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Clinical predictors of knee mechanics at return to sport following ACL reconstruction

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Abstract

Purpose—Despite significant rehabilitation, many athletes experience protracted weakness and faulty mechanics following anterior cruciate ligament reconstruction (ACLR). Clinical tests performed early in rehabilitation that predict knee mechanics at return-to-sport are virtually unknown and critically needed to guide clinical decision making. The purpose of this study is to determine if quadriceps strength, Y-Balance anterior reach distance (YB-A), and single-limb step-down test performance (SLSD) conducted 3 months post-ACLR are predictive of knee flexion excursion (KFLEX) and knee extensor moment (KEM) during running 6 months post-ACLR.

Methods—Thirty (16 F) subjects were collected 3 and 6 months post-ACLR. Age 21.3 ± 7.6 years, mass 69.85 ± 11.4 kg, height 1.73 ± 0.09 m. At 3 months post-ACLR, subjects performed isometric quadriceps strength testing, YB-A, and SLSD assessments. At 6 months post-ACLR, subjects underwent 3-D motion analysis while running on an instrumented treadmill. Pearson's correlation coefficients and stepwise multiple regression were used to assess the relationships of 3 month and 6 month variables.

Results—Quadriceps strength ($r=.493$, $p<0.01$), YB-A ($r=.394$, $p=0.03$), and SLSD ($r=.648$, $p<0.01$) were significantly correlated to KFLEX. Quadriceps strength ($.505$, $p<0.01$) and SLSD ($.541$, $p<0.01$) were significantly correlated with KEM, while YB-A ($.276$, $p=0.06$) was not. SLSD and quadriceps strength were predictive of KEM (Adj R^2 .36, $p=.001$) while only SLSD was predictive of KFLEX (Adj R^2 .40, $p<.001$).

Conclusions—After ACLR, better performance in SLSD and quadriceps strength 3 months post-surgery is predictive of improved sagittal plane knee mechanics during running 6 months post-surgery.

Keywords

biomechanics; running; clinical tests; moment; knee rehabilitation

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INTRODUCTION

Anterior cruciate ligament (ACL) tears are one of the most common sports injuries, with an estimated prevalence of >250,000 ACL reconstructions (ACLR) performed annually (14, 23). Unfortunately, despite surgery and rehabilitation, 37 – 55% of individuals do not return to competitive sport (2, 3). Additionally, impairments in quadriceps strength, knee flexion angles, knee extensor moment (KEM), and return-to-sport tests persist for up to 2 years after surgery (20, 24, 34, 37). While much focus has been given to return-to-sport decisions, less has been devoted to determining the factors present early in rehabilitation that predict performance at time of return-to-sport. Identification of these early addressable factors is critical to maximize function as changes in the healthcare environment are resulting in fewer rehabilitation visits for patients after ACLR.

Typically, athletes resume higher level activities such as running, jumping, and sport-specific drills between 3 – 6 months after surgery (20, 24). During this time, they must possess sufficient strength and coordination to perform these tasks without deficits and with proper form. Previous reports show that while this is a common expectation, poor mechanics often persist including reductions in KEM and knee flexion angles (9, 10, 17, 29, 33). If tests performed early in rehabilitation could be developed to determine which patients will have the worst mechanics at time of return-to-sport, then corrective steps can be taken before the athlete becomes injured, learns faulty movement patterns, or is discharged from care.

The ability to assess hopping and running is contraindicated during the first 6 – 8 weeks following surgery due to the graft being weak (5). Without the ability to assess these tasks during this stage, clinicians must use their best judgement to determine which individuals are progressing appropriately through rehabilitation and which may require additional time or intervention prior to return-to-sport. Commonly performed clinical assessments early in rehabilitation include quadriceps isometric strength testing, Y-Balance testing, and single-leg step-down performance (4, 6, 20, 22, 32). The Y-Balance test assesses neuromuscular deficits in dynamic postural control and involves standing on a single limb and reaching in 3 directions (11, 13). At time of return-to-sport following ACLR, differences have been demonstrated in only the anterior reach direction with the ACLR limb demonstrating decreased normalized reach distance (6). Lastly, step-down tasks are often performed as a functional exercise and assessment of neuromuscular control and endurance (7, 24, 38, 39). These assessments are potentially well-suited to be used as clinical predictors of mechanics because they can be performed in the early and intermediate stages of rehabilitation, require little time and equipment, and provide objective information to track patient progress.

