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Associations of Strength and Spatiotemporal Gait Variables With Knee Loading During Gait After Anterior Cruciate Ligament Reconstruction

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Context: Altered knee moments are common during gait in patients after anterior cruciate ligament reconstruction (ACLR). Modifiable factors that influence knee moments and are feasible to record in clinical settings such as strength and spatiotemporal values (eg, step length, step width) have not been identified in persons after ACLR.

Objective: To identify strength and spatiotemporal gait values that can predict knee moments in persons after ACLR.

Design: Cross-sectional study.

Setting: Laboratory.

Patients or Other Participants: Twenty-three individuals with ACLR (14.4 ± 17.2 months post-ACLR).

Main Outcome Measure(s): Peak knee-flexion and -adduction moments were measured while the participants walked at self-selected speeds. Peak isokinetic knee-extensor strength (60°/s) was recorded on a dynamometer, and spatiotemporal gait values were recorded using a pressure walkway. Pearson coefficients were calculated to examine the association of peak knee moments with strength and gait values. Variables correlated with peak knee-flexion and -adduction moments were entered into a stepwise regression model.

Results: Knee-extensor strength and step width were the strongest predictors of knee-flexion moment, accounting for 44% of the variance, whereas stance-phase time and step width were the strongest predictors of knee-adduction moment, explaining 62% of the variance.

Conclusions: The identified spatiotemporal variables could be clinically feasible targets for biofeedback to improve gait after ACLR.

Key Words: knee function, osteoarthritis, walking, biomechanics

Key Points

- Knee strength and several spatiotemporal variables were associated with knee moments during gait and thus may serve as modifiable factors for increasing or decreasing knee loading to improve symmetry.
- The reduced knee-flexion moment after anterior cruciate ligament reconstruction could be increased by increasing step length and knee strength and walking with a narrower step width.
- The reduced knee-adduction moment after anterior cruciate ligament reconstruction could be increased by increasing walking speed, cadence, step length, and knee strength and walking with a narrower step width and shorter stance time.

Anterior cruciate ligament (ACL) tears are one of the most common knee injuries in sports.[1] After injury, ACL reconstruction (ACLR) surgery is often recommended to restore function and dynamic stability of the knee. Although surgical techniques have advanced over time, persons who elect to have ACLR still exhibit an increased risk of developing knee osteoarthritis (OA).[2] For example, up to 50% of persons with ACLR demonstrate degenerative bone changes on radiographic evaluation as early as 5 years after surgery.[3] Despite the alarming rate of developing OA, current ACLR rehabilitation protocols are primarily designed to return patients to their highest level of activity as quickly as possible.[4,5] The lack of targeted rehabilitation interventions to mitigate the factors associated with long-term development of knee OA as part of the ACLR standard of care could be contributing to the poor long-term outcomes.

Mechanical stimuli are essential for maintaining the health and function of articular cartilage. Hence, a commonly hypothesized mechanism of posttraumatic knee OA after ACLR is alterations in knee-joint loading (ie, too much or too little).[6–8] Net knee-adduction and -flexion joint moments are relevant biomechanical variables of knee-joint loading[9,10] that are often altered during gait in persons with ACLR.[9–13] Despite conflicting reports, a frequent finding is decreased joint loading of the involved knee during walking that can persist for up to 24 months post-ACLR and may contribute to the development of knee OA.[12–14]

Altered knee-joint loading is a common and persistent impairment in persons after ACLR, so quantifying knee loading during gait and identifying modifiable factors that influence loading are warranted during rehabilitation. However, quantifying knee-joint loading in the clinic is challenging because these measurements require biomechanical tools (eg, motion capture, force platforms) and analyses that are often unavailable in a clinical setting. In addition, little is known regarding interventions that can be implemented by clinicians to modify knee loading in patients after ACLR. Identifying the variables that inform knee moments and can be addressed during ACLR rehabilitation would be a first step toward bridging the gap between laboratory research findings and clinical practice.

