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original research

Knee Frontal-Plane Biomechanics in Adults With or Without Bone Marrow Edema-Like Lesions After Anterior Cruciate Ligament Injury

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Context: Lateral subchondral bone bruises (BBs) occur frequently with anterior cruciate ligament (ACL) injuries. These BBs are associated with pain during weight bearing, leading individuals to increase medial tibiofemoral loading to alleviate pain laterally. Increased medial tibiofemoral loading may precipitate the development or progression of posttraumatic osteoarthritis; however, no in vivo biomechanical data exist to confirm that lateral BBs increase medial tibiofemoral loading as measured by the external knee-adduction moment (KAM).

Objective: To determine whether lateral BBs after ACL injury increase the external KAM during walking.

Design: Descriptive laboratory study.

Setting: University research laboratory.

Patients or Other Participants: Eleven volunteers with an ACL injury (age = 20.36 ± 4.03 years, height = 177.60 ± 8.59 cm, mass = 79.70 ± 16.33 kg), 12 with an ACL injury and a lateral BB (ACL + BB; age = 19.25 ± 5.58 years, height = 170.71 ± 9.40 cm, mass = 66.79 ± 11.91 kg), and 12 healthy controls (age = 19.67 ± 5.19 years, height = 173.29 ± 11.58 cm, mass = 67.07 ± 11.25 kg) participated.

Intervention(s): We recorded peak KAM during 3 walking trials (1.1 ± 0.6 m/s) in which participants walked over a force platform located in the field of view of a motion-capture system.

Main Outcome Measure(s): Peak KAM was calculated during the first half of stance using standard inverse-dynamics analysis, averaged across trials, and examined via 1-way analysis of variance. Knee pain and function were determined from the International Knee Documentation Committee Subjective Knee Evaluation Form and compared among groups via the Kruskal-Wallis test.

Results: Peak KAM did not differ among groups (ACL injury = 0.14 ± 0.07 $\text{Nm}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$, ACL + BB = 0.21 ± 0.08 $\text{Nm}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$, control = 0.20 ± 0.08 $\text{Nm}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$; $F_{2,35}$ = 3.243, P = .052). Knee-pain frequency and severity were greater in the ACL-injury (frequency = 2.55 ± 1.81, severity = 3.36 ± 1.75; both $P < .001$) and ACL + BB (frequency = 3.58 ± 2.81, severity = 4.08 ± 3.20; both $P < .001$) groups than in the control group (frequency = 0.00 ± 0.00, severity = 0.00 ± 0.00). Knee function was greater in the control group (100.00 ± 0.00) than in the ACL-injury (59.35 ± 17.31; $P < .001$) and ACL + BB (46.46 ± 25.85; $P < .001$) groups.

Conclusions: The ACL + BB groups did not walk with a greater external KAM than the ACL-injury or control groups. Thus, lateral tibiofemoral BB did not influence knee frontal-plane loading after ACL injury.

Key Words: knee-adduction moment, gait, bone bruise

Key Points

- External knee-adduction moment did not differ among anterior cruciate ligament–injury, anterior cruciate ligament–injury plus concomitant lateral bone bruise, and healthy control groups.
- Whereas increased medial knee-joint loading may precipitate knee-joint degeneration, lateral bone bruises may not contribute to this increase in the external knee-adduction moment and medial tibiofemoral loading.

Approximately 80% of all patients with complete anterior cruciate ligament (ACL) injuries present with bone marrow edema-like lesions, or bone bruises (BBs), sustained at the time of injury.[1] These BBs are most common in the lateral tibiofemoral compartment.[2] Whereas the clinical importance of these BBs remains unclear, they have been shown to increase symptoms[3] and disability[3–5] after injury. Specifically, Johnson et al[3] demonstrated that, compared with individuals with an isolated ACL injury, patients with lateral BBs had larger and longer-lasting knee-joint effusions, increased pain, prolonged restoration of normal knee range of motion, and delayed return of nonantalgic gait without the use of assistive devices.

Posttraumatic osteoarthritis (PTOA) of the knee develops in more than 30% of individuals within the first decade and 50% of individuals within the second decade after ACL injury.[6] Whereas the precise cause of PTOA is unknown, it is possible that the large forces that tear the ACL and result in BBs may cause sufficient damage to initiate joint degeneration.[7] As individuals attempt to relieve pain associated with BBs, they may alter their gait to unload the lateral tibiofemoral compartment,[3,8] thereby increasing medial tibiofemoral loading.

