Published in final edited form as:

Am J Sports Med. 2014 December ; 42(12): 2917–2925. doi:10.1177/0363546514552184.

Knee Contact Force Asymmetries in Patients Who Failed Return-to-Sport Readiness Criteria 6 Months After Anterior Cruciate Ligament Reconstruction

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Abstract

Background—After anterior cruciate ligament (ACL) injury, contact forces are decreased in the injured knee when compared with the uninjured knee. The persistence of contact force asymmetries after ACL reconstruction may increase the risk of reinjury and may play an important role in the development of knee osteoarthritis in these patients. Functional performance may also be useful in identifying patients who demonstrate potentially harmful joint contact force asymmetries after ACL reconstruction.

Hypothesis—Knee joint contact force asymmetries would be present during gait after ACL reconstruction, and performance on a specific set of validated return-to-sport (RTS) readiness criteria would discriminate between those who demonstrated contact force asymmetries and those who did not.

Study Design—Descriptive laboratory study.

Methods—A total of 29 patients with ACL ruptures participated in gait analysis and RTS readiness testing 6 months after reconstruction. Muscle and joint contact forces were estimated using an electromyography (EMG)–driven musculoskeletal model of the knee. The magnitude of typical limb asymmetry in uninjured controls was used to define limits of meaningful limb asymmetry in patients after ACL reconstruction. The RTS testing included isometric quadriceps strength testing, 4 unilateral hop tests, and 2 self-report questionnaires. Paired *t* tests were used to

assess limb symmetry for peak medial and tibiofemoral contact forces in all patients, and a mixed-design analysis of variance was used to analyze the effect of passing or failing RTS testing on contact force asymmetry.

Results—Among all patients, neither statistically significant nor meaningful contact force asymmetries were identified. However, patients who failed RTS testing exhibited meaningful contact force asymmetries, with tibiofemoral contact force being significantly lower for the involved knee. Conversely, patients who passed RTS testing exhibited neither significant nor meaningful contact force asymmetries.

Conclusion—Joint contact force asymmetries during gait are present in some patients 6 months after ACL reconstruction. Patients who demonstrated poor functional performance on RTS readiness testing exhibited significant and meaningful contact force asymmetries.

Clinical Relevance—When assessing all patients together, variability in the functional status obscured significant and meaningful differences in contact force asymmetry in patients 6 months after ACL reconstruction. These specific RTS readiness criteria appear to differentiate between those who demonstrate joint contact force symmetry after ACL reconstruction and those who do not.

Keywords

ACL; reconstruction; knee; contact force

A rupture of the anterior cruciate ligament (ACL) is a common knee injury, and young, active patients often undergo ligament reconstruction.³⁰ Expectations after surgery include the restoration of knee stability, return to preinjury function, and protection against further knee injuries.³⁰ However, ACL reconstruction (ACLR) does not prevent early osteoarthritic changes in the injured knee.^{26,31,33}

Mechanical factors including altered kinematics, contact forces, and stresses may contribute to the development of osteoarthritis after ACL injuries.^{4,7,17} Changes to the mechanical environment in the knee are believed to initiate a cascade of tissue-level remodeling that results in an imbalance in cartilage homeostasis,^{4,17} thereby contributing to eventual cartilage atrophy and leading to osteoarthritis. Nonetheless, the mechanical environment of the knee after an ACL injury and reconstruction is not well understood. While altered knee contact kinematics are known to exist after ACL injuries^{3,8,16,28} and can persist after reconstruction,^{1,10,23} joint contact forces in the ACL-injured knee are less well described. Joint contact force is the magnitude of load that is applied perpendicular to the articular surface and represents the compressive loading of the joint as a whole. Contact forces are decreased in the ACL-deficient knee during gait,¹³ but whether they normalize or increase after ACLR is unknown. If decreased loading of the injured knee persists, it may prompt deconditioning of the articular cartilage⁶ and lead to structural failure of the tissue with the resumption of normal or excessive loads in the future. Knowledge of knee joint contact forces after ACLR will improve our understanding of the mechanical environment of the knee and its potential effect on the development of osteoarthritis in these patients.

