Published in final edited form as:

Clin Biomech (Bristol, Avon). 2014 May ; 29(5): 531–536. doi:10.1016/j.clinbiomech.2014.03.011.

Clinically-Relevant Measures Associated with Altered Contact Forces in Patients with Anterior Cruciate Ligament Deficiency

Emily S. Gardinier, PhD¹, Kurt Manal, PhD^{2,3}, Thomas S. Buchanan, PhD^{2,3}, and Lynn Snyder-Mackler, PT, ScD, FAPTA^{2,4}

¹School of Kinesiology, University of Michigan, Ann Arbor, MI, USA

²Delaware Rehabilitation Institute, University of Delaware, Newark, DE, USA

³Department of Mechanical Engineering, University of Delaware, Newark, DE, USA

⁴Department of Physical Therapy, University of Delaware, Newark, DE, USA

Abstract

Background—Knee joint contact forces are altered after anterior cruciate ligament injury during walking and may be related to clinically-relevant measures of impairments or self-reported function. The purpose of this study was to investigate the association of several clinically-relevant measures with altered knee contact forces in patients with anterior cruciate ligament injury.

Methods—Data for this study represent a cross-sectional observational analysis of thirty-seven (23 M, 14 F) patients with complete unilateral anterior cruciate ligament injury. Gait analysis with electromyography was used to obtain estimates of tibiofemoral joint contact force using an electromyography-driven musculoskeletal model. Multivariable linear regression was used to identify measures associated with tibiofemoral joint contact force.

Findings—Involved knee extensor muscle strength and patient-reported knee function on the Global Rating Scale of Perceived Function were significantly associated with peak tibiofemoral contact force for the involved limb. Patients who were stronger and who perceived higher knee function walked with greater contact forces on their involved knees. After controlling for walking speed, involved extensor strength explained 8.9% of the variance in involved peak tibiofemoral contact force and score on the Global Rating Scale explained an additional 9.4% of the variance.

Interpretation—Improvements in involved quadriceps strength and overall function as measured by patient self-report may be important for increasing involved limb contact forces, thereby restoring loading symmetry in these patients who demonstrate decreased involved limb loading after injury. These results highlight the potential value of studying the recovery of strength, self-reported function and joint loading symmetry in patients with anterior cruciate ligament injury.

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Correspondence should be addressed to: Emily S. Gardinier, 1206 CCRB, 401 Washtenaw Avenue, Ann Arbor, MI 48109, UNITED STATES, egardin@umich.edu, ph: (734) 763-9157.

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Keywords

ACL injury; Contact Force; Quadriceps Strength; Patient-reported Function

Introduction

The risk for developing osteoarthritis is increased after anterior cruciate ligament (ACL) injury (Lohmander et al., 2007; Øiestad et al., 2009) and altered loading of the injured knee may contribute to the development of osteoarthritis in these patients (Griffin and Guilak, 2005). Individuals with ACL rupture walk with decreased contact forces on their involved knees (Gardinier et al., 2012a), and this altered loading is evident despite these patients having resolved effusion, range of motion, pain and obvious gait impairments at the time of testing. However, the utility of other clinically-relevant measures in explaining altered loading after injury has not been investigated.

Movement strategies adopted by patients after ACL injury are likely influenced by a constellation of factors including both physical impairments resulting from injury and behavioral adaptations resulting from the experience of functional instability. Clinically-relevant measures that have been shown to differentiate between ACL-injured patients with and without movement asymmetries include a multi-component functional classification exam (Chmielewski et al., 2001; Rudolph et al., 2001) and a functional return-to-sport assessment (Di Stasi et al., 2013). These assessments include performance-based as well as patient-reported test components. Other clinically-relevant measures that have been related to altered movement strategies include quadriceps strength (Lewek et al., 2002; Snyder-Mackler et al., 1991), knee effusion (Torry et al., 2000), time from injury (Wexler and Hurwitz, 1998), and self-reported function (Lewek et al., 2002). Identifying relationships between clinically-relevant measures and altered joint loading will highlight the rehabilitation constructs that are associated with normal and symmetrical loading, and will likewise promote the development of interventions that effectively target aberrant joint loading in these patients.

