Identification of strength and spatiotemporal gait parameters associated with knee loading during gait in persons after anterior cruciate ligament reconstruction

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Identification of Strength and Spatiotemporal Gait Parameters Associated with Knee Loading During Gait in Persons after Anterior Cruciate Ligament Reconstruction

ABSTRACT

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

Objective: The objective was to identify strength and spatiotemporal gait parameters that can predict knee moments in persons after ACLR.

Design: Cross-Sectional Study

Setting: Laboratory

Patients: Twenty-three participants with ACLR (14.4 ± 17.2 months post-ACLR) participated.

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

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

Conclusions: The spatiotemporal variables that were identified could be clinically feasible targets for biofeedback to improve gait after ACLR.
Keywords: anterior cruciate ligament, knee function, osteoarthritis, walking; biomechanics

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Key Points:

- Knee strength and several spatiotemporal variables were associated with knee moments during gait and thus may serve as modifiable factors to increase or decrease knee loading to improve symmetry.

- The reduced ACLR knee flexor moment could be increased by increasing step length and knee strength, and walking with a narrower step width.

- The reduced ACLR knee adduction moment 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. While 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 exhibit degenerative bone changes measured via 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 quick as possible.\(^4,5\) The lack of targeted rehabilitation interventions to mitigate factors associated with long-term development of knee OA as part of ACLR standard-of-care could be contributing to the poor long-term outcomes.

Mechanical stimuli are essential to maintain health and function of articular cartilage. Hence, a commonly hypothesized mechanism of post-traumatic knee OA after ACLR is alterations in knee joint loading (i.e. 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 commonly altered during gait in persons with ACLR.\(^9-13\) Despite conflicting reports, a common finding is decreased knee 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.\(^12-14\)

Since altered knee joint loading is a common and persistent impairment in persons after ACLR, quantifying knee loading during gait and identifying modifiable factors that influence loading is warranted during rehabilitation. However, quantifying knee joint loading in the clinic is challenging because these measurements require biomechanical tools (e.g. 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 variables that are informative of knee joint moments and
feasible to be incorporated into ACLR rehabilitation would be a first step toward bridging the
gap between laboratory research findings and clinical practice.

Several factors could contribute to altered knee joint loading after ACLR that could be
quantified and used as rehabilitation targets in clinical settings. Based on the principles of
inverse dynamics calculations, joint moments are determined by the joint reaction force vectors,
the moment arms of the joint reaction force vectors, and the kinematics of the joint (e.g., angular
acceleration). Thus, gait impairments after ACLR that change the joint reaction force moment
arm (e.g. step length and width) could result in reduced knee loading. Indeed, decreasing step
length and increasing step width in healthy participants with feedback has been shown to
decrease the knee flexor and adductor moments, respectively.\textsuperscript{15, 16} In addition, quadriceps
weakness is a common, persistent impairment that could contribute to reduced knee loading
ability since the knee extensors are responsible for controlling knee angular motion. Thus, the
purpose of this study was to determine whether variables that are feasible to assess and modify
during rehabilitation in a clinical setting (e.g. spatiotemporal gait parameters and knee muscle
strength) are informative of external knee flexion and adduction moments during gait. We
hypothesized that variables that may be indicative of the magnitude of joint forces (e.g., walking
speed, cadence), moment arms (e.g., step length/width), or control of the angular motion of the
knee (e.g. knee muscle strength, swing/stance time) would be associated with knee flexion and
adduction moments during gait.

\textbf{METHODS}

\textbf{Participants:}
We recruited 23 participants with primary unilateral ACLR (13 men/10 women, Mean [SD] 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), a sample size of 23 ACLR participants would achieve a statistical power greater than 80% for detecting a significant correlation of 0.5 between knee moments and spatiotemporal gait parameters. Increased risk of early knee OA development has been well documented in patients following ACLR. Thus, to minimize the potential 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).

Participants were excluded if they reported a current lower extremity injury or medical condition that would impair performance of the tasks described below. Prior to participation, all procedures were explained to each participant and informed consent was obtained as approved by the Institutional Review Board.