Thus, the purpose of this study was to determine if quadriceps isometric strength, Y-Balance test anterior reach (YB-A) performance, and single-leg step-down (SLSD) performance 3 months after ACLR are predictive of knee flexion angle excursion (KFLEX) and KEM during running 6 months after ACLR. We hypothesized that individuals with weaker quadriceps and poorer performance in the YB-A and SLSD 3 months after surgery would demonstrate reduced KEM and KFLEX during running at 6 months and that 3-month testing would be predictive of 6-month performance.

METHODS

Subjects

Following a protocol approved by the university institutional review board, thirty subjects (14 males, 16 females, age 21.3 ± 7.6 years, mass 69.85 ± 11.4 kg, height 1.73 ± 0.09 m) (mean $\pm$ SD) with a unilateral reconstructed ACL provided their written informed consent. The subjects reported a pre-surgery Tegner Activity Scale Rating of 8.5 ± 1.3 (mean $\pm$ SD). All participants were tested at 3 and 6 months post-operatively. In order to qualify to be tested at 6 months, subjects were required to be cleared by the surgeon to return-to-sport and have completed rehabilitation. All ACLR's were performed by 1 of 2 surgeons from the same orthopedic practice. Potential subjects were excluded if they had a history of multiple ACL injuries or if a total knee dislocation occurred at the time of injury, but concurrent meniscus repair or meniscectomy may have been performed at the time of ACLR. Twelve subjects underwent an isolated ACLR, 17 had a meniscus repair in addition to an ACLR, and 1 subject had a partially torn medial collateral ligament in addition to an ACLR.

Isometric Quadriceps Strength

Three months post-ACLR, quadriceps strength was assessed on the operative limb of each participant using a hand-held dynamometer (Lafayette Instruments, Lafayette, IN) and a stabilization strap. This method of hand-held dynamometry has been shown to be reliable and valid in assessing isometric quadriceps strength when compared to an electromechanical dynamometer (15, 19). Subjects were seated with hips and knees flexed to 90° while the strap held the dynamometer against the anterior tibia on the distal one-third of the segment. Each participant performed two practice trials and three test trials, each for a duration of 5 seconds. Subjects were asked to push into the dynamometer with an increasing force during the first three seconds and to hold their maximum force for the final two seconds. Peak force during the final two seconds of the three test trials were averaged for each participant.

Y-Balance Anterior Reach

Three months post-ACLR, each participant completed the anterior reach of the YB-A. After a demonstration from the examiner, the subjects stood in single leg stance on the involved limb and performed a maximal anterior reach with the non-operative limb. Subjects were required to maintain a single-limb stance, the heel of the stance limb in contact with the surface, and not allow weight acceptance with the reaching limb for the trial to be recorded. Based on learning effects noted with the Y-Balance test, six practice trials were performed before the three recorded trials (16). Reach distance for each trial was normalized to limb length (greater trochanter to lateral malleolus).

Single-Leg Step-Down Test

To perform the SLSD test, subjects stood on an 8-inch wooden box, assumed a single-limb stance, and performed a squat which required the heel of the free leg to make contact with a scale on the floor to confirm a successful trial. Subjects were required to make contact with the scale but not exceed 10% of body weight in order to prevent weight transfer off of the test limb. Upon contacting the scale, subjects returned to the start position. Subjects were

asked to complete as many step-downs as possible in 60 seconds. Step-downs were not counted if the subject did not make contact with the scale, transferred >10% of body weight onto their free limb when contacting the scale, or did not fully return to the starting position.