Knee joint loading asymmetries may be detrimental not only in the long term, leading to osteoarthritis, but also in the immediate term after surgery. The rate of sustaining a second ACL injury approaches 1 in 5 for young patients^{27,35,39} and may be highest in the first 7 months after reconstruction.²⁷ Biomechanical asymmetries during sport-relevant movements such as a drop jump are related to the risk of reinjury.³⁵ Although 6 months after ACLR is a common time for patients to attempt to return to preinjury activities, marked functional and biomechanical asymmetries are evident at this time.^{18,32,11} The contention that these asymmetries represent an increased risk for sustaining a second ACL injury has prompted the use of objective functional criteria to identify patients who are ready to safely resume sports rather than a temporal milestone.^{22,32} Functional performance on one such criterion-based return-to-sport (RTS) readiness test has been linked to the presence of kinematic and kinetic asymmetries after ACLR¹¹ and may also be useful in identifying patients who demonstrate joint contact force asymmetries that may signify an increased risk for subsequent injury.

The estimation of muscle and joint contact forces in patients with an ACL injury is nontrivial because patients demonstrate varied neuromuscular adaptations after injuries.^{24,38,44} Muscle forces are a major determinant of joint loading,⁴⁵ and consequently, the relationship between joint moment and contact force is not straightforward,⁴³ particularly when muscles are coactivated. An electromyography (EMG)-driven musculoskeletal model utilizes recorded muscle activity in the estimation of muscle forces and is therefore uniquely suited to estimate joint loading in patients with ACL injuries. Using this modeling approach, we have shown that joint contact forces are decreased during walking in patients with ACL deficiencies.¹³ Early reductions in joint loading, especially if persistent in the months and years after the injury, may prompt deconditioning of the articular cartilage and increase the risk of damage with the resumption of normal or increased loads at a later time. Estimates of joint contact forces after ACLR will provide insight into the role that joint loading plays in the risk for joint degenerative changes in the ACL-injured knee.

Therefore, the purpose of this study was to determine whether knee joint contact force asymmetries during gait exist 6 months after ACLR and to investigate whether the presence of contact force asymmetries was associated with functional performance on a battery of clinical tests. We hypothesized that meaningful and significant asymmetries would be present at this 6-month milestone when patients are often cleared to return to preinjury sports. We also hypothesized that performance on a specific set of RTS readiness criteria² would discriminate between those who demonstrated contact force asymmetries and those who did not.

MATERIALS AND METHODS

Participants

A total of 29 patients were included in the present study. All patients were recruited through the University of Delaware Physical Therapy Clinic and were selected based on the following inclusion criteria: age between 13 and 55 years; regular participation in jumping, cutting, or pivoting sports before the injury (> 50 h/y in International Knee Documentation

Committee [IKDC] level I/II activities²⁰); a complete unilateral ACL rupture (> 3 -mm side-to-side difference in anterior tibial translation using a KT-1000 arthrometer [MedMetrics] and confirmed by magnetic resonance imaging); and presence of characteristic dynamic knee instability after the ACL injury (classified functionally as a noncopers¹² preoperatively). Exclusion criteria were a contralateral knee injury, grade III sprain to other knee ligaments, symptomatic meniscal tear, or large articular cartilage defect greater than 2 cm². Patients underwent ACLR with either a hamstring tendon autograft ($n = 12$) or allograft ($n = 17$). A criterion-based postoperative rehabilitation protocol² that focused on the resolution of joint effusion, range of motion deficits, quadriceps strength impairments, and functional limitations was used. Patients underwent gait analysis and RTS readiness testing 6 months after ACLR. These data were collected prospectively as part of a randomized clinical trial on the effectiveness of preoperative rehabilitation^{11,19} ($n = 21$) or subsequent case series investigating specialized postoperative rehabilitation ($n = 8$). Uninjured participants were also recruited from the university community to quantify the typical interlimb contact force asymmetry in a reference population. Participants were included as controls if they had no symptomatic lower extremity injury, had no history of lower extremity orthopaedic injuries requiring surgery, and were regular participants in IKDC level I/II activities. This work was approved by the University of Delaware Human Subjects Review Board, and all participants gave informed consent before being enrolled. The study is registered at [ClinicalTrials.gov](https://clinicaltrials.gov/ct2/show/study/NCT01773317) (NCT01773317).