**Procedures:**

The kinematics of the lower extremity and ground reaction forces during overground walking were recorded using an 8-camera motion analysis system (Vicon; Oxford Metrics, Oxford, UK) at 250 Hz and force plates at 1000 Hz (AMTI, Newton, USA), respectively. Reflective markers were placed on anatomical landmarks following a procedure reported by Tsai et al. 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 participant.

Visual3D (C-motion, Rockville, MD) was used to process the raw coordinate data 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, and joint coordinate systems were established based on ISB recommendations. Joint kinematics were calculated using Euler angles with the following order of rotations: flexion/extension, abduction/adduction, and internal/external rotation. Three-dimensional net joint moments were calculated using inverse dynamics equations 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 the end of the stance phase was determined based on a threshold of 20 N in the vertical ground reaction force.

Spatial/temporal gait parameters (e.g. step length, stance time, etc.), and knee muscle strength were considered feasible to be assessed clinically and thus were examined as predictors of knee joint moments in the present study. Spatial/temporal gait parameters were assessed by instructing the participants to walk at the same self-selected speed across a 16-foot pressure walkway (GAITRite-RE16, CIR Systems Inc., Franklin, NJ, USA) four times to obtain at least 10 foot-prints/steps for each leg. Specifically, cadence, step length, foot progression angle (i.e. the angle between the line of progression and the midline of the footprint), step width (i.e. the distance from the heel center of the reference foot to the line of progression of the opposite foot), and stance time (as a % of gait cycle) were derived by the GAITRite software. Step length and width were normalized to the body height of each participant.

Maximal concentric isokinetic knee muscle strength at 60°/sec was recorded with a KinCom dynamometer (Isokinetic International, Chattanooga, TN, USA). Participants were seated on 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 (i.e. femoral epicondyles) and the lever arm of the dynamometer was recorded. Weight of the limb was controlled using gravity correction prior to testing for each limb. Verbal instructions were given prior to testing to fold their arms across the chest and extend and flex the lower leg as hard and as fast as possible through the full range of motion (i.e. 0 to 90° of knee flexion). Each participant was first given 2 practice trials. A total of 4 successful trials (i.e., going through the full range of motion, arms across chest, etc.) were recorded. The peak extensor moments from the highest 3 trails were then averaged and normalized to body mass (Nm/kg) for subsequent statistical analyses.

Statistical Analysis:

Statistical analyses were completed with SPSS v.25 using a significance level of \( p \leq 0.05 \) (SPSS v. 25, IBM, Armonk, NY, USA). Between limb differences in peak knee flexion and adduction moments, spatiotemporal variables and peak knee extensor strength were examined with paired t-tests. Pearson correlation coefficients (r) were used to examine the association between each of the variables (i.e. spatial/temporal gait parameters, and maximal isokinetic knee muscle strength) with the peak knee flexion and adduction moment in the ACLR limb during walking. To determine variables associated with between-limb differences in knee joint moments, the between-limb differences (i.e., surgical leg minus uninjured leg) were calculated for the peak knee flexion and adduction moments and each predictor variable as appropriate. Pearson correlation coefficients (r) were then used to examine the association of the between-limb differences in each of the predictor variables with the between-limb differences in the peak knee flexion and adduction moments. An absolute value of the correlation coefficient of 0.75,
0.5, and 0.25 was considered to be excellent, moderate, and fair, respectively. Variables that were significantly correlated with the knee joint moments were then included in a step-wise regression (i.e., the Stepwise method provided in SPSS; variable entry: \( p < 0.05 \); variable removal: \( p > 0.10 \)) to identify the variables with the strongest associations with the peak knee flexion and peak adduction moments.