Three-dimensional Gait Analysis

Using a previously reported marker set, 56 reflective markers were placed on the subject (26). Thirty-one of these markers were placed on anatomical landmarks including: sternal notch, spinous process of C7, bilateral superior acromion processes, bilateral superior iliac crests, posterior L5/S1 vertebral joint, bilateral greater trochanters, bilateral posterior superior iliac spines, bilateral anterior superior iliac spines, bilateral medial and lateral distal femurs, bilateral medial and lateral proximal tibias, bilateral medial and lateral malleoli, bilateral 1st and 5th metatarsal heads, and bilateral distal foot. Twenty-five tracking markers were attached including four rigid plates secured to bilateral thigh and shank with 4 markers on each plate. Three tracking markers identifying proximal, distal, and lateral heel were secured to the rearfoot of each shoe. To minimize the influence of footwear, all subjects wore neutral running shoes (New Balance 662, New Balance Athletic Shoe Inc., Boston, MA, USA). After allowing a 5-minute warm-up, the subjects ran at a self-selected test speed (mean 2.67 ± 0.29 m/s) on an instrumented treadmill (Bertec, Columbus, OH, USA), whereas force plate data were recorded at 1200 Hz and marker trajectories were collected with a 10 camera motion analysis system (Motion Analysis Corp, Santa Rosa, CA, USA) at 200 Hz.

Filtering, joint angle calculations, and inverse dynamics were performed using Visual3D software (C-motion, Germantown, MD, USA). Marker locations were filtered at 8 Hz and force data filtered at 35 Hz using a fourth-order, low-pass, zero-lag Butterworth filter. The moments were normalized the body mass and height. The angle and moments were calculated using Cardan XYZ angle rotation with distal segments referenced to the proximal model (25). Peak KEM and KFLEX were extracted using custom MATLAB code (MathWorks Inc., Natick, MA, USA). KEM and KFLEX from individual strides were analyzed during the stance phase for the operative limb in each subject.

Statistical Analysis

Using PASW Statistics Version 18.0 (SPSS Inc, Chicago, IL, USA), Pearson's correlation coefficients were calculated to assess the relationships between the 3-month objective assessments to 6-month knee sagittal plane variables. Statistical significance was defined as $p < 0.05$. Significant correlations were then entered into a stepwise multiple linear regression to determine the predictability of 3-month assessments on 6-month running variables.

RESULTS

Correlation and Regression

The mean and standard deviation of all variables are reported in Table 1. Significant positive relationships were found between all 3-month assessments and 6-month KFLEX (Table 2).

Three-month quadriceps strength and SLSD performance were significantly related to 6-month KEM, but the YB-A was not significant. Stepwise regression found only SLSD ($b =$

0.28±.06, p=0.000) as predictive of KFLEX (Table 3). The overall model fit for predicting KFLEX was adjusted $r^2 = 0.40$.

In predicting of KEM, the stepwise multiple linear regression showed SLSD ($b = 0.009 \pm .004$, $p = 0.017$) and quadriceps strength ($b = 0.011 \pm .005$, $p = 0.037$) as predictive with an overall model fit of adjusted $r^2 = 0.36$ (Table 4). Variance inflation factors (VIF) were calculated to determine the severity of multicollinearity in the regression equations. All variance inflation factor values were less than 1.6, indicating low collinearity for the predictor variables.

Prediction of Knee Flexion Excursion

The following prediction equation was generated from the regression model (Table 3):

$$(\text{Est KFLEX}) = (17.12) + (0.28) * (\text{SLSD}).$$

This equation has two distinct uses: 1) calculating a patient's expected KFLEX at 6 months, or 2) determining the number of step-downs a patient would need to perform at 3 months in order to achieve a certain KFLEX at 6 months. In the first case, the calculation requires entering the number of step-downs into the equation and completing the calculation. For example, a patient who completed 19 step-downs would have an estimated 22.5° of KFLEX during running 6 months after surgery.