Gait Analysis

Using a patient-specific EMG-driven model of the knee, muscle forces were estimated and then used to calculate the joint contact force for the stance phase of gait. This modeling approach is valid²⁹ and repeatable¹⁵ in estimating knee contact forces and has been described in detail previously.^{5,14}

Three-dimensional overground gait analysis was performed using a passive optoelectric system with 8 cameras (VICON, Oxford Metrics Ltd) and a 6-component embedded force platform (Bertec Corp). Retroreflective markers were placed over anatomic landmarks (iliac crests, greater trochanters, femoral epicondyles, malleoli, first and fifth metatarsal heads) to identify joint centers, and rigid thermoplastic shells with clusters of 4 markers were used to track bilateral lower extremity segment motions as described previously.¹⁴ Analog and video data were synchronously sampled at 120 and 1080 Hz, with low-pass filters applied to marker (cutoff, 6 Hz) and ground-reaction force data (cutoff, 25 Hz). Visual3D (C-Motion Inc) was used to calculate lower extremity kinematics and kinetics in the stance phase. Surface EMG signals were recorded with the MA-300 system (Motion Lab Systems) from the vastus medialis and vastus lateralis, rectus femoris, semitendinosus, long head of the biceps femoris, and medial and lateral gastrocnemii. Electrode placement followed SEINAM sensor location guidelines.²¹ Maximal isometric volitional contractions were performed to elicit maximal EMG results for normalization. The EMG data were sampled at 1080 Hz, high-pass filtered (30 Hz), rectified, and low-pass filtered (6 Hz) to create a linear envelope. Linear envelopes were normalized to the maximum value found during isometric or walking trials. The EMG signal for the vastus intermedius was defined as being equal to the average of the vastus medialis and vastus lateralis linear envelopes. The EMG signals for

the semimembranosus and short head of the biceps femoris were equal to the linear envelopes for the semitendinosus and the long head of the biceps femoris, respectively.

Knee Contact Forces

Muscle forces were first estimated using a patient-specific EMG-driven musculoskeletal model of the knee^{14,29} (Figure 1), which is summarized briefly here. For a greater detail, we refer the reader to the original model description.^{5,14} This model gives repeatable joint contact force estimates between days¹⁵ and has been validated against known joint contact forces for a patient with a force-recording knee prosthesis.²⁹

Gait analysis was performed with EMG-provided model inputs (Figure 1, box at left). The activation dynamics portion of the model characterized the transformation from EMG (the neural signal) to muscle activation, and the contraction dynamics portion of the model characterized the transformation from activation to muscle force. The musculoskeletal geometry portion of the model containing 10 muscle-tendon actuators (Simm 4.0.2,⁹ Musculographics) was scaled according to anthropometric dimensions of each patient and characterized the transformation from muscle forces to joint moments.

The model was calibrated for each patient using the stance phase of a single walking trial to estimate muscle parameters that are difficult to accurately measure *in vivo*, including optimal muscle fiber length and tendon slack length. During model calibration (Figure 1, gray arrows), muscle parameters that characterized the activation and contraction dynamics portions of the model were iteratively adjusted so that the resultant muscle forces produced a flexion/extension muscle moment that matched the sagittal plane knee moment derived from gait analysis. Adjustable muscle parameters were allowed to vary within physiological bounds (see Gardinier et al¹⁴ for limits used). After calibration, joint kinematics and EMG were used to estimate muscle forces for the stance phase of 3 walking trials (Figure 1, black arrows).

Medial contact force was calculated using a frontal plane moment-balancing algorithm (Figure 2).¹³ The external knee adduction moment derived from gait analysis was expressed about the contact point in the lateral compartment. This external moment was balanced internally by moments due to muscle forces about the lateral contact point and by the contact force acting at the medial contact point, with a moment arm equal to the distance between contact points. Lateral compartment contact force was similarly calculated by balancing the adduction moment about the medial contact point; tibiofemoral contact force equaled the sum of the force in the medial and lateral compartments. The variables of interest were peak medial compartment contact force and peak tibiofemoral compartment contact force in the first half of the stance phase. Contact forces were normalized to body weight (BW), and the mean of 3 trials was used for analysis.

RTS Readiness Testing

Return-to-sport readiness testing was performed to examine the association of joint contact force asymmetries (derived from a computational model) with functional performance on a battery of clinical tests. Testing included the following components: isometric quadriceps strength testing, a series of 4 single-legged hop tests, completion of the Knee Outcome

Survey–Activities of Daily Living subscale (KOS-ADLS), and global rating scale (GRS) questionnaires. To pass the test and be cleared to return to sporting activities, patients needed to demonstrate 90% quadriceps strength symmetry, 90% limb symmetry on 4 hop tests, a 90% KOS-ADLS score, and a 90% GRS score.² If patients failed to obtain a 90% score on any single criterion, they were not given a passing score on the RTS readiness test.