Identifying relationships between altered contact forces and clinically-relevant measures will also expand the impact and relevance of modeling estimates for clinical practice. Currently, estimates of muscle and joint contact forces in vivo requires a musculoskeletal modeling approach and cannot be well-approximated using muscle activity (Meyer et al., 2013) or joint moments (Walter et al., 2010) alone. Musculoskeletal models used to estimate muscle and joint contact forces are necessarily complex and generating these model estimates requires gait analysis data, customized software and significant post-processing (Erdemir et al., 2007). Consequently, estimates of joint contact force are currently not widely available in the clinical setting. A better understanding of the patient-specific factors that relate to altered contact forces will help clinicians identify patients who likely demonstrate altered loading using clinically-available assessments.

The purpose of this study was to investigate the association of several clinically-relevant measures with altered knee contact forces in patients with ACL injury. We hypothesized that a combination of clinically-relevant measures including both performance-based and

patient-reported measures would explain a significant portion of the variance in involved knee contact forces.

Methods

Subjects

Data for this study represent a cross-sectional observational analysis from thirty-seven (23 M, 14 F) participants with complete unilateral ACL injury who completed functional and biomechanical testing in our lab. Data were collected prospectively as part of either a randomized clinical trial (n=25) (Hartigan et al., 2010) or subsequent case series (n=12) and thirty of these patients were included in our primary analysis of knee joint contact forces after acute ACL injury (Gardinier et al., 2012a). All patients were recruited through the University of Delaware Physical Therapy Clinic. This work was approved by institutional Human Subjects Review Board and all participants provided informed consent prior to study enrollment.

Study inclusion criteria were: (1) regular pre-injury participation in IKDC level I/II (jumping, cutting or pivoting) sports (Hefti et al., 1993), (2) age between 13 and 55 years, (3) complete unilateral ACL rupture confirmed through clinical examination and MRI and (4) functional classification as a noncopper (i.e. demonstrating characteristic dynamic knee instability after injury) according to the criteria described by Fitzgerald and colleagues (Fitzgerald et al., 2000). Knee range of motion, effusion, pain, and obvious gait impairments were treated and resolved before testing in accordance with the impairment treatment protocol described by Hurd and colleagues (Hurd et al., 2008). Prior to entering the study, patients underwent physical examination by a licensed physical therapist. Before participating in study testing, patients were required to demonstrate full knee extension (0 degrees), exhibit minimal knee effusion (grade of 1+ or less using the modified stroke test (Adams et al., 2012)), report no knee pain with hopping up and down on the involved limb and demonstrate no visually obvious gait impairments when assessed by the therapist. Study exclusion criteria were presence of a full-thickness chondral defect $\geq 1 \text{ cm}^2$, symptomatic meniscus tear or concomitant grade III rupture to other knee ligaments.

Clinical Testing

Patients were asked to report the number of times they had experienced their knee giving way (e.g. sensation of buckling or shifting) since their injury. Time since injury was also recorded. Isometric knee extensor strength was then tested using the burst superimposition technique (Snyder-Mackler et al., 1995). Patients were seated in a KIN-COM dynamometer (Chattanooga Corp., Chattanooga, TN, USA) A supramaximal burst of electrical current was delivered via two 3"x5" self-adhesive electrodes applied to the testing limb while the patient performed a maximal effort kick to elicit maximal force. Maximum volitional force was the maximal force output prior to the burst, and activation ratio was the maximum volitional force divided by maximum force output resulting from the supramaximal burst. If activation ratio was less than 95% (operationally defined as normal (Chmielewski et al., 2004)), the test was repeated up to two more times in order to achieve a true maximal volitional effort.

The highest maximum volitional force measurement was normalized to body mass and tibia length for analysis.

After strength testing, patients completed 3 self-report outcomes: the Knee Outcome Survey Activities of Daily Living Scale (KOS-ADLS)(Irrgang et al., 1998) and the Global Rating Scale of perceived function (GRS) and the International Knee Documentation Committee 2000 subjective form (IKDC 2000)(Irrgang et al., 2001). The KOS-ADLS contains 14 items that assess patients' perceived limitations related to various impairments and daily activities (Irrgang et al., 1998) and gives a score expressed as a percentage of the 70-point maximum score. The KOS-ADLS is a reliable, valid, and responsive instrument for the assessment of functional limitations that result from a wide range of knee pathologies (Irrgang et al., 1998). The GRS 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 zero representing an inability to perform any activity and 100 representing their knee function prior to injury, including sports participation. The IKDC 2000 (Irrgang et al., 2001) contains 20 items and gives a score expressed as a percentage of the 87-point maximum score. The IKDC 2000 is a valid and reliable instrument for assessing patients' symptoms, function, and sports activity in patients with a variety of knee problems (Higgins et al., 2007; Irrgang et al., 2001). All scores were calculated after clinical testing was completed.