For the second use, the number of required step-downs can be calculated by entering the desired KFLEX and solving the equation for the number of step-downs. For example, in order to achieve a KFLEX value of 25° 6 months after surgery, a patient would need to perform 28 step-downs 3 months after surgery. This value is derived by solving the prediction equation for the number of step-downs performed in the SLSD test.

$$(\text{Est KFLEX}) = (17.12) + (0.28) * (\text{SLSD}).$$

$$(25^\circ) = (17.12) + (0.28) * (\text{SLSD})$$

$$(25 - 17.12) = (0.28) * (\text{SLSD})$$

$$(7.88) / (0.28) = 28.1 = (\text{SLSD}).$$

Since the test is not designed to account for partial step-downs, this value was rounded down to 28 step-downs as predictive of achieving 25° of KFLEX.

Prediction of Knee Extensor Moment

The model resulted in the following prediction equation to determine KEM (Table 4):

$$(\text{Est KEM}) = (0.342) + (0.009) * (\text{SLSD}) + (0.011) * (\text{quadriceps strength})$$

As explained previously, this equation has two uses. To calculate the estimated KEM, enter the number of step-downs performed and the quadriceps strength value. For example, in a patient who performs 24 step-downs with quadriceps strength of 25 N, we would predict a KEM of 0.83 N·m/kg. Conversely, if the goal is for the patient to achieve a KEM of 1.0 N·m/kg at 6 months and the patient performs 28 step-downs at 3 months, that patient would need to generate at least 36.9 N of isometric torque. We derived this value from solving for quadriceps strength in the prediction equation.

$$(\text{Est KEM}) = (0.342) + (0.009) * (\text{SLSD}) + (0.011) * (\text{quadriceps strength})$$

$$(1.0) = (0.342) + (0.009) * (28) + (0.011) * (\text{quadriceps strength})$$

$$(1.0 - 0.342 - 0.252) = (0.011) * (\text{quadriceps strength})$$

$$(0.406) / (0.011) = 36.9 = \text{quadriceps strength}$$

Thus, we would predict a patient who performs 28 step-downs and produces 36.9 N of isometric quadriceps torque at 3 months after surgery to generate a KEM of 1.0 N·m/kg during running at 6 months after surgery.

DISCUSSION

The purpose of this study was to determine the predictive ability of 3-month post-operative testing of quadriceps isometric strength, YB-A, and SLSD performance on 6-month post-op KFLEX and KEM during running. We found that all three tests were significantly positively associated with KFLEX, and that strength testing and SLSD were significantly positively associated with KEM during running. Of these tests, only SLSD was predictive of both the KEM and KFLEX.

Single-Leg Step-Down Test

We have shown, for the first time, a simple timed SLSD test performed 3 months after surgery is predictive of KEM and KFLEX 6 months after surgery. This test alone predicted nearly 40% of the variance in KFLEX during running. The stronger relationship seen in the SLSD test versus the other tests may be due to it involving repetitive eccentric and concentric contractions of the quadriceps. Additionally, since the test is performed in a single-leg stance for one minute and the patient cannot shift greater than 10% of their body weight onto the opposite limb, the test challenges the balance and endurance of the reconstructed limb. This type of prolonged, cyclical loading and muscle activity occurs

during running and sporting activities and could be a better simulation of task demands that the patient will face upon returning to sport. Reductions in knee flexion angle have repeatedly been demonstrated after ACLR, with evidence suggesting that this variable is able to discriminate between those who successfully return-to-sport and those that do not (12). Thus, the SLSD performance could be an early indicator of future difficulties in returning to sport. However, this is speculative and requires additional study.

Isometric Quadriceps Strength

The association of quadriceps strength and function is consistent with previous findings that improved quadriceps strength is an important factor in a successful outcome after ACLR (21, 27, 30, 31, 34). Additionally, at the time of return-to-sport, patients with greater quadriceps strength and symmetry had greater knee flexion angles and KEM during a hopping tasks(27). Our results expand upon these previous findings by demonstrating the relationship of quadriceps strength in earlier phases of rehabilitation to mechanics at the time of return-to-sport. Quadriceps strength was less predictive of KEM and was not included in the final model for predicting KFLEX. This may be due to the fact that isolated isometric testing does not directly translate to dynamic tasks. Dynamic activities impose demands that require adequate force production within specific time windows in order for successful completion of the task. More than 300 milliseconds are required to achieve peak knee strength, while stance time for running and other dynamic tasks is less than 250 ms (1, 35, 36). Given these timing demands, peak isometric strength testing may not simulate running as well as the SLSD, possibly accounting for the differences in their contribution to the regression model.

