons without central sensitization after TKA due to CPM being absent in those with central sensitization.[52,53]

The results revealed that the KOOS-JR was not as sensitive as the KOOS in detecting change with this subject. She did not achieve the MIC on the KOOS-JR, but she did on the KOOS subscales. The KOOS may be better to detect change in patients who are at higher levels of function/sport. As younger, more active people elect to have TKAs, the KOOS

Table 3. Isokinetic Strength Testing (concentric/concentric); 180° / second

	Baseline 1 (POW 12)	Baseline 2 (POW 16)	BFR 1 (POW 20)	BFR 2 (POW 25)	Long-term follow up (POW 42)
Knee Extensors (Quadriceps)					
Peak Torque, N-m (Peak Torque % BW): Uninvolved	127.3 (137.4 %)	129.4 (139.7 %)	131.4 (141.9 %)	123.2 (133.0 %)	126.2 (136.2 %)
Peak Torque, N-m (Peak Torque % BW): Involved	67.5 (72.9 %)	77.8 (84.0 %)	85.2 (92.0 %)	92.4 (99.8 %)	97.9 (105.7 %)
Average Power, Watts: Uninvolved	223.2	230.2	235.7	225.2	228.4
Average Power, Watts: Involved	117.2	143.8	156.8	166.9	177.6
Knee Flexors (Hamstrings)					
Peak Torque, N-m (Peak Torque % BW): Uninvolved	48.2 (52.1 %)	49.0 (52.9 %)	49.2 (53.1 %)	52.9 (57.1 %)	47.9 (51.7 %)
Peak Torque, N-m (Peak Torque % BW): Involved	27.1 (29.3 %)	34.7 (37.5 %)	37.8 (40.8 %)	49.7 (53.7 %)	43.6 (47.1 %)
Average Power, Watts: Uninvolved	94.1	95.8	86.0	97.6	89.6
Average Power, Watts: Involved	24.7	50.4	59.8	75.7	65.7

Abbreviations: POW, postoperative week; BFR, blood flow restriction; N-m, Newton-meters; % BW, percentage body weight

Table 4. Isometric Strength Testing, knee at 60° flexion

	Baseline 1 (POW 12)	Baseline 2 (POW 16)	BFR 1 (POW 20)	BFR 2 (POW 25)	Long-term follow-up (POW 42)
Knee Extensors (Quadriceps)					
Peak Torque, N-m (Peak Torque % BW): Uninvolved	239.9 (240.3 %)	211.5 (212.1 %)	241.2 (236.5 %)	204.3 (215.7 %)	219.7 (232.7 %)
Peak Torque, N-m (Peak Torque % BW): Involved	98.4 (99.2%)	140.2 (143.2 %)	144.0 (152.6 %)	168.2 (176.8 %)	168.5 (176.0 %)
Knee Flexors (Hamstrings)					
Peak Torque, N-m (Peak Torque % BW): Uninvolved	57.4 (60.3 %)	59.0 (62.0 %)	51.8 (52.2 %)	62.5 (62.0 %)	64.7 (64.5 %)
Peak Torque, N-m (Peak Torque % BW): Involved	32.0 (32.2 %)	44.0 (45.8 %)	39.4 (41.7 %)	50.0 (49.8 %)	52.9 (54.5 %)

Abbreviations: POW, postoperative week; BFR, blood flow restriction; N-m, Newton-meters; % BW, percentage body weight

may be more sensitive to changes compared to the KOOS-JR. This should be further investigated to determine the most responsive PROMs for patients with TKA.[54]

Strength testing via the Biodex demonstrated objective changes in knee extension strength that exceeded the SEM. At baseline, quadriceps peak torque in the operative LE was only 41% that of the non-operative LE. This improved to 82% of the non-operative LE at POW 25. Similarly, average power of the involved quadriceps improved from 52% to 77% of non-operative LE during that same time. Involved hamstring peak torque improved from 56% to 82% of the uninvolved, while involved hamstring average power improved from 26% to 77% during this same period. While the strength improvements demonstrated by this subject are likely, in part, associated with natural progression postoperatively, most patients do not achieve 70-80% strength of the non-operated LE until closer to one year postoperatively.[55] The incorporation of BFR may have allowed this patient to achieve these strength and power gains more quickly and was accompanied by significant improvement in function measures including walking speed, SCT, and CST. Achieving symmetry in strength between the postop-

erative and non-operative LE has been shown to be important in normalizing movement patterns and improving functional performance post-TKA.[56,57] While it remains unclear if faster achievement of strength symmetry results in improved function in the long-term, many patients lag their healthy counterparts with regards to strength and functional performance six months postoperatively.[58] Bade et al. suggest that more aggressive postoperative rehabilitation may be needed to normalize strength and function for patients undergoing TKA.[58] Home BFR implementation may allow for earlier strength gains and promotion of strength symmetry between limbs sooner without overloading the still healing joint and offering therapeutic pain modulation. In addition, the use of BFR daily at home as compared to in the clinic may provide opportunities for strength and power gains. Pain modulation and BFR dosing should be explored in those with TKA in future studies.

The strengths of this case report include the comprehensive complement of tests and instruments used to measure the change in this subject after TKA. This case report utilized a pragmatic means to address pain, strength, power, and functional complaints. This case report provides support for the utilization of PROMs in more athletic individuals following TKA, which is not currently reported, and that home BFR use may have contributed to the pain reduction within a strengthening program during TKA rehabilitation.

Limitations of this case report include limited control over the HEP protocol, the amount of pressure through the BFR device, the lack of arterial occlusion measurement, and that no cause-effect relationship can be determined. These limitations, while impacting the support of efficacy of the use of BFR, highlight the potential effectiveness of BFR through a patient-centered approach. Please see Supplemental File 1 for patient perspectives on the procedures utilized in this Case Report.

CONCLUSION

In this case, BFR was well-tolerated and appeared to be a safe adjunct to rehabilitation. The subject demonstrated improvements in pain measures, function, strength, and power during the treatment period. The KOOS appeared to be better able to assess change in this subject's function versus the KOOS-JR, perhaps due to her athletic nature, and should be considered in clinical practice in those with TKA. QST may be critical in identifying those who will benefit from BFR.

CONFLICTS OF INTEREST

The authors report no conflicts of interest.

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SUPPLEMENTARY MATERIALS

Supplemental File 1

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