All patients included in this study reported no pain with hopping immediately prior to clinical testing. Nonetheless, we assessed the potential association of knee pain and joint loading by categorizing each patient's response to the first item on the KOS-ADLS (which asks to what degree the experience of knee pain affects their usual daily activities). If patients reported that they did not have pain with daily activities (item score = 5), they were categorized as having no pain. If patients reported having any pain (item score = 4), they were categorized as having knee pain for the purposes of this study.

Biomechanical Testing

Patients were asked to walk at their self-selected, intentional speed down a 20-m walkway. An 8-camera video system (sampling rate 120 Hz) (VICON, Oxford Metrics Ltd., London, UK) with embedded force platform (sampling rate 1080 Hz) (Bertec Corporation, Worthington, OH, USA) were used to record marker trajectories and ground reactions. Passive retro-reflective markers (Gardinier et al., 2012b) were used to define anatomical coordinate systems and track limb motion during gait. Surface electromyography (EMG) was recorded using an MA-300 EMG System (sampling rate 1080 Hz) (Motion Lab Systems, Baton Rouge, LA, USA) and was used as input to the musculoskeletal model for estimation of muscle forces.

Muscle forces were estimated using an EMG-driven musculoskeletal model of the knee (Buchanan et al., 2004; Gardinier et al., 2012b) that has demonstrated good repeatability (Gardinier et al., 2013) and high accuracy when validated using *in vivo* contact force data recorded from an instrumented knee prosthesis (Manal and Buchanan, 2013). The lower extremity anatomical model (SIMM 4.0.2, Musculographics, Chicago, IL, USA (Delp et al., 1990)) contained 10 musculotendon actuators for the knee and was scaled according to anatomical dimensions captured by the retro-reflective markers. For model calibration,

adjustable model parameters that characterized the subject-specific EMG-to-force relationship were allowed to vary within limits as specified previously (Gardinier et al., 2012b). After calibrating the model for each subject, muscle forces were predicted for 3 walking trials. Medial and lateral compartment contact force was calculated as described in the primary analysis of knee joint contact forces (Gardinier et al., 2012a). Contact forces were normalized to body weight (BW) and tibiofemoral contact force equaled the sum of medial and lateral contact forces. Peak tibiofemoral contact force occurred in early stance phase, and the average value from 3 walking trials was used for analysis.

Regressions

Linear regression with back-wise entry method was used to investigate the association of clinically-relevant measures with involved limb peak tibiofemoral contact forces. Measures that were considered for selection were (in testing order): time from injury to testing, reported experience of more than 1 give-way since injury (Yes/No), maximal knee extensor strength, KOS-ADLS score, GRS score and IKDC 2000 score. Before the selection procedure, the data were checked for extremes and cases were eliminated as outliers if their value was greater than 3 standard deviations from the group mean. Self-selected walking speed was entered into Block 1 of all regressions in order to account for its positive relationship with knee contact forces (Zhao et al., 2007).

Initial partial correlations were performed to assess the relationship between each clinically-relevant measure and peak tibiofemoral contact force, while controlling for walking speed. The combined predictive ability of the most promising clinical measures was subsequently assessed in a final multivariate regression. For constructing final multivariate regressions, sample size was used to guide the number of independent variables allowed in the model. In order to test a model as complex as the sample size would permit and yet avoid over-fitting the data, no more than 1 independent variable per 10 observations was allowed. Clinically-relevant measures were selected based on clinical judgment and strength of their association with the dependent variable derived from initial correlations. Accordingly, one each of the performance-based and patient-reported measures that demonstrated the strongest association with peak tibiofemoral contact force was selected and entered hierarchically in testing order.

For comparison with the involved limb, clinically relevant measures associated with peak uninvolved tibiofemoral contact forces were analyzed in a separate multivariate regression using measures complimentary to those chosen for the involved limb regressions. Statistical procedures were performed using IBM SPSS Statistics 21. A p-value less than 0.05 was considered to be statistically significant.