Y-Balance Anterior Reach

Our results indicate that better performance in the YB-A at 3 months was associated with greater KFLEX, but not with KEM during running at the 6 month mark. However, YB-A performance was not included in the final predictive model for either variable. Between limb differences in YB-A performance have been reported at time of return-to-sport after ACLR(6) and are predictive of future injury in a healthy population(8). It is likely that the YB-A was not predictive of KEM and KFLEX due to the YB-A being more of a global assessment of neuromuscular control. Additionally, impairments in joints other than the knee could have affected performance during the YB-A, that would not be related to knee mechanics at 6 months. For example, variables such as ankle dorsiflexion range of motion were not assessed but have been shown to be a significant predictor of YB-A performance (18). There is currently no evidence linking Y-Balance test performance to mechanical variables during running. Furthermore, the YB-A may not adequately simulate the demands of running. Even though the YB-A requires eccentric control of knee flexion, it is not repetitive in a manner similar to running. Thus, the YB-A may detect postural control deficits after ACLR, but, in our sample, it did not predict future knee mechanics during running.

Prediction Equations

The prediction equations presented provide clinicians with a tool to assess patient progress towards sufficient KFLEX and KEM during running. No normative data for optimal KFLEX

or KEM after ACLR exists so it is not possible to determine minimum cutoff values for patients 3 months after ACLR. However, the two prediction equations provide a valuable method to calculate a patient's expected future performance earlier in rehabilitation and identify patients who are not making adequate progress. Previous work in patients after ACLR demonstrated that sagittal plane asymmetries increased the risk of a second ACL injury (28). Based on these findings, using the contralateral limb may be the most appropriate benchmark to judge 3-month performance. In our sample, the minimum contralateral KFLEX was 25° and the minimum KEM was 1.0 N·m/kg. Using these values and the prediction equations from this article, a reasonable cutoff value for the SLSD test is 28 step-downs and 36.9 N for quadriceps isometric strength. It should be clearly stated, however, that these cutoff values have not been tested prospectively, and future work is needed to establish cutoff criteria for these assessments.

Limitations

This sample consisted only of patients who were cleared to return to sport drills at 6 months after ACLR and cannot be generalized to individuals at later time points or to patients who were not cleared to return to sporting activities. Additionally, SLSD performance and running mechanics are multifactorial with hip strength and kinematics possibly contributing to knee mechanics during running and performance of the SLSD test. Not all factors were measured in this study, potentially influencing the results. Possible uncontrolled variables include aspirations to return to the previous level of competition, type of sport played, and psychological parameters. However, despite these other variables, performance of the SLSD alone was able to account for up to 40% of the variance in knee mechanics.

CONCLUSION

We have shown that SLSD and quadriceps strength performance at 3 months after surgery are predictive of sagittal plane knee mechanics during running at 6 months post-ACLR. These results suggest that these clinical assessments should be performed during rehabilitation to determine which patients may require additional time or intervention before returning to sport. Determining the predictability of objective assessments on successful return-to-sport represents a critical need for the medical field. As efforts to develop standardized return-to-sport criteria continue, further understanding of how and when patients demonstrate progress towards meeting those criteria is essential in identifying and justifying the need for additional treatment.