Several factors may contribute to altered knee-joint loading after ACLR and could be quantified and used as rehabilitation targets in clinical settings. Based on the principles of inverse dynamics, joint moments are determined by the joint reaction force (JRF) vectors, the moment arms of the JRF vectors, and the kinematics of the joint (eg, angular acceleration). Thus, gait impairments after ACLR that change the JRF moment arm (eg, step length and width) could result in reduced knee-loading. Indeed, decreasing step length and increasing step width in healthy participants with feedback decreased the knee-flexion and -adduction moments, respectively.[15,16] In addition, quadriceps weakness is a common, persistent impairment that could contribute to reduced knee-loading ability because the knee extensors are responsible for controlling knee angular motion. Thus, the purpose of our study was to determine whether variables that are feasible to assess and modify during rehabilitation in a clinical setting (eg, strength and spatiotemporal gait values) inform external knee-flexion and -adduction moments during gait. We hypothesized that variables that may indicate the magnitude of joint forces (eg, walking speed, cadence), moment arms (eg, step length or width), or control of the angular motion of the knee (eg, knee muscle strength, swing or stance time) would be associated with knee-flexion and -adduction moments during gait.

METHODS

Participants

We recruited 23 participants with primary unilateral ACLR (13 men and 10 women, age = 25.1 ± 6.3 years, height = 174.7 ± 12.0 cm, mass = 76.0 ± 21.9 kg). Based on the data recorded from healthy individuals (unpublished data), we calculated that a sample size of 23 ACLR participants would achieve statistical power of greater than 80% for detecting a significant correlation of 0.5 between knee moments and spatiotemporal gait values. Increased risk of early knee OA development has been well documented in patients after ACLR.[3] Thus, to minimize the possible influences of knee-joint degeneration on study outcomes, the participants must have had their unilateral surgery within 5 years of testing (time post-ACLR = 14.4 ± 17.2 months). Volunteers were excluded if they reported a current lower extremity injury or medical condition that would impair performance of the tasks described in the next section. The institutional review board approved the protocol before data collection. All procedures were explained to each participant, and informed consent was obtained.

Procedures

Maximal concentric isokinetic knee-muscle strength at 60°/s was recorded with a Kin Com III dynamometer (Isokinetic International). The participant was seated in the chair and secured with straps across the trunk and waist. The limb being tested was secured with a thigh strap and the shank pad attached proximal to the malleoli. The axis of rotation of the dynamometer was aligned with the knee-joint axis (ie, femoral epicondyles), and the lever arm of the dynamometer was recorded. Limb weight was controlled using gravity correction before testing for each limb. Oral instructions were given before testing to fold the arms across the chest and extend and flex the lower leg as hard and as fast as possible through the full range of motion (ie, 0° to 90° of knee flexion). Each participant was given 2 practice trials. Four successful trials (ie, going through the full range of motion with arms across the chest) were recorded. The peak extensor moments from the highest 3 trials were then averaged and normalized to body mass (Nm/kg) for subsequent statistical analyses.

We considered clinical assessment of knee-muscle strength and spatial or temporal gait values (eg, step length, stance time) feasible and thus examined these variables as predictors of knee-joint moments. Spatial or temporal gait values were evaluated by instructing the participant to walk at the same self-selected speed across a 16-ft (4.9-m) pressure walkway (model GAITRite-RE16; CIR Systems Inc) 4 times to provide at least 10 footprints or steps for each leg. Specifically, cadence, step length, *foot progression angle* (ie, the angle between the line of progression and the midline of the footprint), *step width* (ie, the distance from the heel center of the reference foot to the line of progression of the opposite foot), and stance time (as a percentage of gait cycle) were derived by the GAITRite software. Step length and width were normalized to the body height of each participant.

The kinematics of the lower extremity and ground reaction forces (GRFs) during overground walking were recorded using an 8-camera motion-analysis system (Vicon T series; Oxford Metrics PLC) at 250 Hz and force plates at 1000 Hz (model OPT464508-2K-STT; Advanced Mechanical Technology, Inc), respectively. Reflective markers were placed on anatomical landmarks following the method reported by Tsai et al.[8] Each participant was instructed to walk at a self-selected speed (1.37 ± 0.17 m/s). Three successful steps (foot completely inside the force plate) were recorded bilaterally for each individual.

