Gait & Posture 69 (2019) 91–95

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Full length article

Changes in stair ascent biomechanics two to eight years after ACL reconstruction are associated with patient-reported outcomes

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ARTICLE INFO

Keywords:
ACL reconstruction
Stair ascent
Compensatory movement
Kinetics
Patient-reported outcomes

ABSTRACT

Background: Anterior cruciate ligament (ACL) injury is often followed by quadriceps deficits that are apparent with gait analysis. The deficit frequently remains after ACL reconstruction (ACLR). As such, evaluation of ACLR patients could be enhanced by a simple method to detect quadriceps deficits. Analyzing forward trunk flexion during stair ascent has been suggested as an assessment of quadriceps function that can be visualized with relatively simple instrumentation.
Aim: The purpose of this study was to determine if trunk flexion angle (TFA) during stair ascent is associated with quadriceps function (as measured by the peak knee flexion moment (KFM)) at 2 and 8 years post-ACLR and if changes are associated with patient-reported outcomes (PRO).
Methods: Fourteen subjects with unilateral primary ACLR performed three stair-ascending trials at two-time periods: 2 years (baseline) and 8 years (follow-up) post-ACLR. Paired Student *t*-tests determined differences in KFM and TFA. Associations between KFM, TFA, and PRO were determined through Pearson correlations.
Results: Peak KFM during stair ascent significantly increased from baseline to follow-up ($p = 0.01$). Though there was no significant difference in TFA ($p = 0.84$) compared to baseline, 50% of subjects showed decreases in TFA. Further, subjects with reduced TFA during stair ascent at follow-up had significantly increased peak KFM ($p = 0.029$) and improvements in PRO ($p = 0.001$).
Discussion: The results suggest that TFA during stair ascent can provide a simple method to assess changes in quadriceps function and pain over time following ACLR. Further analysis is needed to draw conclusions between knee osteoarthritis development and increases in TFA.

1. Introduction

Anterior cruciate ligament (ACL) rupture is the most frequent knee injury among young athletes and the most common diagnosis in orthopedic sports medicine [1]. Research evidence indicates that 39%–56% of young adults 30 years of age or younger, at the time of the ACL injury or ACL reconstruction (ACLR), develop radiographic knee osteoarthritis (OA) 8–12 years later [2]. Quadriceps deficits, reflected in reduced or avoided quadriceps contraction [3–5], quadricpes muscle weakness [5,6], impaired neuromuscular control, or compensatory movements [7], have been reported as a common condition associated with ACL injury and are related to the knee flexion moment (KFM) during walking [3,8]. The KFM has been previously defined as a surrogate for net quadriceps moment (balance between knee extensor and flexor muscle moments) [9,10]. Further, quadriceps strength deficits have been linked to the development and progression of knee OA [11,12]. Thus, assessment of ambulatory quadriceps function in patients with ACLR is potentially an important consideration in the evaluation of the overall risk for developing knee OA.

A number of gait studies have observed that quadriceps deficits in patients following ACLR are often exhibited in the form of a reduced knee flexion moment (KFM) [6,10,13] during the midstance of gait. The reduction of the KFM during walking is clinically important since it is reported as a significant predictor of knee OA [14–16], OA progression [17] and related to knee pain [18]. Previous studies have shown that reductions in knee pain [19,20] resulted in an increased KFM during walking and increased pain resulted in reduced KFM [18]. Therefore, the KFM has been shown to provide an objective surrogate measure of

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https://doi.org/10.1016/j.gaitpost.2019.01.029
Received 22 October 2018; Received in revised form 8 January 2019; Accepted 19 January 2019
0966-6362/

changes in pain as well as net quadriceps moment.

Tasks such as stair ascent require greater quadriceps demand [21] and provide potentially greater sensitivity in detecting KFM differences in ACLR knees [5]. Therefore, it might be possible to detect patterns of movement used to adapt to quadriceps deficits that can be visualized during stair climbing without the need for full gait laboratory instrumentation. For example, patients with severe knee OA have been shown to adopt a distinctive compensatory pattern of movement during stair ascent using increased trunk flexion angle (TFA) to reduce KFM [22]. This increased TFA and decreased KFM during stair ascent could be related to an adaptive response to relieve pain during the activity [20]. Consequently, the magnitude of the TFA during stair ascent could be a useful marker of quadriceps function after ACLR without the need for a full gait analysis.