Medial tibiofemoral loading is often measured using the external knee-adduction moment (KAM). The KAM represents the torque acting on the knee joint in the frontal plane, which rotates the tibial medially relative to the femur during walking. Thus, it serves as a surrogate measure of medial tibiofemoral loading during gait.[9,10] Briem et al[11] suggested that joint moments not only indicate compartmental loading

Table. Participant Demographics

Characteristic	Group, Mean ± SD Anterior Cruciate Ligament Injury[a]	Anterior Cruciate Ligament Injury[a] and Bone Bruise[b]	Healthy Control[b]	*P* Value
Age, y	20.36 ± 4.03	19.25 ± 5.58	19.67 ± 5.19	.87
Height, cm	177.60 ± 8.59	170.71 ± 9.40	173.29 ± 11.58	.27
Mass, kg	79.70 ± 16.33[c,d]	66.79 ± 11.91	67.07 ± 11.25	.041
2000 International Knee Documentation Committee Subjective Knee Evaluation Form score	59.35 ± 17.31[d]	46.46 ± 25.85[d]	100.00 ± 0.00	<.001
Knee-pain frequency[e]	2.55 ± 1.81[d]	3.58 ± 2.81[d]	0.00 ± 0.00	<.001
Knee-pain severity[f]	3.36 ± 1.75[d]	4.08 ± 3.20[d]	0.00 ± 0.00	<.001
Time from injury to gait testing, d	147.18 ± 124.24[c]	44.58 ± 40.12	Not applicable	.01

[a] This group comprised 11 participants, 25% (n = 3) of whom were female.
[b] This group comprised 12 participants, 58% (n = 7) of whom were female.
[c] Indicates different from the anterior cruciate ligament–injury and bone-bruise groups.
[d] Indicates different from the control group.
[e] Participants rated their knee-pain frequency using question 2 of the 2000 International Knee Documentation Committee Subjective Knee Evaluation Form, with the anchors of 0 (*never*) and 10 (*constant*).
[f] Participants rated their knee-pain severity using question 3 of the 2000 International Knee Documentation Committee Subjective Knee Evaluation Form, with the anchors of 0 (*no pain*) and 10 (*worst pain imaginable*).

but may also indicate compensatory movement strategies designed to relieve pain. Altered frontal-plane knee-joint biomechanics have been demonstrated after ACL reconstruction, leading to increased KAM.[12,13] With PTOA commonly developing in the medial tibiofemoral compartment,[14] this adaptation is potentially hazardous. However, to date, no in vivo biomechanical studies have been conducted to confirm that altered frontal-plane biomechanics after ACL injury are related to lateral tibiofemoral BBs. Given the potential implications for developing PTOA, we need to determine whether such a gait maladaptation exists and whether necessary measures to restore normal frontal-plane knee-joint loading should be established and implemented. Therefore, the purpose of our study was to determine whether individuals with an ACL injury and a lateral tibiofemoral BB (ACL + BB) walked with a greater external KAM than individuals with an ACL injury and no BB (ACL injury) and healthy individuals. Furthermore, we examined the association between BB size and KAM and knee pain and function. We hypothesized that the ACL + BB group would demonstrate greater peak KAM than the ACL-injury and healthy control groups and that larger BBs would be associated with greater impairments.

METHODS

Participants

Eleven volunteers with ACL injury, 12 with ACL + BB, and 12 serving as healthy control participants were recruited from a single sports medicine clinic to participate in this study (Table). All participants with ACL injury had a unilateral, primary, complete ACL rupture and no greater than a grade II collateral ligament sprain as assessed via magnetic resonance imaging (MRI). To be included in the ACL + BB group, participants had to have sustained a BB in the lateral tibiofemoral compartment only. Individuals with concomitant meniscal injuries were not excluded from participation. The injured limb in all participants with ACL injury and ACL + BB or a limb matched to the ACL + BB group in healthy control participants was used as the test limb. All testing sessions occurred preoperatively, with MRI obtained first and 28.33 ± 18.29 days elapsing between MRI and gait assessment. All participants received standard-of-care treatment, which included exercises to improve range of motion and reduce swelling, between their initial physician visit and surgery. No strengthening exercises were prescribed preoperatively. All participants provided written informed consent, and the study was approved by the institutional review board of the University of Michigan Medical School.

Magnetic Resonance Imaging and BB Assessment

The presence or absence of a lateral tibiofemoral compartment BB was determined from the diagnostic MRI of each participant with ACL injury and ACL + BB (Figure 1). A series of proton density–weighted, fast-spin

Figure 1. Representative figure of lateral tibiofemoral bone bruises.