Results

Patients were, on average, 28.9 years (SD 10.4, range 14 – 47) in age with height of 1.74 m (SD 0.10) and body mass of 83.19 kg (SD 16.87). Twenty (20) patients (54%) had experienced more than 1 episode of their knee giving-way since their injury. Average time from injury to testing was 8.43 weeks (SD 7.84, range 2 – 40). Maximum isometric knee extensor strength was lower for the involved limb (mean 33.00 N/kg*m, SD 7.09) than the

uninvolved limb (mean 38.13 N/kg*m, SD 7.98). Mean KOS-ADLS score was 77.8 % (SD 13.3), mean GRS score was 65.7% (SD 19.2) and mean IKDC 2000 score was 58.6% (SD 13.3). Twelve patients (33%) reported no knee pain with daily activities (KOS pain item score = 5). Mean walking speed was 1.56 m/s (SD 0.13). As expected, peak tibiofemoral force was significantly lower for the involved limb (mean 3.69 BW, SD 0.76) than the uninvolved limb (mean 4.28 BW, SD 0.74; $t=-4.031$, $P<.001$).

Initial partial correlations for all clinically relevant measures that were considered revealed positive relationships for all predictors except KOS-ADLS Pain (Table 1). After controlling for self-selected walking speed, decreased involved tibiofemoral contact forces were associated with decreased extensor strength, testing sooner after injury, lower KOS-ADLS, GRS and IKDC scores, report of pain in daily activities and report of more than one give-way episode since injury.

Involved knee extensor strength and GRS score were the performance-based and patient-reported measures that demonstrated the strongest individual associations with peak contact force (Table 1). Positive correlation coefficients for the selected measures indicated positive relationships with peak contact force. The three measures selected for the final multivariate regression were walking speed, involved extensor strength and GRS score.

Self-selected walking speed was a significant predictor of peak tibiofemoral contact force during gait (Table 2, Block 1) and explained 24% of the inter-subject variance. After accounting for walking speed, involved extensor strength significantly improved the model's predictive ability, explaining an additional 9.6% of the variance (Table 2, Block 2). The addition of GRS score significantly further improved the model's predictive ability, explaining an additional 10.0% of the variance (Table 2, Block 3). The final model for predicting involved tibiofemoral contact force included self-selected walking speed, involved knee extensor muscle strength and GRS score (Table 2). The most important predictor in the final model was walking speed, followed by GRS score and extensor strength (Table 2, β 's). Although involved extensor strength significantly contributed to the model upon its entry in Block 2, it did not remain significant when GRS score was added in Block 3. Variance inflation factor (VIF) and tolerance indicated that there was no problematic multicollinearity among the final predictors ($VIF < 1.5$, tolerance > 0.7).

For comparison with the involved limb, predictive factors for peak uninvolved tibiofemoral contact force were analyzed in a separate regression. Walking speed was a significant predictor of peak contact force for the uninvolved knee (Table 3), explaining a similar proportion of the variance for the uninvolved limb (18.2%) as it did for the involved. Neither uninvolved extensor strength nor GRS score significantly improve the model's predictive ability. Therefore, the final model for predicting uninvolved tibiofemoral contact force included walking speed only.

Discussion

This study demonstrates the utility of clinically-relevant measures in predicting altered contact forces in patients with ACL injury. Our major finding was that involved knee

extensor muscle strength and patient-reported knee function via the GRS were significantly associated with peak tibiofemoral contact force for the involved limb. Patients who were stronger and who reported higher knee function walked with greater contact forces in their involved limbs.

Our finding that knee extensor strength was positively related to peak tibiofemoral contact force is supported by previous work relating quadriceps strength deficits to decreased peak knee flexion angles and moments during gait in patients with ACL injury (Hartigan et al., 2012; Lewek et al., 2002; Rudolph et al., 2001; Snyder-Mackler et al., 1991). Quadriceps weakness is thought to impair eccentric control of knee flexion in early stance and to prompt the truncated knee flexion excursions and reduced knee moments observed in these patients (i.e. stiff-knee gait). Even though quadriceps utilization during normal gait is typically less than 30% of maximum activation, quadriceps strength deficits of only 20% were associated with altered movement patterns in one study (Lewek et al., 2002), demonstrating that small strength deficits can result in significant gait asymmetries. The results from this study expand upon previous work relating quadriceps weakness, aberrant kinematics and kinetics by establishing a link between quadriceps weakness and decreased joint contact forces in patients with ACL injury.