**RESULTS**

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

The peak knee adduction moment during gait for the ACLR leg was positively correlated with walking speed, cadence, and step length of the ACLR leg (Table 2). The peak knee adduction moment was also negatively correlated with step width and stance phase time (Table 2). Therefore, walking speed, cadence, step length, step width, and stance phase time were included in the subsequent step-wise regression analysis. Among these 5 variables that were significantly associated with the peak knee adduction moment, results of the step-wise regression
indicated that stance phase time and step width were the most dominant predictors (Figure 2),
together accounting for 61% of the data variance in peak knee adduction moment (Table 4).
The between-limb difference in the peak knee flexion and adduction moments were not
associated with any spatiotemporal gait variable or knee muscle strength (Table 5).

DISCUSSION

This study aimed to determine whether variables that are feasible to evaluate and modify
in a clinical setting were informative of 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 to 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 time. Among those, step width and knee extensor strength were the
dominant predictors accounting for a fair proportion of the variance (44%) in the peak knee
flexion moment across participants, whereas stance time and step width together accounted for
62% of the data 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
ground reaction force (GRF) and the subsequent joint reaction force (JRF), 2) the moment arm of
the GRF/JRF to the joint, and 3) the angular acceleration of the segment/joint of interest during a
dynamic movement. Thus, factors that change the moment arm of the GRF/JRF to the joint (e.g. step length, step width) or accelerate/decelerate the angular motion of the knee (e.g. knee muscle strength, stance time) are expected to have an impact on the knee joint moments during walking.

Consistent with the findings of this study, decreased knee flexion and/or adduction moments have been commonly observed in the surgical limbs after ACLR when compared to the contralateral uninjured limbs\textsuperscript{13, 19, 20} or to healthy controls.\textsuperscript{9, 10, 21} However, increased knee joint moments have also been reported in participants with ACLR compared to healthy controls.\textsuperscript{22}

Since too little or too much loading is believed to contribute to early knee OA,\textsuperscript{10, 11, 13, 14} correcting altered knee loading profiles during rehabilitation in patients after ACLR is a much-needed addition to current clinical care.

Several spatiotemporal variables were identified in this study that correlated with knee moments and thus may serve as objective targets to assist in normalizing altered knee loading profiles after ACLR (e.g. gait training to modify step length, stance time and/or step width during gait). For example, the findings from this study suggest patients with reduced knee flexion and adduction moments could be provided feedback to decrease step width and increase step length during walking to increase their knee moments. These findings are in general agreement with prior studies that have had healthy participants modify their step width and step length during a single session.\textsuperscript{15, 16}

This study additionally suggests patients cues to reduce stance time could be used to increase the peak knee adduction moment in those exhibiting reduced knee adduction moment. Simple strategies to modify step width and length could include placing targets on the floor\textsuperscript{15, 16} with a metronome to assist with pacing. An important consideration, highlighted by Favre et al. 2016, is that cues to change a single gait parameter such as step width can result in other
involuntary changes to gait (e.g. foot progression angle). In addition, a single gait retraining

232 target may influence both sagittal and frontal plane knee moments. Thus, future research is

233 needed to determine whether modifications of the variables identified in this study can normalize

234 the altered knee loading in patients after ACLR and thus delay onset and/or severity of knee OA.

235

Knee extensor weakness is a common persistent impairment\textsuperscript{23,24} that was also observed

236 in this study. Since the knee extensors function to eccentrically control knee flexion during

237 weight acceptance, a positive correlation between knee strength and the peak knee flexion

238 moment was not surprising. This positive correlation suggests that strength improvements could

239 result in increased knee flexion moments.\textsuperscript{25} However, whether weakness is responsible for

240 decreased knee loading or alternatively that the altered movement pattern perpetuates the knee

241 weakness remains an open question.

242

Asymmetry in knee net joint moments between limbs during walking is a common

243 finding after ACLR and a potential marker of early knee OA risk.\textsuperscript{12,13} As such, between-limb

244 differences of the clinical predictor variables were also evaluated as predictors of between-limb

245 differences in knee flexion and adduction moments. However, no variables evaluated in this

246 study were associated with the between-limb difference in knee flexion or adduction moment.