Isometric quadriceps strength was measured using the burst superimposition technique⁴⁰ to achieve a true maximal volitional effort. Patients were seated in a KIN-COM dynamometer (Chatanooga Corp) with their knee secured in 90° of flexion. For the test, patients received a resting burst of stimulation to the anterior thigh (10 pulses at 100 pps for 600 μs with 65 V) and were then prompted by the therapist to kick as hard as they could. A supramaximal 130-V burst was delivered during the maximal effort, eliciting maximal force. If the ratio of maximal volitional force to supramaximal burst force was less than 95%, the test was repeated up to 3 times to achieve a true maximal volitional effort.

A series of unilateral hop tests³⁴ were then completed. These 4 hop tests have demonstrated good test-retest reliability in healthy young adults³⁷ and in patients after ACLR.³⁶ Patients performed 2 practice trials, and the subsequent 2 trials were recorded and averaged for analysis. The hop tests consisted of the single-legged hop for distance, triple-hop for distance, crossover hop for distance, and 6-m timed hop. A limb symmetry index for each test was calculated as follows:

$$\text{limb symmetry index} = \left(\frac{\text{involved distance}}{\text{uninvolved distance}} \times 100 \right) \text{ or } \left(\frac{\text{uninvolved time}}{\text{involved time}} \times 100 \right).$$

After completing the hop tests, patients completed 2 self-reported questionnaires: the KOS-ADLS and GRS. The KOS-ADLS contains 14 items that evaluate the patients' perceived limitations related to various impairments and daily activities²⁵ and gives a score expressed as a percentage of the 70-point maximum score. The GRS of perceived function consists of a single item in which patients are asked to score their perceived overall knee function on a scale of 0 to 100, with 0 representing an inability to perform any activity and 100 representing their knee function before injury.

Statistical Analysis

Meaningful limb asymmetries were operationally defined as being significantly different from the typical limb asymmetry observed in 13 uninjured controls (8 male, 5 female; 7 IKDC level I, 6 level II; mean age, 21.0 ± 2.5 years; mean body mass, 76.0 ± 16.4 kg; mean height, 1.74 ± 0.12 m; mean walking speed, 1.54 ± 0.19 m/s). For this study, the typical interlimb difference in contact force for uninjured controls was estimated as

$$\text{standard error of measurement} = SD \times \sqrt{1 - ICC},$$

where SD is the standard deviation of all observations, and ICC is the limb-to-limb intraclass correlation coefficient. The smallest meaningful interlimb difference was estimated as

$$\text{meaningful interlimb difference} = 1.96 \times \sqrt{2} \times \text{standard error of measurement},$$

where 1.96 corresponds to a 95% CI. Interlimb differences in contact force that were greater than the estimated smallest meaningful difference were designated as meaningful asymmetries.

Limb symmetry for peak tibiofemoral and medial compartment contact forces for all patients was assessed using paired *t* tests. The interlimb difference equaled the involved minus the uninvolved peak force, with negative values representing lower force for the involved knee.

Mixed-design analyses of variance (ANOVAs) were performed to analyze the effect of passing or failing the RTS readiness test on joint contact forces. The design included the within-patient factor of limb (involved, uninvolved), between-patient factor of RTS group (pass, fail), and covariate of self-selected walking speed. All statistical analyses were performed using SPSS Statistics v 21 (IBM Corp); a significance level of .05 was used.

RESULTS

Based on typical asymmetries observed in uninjured controls (Table 1), interlimb differences in the peak medial compartment contact force of 0.42 BW and peak tibiofemoral compartment contact force of 0.71 BW were defined as being meaningful. Among all patients 6 months after ACLR, the mean absolute interlimb difference for the peak medial compartment contact force was meaningful (0.47 ± 0.34 BW). However, the mean peak medial compartment contact force was not significantly different between limbs (involved, 2.72 ± 0.65 BW; uninvolved, 2.90 ± 0.66 BW; $t(29) = 1.784$; $P = .085$) (Figure 3). The mean absolute interlimb difference for the peak tibiofemoral compartment contact force was not meaningful (0.69 ± 0.63 BW). Similarly, the mean peak tibiofemoral compartment contact force was not significantly different between limbs (involved, 3.95 ± 1.01 BW; uninvolved, 4.18 ± 0.76 BW; $t(29) = 1.351$; $P = .188$) (Figure 3).