In light of the significant relationship between knee extensor strength and peak tibiofemoral contact force for the involved knee, the lack thereof for the uninvolved knee is particularly interesting. This finding raises the question of whether quadriceps weakness in the involved limb is associated not only with involved knee loading but uninvolved loading as well (i.e. the effect of quadriceps weakness “overflows” to impact the uninvolved limb). We tested for the presence of this overflow effect, but found that after accounting for walking speed in the model, involved extensor strength was not significantly associated with uninvolved tibiofemoral contact force (model $R^2=.005$, Sig. F Change=.645). Thus, our data indicate that extensor muscle strength of neither the involved limb nor the uninvolved limb is a major determinant of peak contact force for the intact knee. While muscle weakness appears to be relevant for decreased loading of the injured knee during walking, these data suggest that muscle strength is not directly related to the magnitude of loading in the intact knee.

Patients' rating of knee function on the GRS was also a significant predictor of involved limb contact force in the present study, with those reporting higher knee function demonstrating greater involved limb contact forces. No previous studies have identified a relationship between GRS score and gait biomechanics, but patient reported function has been related to knee flexion moments in individuals with ACL reconstruction using the KOS-ADLS (Lewek et al., 2002). Patient apprehension and low confidence in knee function may be the link between self-reported knee function and altered involved limb contact forces. Because the GRS contains a single item in which patients are asked to rate their current knee function relative to their pre-injury knee function, the response draws upon the patient's collective experience since injury. It is conceivable that those who lack confidence and also report poorer function may be unwilling to place normal demands on their involved knee, adopting movement strategies that favor their involved knee, consequently loading it less during gait. Perceived function as assessed with the KOS-ADLS and IKDC2000 questionnaires was also positively related to involved contact forces in this study (Table 1).

Although none of these patient-reported measures directly capture constructs of apprehension or fear, there does appear to be a consistent relationship between perceived function and joint loading in these data.

Patient-reported pain on the first item of the KOS-ADLS was inversely related to peak involved contact force, indicating that patients who reported knee pain during their usual daily activities tended to walk with decreased involved tibiofemoral contact force. The direction of this relationship between pain and aberrant loading during gait is not surprising, as the experience of pain when loading the injured limb could conceivably prompt patients to load their injured limb less. Nonetheless, the association of reported pain during daily activities and decreased involved limb contact force was not significant for the patients in this study, who received treatment for significant pain, effusion, range of motion and obvious gait impairments prior to testing.

When entered in subsequent blocks of the linear regression, involved extensor strength and GRS each explained a similar amount of the variance in contact force (about 10%). However, the coefficient for involved extensor strength was no longer significant upon the entry of GRS into the model (Table 2). Although final regression statistics imply that the most parsimonious model for predicting involved contact force would include walking speed and GRS only, excluding strength from the model would fail to account for potential bias introduced by the order of clinical testing. Patients performed strength testing and received feedback on their performance before completing self-report assessments. Therefore it is possible that knowledge of their performance on strength testing may have impacted their scoring of the assessments, particularly the GRS. Consequently, all three measures were retained in the final model.

This study has some limitations. This study included patients with functional knee instability after ACL injury (Fitzgerald et al., 2000) and these results should not be generalized to all patients with ACL injury. The final regression model explained 41% of the variance in involved limb peak tibiofemoral contact force during gait. There may be other clinically-relevant measures that would further enrich the model. However, sample size considerations and prospective study design significantly limited the number and types of clinically-relevant measures that could be assessed in the present study. In this study, we had no clinical assessment that directly captured fear of further injury and pain-related fear of movement, such as the shortened version of the Tampa Scale for Kinesiophobia (Chmielewski et al., 2008; Woby et al., 2005). Kinesiophobia may further explain altered knee loading observed in these patients after ACL injury.