In assessing stair ascent as a marker in an ACLR population, it is useful to also consider that the KFM during stair ascent has been shown to be reduced compared to contralateral knees at a single time point after ACLR [4,5]. However, very few studies have investigated these moment reductions longitudinally [6,23] or have looked at associations between quadriceps deficits changes over time and changes in patient-reported outcomes (PRO). Thus, the purpose of this study was to determine longitudinal changes in TFA movement patterns and net quadriceps moment (KFM) during stair ascent in patients 2 and 8 years post-ACLR and whether these changes were associated with changes in PRO. We hypothesized that there will be (1) an increase in peak KFM and (2) a reduction in peak forward TFA during stair ascent from baseline to follow-up. Further, we hypothesized that (3) the reduction in peak TFA over the follow-up period will be correlated with the increase in peak KFM, and (4) that increase in peak KFM and reduction in TFA during stair ascent 2 and 8 years post-ACLR will be associated with improvements in PRO over time. A healthy control group, matched in age, sex, and BMI that performed the same task, were compared to the ACLR cohort.

2. Methods

2.1. Participants

A total of 14 ACLR subjects were recruited for this study, participating at baseline and follow-up. The subjects in this study were part of an initial larger cohort of 42 subjects who underwent gait analysis and completion of PRO approximately 2 years post-ACLR and agreed to further contact by researchers. The follow-up testing at 8 years post-ACLR was not part of the original study protocol. As such, this was considered a convenience sampling that was conducted on previously studied subjects who were available at this time point and limited to those agreeing to be recontacted. All participants had undergone a unilateral primary ACLR surgery (9 female, age: 29.9 ± 6.8 yrs.; BMI: 23.5 ± 2.6 kg/m^2; 7 left knees) and were tested at two time periods post-ACLR. The baseline testing was 2.2 ± 0.3 years post-ACLR and the follow-up session was 7.8 ± 0.6 years post-ACLR. Inclusion criteria for subject recruitment were (a) successful ACL reconstruction based on clinical exam (KT-1000 side-to-side difference < 5 mm), (b) MRI to confirm an intact graft, and (c) self-reported history of knee stability. Exclusion criteria were (a) removal of more than 25% of the meniscus, (b) clinical instability of the reconstructed knee, (c) history of other serious ligamentous injury to either lower limb, and/or (d) a history of surgical procedures performed on either lower limb. The ACLR cohort was matched to a control group that included 14 healthy subjects with no prior history of lower limb trauma. The controls were matched by age, sex, and BMI to the 8-year follow-up ACLR cohort as data shows before the age of 45 years gait is stable [24]. IRB-approved informed consent form was obtained by subjects in both groups.

2.2. Motion analysis

The stair ascent task included three successful stair-ascending trials at a self-selected speed, using a two-step staircase: the first step height was 20.5 cm and the height difference between first and second step was 22 cm, with a multicomponent force plate (Bertec, Columbus, OH) embedded under the first step. A trial was considered successful if the foot of the leg being tested fully stepped on the force plate. Subjects performed all trials without additional assistance via rails wearing their own walking shoes in the same laboratory at two-time periods, approximately 2 years and 8 years following ACLR. Kinematic data were collected with an optoelectronic motion capture system (Qualisys Medical, Gothenburg, Sweden). All kinetic and kinematic data were synchronized and recorded at 120 Hz. Kinematics and kinetics were analyzed with the software application BioMove [25] (Stanford University, CA) using the point cluster technique (PCT) [26] following previously described methods [26–28]. The peak KFM was operationally defined by an external moment in the tibial anatomical frame based upon palpable bony landmarks measured during a standing reference trial [27]. The moment was thereafter calculated using an inverse dynamics approach [29] with the foot, lower leg, and thigh segments idealized as rigid bodies with scaled inertial properties taken from the literature [30]. The KFM was taken as the maximum value during the first half of stance phase and normalized to percent body weight and height (%Bw*Ht) to better allow comparison between subjects. The forward trunk lean angle (TFA) was calculated as the difference between anatomical frames for the pelvis [31] and the trunk [25] (Fig. 1). The peak KFM, peak TFA and force plate (FP) contact time were averaged for each subject. Subjects were asked to complete the Knee Injury and Osteoarthritis Outcome Score (KOOS) [32] questionnaire at baseline and at follow-up. Since changes in KFM [18] and TFA [20] can be related to pain and an attempt to relieve pain, the KOOS Pain subscale was selected as the primary outcome for this study. For the KOOS Pain subscale, higher the scores (maximum score of 100 points) represent better outcomes.