Visual3D (version 2021.06.2; C-Motion Inc) was used to process the raw coordinate data in order to compute segmental kinematics and kinetics for both limbs. The trajectory data of the reflective markers were filtered using a fourth-order, zero-lag Butterworth 12-Hz low-pass filter. The local coordinate systems of the pelvis, thigh, shank, and foot were derived from a standing calibration trial. Hip-joint center was estimated using the greater trochanter method,[17] and joint coordinate systems were established based on the International Society of Biomechanics

Table 1. Between-Limbs Comparison of Knee-Strength and Walking Variables

Variable	Limb: Anterior Cruciate Ligament Reconstruction (Mean ± SD)	Limb: Uninjured (Mean ± SD)	Between-Limbs Difference	*P* Value
Maximal isokinetic knee-extensor strength, Nm/kg	1.65 ± 0.53	2.23 ± 0.46	−0.58 ± 0.33	<.001[a]
Peak knee-flexion moment, % BH·BW	3.00 ± 1.84	3.85 ± 1.86	−0.85 ± 1.43	.009[a]
Peak knee-adduction moment, % BH·BW	2.76 ± 0.66	3.06 ± 0.92	−0.30 ± 0.58	.024[a]
Step length, % of BH	41.0 ± 3.7	41.6 ± 3.7	−0.58 ± 1.56	.088
Foot progression angle, °	3.1 ± 5.1	2.3 ± 4.6	0.8 ± 5.4	.481
Step width, % of BH	6.2 ± 1.6	6.2 ± 1.6	0.03 ± 0.26	.606
Stance-phase time, % of gait cycle	62.2 ± 1.4	62.9 ± 1.5	−0.7 ± 1.1	.007[a]

Abbreviations: BH, body height; BW, body weight.

[a] Denotes a significant between-limbs difference.

recommendations.[18] Joint kinematics were calculated using Euler angles with the following order of rotations: flexion or extension, abduction or adduction, and internal or external rotation.

Three-dimensional net joint moments were determined using inverse-dynamics equations[8] and reported as external moments. Peak knee-flexion and -adduction moments during the first half of the stance phase of gait were identified and normalized to body weight and height (% BW·BH) for each walking trial. The beginning and end of the stance phase were determined based on a threshold of 20 N in the vertical GRF.

Statistical Analysis

Statistical analyses were completed with SPSS (version 25; IBM Corp) using a significance level of $P \leq .05$. Between-limbs differences in peak knee-flexion and -adduction moments, peak knee-extensor strength, and spatiotemporal variables were examined with paired *t* tests. We calculated the Pearson correlation coefficient (*r*) to evaluate the association between each of the variables (ie, maximal isokinetic knee-muscle strength and spatial or temporal gait values) with the peak knee-flexion and -adduction moment in the ACLR limb during walking. To identify the variables associated with between-limbs differences in knee-joint moments, the between-limbs differences (ie, surgical leg minus uninjured leg) were computed for the peak knee-flexion and -adduction moments and each predictor variable as appropriate. The Pearson correlation coefficient (*r*) was then used to explore the association of the between-limbs differences in each of the predictor variables with the between-limbs differences in the peak knee-flexion and -adduction moments. Absolute values of the correlation coefficients of 0.75, 0.5, and 0.25 was considered *excellent*, *moderate*, and *fair*, respectively. Variables that were significantly correlated with knee-joint moments were then included in a stepwise regression (ie, the stepwise method provided in SPSS; variable entry: $P <$ .05; variable removal: $P >$ .10) to identify the variables with the strongest associations with the peak knee-flexion and -adduction moments.

RESULTS

Decreased peak knee-extensor strength, peak knee-flexion and -adduction moment, and stance time were observed for the ACLR leg compared with the uninjured leg (Table 1). The peak knee-flexion moment for the ACLR leg during gait was positively correlated with knee-extensor strength and step length and negatively correlated with step width of the ACLR leg (Table 2). Therefore, knee-extensor strength, step length, and step width were included in the subsequent stepwise regression analysis. Among these 3 variables that were significantly associated with the peak knee-flexion moment, the stepwise regression indicated that knee-extensor strength and step width were the most dominant predictors (Figure 1), together accounting for 43% of the variance in the peak knee-flexion moment (Table 3).

The peak knee-adduction moment for the ACLR leg during gait was positively correlated with walking speed, cadence, and step length of the ACLR leg (Table 2). The peak knee-adduction moment was also negatively correlat-

Table 2. Associations of Strength and Spatiotemporal Gait Variables With Peak Knee-Flexion and -Adduction Moments (% BH·Body Weight) During Gait

Variable	Peak Knee-Flexion Moment: Pearson *r*	Peak Knee-Flexion Moment: *P* Value	Peak Knee-Adduction Moment: Pearson *r*	Peak Knee-Adduction Moment: *P* Value
Maximal isokinetic knee-extensor strength, Nm/kg	0.53	.011[a]	0.38	.079
Walking speed, % BH/s	0.28	.193	0.67	<.001[a]
Cadence, steps/min	0.08	.734	0.61	.002[a]
Step length, % of BH	0.46	.026[a]	0.56	.006[a]
Foot progression angle, °	0.06	.779	−0.08	.721
Step width, % of BH	−0.55	.007[a]	−0.63	.001[a]
Stance-phase time, % of gait cycle	0.11	.614	−0.69	<.001[a]

Abbreviation: BH, body height.