This is the first study to investigate the relationships between clinically-relevant measures and joint contact forces in patients with ACL-deficiency. Although these results do not infer causality, they highlight the potential value of studying the recovery of strength, self-reported function and joint loading symmetry in patients with ACL injury. Improvements in involved quadriceps strength and overall function as measured by patient self-report may be important for increasing involved limb contact forces, thereby restoring loading symmetry in these patients who demonstrate decreased involved limb loading after injury (Gardinier et al., 2012a). While the impact of early decreased contact forces on the development of

osteoarthritis after ACL injury is yet unknown, rehabilitation presents an opportunity for early intervention. Knowledge of the rehabilitation constructs that underlie aberrant joint loading will promote the development of interventions to restore normal and symmetrical joint contact forces. Future work should investigate the recovery of strength, self-reported function and normal joint contact forces over time in patients with ACL injury.

Conclusions

Clinically-relevant measures of involved knee extensor muscle strength and patient-reported knee function were significantly associated with peak tibiofemoral contact force for the involved limb in this study. Patients who were stronger and who perceived higher knee function walked with greater contact forces on their involved knees. These results highlight the potential value of studying the recovery of strength, self-reported function and joint loading symmetry in patients with ACL injury.

Acknowledgments

The authors acknowledge Wendy Hurd, Erin Hartigan and Stephanie Di Stasi for their assistance with patient recruitment and data collection, and Kristen Stump for her assistance with data processing. We also acknowledge Dr. Michael J. Axe for his patient referrals and the University of Delaware Physical Therapy Clinic for their excellent care provided to our patients. This work was supported by the National Institutes of Health (P30 GM103333, P20 RR016458, R01 AR046386, R01 AR048212, S10 RR022396). The study sponsor had no involvement in the study design; in the collection, analysis and interpretation of data; in the writing of the manuscript; or in the decision to submit the manuscript for publication.

References

- Adams D, Logerstedt DS, Hunter-Giordano A, Axe MJ, Snyder-Mackler L. Current concepts for anterior cruciate ligament reconstruction: a criterion-based rehabilitation progression. *J Orthop Sports Phys Ther.* 2012; 42:601–14.10.2519/jospt.2012.3871 [PubMed: 22402434]
- Buchanan TS, Lloyd DG, Manal K, Besier TF. Neuromusculoskeletal modeling: Estimation of muscle forces and joint moments and movements from measurements of neural command. *J Appl Biomech.* 2004; 20:367–395. [PubMed: 16467928]
- Chmielewski TL, Jones D, Day T, Tillman SM, Lentz TA, George SZ. The Association of Pain and Fear of Movement/Reinjury With Function During Anterior Cruciate Ligament Reconstruction Rehabilitation. *J Orthop Sports Phys Ther.* 2008; 38:746–753. [PubMed: 19047767]
- Chmielewski TL, Rudolph KS, Fitzgerald GK, Axe MJ, Snyder-Mackler L. Biomechanical evidence supporting a differential response to acute ACL injury. *Clin Biomech.* 2001; 16:586–591.
- Chmielewski TL, Stackhouse S, Axe MJ, Snyder-Mackler L. A prospective analysis of incidence and severity of quadriceps inhibition in a consecutive sample of 100 patients with complete acute anterior cruciate ligament rupture. *J Orthop Res.* 2004; 22:925–30.10.1016/j.orthres.2004.01.007 [PubMed: 15304261]
- Delp SL, Loan JP, Hoy MG, Zajac FE, Topp EL, Rosen JM. An interactive graphics-based model of the lower extremity to study orthopaedic surgical procedures. *IEEE Trans Biomed Eng.* 1990; 37:757–67.10.1109/10.102791 [PubMed: 2210784]
- Di Stasi SL, Logerstedt D, Gardinier ES, Snyder-Mackler L. Gait Patterns Differ Between ACL-Reconstructed Athletes Who Pass Return-to-Sport Criteria and Those Who Fail. *Am J Sports Med.* 2013.10.1177/0363546513482718
- Erdemir A, McLean S, Herzog W, van den Bogert AJ. Model-based estimation of muscle forces exerted during movements. *Clin Biomech.* 2007; 22:131–154.
- Fitzgerald GK, Axe MJ, Snyder-Mackler L. A decision-making scheme for returning patients to high-level activity with nonoperative treatment after anterior cruciate ligament rupture. *Knee Surgery, Sport Traumatol Arthrosc.* 2000; 8:76–82.