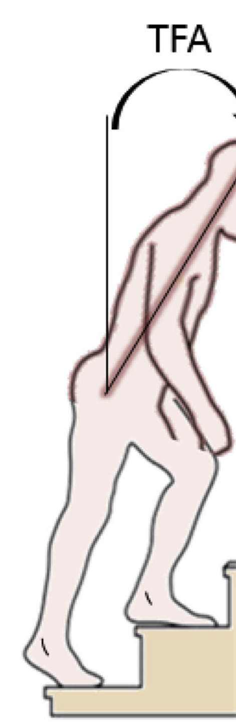

Fig. 1. Forward Trunk Flexion Angle (TFA) in the sagittal plane during stair ascent.

Table 1
Mean values (SD, % DIF) of the peak KFM, peak TFA, FP contact time and KOOS pain subscale in the ACLR limb in the ACL cohort at 2 and 8 years post ACLR and in the healthy control knees.

	2 year post-ACLR ACLR limb	8 years post-ACLR ACLR limb	Healthy Control
KFM (%Bw*Ht)	5.52 (1.47, 19.8%)	6.26 (1.2, 8.59%)*	6.92 (0.93)**
TFA (deg)	7.06 (1.85, 7.52%)	6.93 (2.62, 6.32%)	6.90 (2.07)
FP contact time (msec)	1073 (425.9, 3.13%)	1074 (118.2, 0.4%)	1106 (152.4)
KOOS pain subscale (%)	96 (6.45, 3.17%)	95 (5.77, 4.11%)	99.57 (1.6)

Notes:
%DIF: % difference in parameters between ACLR timepoint and healthy controls.
SD: Standard deviation.
* Significant difference (p = 0.01) between Baseline (2 yrs.) and Follow-Up (8 yrs.).
** Significant difference (p = 0.006) between Baseline (2 yrs.) and Healthy Control.

2.3. Statistical analysis

Changes in peak KFM in the ACLR limb, peak TFA and FP contact time between baseline and follow-up were calculated with paired two-tailed Student's *t*-tests. Pearson correlation coefficients were used to determine correlations between changes in gait variables and PRO (KOOS Pain). Independent Student's *t*-tests were used to compare the ACLR limbs data at baseline and follow-up with the control group ($\alpha = 0.05$). All statistical analyses were performed using SPSS version 23.0 (SPSS Inc., Chicago, IL).

3. Results

The average peak KFM during stair ascent significantly increased (Table 1) from baseline (2 years post-ACLR) to follow-up (8 years post-ACLR) (Baseline: 5.52 ± 1.47% Bw*Ht, Follow-up: 6.26 ± 1.2% Bw*Ht, p = 0.01), with 12 out of 14 subjects exhibiting an increase in peak KFM at follow-up. In comparison to healthy controls, the ACLR population demonstrated a peak KFM during stair ascent at baseline that was significantly lower in the ACLR limb (p = 0.006) than the healthy controls (peak KFM = 6.92 ± 0.93% Bw*Ht) and that was not significantly different (p = 0.12) than the healthy cohort at follow-up in the ACLR limb. Over the follow-up period there was no significant change in peak TFA during stair ascent on average over all ACLR subjects (Baseline: 7.06 ± 1.85°, Follow-up: 6.93 ± 2.62°; p = 0.84). Further the TFA (6.90 ± 2.07°) between the healthy subjects and ACLR subjects demonstrated no significant differences at baseline (p = 0.83) or follow-up (p = 0.97) for the ACLR limb. However, there were substantial between-subject variations in TFA in the ACLR cohort at the follow-up period with half of the subjects (n = 7) exhibiting an increased TFA, and the other half a decreased TFA. Furthermore, the change in TFA during stair ascent over time was directly correlated with the change in peak KFM (Fig. 2, R = −0.58, p = 0.029). The subjects who reduced their peak KFM increased TFA from baseline to follow-up while subjects reducing their TFA increased their KFM. Over the follow up period there was no significant change in FP contact time on average over all ACLR subjects (p = 0.99) and between healthy and ACLR subjects at baseline (p = 0.81) and follow-up (p = 0.51).

An increase in KFM during stair ascent between baseline and follow-up was directly associated with improved KOOS Pain scores, as reported by patients at the follow-up visit (Fig. 3, R = 0.81, P = 0.001).

Similarity indicated was the direct correlation between decreased TFA on the stair ascent task and improved KOOS Pain at the follow-up period (Fig. 4, R = −0.62, P = 0.024).