[a] Denotes a significant correlation.

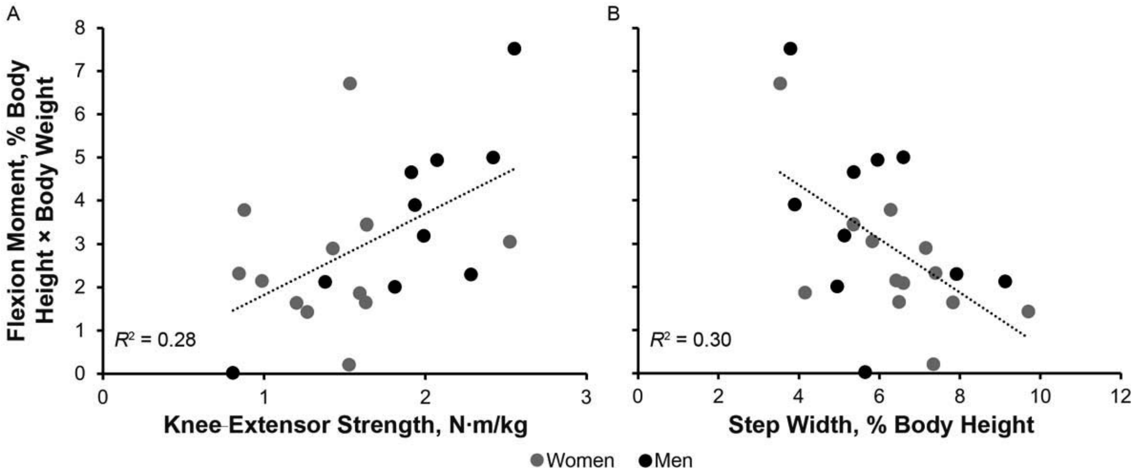

Figure 1. Association of peak knee-flexion moment with, A, isokinetic knee-extensor strength and, B, step width during gait.

ed with step width and stance-phase time (Table 2). Thus, walking speed, cadence, step length, step width, and stance-phase time were included in the subsequent stepwise regression analysis. Among these 5 variables that were significantly associated with the peak knee-adduction moment, the stepwise regression demonstrated that stance-phase time and step width were the most dominant predictors (Figure 2), together accounting for 61% of the variance in peak knee-adduction moment (Table 4).

The between-limbs differences in the peak knee-flexion and -adduction moments were not associated with knee-muscle strength or any spatiotemporal gait variable (Table 5).

DISCUSSION

In this study, we aimed to determine whether variables that are feasible to evaluate and modify in a clinical setting informed knee-joint loading during gait after unilateral ACLR. Several variables were significantly associated with peak knee-flexion and -adduction moments. A greater knee-flexion moment during gait had a fair to moderate association with greater knee-extensor strength, longer step length, and narrower step width. When compared with the knee-flexion moment, associations of the examined measures with the knee-adduction moment were stronger. Specifically, greater knee-adduction moment during gait was moderately to strongly correlated with a faster walking speed, increased cadence, longer step length, narrower step width, and shorter stance-phase time. Among those variables, knee-extensor strength and step width were the dominant predictors, accounting for a fair proportion of the variance (44%) in the peak knee-flexion moment, whereas step width and stance-phase time together accounted for 62% of the variance in the peak knee-adduction moment.

The associations between the predictor variables evaluated and knee-flexion and -adduction moments during gait can be explained, in part, by biomechanical principles that influence net joint moment calculations. The net joint moment is primarily determined by (1) the GRF and the subsequent JRF, (2) the moment arm of the GRF/JRF to the joint, and (3) the angular acceleration of the segment or joint of interest during a dynamic movement. Thus, factors that change the moment arm of the GRF/JRF to the joint (eg, step length, step width) or accelerate or decelerate the angular motion of the knee (eg, knee-muscle strength, stance-phase time) are expected to affect knee-joint moments during walking.