247 These data indicate the variables used in the present study were less sensitive as predictors of

248 between-limb asymmetry in knee joint moments.

249

In the present study, a pressure walkway and isokinetic dynamometer were used to

250 quantify the spatiotemporal parameters of gait and knee muscle strength, respectively. The

251 findings of this study serve as a first step to emphasize the potential value of assessing patients’

252 spatiotemporal gait parameters (e.g., step length, width, cadence, etc.) and muscle strength to

253 modulate knee joint moments after ACLR. The pressure walkway was selected since it provides
accurate spatiotemporal gait parameters\textsuperscript{26, 27} that could be collected quickly in a clinical setting and has been used to assess functional outcomes in patients after ACLR.\textsuperscript{28} Therefore, the pressure walkway is one possible objective low-tech solution to addressing a persistent clinical problem after ACLR. Moreover, prior studies indicate simple strategies such as placing marks on the floor can be used to change spatiotemporal gait parameters that influence knee joint loading.\textsuperscript{15, 16} Importantly, some spatiotemporal characteristics like step length may be altered by changing cadence while walking on a treadmill, whereas manipulating step length overground is likely more specific to usual conditions. However, walking speed and stride/step lengths must be monitored and manipulated during overground walking while the constant speed during treadmill walking may allow participants to focus on 1 parameter.

We acknowledge that many current and emerging technologies, such as inertial sensors, could also yield valid spatiotemporal gait information and additionally lower extremity joint angles when compared to motion capture systems.\textsuperscript{29, 30} Future research should additionally evaluate whether the same spatiotemporal measurements recorded using alternative tools and/or incorporating additional measurements can achieve similar or improved knee joint loading information. For example, including additional factors such as 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 to influence the knee adduction moment.\textsuperscript{16}

Several limitations in the present study must be acknowledged. First, given the cross-sectional experimental design, casual relationships between the variables evaluated and knee joint moments cannot be established based on the results of our correlation/regression analyses. In addition, participants’ knee moments during gait were quantified using the motion capture system and spatiotemporal gait parameters were quantified using the pressure walkway during
separate walking trials. While we expect 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 parameters concurrently due to the limitation of the technology could influence the relationships among the variables. Lastly, we combined patients with different characteristics such as sex and time post-ACLR. Future studies with a larger sample would allow patient variables to be included in the regression analysis.

**Conclusion**

This study is a first step toward bridging the research to clinic gap, as it identified several variables predictive of knee joint moments that we propose can feasibly be evaluated in a clinical setting. Among the identified variables, step width, step length, stance duration and knee extensor strength were the dominant variables that were 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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Figure Captions

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

Figure 2. Association of the peak knee adduction moment with stance phase time (A) and step width (B) during gait.
Table 1. Between Limb Comparison Of Walking Variables And Knee Strength (mean ± SD)

| Variable                                      | ACLR Leg   | Uninjured Leg | Between-Limb Difference | P Value |
|-----------------------------------------------|------------|---------------|-------------------------|---------|
| Peak knee flexion moment (% BH*BW)            | 3.00 ± 1.84| 3.85 ± 1.86   | -0.85 ± 1.43            | 0.009\(^a\) |
| Peak knee adduction moment (% BH*BW)          | 2.76 ± 0.66| 3.06 ± 0.92   | -0.30 ± 0.58            | 0.024\(^a\) |
| Step length (% of BH)                         | 41.0 ± 3.7 | 41.6 ± 3.7    | -0.58 ± 1.56            | 0.088   |
| Foot progression angle (°)                    | 3.1 ± 5.1  | 2.3 ± 4.6     | 0.8 ± 5.4               | 0.481   |
| Step width (% of BH)                          | 6.2 ± 1.6  | 6.2 ± 1.6     | 0.03 ± 0.26             | 0.606   |
| Stance time (% of gait cycle)                 | 62.2 ± 1.4 | 62.9 ± 1.5    | -0.7 ± 1.1              | 0.007\(^a\) |
| Maximal isokinetic knee extensor strength (Nm/kg) | 1.65 ± 0.53| 2.23 ± 0.46   | -0.58 ± 0.33            | <0.001\(^a\) |