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REFERENCES

1. Aagaard P, Simonsen EB, Andersen JL, Magnusson P, Dyhre-Poulsen P. Increased rate of force development and neural drive of human skeletal muscle following resistance training. *J Appl Physiol.* 2002; 93(4):1318–1326. [PubMed: 12235031]
2. Ardern CL, Taylor NF, Feller JA, Webster KE. Fifty-five per cent return to competitive sport following anterior cruciate ligament reconstruction surgery: an updated systematic review and meta-analysis including aspects of physical functioning and contextual factors. *Br J Sports Med.* 2014; 48(21):1543–1552. [PubMed: 25157180]
3. Ardern CL, Webster KE, Taylor NF, Feller JA. Return to sport following anterior cruciate ligament reconstruction surgery: a systematic review and meta-analysis of the state of play. *Br J Sports Med.* 2011; 45(7):596–606. [PubMed: 21398310]
4. Barber-Westin SD, Noyes FR. Objective criteria for return to athletics after anterior cruciate ligament reconstruction and subsequent reinjury rates: a systematic review. *Phys Sportsmed.* 2011; 39(3):100–110. [PubMed: 22030946]
5. Butler DL, Grood ES, Noyes FR, Olmstead ML, Hohn RB, Arnoczky SP, et al. Mechanical properties of primate vascularized vs. nonvascularized patellar tendon grafts; changes over time. *J Orthop Res.* 1989; 7(1):68–79. [PubMed: 2908914]
6. Clagg S, Paterno MV, Hewett TE, Schmitt LC. Performance on the modified star excursion balance test at the time of return to sport following anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther.* 2015; 45(6):444–452. [PubMed: 25899211]
7. Crossley K, Bennell K, Green S, Cowan S, McConnell J. Physical therapy for patellofemoral pain: a randomized, double-blinded, placebo-controlled trial. *Am J Sports Med.* 2002; 30(6):857–865. [PubMed: 12435653]
8. Dallinga JM, Benjaminse A, Lemmink KA. Which screening tools can predict injury to the lower extremities in team sports?: a systematic review. *Sports Med.* 2012; 42(9):791–815. [PubMed: 22909185]
9. Daniel DM, Stone ML, Dobson BE, Fithian DC, Rossman DJ, Kaufman KR. Fate of the ACL-injured patient. A prospective outcome study. *Am J Sports Med.* 1994; 22(5):632–644. [PubMed: 7810787]
10. de Jong SN, van Caspel DR, van Haeff MJ, Saris DB. Functional assessment and muscle strength before and after reconstruction of chronic anterior cruciate ligament lesions. *Arthroscopy.* 2007; 23(1):21–28. 8 e1-3. [PubMed: 17210423]
11. Delahunt E, Chawke M, Kelleher J, Murphy K, Prendiville A, Sweeny L, et al. Lower limb kinematics and dynamic postural stability in anterior cruciate ligament-reconstructed female athletes. *J Athl Train.* 2013; 48(2):172–185. [PubMed: 23672381]
12. 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; 41(6):1310–1318. [PubMed: 23562809]
13. Fitzgerald D, Trakarnratanakul N, Smyth B, Caulfield B. Effects of a wobble board-based therapeutic exergaming system for balance training on dynamic postural stability and intrinsic motivation levels. *J Orthop Sports Phys Ther.* 2010; 40(1):11–19. [PubMed: 20044704]
14. Frank CB, Jackson DW. The science of reconstruction of the anterior cruciate ligament. *J Bone Joint Surg Am.* 1997; 79(10):1556–1576. [PubMed: 9378743]
15. Hansen EM, McCartney CN, Sweeney RS, Palimenio MR, Grindstaff TL. Hand-held Dynamometer Positioning Impacts Discomfort During Quadriceps Strength Testing: A Validity and Reliability Study. *Int J Sports Phys Ther.* 2015; 10(1):62–68. [PubMed: 25709864]
16. Hertel J. Sensorimotor deficits with ankle sprains and chronic ankle instability. *Clin Sports Med.* 2008; 27(3):353–370. [PubMed: 18503872]
17. Ingersoll CD, Grindstaff TL, Pietrosimone BG, Hart JM. Neuromuscular consequences of anterior cruciate ligament injury. *Clin Sports Med.* 2008; 27(3):383–404. [PubMed: 18503874]
18. Kang MH, Kim GM, Kwon OY, Weon JH, Oh JS, An DH. Relationship Between the Kinematics of the Trunk and Lower Extremity and Performance on the Y-Balance Test. *PM R.* 2015