- Gardinier ES, Manal K, Buchanan TS, Snyder-Mackler L. Altered loading in the injured knee after acute ACL rupture. *J Orthop Res.* 2012a; 31:458–64. [PubMed: 23097309]
- Gardinier ES, Manal K, Buchanan TS, Snyder-Mackler L. Gait and neuromuscular asymmetries after acute anterior cruciate ligament rupture. *Med Sci Sports Exerc.* 2012b; 44:1490–6.10.1249/MSS.0b013e31824d2783 [PubMed: 22330021]
- Gardinier ES, Manal K, Buchanan TS, Snyder-Mackler L. Minimum detectable change for knee joint contact force estimates using an EMG-driven model. *Gait Posture.* 2013;1–3.10.1016/j.gaitpost.2013.03.014
- Griffin TM, Guilak F. The role of mechanical loading in the onset and progression of osteoarthritis. *Exerc Sport Sci Rev.* 2005; 33:195–200. [PubMed: 16239837]
- Hartigan EH, Axe MJ, Snyder-Mackler L. Time line for noncopers to pass return-to-sports criteria after anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther.* 2010; 40:141–154. [PubMed: 20195019]
- Hartigan EH, Zeni J, Di Stasi S, Axe MJ, Snyder-Mackler L. Preoperative predictors for noncopers to pass return to sports criteria after ACL reconstruction. *J Appl Biomech.* 2012; 28:366–73. [PubMed: 22983930]
- Hefti F, Muller W, Jakob RP, Staubli HU, Hefti E, Müller W, Stäubli H. Evaluation of knee ligament injuries with the IKDC form. *Knee Surgery, Sport Traumatol Arthrosc.* 1993; 1:226–234.
- Higgins LD, Taylor MK, Park D, Ghodadra N, Marchant M, Pietrobon R, Cook C. Reliability and validity of the International Knee Documentation Committee (IKDC) Subjective Knee Form. *Jt Bone Spine.* 2007; 74:594–9.10.1016/j.jbspin.2007.01.036
- Hurd WJ, Axe MJ, Snyder-Mackler L. A 10-year prospective trial of a patient management algorithm and screening examination for highly active individuals with anterior cruciate ligament injury: Part 1, outcomes. *Am J Sports Med.* 2008; 36:40–47. [PubMed: 17940141]
- Irrgang JJ, Anderson AF, Boland AL, Harner CD, Kurosaka M, Neyret P, Richmond JC, Shelborne KD. Development and validation of the international knee documentation committee subjective knee form. *Am J Sports Med.* 2001; 29:600–13. [PubMed: 11573919]
- Irrgang JJ, Snyder-Mackler L, Wainner RS, Fu FH, Harner CD. Development of a patient-reported measure of function of the knee. *J Bone Jt Surg Am Vol.* 1998; 80:1132–45.
- Lewek M, Rudolph K, Axe M, Snyder-Mackler L. The effect of insufficient quadriceps strength on gait after anterior cruciate ligament reconstruction. *Clin Biomech.* 2002; 17:56–63.
- Lohmander LS, Englund PM, Dahl LL, Roos EM. The long-term consequence of anterior cruciate ligament and meniscus injuries: osteoarthritis. *Am J Sports Med.* 2007; 35:1756–69.10.1177/0363546507307396 [PubMed: 17761605]
- Manal K, Buchanan TS. An electromyogram-driven musculoskeletal model of the knee to predict in vivo joint contact forces during normal and novel gait patterns. *J Biomech Eng.* 2013; 135:021014.10.1115/1.4023457 [PubMed: 23445059]
- Meyer AJ, D’Lima DD, Besier TF, Lloyd DG, Colwell CW, Fregly BJ. Are external knee load and EMG measures accurate indicators of internal knee contact forces during gait? *J Orthop Res.* 2013; 31:921–9.10.1002/jor.22304 [PubMed: 23280647]
- Øiestad BE, Engebretsen L, Storheim K, Risberg MA. Knee osteoarthritis after anterior cruciate ligament injury: a systematic review. *Am J Sports Med.* 2009; 37:1434–43.10.1177/0363546509338827 [PubMed: 19567666]
- Rudolph KS, Axe MJ, Buchanan TS, Scholz JP, Snyder-Mackler L. Dynamic stability in the anterior cruciate ligament deficient knee. *Knee Surgery, Sport Traumatol Arthrosc.* 2001; 9:62–71.
- Snyder-Mackler L, Delitto A, Stralka SW, Bailey SL. Use of electrical stimulation to enhance recovery of quadriceps femoris muscle force production in patients following anterior cruciate ligament reconstruction. *Phys Ther.* 1995; 75:237–238. [PubMed: 7870754]
- Snyder-Mackler L, Ladin Z, Schepsis A, Young J. Electrical stimulation of the thigh muscles after reconstruction of the anterior cruciate ligament. *J Bone Jt Surg Am Vol.* 1991; 73:1025–1036.
- Torry MR, Decker MJ, Viola RW, O’Connor DD, Steadman JR. Intra-articular knee joint effusion induces quadriceps avoidance gait patterns. *Clin Biomech (Bristol, Avon).* 2000; 15:147–59.