Abbreviations: BH, body height; BW, body weight
\(^a\) denotes a significant between limb difference
Table 2. Associations Of Spatiotemporal Gait Parameters And Strength With The Peak Knee Flexion And Adduction Moments During Gait.

| Parameter                        | Peak Knee Flexion Moment (% BH*BW) | Pearson’s r | P Value | Peak Knee Adduction Moment (% BH*BW) | Pearson’s r | P Value |
|----------------------------------|-------------------------------------|-------------|---------|--------------------------------------|-------------|---------|
| Walking speed (% BH/sec)         | 0.28                                | 0.193       |         | 0.67                                 | <0.001 a    |         |
| Cadence (step/min)               | 0.08                                | 0.734       |         | 0.61                                 | 0.002 a     |         |
| Step length (% of BH)            | 0.46                                | 0.026 a     |         | 0.56                                 | 0.006 a     |         |
| Foot progression angle (°)       | 0.06                                | 0.779       | -0.08   | 0.721                                |             |         |
| Step width (% of BH)             | -0.55                               | 0.007 a     | -0.63   | 0.001 a                              |             |         |
| Stance time (% of Gait Cycle)    | 0.41                                | 0.614       | -0.69   | <0.001 a                             |             |         |
| Maximal isokinetic knee extensor strength (Nm/kg) | 0.53 | 0.011 a | 0.38 | 0.079 |
Table 3. Primary Predictors Of The Peak Knee Flexion Moment (%BW·BH) During Gait Determined By Stepwise Regression Analyses.

| Step/Model | Predictor Name                                         | Unstandardized Coefficient | Standardized Coefficient | Variable P Value | R² Change | Total R² |
|------------|--------------------------------------------------------|----------------------------|--------------------------|------------------|-----------|----------|
| 1          | Constant                                               | 6.845                      | NA                       | <0.001           | 0.296     | 0.296    |
|            | Step Width (% of BH)                                   | -0.617                     | -0.544                   | 0.009            |           |          |
| 2          | Constant                                               | 3.644                      | NA                       | 0.076            | 0.138     | 0.433    |
|            | Step Width (% of BH)                                   | -0.468                     | -0.413                   | 0.036            |           |          |
|            | Isokinetic Knee Extensor Strength (% BW*BH)            | 1.387                      | 0.394                    | 0.045            |           |          |
Table 4. Primary Predictors Of The Peak Knee Adduction Moment (%BW·BH) During Gait 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                       | <0.001           | 0.472      | 0.472     |
|            | Stance Time (% of Gait Cycle)        | -0.327                     | -0.687                   | <0.001           |            |           |
| 2          | Constant                             | 18.971                     | NA                       | <0.001           | 0.140      | 0.612     |
|            | Stance Time (% of Gait Cycle)        | -0.244                     | -0.512                   | 0.003            |            |           |
|            | Step Width (% of BH)                 | -0.169                     | 0.413                    | 0.014            |            |           |
| Walking speed (% BH/sec) | Between-limb difference in peak knee flexion moment (% BH*BW) Pearson’s r | -0.36 | 0.095 | Between-limb difference in peak knee adduction moment (% BH*BW) Pearson’s r | -0.27 | 0.221 |
| Cadence (step/min) | -0.27 | 0.220 | -0.08 | 0.710 |
| Step length (% of BH) | 0.39 | 0.067 | 0.13 | 0.543 |
| Foot progression angle (°) | -0.02 | 0.945 | 0.01 | 0.953 |
| Step width (% of BH) | 0.08 | 0.932 | -0.07 | 0.768 |
| Stance time (% of gait cycle) | 0.12 | 0.596 | -0.25 | 0.256 |
| Maximal isokinetic knee extensor strength (Nm/kg) | 0.34 | 0.117 | -0.38 | 0.086 |

Abbreviations: BH, body height; BW, body weight