Consistent with our findings, decreased knee-flexion or -adduction moments or both have been commonly observed in surgical limbs after ACLR when compared with the contralateral uninjured limbs[13,19,20] or the limbs of healthy control participants.[9,10,21] However, increased knee-joint moments have also been reported in participants with ACLR compared with healthy control individuals.[22] Because too little or too much loading is believed to contribute to early knee OA,[10,11,13,14] correcting altered knee-loading profiles during rehabilitation after ACLR is a much-needed addition to current clinical care.

Several spatiotemporal variables correlated with knee moments and therefore may serve as objective targets to assist in normalizing altered knee-loading profiles after ACLR (eg, gait training to modify step length, step width, or stance-phase time during gait). For example, our results suggest that patients with reduced knee-flexion and

Table 3. Primary Predictors of Peak Knee-Flexion Moment (% BH·Body Weight) During Gait as Determined by Stepwise Regression Analyses

Step/Model	Predictor	Unstandardized Coefficient	Standardized Coefficient	Variable P Value	R^2 Change	Total R^2
1	Constant	6.845	NA	<.001	0.296	0.296
	Step width, % of BH	−0.617	−0.544	.009		
2	Constant	3.644	NA	.076	0.138	0.433
	Step width, % of BH	−0.468	−0.413	.036		
	Isokinetic knee-extensor strength, % BH·body weight)	1.387	0.394	.045		

Abbreviations: BH, body height; NA, not applicable.

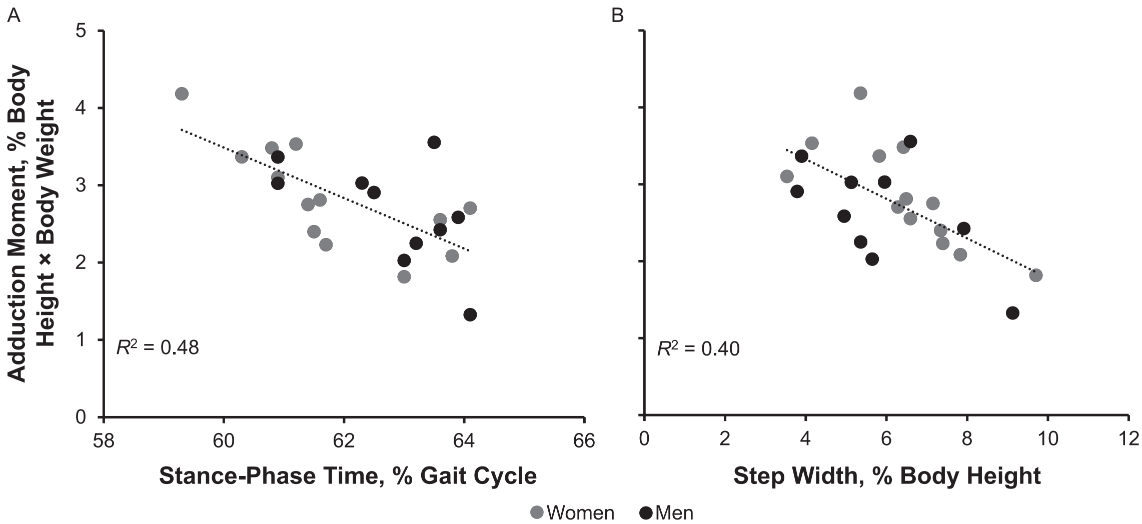

Figure 2. Association of peak knee-adduction moment with, A, stance-phase time and, B, step width during gait.

-adduction moments could be provided feedback to increase step length and decrease step width during walking in order to increase their knee moments. These findings are in general agreement with those of prior studies[15,16] in which healthy participants modified their step length and step width during a single session.

Also, patient cues to reduce stance-phase time could be used to increase the peak knee-adduction moment in those exhibiting a reduced knee-adduction moment. Simple strategies to modify step length and width could include placing targets on the floor[15,16] and using a metronome to assist in pacing. An important consideration, highlighted by Favre et al in 2016,[16] is that cues to change a single gait variable, such as step width, can result in other involuntary changes to gait (eg, foot progression angle). Furthermore, a single gait-retraining target may influence both sagittal- and frontal-plane knee moments. Thus, research is needed to determine whether modifications of the variables identified in this study can normalize altered knee loading in patients after ACLR and thereby delay the onset or reduce the severity (or both) of knee OA.