19. Kim WK, Kim DK, Seo KM, Kang SH. Reliability and validity of isometric knee extensor strength test with hand-held dynamometer depending on its fixation: a pilot study. *Ann Rehabil Med*. 2014; 38(1):84–93. [PubMed: 24639931]
20. Kvist J. Rehabilitation following anterior cruciate ligament injury: current recommendations for sports participation. *Sports Med*. 2004; 34(4):269–280. [PubMed: 15049718]
21. Lepley LK. Deficits in Quadriceps Strength and Patient-Oriented Outcomes at Return to Activity After ACL Reconstruction: A Review of the Current Literature. *Sports Health*. 2015; 7(3):231–238. [PubMed: 26131300]
22. Loudon JK, Wiesner D, Goist-Foley HL, Asjes C, Loudon KL. Intrarater Reliability of Functional Performance Tests for Subjects With Patellofemoral Pain Syndrome. *J Athl Train*. 2002; 37(3):256–261. [PubMed: 12937582]
23. Majewski M, Susanne H, Klaus S. Epidemiology of athletic knee injuries: A 10-year study. *Knee*. 2006; 13(3):184–188. [PubMed: 16603363]
24. Myer GD, Paterno MV, Ford KR, Quatman CE, Hewett TE. Rehabilitation after anterior cruciate ligament reconstruction: criteria-based progression through the return-to-sport phase. *J Orthop Sports Phys Ther*. 2006; 36(6):385–402. [PubMed: 16776488]
25. Noehren B, Pohl MB, Sanchez Z, Cunningham T, Lattermann C. Proximal and distal kinematics in female runners with patellofemoral pain. *Clin Biomech*. 2012; 27(4):366–371.
26. Noehren B, Sanchez Z, Cunningham T, McKeon PO. The effect of pain on hip and knee kinematics during running in females with chronic patellofemoral pain. *Gait Posture*. 2012; 36(3):596–599. [PubMed: 22749951]
27. Palmieri-Smith RM, Lepley LK. Quadriceps Strength Asymmetry After Anterior Cruciate Ligament Reconstruction Alters Knee Joint Biomechanics and Functional Performance at Time of Return to Activity. *Am J Sports Med*. 2015; 43(7):1662–1669. [PubMed: 25883169]
28. Paterno MV, Ford KR, Myer GD, Heyl R, Hewett TE. Limb asymmetries in landing and jumping 2 years following anterior cruciate ligament reconstruction. *Clin J Sport Med*. 2007; 17(4):258–262. [PubMed: 17620778]
29. Paterno MV, Schmitt LC, Ford KR, Rauh MJ, Myer GD, Huang B, et al. Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. *Am J Sports Med*. 2010; 38(10):1968–1978. [PubMed: 20702858]
30. Petschnig R, Baron R, Albrecht M. The relationship between isokinetic quadriceps strength test and hop tests for distance and one-legged vertical jump test following anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther*. 1998; 28(1):23–31. [PubMed: 9653687]
31. Pietrosimone BG, Lepley AS, Ericksen HM, Gribble PA, Levine J. Quadriceps strength and corticospinal excitability as predictors of disability after anterior cruciate ligament reconstruction. *J Sport Rehabil*. 2013; 22(1):1–6. [PubMed: 22951289]
32. Piva SR, Fitzgerald K, Irrgang JJ, Jones S, Hando BR, Browder DA, et al. Reliability of measures of impairments associated with patellofemoral pain syndrome. *BMC Musculoskelet Disord*. 2006; 7:33. [PubMed: 16579850]
33. Schmitt LC, Paterno MV, Ford KR, Myer GD, Hewett TE. Strength Asymmetry and Landing Mechanics at Return to Sport after Anterior Cruciate Ligament Reconstruction. *Med Sci Sports Exerc*. 2015; 47(7):1426–1434. [PubMed: 25373481]
34. Schmitt LC, Paterno MV, Hewett TE. The impact of quadriceps femoris strength asymmetry on functional performance at return to sport following anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther*. 2012; 42(9):750–759. [PubMed: 22813542]
35. Silder A, Besier T, Delp SL. Running with a load increases leg stiffness. *J Biomech*. 2015; 48(6):1003–1008. [PubMed: 25728581]
36. Stone MH, Sands WA, Carlock J, Callan S, Dickie D, Daigle K, et al. The importance of isometric maximum strength and peak rate-of-force development in sprint cycling. *J Strength Cond Res*. 2004; 18(4):878–884. [PubMed: 15574097]
37. Thomee R, Kaplan Y, Kvist J, Myklebust G, Risberg MA, Theisen D, et al. Muscle strength and hop performance criteria prior to return to sports after ACL reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2011; 19(11):1798–1805. [PubMed: 21932078]