4. Discussion

This study provides insights into the modifications during activities of daily living in people after ACLR and the possible impact of these changes on long-term patient outcomes. Testing the first hypothesis

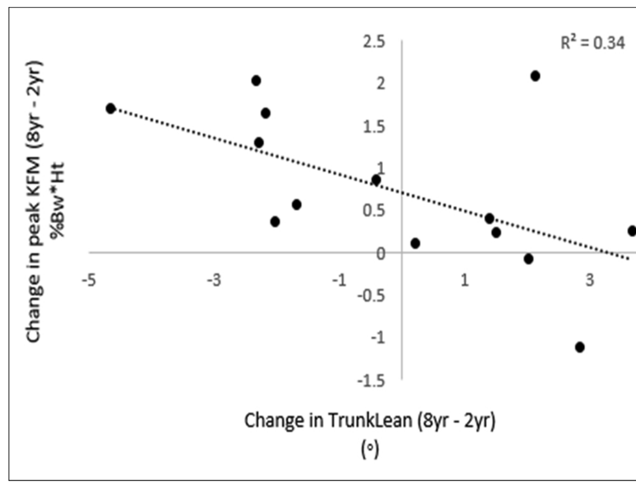

Fig. 2. Changes in peak TFA during stair ascent are correlated with changes in peak KFM between baseline and follow-up (2 and 8-years post-ACLR).

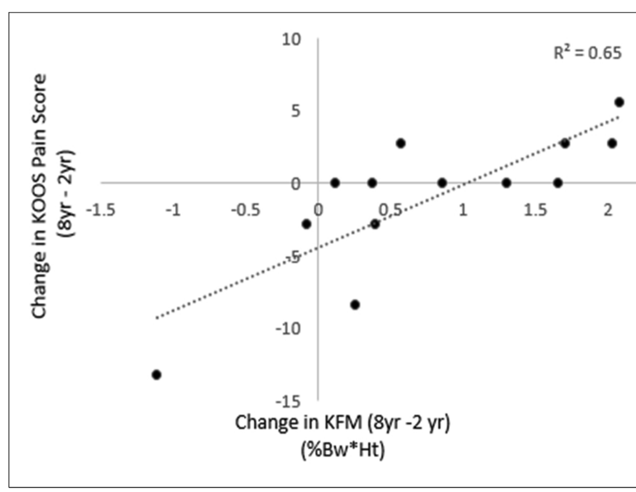

Fig. 3. Increases in peak KFM during stair ascent are correlated to improved KOOS Pain scores between baseline and follow-up (2 and 8-years post-ACLR).

indicated that the ACLR knee had a lower than healthy control peak KFM at 2 years and increased significantly to levels that were not significantly different from healthy controls at 8 years following ACLR. This finding supports previous work showing reduced KFM 2 years post-ACLR [5,33] and is suggestive of weakened net quadriceps contraction [9,10] early after ACLR [34,35]. However, the finding that the average peak KFM was no longer significantly different from that of controls at 8-years post-ACLR suggests long-term continued change in KFM that is consistent with the potential that improvement in muscle function can

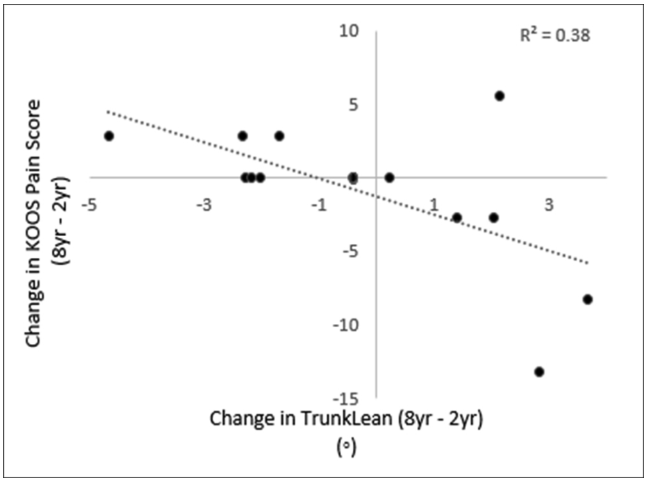

Fig. 4. Reductions in peak TFA during stair ascent are correlated to improved KOOS Pain scores between baseline and follow-up (2 and 8-years post-ACLR).

take place over a substantial time past ACLR in some patients.