MRI scans completed using a 3-T scanner (model Achieva 3T Quasar Dual; Philips Electronics, Andover, MA) with a 1-mm–slice thickness, 0.5-mm–slice spacing, 160-mm field of view, 15-millisecond echo time, 4000- to 6500-millisecond repetition time, and 456 × 275 matrix.

For participants in the ACL + BB group and each image in which the BB appeared for both the tibia and the femur, the BB borders were traced by hand using ImageJ software (version 142q; National Institutes of Health, Bethesda, MD) and a pen tablet (model Intuos4; Wacom Technology Corporation, Vancouver, WA).[15] The maximum values for the tibial and femoral BBs among all slices were used to quantify the peak area (mm^2) of the contusion for the respective bones. A single investigator (A.C.T.) with high intrarater reliability (intraclass correlation coefficient = 0.988) completed all measurements.

Knee-Pain and Knee-Function Assessment

All participants rated their knee function using the 2000 International Knee Documentation Committee (IKDC) Subjective Knee Evaluation Form.[16] Knee-pain frequency, ranging from 0 (*never*) to 10 (*constant*), and severity, ranging from 0 (*no pain*) to 10 (*worst pain imaginable*), were determined using questions 2 and 3, respectively, from the IKDC form.

Gait Assessment

We recorded participants' frontal-plane knee biomechanics during overground walking. Participants were outfitted with 32 retroreflective markers attached bilaterally over the anterior-superior iliac spine, posterior-superior iliac spine, iliac crest, greater trochanter of the femur, distal thigh, lateral and medial femoral epicondyles, tibial tuberosity, lateral and distal shanks, lateral and medial malleoli, head of the second metatarsal, base of the fifth metatarsal, dorsal navicular, and posterior calcaneus.[17] We tracked the retroreflective markers via an 8-camera, high-speed (240-Hz) motion-capture system (Vicon Motion Systems Ltd, London, United Kingdom). Joint kinematics were calculated based on the 3-dimensional (3D) coordinates of these markers. Ground reaction force data were recorded as participants walked over a force platform (model OR6-7; AMTI, Watertown, MA) sampling at 1200 Hz and located in the field of view of the motion-capture system.

Participants performed 3 successful walking trials at a rate of 1.1 ± 0.6 m/s along a 4-m walkway. We measured gait speed using a stopwatch synchronized with 2 photoelectric sensors (model Cutler-Hammer SMPR3-HD; Eaton Corporation, Cleveland, OH). Successful trials necessitated that the foot of the test limb land entirely within the center of the force platform without normal gait being disrupted. Before testing, participants performed practice trials to familiarize themselves with the task.

Data Analysis

Biomechanical data were time normalized to 100% of the stance phase, with initial contact and toe-off equaling the instant when the vertical ground reaction force first exceeded and then fell below 10 N, respectively.[18,19] On the basis of the time-normalized data, the peak external KAM was extracted during the first 50% of the stance phase because this represented a time when the KAM reached its maximal value during walking. Visual 3D software (C-Motion Inc, Rockville, MD) was used to define the kinematic model from a static video recording with the participant standing in a neutral position.[20] Joint rotations were calculated from the 3D-marker trajectories during each walking trial using a Cardan rotation sequence[21] and expressed relative to the participant's static position.[18] The synchronous ground reaction force and kinematic data were filtered using a fourth-order, zero-lag, low-pass Butterworth filter with a 12-Hz cutoff frequency and submitted to a standard inverse-dynamics analysis in Visual 3D. Kinetic outputs were normalized to participant mass (kg) and height (m)[22] and converted to external joint moments.

Statistical Analysis

We assessed participant demographics and differences in peak external KAM among groups using a 1-way analysis of variance. Differences in knee-pain frequency and severity and knee function among groups were examined via Kruskal-Wallis and Mann-Whitney *U* tests. The mean ± standard deviation peak areas of the tibial and femoral BBs were also calculated. Associations of BB size with KAM and knee pain and function were identified using Pearson product moment and Spearman rank correlations. We set the α level a priori at .05. Statistical analysis was completed in SPSS software (version 21; IBM Corp, Armonk, NY). Cohen d effect sizes were determined in Excel (version 2008; Microsoft Corporation, Redmond, WA) using pooled standard deviations. Effect sizes were interpreted according to the Cohen[23] definitions of *small* (0.2), *medium* (0.5), and *large* (0.8) effects.