- Walter JP, D'Lima DD, Colwell CW, Fregly BJ. Decreased Knee Adduction Moment Does Not Guarantee Decreased Medial Contact Force during Gait. *J Orthop Res.* 2010; 28:1348–1354.10.1002/jor.21142 [PubMed: 20839320]
- Wexler G, Hurwitz D. Functional gait adaptations in patients with anterior cruciate ligament deficiency over time. *Clin Orthop Relat Res Relat Res.* 1998
- Woby SR, Roach NK, Urmston M, Watson PJ. Psychometric properties of the TSK-11: a shortened version of the Tampa Scale for Kinesiophobia. *Pain.* 2005; 117:137–44.10.1016/j.pain.2005.05.029 [PubMed: 16055269]
- Zhao D, Banks SA, Mitchell KH, Lima DDD Jr, CWC, Fregly BJ. Correlation between the Knee Adduction Torque and Medial Contact Force for a Variety of Gait Patterns. *J Orthop Res.* 2007:789–797.10.1002/jor [PubMed: 17343285]

Initial partial correlations for all clinically-relevant measures and involved peak tibiofemoral contact force while controlling for walking speed. Partial correlations are adjusted for self-selected walking speed. Asterisk (*) denotes significance at the 0.05 level; all probabilities are two-tailed. DF is degrees of freedom.

Table 1

Category	Independent Variable	Scale	Zero-Order Correlation Coefficient	Partial Correlation Coefficient	Sig.	DF
Covariate	Walking Speed	m/s	.522			
	Involved Extensor Strength	N/kg*m	.293	.370	.026 *	34
	Time Injury to Testing [†]	wk	-.069	.120	.485	34
Performance-Based	Log (Time Injury to Testing)	log ₁₀ (wk)	-.002	.218	.201	34
	KOS-ADLS	%	.199	.267	.121	33
	KOS-ADLS Pain	n=0, y=1	-.316	-.247	.153	33
Patient-Reported	GRS	%	.263	.512	.002 *	33
	IKDC 2000	%	.270	.252	.164	30
	More than 1 Give-way	n=0, y=1	-.008	.068	.694	34

[†] Data were log-transformed for analysis because the distribution exhibited rightward skew.

Final multivariate linear regressions (N=36) for predicting involved limb peak tibiofemoral contact force. Model R² is the change in model R² relative to the previous block.

Table 2

Block	Independent Variables	Model R ²	Model R ²	Model F Change Sig.	Model Sig.	β	β Sig.
1	Walking Speed	.240	.240	.002 *	.002 *	.490	.002 *
2	Walking Speed Involved Extensor Strength	.336	.096	.037 *	.001 *	.557 .316	.001 * .037 *
3	Walking Speed Involved Extensor Strength GRS	.436	.100	.023 *	<.001 *	.631 .137 .379	<.001 * .384 .023 *

Asterisk (*) denotes significance at the 0.05 level. β is the standardized regression coefficient. Shading corresponds to the final model.

Final multivariate linear regressions (N=36) for predicting unininvolved limb peak tibiofemoral contact force. Model R² is the change in model R² relative to the previous block.

Table 3

Block	Independent Variables	Model R ²	Model R ²	F Change Sig.	Model Sig.	β	β Sig.
1	Walking Speed	0.197	0.197	.007 *	.007 *	.444	.007 *
2	Walking Speed Uninvolved Extensor Strength	0.221	0.023	.330	.016 *	.443 -.152	.007 * .330
3	Walking Speed Uninvolved Extensor Strength GRS	0.253	0.032	.250	.024 *	.499 -.183 .190	.004 * .247 .250

Asterisk (*) denotes significance at the 0.05 level. β is the standardized regression coefficient. Shading corresponds to the final model.