After stratifying patients by performance on the RTS readiness test, there were no significant differences between the pass and fail groups for body mass, height, age, walking speed, time from injury to ACLR, or time from ACLR to testing (Table 2). Peak contact forces were lower for the involved knees in both groups, with the exception of peak medial compartment contact force for the pass group (Table 3 and Figure 4).

The ANOVA for peak medial compartment contact force revealed no significant limb $\times$ RTS group interaction, indicating that peak medial compartment contact force asymmetry was not significantly different between the pass and fail groups (Table 4 and Figure 5). Walking speed, the covariate, was significantly related to peak medial compartment contact

force (Table 4). While the main effect of limb approached significance ($P = .085$), there were no other significant main effects or interactions (Table 4). Nonetheless, the mean absolute interlimb difference in the peak medial compartment contact force for the fail group was meaningful (0.61 ± 0.41 BW), while that of the pass group was less than the smallest meaningful difference (0.36 ± 0.23 BW).

The ANOVA for peak tibiofemoral compartment contact force revealed a significant limb $\times$ RTS group interaction, indicating that peak tibiofemoral compartment contact force asymmetry was significantly different for the pass and fail groups (Table 5 and Figure 5). Peak tibiofemoral compartment contact force was significantly related to walking speed, and there were no other significant main effects or interactions. Further investigation revealed no significant between-limb difference in the peak tibiofemoral compartment contact force for the pass group ($t(16) = 0.158$; $P = .877$), and the mean absolute interlimb difference was not meaningful for this group (0.63 ± 0.63 BW). However, those in the fail group demonstrated significantly lower peak force for the involved knee compared with their uninvolved knee ($t(11) = 2.579$; $P = .026$). The mean interlimb difference in the peak tibiofemoral compartment contact force for the fail group was also greater than the smallest meaningful difference (0.78 ± 0.63 BW).

DISCUSSION

The purpose of this study was to determine whether knee contact force asymmetries exist 6 months after ACLR and whether functional deficits as identified by a criterion-based RTS readiness test² are associated with persistent joint contact force asymmetries at this time. Our primary finding was that joint contact force asymmetries are present in some patients during walking 6 months after ACLR and that the subgroup of patients who failed the RTS readiness test exhibited significant and meaningful loading asymmetries.

Patients in this study who failed RTS readiness testing exhibited decreased contact force for the involved limb during walking, which is a pattern similar to that described in patients with acute ACL injuries.¹³ Peak tibiofemoral contact force was significantly lower for the involved knee of the patients who failed RTS readiness testing, and the mean absolute interlimb differences for both medial and tibiofemoral contact forces exceeded the smallest meaningful difference threshold. The presence of meaningfully decreased contact forces in the involved knee 6 months after ACLR indicates that early postinjury joint loading adaptations either persist or resume after ACLR and postoperative rehabilitation in some patients.

Conversely, among patients who passed RTS readiness testing in this study, the magnitude of interlimb differences for both medial and tibiofemoral contact forces was not meaningful. In this group of patients, early loading asymmetries appear to be ameliorated after ACLR and postoperative rehabilitation. Furthermore, these results indicate that patients who no longer demonstrate contact force asymmetries during gait may be readily identifiable by functional testing in the clinical setting. The persistence of asymmetries in some patients and the recovery of symmetry in others at the 6-month postoperative milestone typify the variable recovery trajectory after ACLR^{11,19} and underscore the need for criterion-based

functional tests to assess the recovery of functional symmetry and to guide clinical decision making after ACLR.

The present study draws a useful parallel between functional performance as assessed in a clinical setting and joint loading symmetry as estimated using a specialized musculoskeletal model. Classifying patients by performance on a set of RTS readiness criteria elucidated meaningful loading asymmetries in the group of poorer functioning patients. This builds on previous work that demonstrated the potential for this same set of rigorous RTS readiness criteria to discriminate between those who do and do not demonstrate persistent kinematic asymmetries after ACLR.¹¹ More broadly, these studies illustrate the way in which the recovery of symmetrical knee function may reflect the recovery of movement and joint loading symmetry during daily activities.