RESULTS

The ACL-injury group had greater mass than the ACL + BB and control groups ($P = .041$; Table). The ACL + BB group presented with lateral femoral (n = 12) and tibial (n = 12) BBs of 19.27 ± 18.93 mm^2 and 11.56 ± 11.76 mm^2, respectively.

The peak external KAM did not differ among groups during overground walking ($F_{2,35} = 3.243$, $P = .052$; Figure 2). We observed a small effect size between the ACL + BB and control groups (Cohen d = 0.17; 95% confidence interval [CI] = –0.66, 0.94). Large effect sizes were present between the ACL + BB and ACL-injury groups (Cohen d = –0.92; 95% CI = –1.75, –0.03) and between the ACL-injury and control groups (Cohen d = 0.93; 95% CI = 0.04, 1.75).

Knee-pain frequency ($P < .001$) and severity ($P < .001$) were greater in the ACL-injury and ACL + BB groups than in the control group (Table). We did not observe differences for knee-pain frequency ($P = .41$) or severity ($P = .79$) between the ACL-injury and ACL + BB groups. Subjective knee function was greater in the control group than in the ACL-injury and ACL + BB groups ($P < .001$). We noted no differences in IKDC scores between the ACL-injury and ACL + BB groups ($P = .08$).

No associations existed among tibial BB area and KAM ($r = –0.458$, $P = .14$), knee-pain frequency ($\rho = 0.107$, $P = .74$) or severity ($\rho = –0.197$, $P = .54$), and knee function ($\rho = 0.371$, $P = .24$). Finally, we identified no associations among femoral BB area and KAM ($r = –0.108$, $P = .74$),

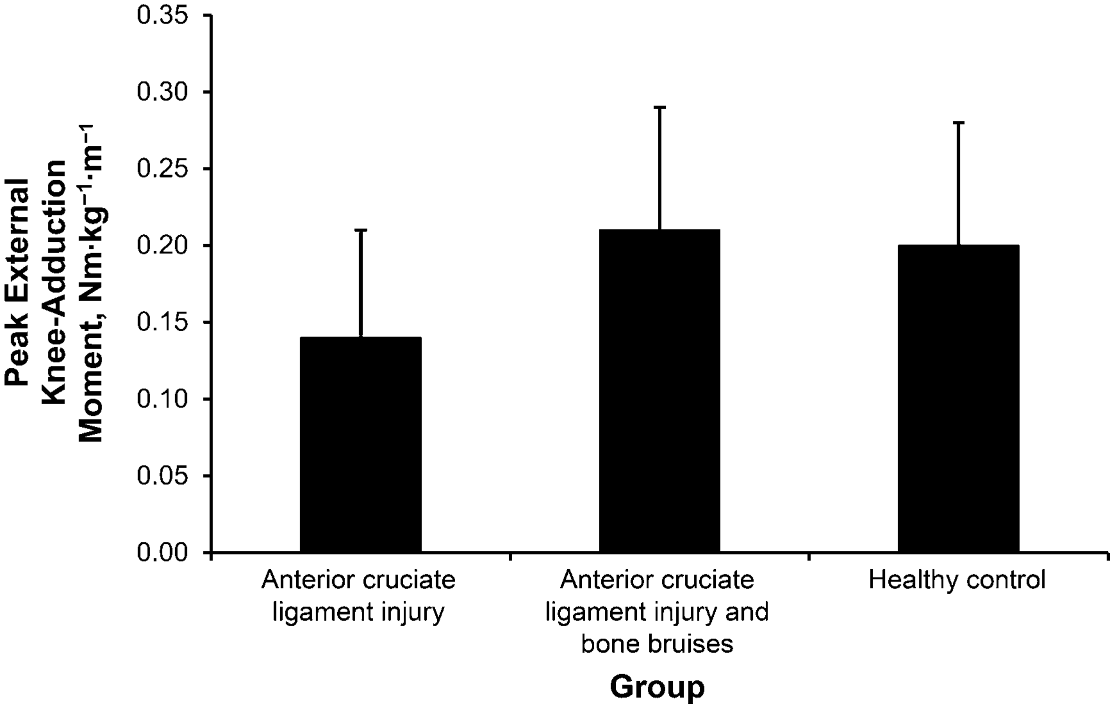

Figure 2. Peak external knee-adduction moment (Nm·kg^{-1}·m^{-1}) for each group.

knee-pain frequency (ρ = –0.327, *P* = .30) or severity (ρ = –0.155, *P* = .63), and knee function (ρ = 0.039, *P* = .91).