38. Witvrouw E, Danneels L, Van Tiggelen D, Willems TM, Cambier D. Open versus closed kinetic chain exercises in patellofemoral pain: a 5-year prospective randomized study. *Am J Sports Med.* 2004; 32(5):1122–1130. [PubMed: 15262632]
39. Witvrouw E, Lysens R, Bellemans J, Peers K, Vanderstraeten G. Open versus closed kinetic chain exercises for patellofemoral pain. A prospective, randomized study. *Am J Sports Med.* 2000; 28(5):687–694. [PubMed: 11032226]

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Table 1

Summary of Results for 3 month clinical tests and 6 month running variables

Variable	Mean±SD	95% Confidence Interval
Quadriceps Strength (N)	25.4±10.3	21.7 – 29.1
SLSD (# of step-downs/minute)	24.6±13.9	19.6 – 29.6
YB-A (% leg length)	57.92±8.25	54.9 – 60.9
KFLEX (°)	24.06±6.09	21.9 – 26.2
KEM (N·m/kg)	0.86±0.32	0.74 – 0.97

Presented as Mean±SD and 95% Confidence Interval. 3 month variables include: Quadriceps Strength, SLSD, and YB-A. 6 month running variables are Knee Flexion Excursion (KFLEX) and Knee Extensor Moment (KEM).

Table 2

Correlation Matrix of 3 month clinical tests to 6 month running variables

Pearson's Correlations	KFLEX	KEM
Quadriceps Strength	0.493 (0.006) **	0.505 (0.004) **
SLSD	0.648 (0.000) **	0.541 (0.002) **
YB-A	0.394 (0.031) *	0.276 (0.059)

Presented as Correlation Coefficient (p-value). 3 month variables include: Quadriceps Strength, SLSD, and YB-A. 6 month running variables are Knee Flexion Excursion (KFLEX) and Knee Extensor Moment (KEM).

* significant (p<.05)

** significant (p<.01)

Table 3
Summary of Stepwise Multiple Linear Regression Analyses for Clinical Predictors of Knee Flexion Excursion

Predictor Variable	b	t	p	95% Confidence Interval for b	
				lower bound	upper bound
(Constant)	17.12	9.70	.000	15.35	18.89
SLSD	0.28	4.50	.000	0.22	0.35

Adjusted R² = .40; F(1,28)=20.28; p<0.001
b = coefficient for predictor variable
t = test statistic
p = p-value of predictor variable
Significance defined as .05

Summary of Stepwise Multiple Linear Regression Analysis for Clinical Predictors of Knee Extensor Moment

Table 4

Predictor Variable	b	t	p	95% Confidence Interval for b	
				lower bound	upper bound
(Constant)	0.342	2.519	.018	.206	.478
SLSD	0.009	2.549	.017	.005	.013
Quadriceps Strength	.011	2.198	.037	.006	.016

Adjusted R² = .36; F(2,27)=8.993; p=0.001

b = coefficient for predictor variable

t = test statistic

p = p-value of predictor variable

Significance defined as 0.05