Knee-extensor weakness is a common persistent impairment[23,24] that was also observed in this study. The knee extensors function to eccentrically control knee flexion during weight acceptance, so a positive correlation between knee strength and peak knee-flexion moment was not surprising. This positive correlation suggests that strength improvements could result in increased knee-flexion moments.[25] However, whether weakness is responsible for decreased knee loading or, alternatively, the altered movement pattern perpetuates the knee weakness remains an open question.

Asymmetry in knee net joint moments between limbs during walking is a typical finding after ACLR and a potential marker of early knee OA risk.[12,13] As such, we also evaluated between-limbs differences of the clinical predictor variables as predictors of between-limbs differences in knee-flexion and -adduction moments. However, none of the variables we assessed were associated with the between-limbs difference in knee-flexion or -adduction moment. These data indicate that the measured variables were less sensitive as predictors of between-limbs asymmetry in knee joint moments.

In the present study, an isokinetic dynamometer and a pressure walkway were used to quantify knee-muscle strength and the spatiotemporal variables of gait, respectively. Our findings serve as a first step in emphasizing the potential value of assessing patients' muscle strength and spatiotemporal gait variables (eg, cadence, step length, step width) to modulate knee-joint moments after ACLR. The pressure walkway was selected because it provides accurate spatiotemporal gait values[26,27] that can be collected quickly in a clinical setting and has been used to assess functional outcomes in patients after ACLR.[28] Therefore, the pressure walkway is one objective low-technology solution for addressing a persistent clinical problem after ACLR. Moreover, prior authors[15,16] indicated that simple strategies, such as placing marks on the floor, could be implemented to change spatiotemporal gait values that influence knee-joint loading. Importantly, some spatiotemporal characteristics, such as step length, may be altered by changing cadence

Table 4. Primary Predictors of Peak Knee-Adduction Moment (% BH·Body Weight) During Gait as Determined by Stepwise Regression Analyses

Step/Model	Predictor Name	Unstandardized Coefficient	Standardized Coefficient	Variable *P* Value	R^2 Change	Total R^2
1	Constant	23.089	NA	<.001	0.472	0.472
	Stance time, % of gait cycle	−0.327	−0.687	<.001		
2	Constant	18.971	NA	<.001	0.140	0.612
	Stance-phase time, % of gait cycle	−0.244	−0.512	.003		
	Step width, % of BH	−0.169	0.413	.014		

Abbreviations: BH, body height; NA, not applicable.

Table 5. Associations of Strength and Spatiotemporal Gait Variables With Between-Limbs Differences in Peak Knee-Flexion or -Adduction Moments During Gait

	Peak Knee Moment Between-Limbs Difference, % BH·Body Weight			
	Flexion		Adduction	
Variable	Pearson *r*	*P* Value	Pearson *r*	*P* Value
Maximal isokinetic knee-extensor strength, Nm/kg	0.34	.117	−0.38	.086
Walking speed, % BH/s	−0.36	.095	−0.27	.221
Cadence, steps/min	−0.27	.220	−0.08	.710
Step length, % of BH	0.39	.067	0.13	.543
Foot progression angle, °	−0.02	.945	0.01	.953
Step width, % of BH	0.08	.732	−0.07	.768
Stance-phase time, % of gait cycle	0.12	.596	−0.25	.256

Abbreviation: BH, body height.

while walking on a treadmill, whereas manipulating step length overground is likely more condition specific. However, walking speed and stride or step lengths must be monitored and manipulated during overground walking, whereas the constant speed during treadmill walking may allow participants to focus on 1 factor.

We acknowledge that many current and emerging technologies, such as inertial sensors, could also yield valid spatiotemporal gait information plus lower extremity joint angles when compared with motion-capture systems.[29,30] Future investigators should evaluate whether using alternative tools to measure the same spatiotemporal variables, incorporating more measurements, or both can supply similar or improved knee-joint loading information. For example, including peak knee-flexion angle would likely improve the regression model for knee-flexion moment and including frontal-plane trunk-lean angle could be a helpful variable for influencing the knee-adduction moment.[16]

Several limitations in our study must be acknowledged. First, given the cross-sectional experimental design, causal relationships between the variables evaluated and knee-joint moments cannot be established based on the correlation or regression analyses. Moreover, participants' knee moments during gait were quantified using the motion-capture system, and spatiotemporal gait variables were quantified using the pressure walkway during separate walking trials. Although we expected comparable gait mechanics during all walking trials, given that the participants walked at their self-selected speeds, the inability to quantify knee moments and spatiotemporal gait variables concurrently due to the limitations of the technology could have influenced the relationships among the variables. Lastly, our patients had different characteristics with respect to factors such as sex and time post-ACLR. Future studies with a larger sample would allow patient characteristics to be included in the regression analysis.