In patients who were between 1 and 5 years after ACLR, Tsai and colleagues⁴¹ reported increased tibiofemoral contact forces in the involved limb during a unilateral drop-land task. While the difference in task and patient population between their study and the present one is noteworthy, differences in the time of testing and patient functional status may also explain their finding of an opposite trend for involved contact force after ACLR. Another study by Tsai and Powers⁴² highlights the effect that the adopted movement strategy can have on contact forces. Patients with varying levels of functional limitations will likely adopt different movement strategies in a particular task. Therefore, patient functional status is an important factor to consider when comparing joint contact force between study cohorts.

Whether the decreased contact forces in the involved knee of patients in the fail group in the present study are related to the reinjury risk or are potentially harmful to long-term joint health remains unknown. The magnitude of contact force asymmetries identified in patients who failed RTS readiness testing may be increased in sport-relevant activities that are more demanding than gait, thereby increasing the risk for reinjury to the ACL when patients return to preinjury activities. Secondly, the persistence of altered contact forces, especially in an activity as common as walking,⁴ may also represent a significant factor in the development of osteoarthritis in the years after an ACL injury and reconstruction, even if a patient does not resume preinjury sports. Prolonged decreased loading of the injured knee may result in atrophic, stress-deprived cartilage that is vulnerable to injuries with the resumption of normal daily activity. Because movement strategies that affect joint contact forces are modifiable,⁴² rehabilitation after ACLR presents an opportunity to intervene in the joint degenerative process. Additional training may maximize function and restore normal and symmetrical joint loading, potentially protecting against a second ACL injury in the short term and also maximizing knee joint health in the long term.

An important strength of this study is the use of an EMG-driven modeling approach to estimate muscle and joint contact forces. Because altered muscle activations are observed in patients with an ACL injury and reconstruction, the task of partitioning forces among muscles in this patient population is not trivial. A patient-specific musculoskeletal model that incorporates recorded muscle activity in its estimation of muscle forces is uniquely suited to estimate muscle and joint contact forces after ACLR. One limitation of this study is the inability to define a clinically meaningful magnitude for contact force asymmetries. It is

difficult to set forth a magnitude of contact force asymmetry that constitutes clinically meaningful asymmetry without the ability to link asymmetry magnitudes to outcomes such as the incidence of radiographic osteoarthritis or a second ACL injury. Therefore, our goal for this study in estimating a magnitude for meaningful asymmetry was to provide a benchmark for what constitutes an abnormal degree of asymmetry. Studies linking asymmetry magnitudes to clinical outcomes such as the incidence of radiographic osteoarthritis or a second ACL injury are needed. The cross-sectional design of the present study limits our ability to quantify the effects of ACLR and postoperative rehabilitation on joint contact force symmetry in these patients. Longitudinal studies are needed to better characterize the early loading profiles of patients with ACL injuries. However, the sixth postoperative month remains a critical time for RTS decision making in this population, and the results of the present study underscore the importance of using functional performance-based criteria to evaluate patients at this time.

CONCLUSION

To our knowledge, this is the first study to describe joint contact forces during gait in patients with ACLR and to elucidate differences in loading symmetry based on functional performance on a set of clinical tests. When assessing all patients together, the variability in functional status obscured significant and meaningful differences in contact force asymmetry, highlighting the functional variability of this patient group 6 months after ACLR. However, joint contact force asymmetries during walking were apparent 6 months after ACLR among patients who demonstrated poor functional performance on an RTS readiness test,² underscoring the potential discriminative value of criterion-based functional tests at this 6-month postoperative milestone. These specific RTS readiness criteria appear to differentiate between those who demonstrate joint contact force symmetry after ACLR and those who do not.

ACKNOWLEDGMENT

The authors acknowledge Kristen Stump for her assistance with data processing.

One or more of the authors has declared the following potential conflict of interest or source of funding: This work was supported by grants from the National Institutes of Health (P30 GM103333, R01 AR046386, R01 AR048212, S10 RR022396) and by the Foundation for Physical Therapy Promotion of Doctoral Studies Scholarships awarded to Stephanie Di Stasi during her doctoral work at the University of Delaware.

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Figure 1.

Schematic of the procedure for estimating muscle forces. Gait analysis with electromyography (EMG)—provided model inputs (box at left). During calibration (gray arrows), muscle parameters that governed the activation and contraction dynamics portions of the model were iteratively adjusted so that the resultant muscle forces produced a flexion/extension muscle moment that matched the sagittal plane knee moment derived from gait analysis. After calibration, joint kinematics and EMG were used to estimate muscle forces for novel gait trials (black arrows).