DISCUSSION

Lateral tibiofemoral BBs occur frequently with ACL ruptures, increasing symptoms and prolonging disability after injury.[3] Whereas it seems possible that individuals may increase medial joint loading during gait to alleviate pain, our results did not support the presence of this biomechanical adaptation.

The KAM in the ACL + BB group was not greater than that in the ACL-injury group and was nearly identical to that in the control group. Although researchers[12,13] have demonstrated that greater medial compartment loading occurs during walking after ACL reconstruction, on the basis of our results, it does not appear that lateral BBs sustained concurrently with ACL injury contribute to these altered frontal-plane biomechanics. However, in these previous studies, the KAMs were substantially larger than those we reported, and the participants were tested postoperatively. In fact, Butler et al[12] tested participants an average of 5 years postoperatively, a time when radiographic osteoarthritis may be influencing lower extremity biomechanics.[24–26]

When comparing KAM in the ACL + BB and control groups with the ACL-injury group, we observed strong effect sizes with CIs that did not cross zero. These large effect sizes suggest that participants may have had clinically relevant differences in KAM. The ACL-injury group had a longer time between injury and gait analysis and higher IKDC score than the ACL + BB group. Thus, it is possible that the knee-joint biomechanics and function were starting to reach their preinjury levels in the ACL-injury group, whereas the ACL + BB group was tested sooner after injury and still had an antalgic gait and poor function. Given that an increased KAM has been implicated in osteoarthritis onset[27] and progression,[28] future studies are needed to clarify the association among ACL injury and reconstruction, lateral BBs, and development of increased medial tibiofemoral loading.

Our results disagree with those reported in previous studies, indicating greater pain in patients with ACL + BB than in those with ACL injury and no concurrent subchondral bony damage. We believed that pain relief was the reason that participants with ACL + BB would experience greater KAMs. However, the lack of difference in self-reported pain between the ACL + BB and ACL-injury groups may help to explain the lack of difference in KAM among groups in our study. In addition, it is unclear if nociceptors are present in subchrondral bone, where BBs are located.[8] Thus, pain receptors in the soft tissue surrounding the knee may be the source of pain after ACL injury.[8] Szkopek et al[8] reported a 50% reduction in knee pain 2 weeks after ACL injury, a time when the BB intensity on MRI was at its maximum. Our participants reported for testing more than 2 weeks after initial injury (Table); thus, on the basis of the findings of Szkopek et al,[8] it does not seem likely that pain from the BB itself influenced our results. In fact, we observed no association between BB size and KAM, knee pain, or knee function. It is likely that symptoms decrease as BB intensity decreases. Therefore, by the time our participants reported for testing, it may have been too late to detect any association between the BB and knee pain and function.

Our findings suggested that lateral BBs do not contribute to joint degeneration by altering biomechanics. Approximately 80% of all patients with ACL injuries have concomitant lateral BBs.[1] However, only 50% of all individuals who sustain an ACL injury will develop PTOA.[6] Thus, other factors may be more important in joint degeneration, including meniscal status[29–33] and articular cartilage damage sustained at the time of injury.[3] Future investigations are necessary to determine the precise contributors to PTOA development.

Our study had limitations. Participants were observed at only a single, preoperative time point. Thus, the long-term effect of BBs on gait could not be determined. Furthermore, participants with and those without meniscal injuries were included in this study. Whereas the number of participants in each group and the locations of the meniscal injuries were similar across groups, the presence of meniscal injury may have influenced biomechanics. Investigators should explore KAM in the presence of meniscal injury and BBs to determine the added effect of these injuries. In addition, our sample size was small, and our calculated effect sizes suggested that clinically relevant differences in KAM among groups were present, although our results were not different. Future research with more participants will continue to improve our understanding of the influence of lateral tibiofemoral BBs on gait after ACL injury. Furthermore, we traced BB size by hand and did not use computer software. However, a single author with high intrarater reliability performed all tracings. Finally, Webster et al[34] suggested that changes in KAM after ACL reconstruction are sex specific, with females demonstrating greater KAM than males. No data are available to suggest sex differences in KAM in individuals with ACL deficiency, so we included both men and women in our investigation.

CONCLUSIONS

We observed no differences in the external KAM among individuals with an ACL injury, individuals with ACL + BB, and healthy controls. Therefore, whereas increased medial knee-joint loading purportedly precipitates knee-joint degeneration, lateral BB may not contribute to this hazardous increase in the external KAM and medial tibiofemoral loading.

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