CONCLUSIONS

Our work is a first step in bridging the research-to-clinic gap. We identified several variables that predicted knee-joint moments and that we propose can feasibly be evaluated in a clinical setting. Among the identified variables, knee-extensor strength, step width, step length, and stance-phase duration were the dominant variables associated with peak knee-flexion and -adduction moments. As such, these variables could be used to monitor and guide interventions to modify knee-joint loading during ACLR rehabilitation.

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REFERENCES

1. Hootman JM, Dick R, Agel J. Epidemiology of collegiate injuries for 15 sports: summary and recommendations for injury prevention initiatives. *J Athl Train*. 2007;42(2):311–319.
2. Streich NA, Zimmermann D, Bode G, Schmitt H. Reconstructive versus non-reconstructive treatment of anterior cruciate ligament insufficiency. A retrospective matched-pair long-term follow-up. *Int Orthop*. 2011;35(4):607–613. doi:10.1007/s00264-010-1174-6
3. Sajovic M, Vengust V, Komadina R, Tavcar R, Skaza K. A prospective, randomized comparison of semitendinosus and gracilis tendon versus patellar tendon autografts for anterior cruciate ligament reconstruction: five-year follow-up. *Am J Sports Med*. 2006;34(12):1933–1940. doi:10.1177/0363546506290726
4. 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(7):601–614. doi:10.2519/jospt.2012.3871
5. Kruse LM, Gray B, Wright RW. Rehabilitation after anterior cruciate ligament reconstruction: a systematic review. *J Bone Joint Surg Am*. 2012;94(19):1737–1748. doi:10.2106/JBJS.K.01246
6. Gardinier ES, Di Stasi S, Manal K, Buchanan TS, Snyder-Mackler L. Knee contact force asymmetries in patients who failed return-to-sport readiness criteria 6 months after anterior cruciate ligament reconstruction. *Am J Sports Med*. 2014;42(12):2917–2925. doi:10.1177/0363546514552184
7. Gardinier ES, Manal K, Buchanan TS, Snyder-Mackler L. Altered loading in the injured knee after ACL rupture. *J Orthop Res*. 2013;31(3):458–464. doi:10.1002/jor.22249
8. Tsai LC, McLean S, Colletti PM, Powers CM. Greater muscle co-contraction results in increased tibiofemoral compressive forces in females who have undergone anterior cruciate ligament reconstruction. *J Orthop Res*. 2012;30(12):2007–2014. doi:10.1002/jor.22176
9. Noehren B, Wilson H, Miller C, Lattermann C. Long-term gait deviations in anterior cruciate ligament-reconstructed females. *Med Sci Sports Exerc*. 2013;45(7):1340–1347. doi:10.1249/MSS.0b013e318285c6b6
10. Teng HL, Wu D, Su F, et al. Gait characteristics associated with a greater increase in medial knee cartilage T1rho and T2 relaxation