Figure 2.

Schematic of the calculation of contact force in the medial compartment. KAM_{LC} is the external knee adduction moment expressed about the contact point of the lateral compartment. This external moment is balanced internally by moments due to muscle forces ($Muscle\ Force_i$) acting with moment arms (ma_i) about the lateral contact point and by the contact force acting at the medial contact point (MC Force), with a moment arm equal to the intercondylar distance (d_{LC}).

Figure 3. Peak medial contact force (MCpk) and tibiofemoral contact force (TCpk) for all patients. Points are means, and whiskers are 95% CIs for differences between limbs. BW, body weight.

Figure 4.

(A) Medial and (B) tibiofemoral contact forces for pass and fail groups. Values are non-speed-adjusted group means. BW, body weight.

Figure 5. Peak (A) medial compartment and (B) tibiofemoral contact force for pass and fail groups. Points are speed-adjusted means, and whiskers are 95% CIs. BW, body weight.

TABLE 1Smallest Meaningful Difference Thresholds for Medial and Tibiofemoral Contact Forces^a

	Left Limb, Mean $\pm$ SD	Right Limb, Mean $\pm$ SD	Between-Limb ICC	Meaningful Difference
Medial contact force, BW	3.04 $\pm$ 0.50	3.13 $\pm$ 0.48	0.900	0.42
Tibiofemoral contact force, BW	4.69 $\pm$ 0.86	4.34 $\pm$ 0.76	0.902	0.71

^aValues are estimated from 13 uninjured control participants using a 95% CI. BW, body weight; ICC, intraclass correlation coefficient.

TABLE 2Demographics for Patients Subgrouped by Return-to-Sport Status^a

	Pass Group	Fail Group	P Value
Sex, male:female, n	9:8	8:4	.703
Mass, kg	80.06 ± 15.14	82.07 ± 16.31	.735
Height, m	1.71 ± 0.11	1.74 ± 0.07	.504
Age, y	28.0 ± 10.7	30.3 ± 10.8	.573
Walking speed, m/s	1.52 ± 0.14	1.58 ± 0.11	.213
Time from injury to ACLR, wk	12.5 ± 6.8	21.3 ± 14.1	.064
Graft type, allograft:autograft, n	9:8	8:4	.703
Time from ACLR to testing, wk	25.8 ± 2.9	27.2 ± 2.9	.229

^aValues represent mean ± SD except where indicated otherwise. ACLR, anterior cruciate ligament reconstruction.

TABLE 3Contact Forces for Those Who Passed and Those Who Failed RTS Readiness Testing^a

	Pass		Fail	
	Unadjusted Mean	Adjusted Mean (95% CI)	Unadjusted Mean	Adjusted Mean (95% CI)
Peak medial contact force				
Involved limb	2.74	2.79 (2.48-3.11)	2.68	2.61 (2.23-2.99)
Uninvolved limb	2.79	2.84 (2.54-3.15)	3.06	2.98 (2.62-3.34)
Peak tibiofemoral contact force				
Involved limb	4.14	4.24 (3.78-4.69)	3.69	3.55 (3.01-4.10)
Uninvolved limb	4.11	4.17 (3.81-4.53)	4.29	4.20 (3.77-4.63)

^aUnits of measurement are body weights. Adjustments are for walking speed. RTS, return to sport.

TABLE 4Main Effects and Interactions From Analysis of Variance for Peak Medial Compartment Contact Force^a

	Degrees of Freedom	F Ratio	P Value
Effect			
Speed (covariate)	(1,26)	6.583	.016 ^b
Limb	(1,26)	4.181	.051
RTS group	(1,26)	0.012	.912
Interaction			
Limb × speed	(1,26)	0.101	.753
Limb × RTS group	(1,26)	2.256	.145

^aRTS, return to sport.^bStatistically significant.

TABLE 5Main Effects and Interactions From Analysis of Variance for Peak Tibiofemoral Compartment Contact Force^a

	Degrees of Freedom	F Ratio	P Value
Effect			
Speed (covariate)	(1,26)	9.056	.006 ^b
Limb	(1,26)	3.152	.088
RTS group	(1,26)	1.485	.234
Interaction			
Limb × speed	(1,26)	1.097	.305
Limb × RTS group	(1,26)	4.574	.042 ^b

^aRTS, return to sport.^bStatistically significant.