Clinical Predictors of Knee Mechanics at Return to Sport after ACL Reconstruction

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ABSTRACT

KLINE, P. W., D. L. JOHNSON, M. L. IRELAND, and B. NOEHREN. Clinical Predictors of Knee Mechanics at Return to Sport after ACL Reconstruction. *Med. Sci. Sports Exerc.*, Vol. 48, No. 5, pp. 790–795, 2016. **Purpose**: Despite significant rehabilitation, many athletes experience protracted weakness and faulty mechanics after anterior cruciate ligament reconstruction (ACLR). Clinical tests performed early in rehabilitation, which 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 (YB-A) reach distance, and single-leg 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 females) subjects were collected 3 and 6 months post-ACLR. Age, 21.3 ± 7.6 yr; 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 three-dimensional motion analysis while running on an instrumented treadmill. Pearson correlation coefficients and stepwise multiple regression were used to assess the relationships of 3-month and 6-month variables. **Results**: Quadriceps strength ($r = 0.493$, $P < 0.01$), YB-A ($r = 0.394$, $P = 0.03$), and SLSD ($r = 0.648$, $P < 0.01$) were significantly correlated to KFLEX. Quadriceps strength (0.505, $P < 0.01$) and SLSD (.541, $P < 0.01$) were significantly correlated with KEM, whereas YB-A (.276, $P = 0.06$) was not. SLSD and quadriceps strength were predictive of KEM (adj R^2, 0.36; $P = 0.001$) whereas only SLSD was predictive of KFLEX (adj R^2, 0.40; $P < 0.001$). **Conclusions**: After ACLR, better performance in SLSD and quadriceps strength 3 months postsurgery is predictive of improved sagittal plane knee mechanics during running 6 months postsurgery. **Key Words:** BIOMECHANICS, RUNNING, CLINICAL TESTS, MOMENT, KNEE REHABILITATION

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 yr after surgery (20,24,34,37). Although much focus has been given to return-to-sport decisions, less has been devoted to determining the factors that are present early in rehabilitation which predict performance at time of return-to-sport. Identification of these early addressable factors is critical to maximize function because changes in the health care 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 and 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 although 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 wk after 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 before return-to-sport. Commonly performed clinical assessments early in rehabilitation include quadriceps isometric strength testing, Y balance (YB) testing, and single-leg step-down (SLSD) performance (4,6,20,22,32). The YB test assesses neuromuscular deficits in dynamic postural control

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and involves standing on a single limb and reaching in three directions (11,13). At time of return-to-sport after 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, YB test anterior (YB-A) reach performance, and 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, 30 subjects (14 males, 16 females; mean ± SD: age, 21.3 ± 7.6 yr; mass, 69.85 ± 11.4 kg; height, 1.73 ± 0.09 m) with a unilateral reconstructed ACL provided their written informed consent. The subjects reported a presurgery Tegner Activity Scale Rating of mean ± SD, 8.5 ± 1.3. All participants were tested at 3 and 6 months postoperatively. 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 were performed by one of two 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 one 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 handheld dynamometer (Lafayette Instruments, Lafayette, IN) and a stabilization strap. This method of handheld dynamometry has been shown to be reliable and valid in assessing isometric quadriceps strength when compared with 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 s. Subjects were asked to push into the dynamometer with an increasing force during the first 3 s and to hold their maximum force for the final 2 s. Peak force during the final 2 s of the three test trials were averaged for each participant.

YB-A 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 nonoperative 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 YB 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).

SLSD 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 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 s. 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 first and fifth metatarsal heads, and bilateral distal foot. Twenty-five tracking markers were attached including four rigid plates secured to bilateral thigh and shank with four markers on each plate. Three tracking markers identifying proximal, distal, and lateral heels were secured to the rear foot 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). After allowing a 5-min warm-up, the subjects ran at a self-selected test speed (mean, 2.67 ± 0.29 $m \cdot s^{-1}$) on an instrumented treadmill (Bertec, Columbus, OH), 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) at 200 Hz.

Filtering, joint angle calculations, and inverse dynamics were performed using Visual3D software (C-motion, Germantown, MD). Marker locations were filtered at 8 Hz, and force data were filtered at 35 Hz using a fourth-order, low-pass, zero-lag

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 (number of step-downs per 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 ($N \cdot m \cdot kg^{-1}$)	0.86 ± 0.32	0.74–0.97

Presented as mean ± SD and 95% confidence interval. Three-month variables include: quadriceps strength, SLSD, and YB-A. Six-month running variables are KFLEX and KEM.

Butterworth filter. The moments were normalized the body mass and height. The angle and moments were calculated using Cardan *X–Y–Z* 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). 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), Pearson 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 $P \leq 0.05$. 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 ($b = 0.28 \pm 0.06$; $P = 0.000$) 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 ($b = 0.009 \pm 0.004$; $P = 0.017$) and quadriceps strength ($b = 0.011 \pm 0.005$; $P = 0.037$) as predictive with an overall model fit of adjusted $r^2 = 0.36$ (Table 4). Variance inflation factors 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.

TABLE 2. Correlation matrix of 3-month clinical tests to 6-month running variables.

Pearson 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). Three-month variables include: quadriceps strength, SLSD, and YB-A. Six-month running variables are KFLEX and KEM.
*Significant at $P < 0.01$.
**Significant at $P < 0.05$.

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	0.000	15.35	18.89
SLSD	0.28	4.50	0.000	0.22	0.35

Adjusted $R^2 = 0.40$; $F(1,28) = 20.28$; $P < 0.001$.
b, coefficient for predictor variable; *t*, test statistic; *P*, *P* value of predictor variable.
Significance defined as ≤0.05.

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 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, 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.

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

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

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

$$7.88/0.28 = 28.1 = \text{SLSD}$$

Because 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 KEM. 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

TABLE 4. Summary of stepwise multiple linear regression analysis for clinical predictors of KEM.

Predictor Variable	*b*	*t*	*P*	95% Confidence Interval for *b*: Lower Bound	Upper Bound
Constant	0.342	2.519	0.018	0.206	0.478
SLSD	0.009	2.549	0.017	0.005	0.013
Quadriceps strength	0.011	2.198	0.037	0.006	0.016

Adjusted $R^2 = 0.36$; $F(2,27) = 8.993$; $P = 0.001$.
Significance defined as ≤0.05.

example, in a patient who performs 24 step-downs with quadriceps strength of 25 N, we would predict a KEM of 0.83 N. Conversely, if the goal is for the patient to achieve a KEM of 1.0 $N{\cdot}m{\cdot}kg^{-1}$ 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 $N{\cdot}m{\cdot}kg^{-1}$ during running at 6 months after surgery.

DISCUSSION

The purpose of this study was to determine the predictive ability of 3-month postoperative testing of quadriceps isometric strength, YB-A, and SLSD performance on 6-month postoperative 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.

SLSD test. We have shown, for the first time, that 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, because the test is performed in a single-leg stance for 1 min 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 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 for successful completion of the task. More than 300 ms are required to achieve peak knee strength, whereas 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.

YB-A 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 the 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, which 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 YB 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 toward sufficient KFLEX and KEM during running. No normative data for optimal KFLEX or KEM after ACLR exist, 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 $N \cdot m \cdot kg^{-1}$. 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 toward meeting those criteria is essential in identifying and justifying the need for additional treatment.

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