times in patients undergoing anterior cruciate ligament reconstruction. *Am J Sports Med*. 2017;45(14):3262–3271. doi:10.1177/0363546517723007
11. Kumar D, Kothari A, Souza RB, Wu S, Benjamin Ma C, Li X. Frontal plane knee mechanics and medial cartilage MR relaxation times in individuals with ACL reconstruction: a pilot study. *Knee*. 2014;21(5):881–885. doi:10.1016/j.knee.2014.06.005
12. Slater LV, Hart JM, Kelly AR, Kuenze CM. Progressive changes in walking kinematics and kinetics after anterior cruciate ligament injury and reconstruction: a review and meta-analysis. *J Athl Train*. 2017;52(9):847–860. doi:10.4085/1062-6050-52.6.06
13. Wellsandt E, Gardinier ES, Manal K, Axe MJ, Buchanan TS, Snyder-Mackler L. Decreased knee joint loading associated with early knee osteoarthritis after anterior cruciate ligament injury. *Am J Sports Med*. 2016;44(1):143–151. doi:10.1177/0363546515608475
14. Pfeiffer SJ, Spang J, Nissman D, et al. Gait mechanics and T1rho MRI of tibiofemoral cartilage 6 months after ACL reconstruction. *Med Sci Sports Exerc*. 2019;51(4):630–639. doi:10.1249/MSS.0000000000001834
15. Allet L, IJzerman H, Meijer K, Willems P, Savelberg H. The influence of stride-length on plantar foot-pressures and joint moments. *Gait Posture*. 2011;34(3):300–306. doi:10.1016/j.gaitpost.2011.05.013
16. Favre J, Erhart-Hledik JC, Chehab EF, Andriacchi TP. General scheme to reduce the knee adduction moment by modifying a combination of gait variables. *J Orthop Res*. 2016;34(9):1547–1556. doi:10.1002/jor.23151
17. Bennett HJ, Shen G, Weinhandl JT, Zhang S. Validation of the greater trochanter method with radiographic measurements of frontal plane hip joint centers and knee mechanical axis angles and two other hip joint center methods. *J Biomech*. 2016;49(13):3047–3051. doi:10.1016/j.jbiomech.2016.06.013
18. Wu G, Siegler S, Allard P, et al; Standardization and Terminology Committee of the International Society of Biomechanics. ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion–part I: ankle, hip, and spine. International Society of Biomechanics. *J Biomech*. 2002;35(4):543–548. doi:10.1016/s0021-9290(01)00222-6
19. Roewer BD, Di Stasi SL, Snyder-Mackler L. Quadriceps strength and weight acceptance strategies continue to improve two years after anterior cruciate ligament reconstruction. *J Biomech*. 2011;44(10):1948–1953. doi:10.1016/j.jbiomech.2011.04.037
20. Zabala ME, Favre J, Scanlan SF, Donahue J, Andriacchi TP. Three-dimensional knee moments of ACL reconstructed and control subjects during gait, stair ascent, and stair descent. *J Biomech*. 2013;46(3):515–520. doi:10.1016/j.jbiomech.2012.10.010
21. Patterson MR, Delahunt E, Caulfield B. Peak knee adduction moment during gait in anterior cruciate ligament reconstructed females. *Clin Biomech (Bristol, Avon)*. 2014;29(2):138–142. doi:10.1016/j.clinbiomech.2013.11.021
22. Butler RJ, Minick KI, Ferber R, Underwood F. Gait mechanics after ACL reconstruction: implications for the early onset of knee osteoarthritis. *Br J Sports Med*. 2009;43(5):366–370. doi:10.1136/bjsm.2008.052522
23. Hunnicutt JL, Xerogeanes JW, Tsai LC, et al. Terminal knee extension deficit and female sex predict poorer quadriceps strength following ACL reconstruction using all-soft tissue quadriceps tendon autografts. *Knee Surg Sports Traumatol Arthrosc*. 2021;29(9):3085–3095. doi:10.1007/s00167-020-06351-4
24. Petersen W, Taheri P, Forkel P, Zantop T. Return to play following ACL reconstruction: a systematic review about strength deficits. *Arch Orthop Trauma Surg*. 2014;134(10):1417–1428. doi:10.1007/s00402-014-1992-x
25. Pietrosimone B, Davis-Wilson HC, Seeley MK, et al. Gait biomechanics in individuals meeting sufficient quadriceps strength cutoffs following anterior cruciate ligament reconstruction. *J Athl Train*. 2021;56(9):960–966. doi:10.4085/425-20
26. McDonough AL, Batavia M, Chen FC, Kwon S, Ziai J. The validity and reliability of the GAITRite system's measurements: a preliminary evaluation. *Arch Phys Med Rehabil*. 2001;82(3):419–425. doi:10.1053/apmr.2001.19778
27. Menz HB, Latt MD, Tiedemann A, Mun San Kwan M, Lord SR. Reliability of the GAITRite walkway system for the quantification of temporo-spatial parameters of gait in young and older people. *Gait Posture*. 2004;20(1):20–25. doi:10.1016/S0966-6362(03)00068-7
28. Papuga MO, Beck CA, Kates SL, Schwarz EM, Maloney MD. Validation of GAITRite and PROMIS as high-throughput physical function outcome measures following ACL reconstruction. *J Orthop Res*. 2014;32(6):793–801. doi:10.1002/jor.22591
29. Poitras I, Dupuis F, Bielmann M, et al. Validity and reliability of wearable sensors for joint angle estimation: a systematic review. *Sensors (Basel)*. 2019;19(7):1555. doi:10.3390/s19071555
30. Hanley B, Tucker CB, Bissas A. Differences between motion capture and video analysis systems in calculating knee angles in elite-standard race walking. *J Sports Sci*. 2018;36(11):1250–1255. doi:10.1080/02640414.2017.1372928

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