Testing the second and third hypotheses demonstrated changes in forward trunk lean (TFA) which were associated with changes in KFM. At the 8 year follow-up, there was a spread in the distribution of the change in the TFA where half (n = 7) of the ACLR patients showed an increase in TFA and the other half (n = 7) showed a decrease in TFA over time. As such, comparing the mean TFA during stair ascent at 2 and 8 years after ACLR were not significantly different due to the bifurcation in the distribution at 8 years. The distribution in the TFA suggests approximately half the patients were likely adapting to weak quadriceps strength deficits since individual changes in peak TFA were significantly and inversely related to changes in peak KFM at 8 years. ACLR subjects with greater increases in KFM showed a reduced forward trunk lean over time (Fig. 5) and subjects that reduced their KFM increased their TFA over time. These findings support the hypothesis that changes in TFA may be a marker for quadriceps recovery, where the KFM was interpreted as a surrogate for net quadriceps moment (net quadriceps and net knee flexor muscle moment) [9,10]. As previously observed in an OA population [22], the forward trunk lean appears to be a compensatory mechanism that reduces quadriceps demand. Hence, the analysis of trunk lean over time may be a useful marker of

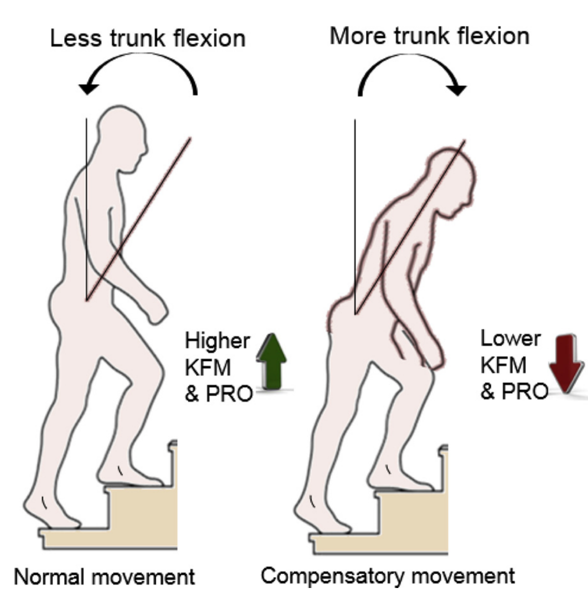

Fig. 5. Adaptive patterns of movement, changes in loading and PRO during stair ascent 2 and 8 years post-ACLR.

quadriceps function post-ACLR.

Increases in peak KFM and reductions in TFA over time were associated with long term improvements in PRO, supporting our fourth hypothesis (Fig. 5). These changes suggest that PRO are associated with modifications in peak KFM [36] and compensatory trunk lean [37] which continue to change through 8 years post-ACLR. The strong correlations between change in KOOS and KFM and between KOOS and TFA suggest that these findings are significant despite the small changes in KOOS pain subscales. It is important to note that the subjects in this study had low pain scores at both study time points which were not indicative of signs of premature OA. Mitigating some of the observed changes in gait and stair mechanics may be useful therapeutic targets for rehabilitation protocols to reduce the risk of developing OA.

The results of this study should be considered in light of the sample size of the subjects available for long-term follow-up (8 years). The current study was drawn from a convenience sampling where the original cohort were not requested to participate in a long term follow-up study. Thus, drop-out numbers were influenced by lack of availability with the exception of those excluded for re-injury and/or injury of the contralateral limb. However, the unique nature of the information obtained over an 8 year prospective study as well as the statistical significance of the results suggest these data provide new insight into the functional changes over a meaningful time frame following ACLR. Moreover, this study showed a strong direct correlation between change in TFA during stair ascent and change in KFM. There are however additional factors that may affect this correlation which are related to human variability, differences in patient activity and the resolution of the measurement system [26]. Another limitation common to studies that examine long term follow-up is the precision in human motion capture techniques as a result of different individuals collecting data at the 2 and 8 year time points. This study mitigated this limitation by maintaining rigorous protocols (including placement of body markers) supervised by the same individual in the same laboratory over the testing period.

In conclusion, this work demonstrates that adaptive patterns of movement during stair ascent change from 2 to 8 years post-ACLR and suggests that biomechanical markers obtained 2 and 8 years post-ACLR may be useful to understand patient reported outcomes in this population. Stair ascent is a more strenuous daily activity than walking because it requires higher ranges of motion, loading, and muscle activation. This task may point to deficits post-ACLR that are possible to visualize in a manner that would not necessarily be visible during walking or require a complex gait lab to assess. Consequently, analyzing forward trunk lean during stair ascent could be a useful objective functional marker for evaluating ACLR patient recovery status and quadriceps function and could provide additional information that is potentially clinically relevant for the early assessment of OA risk in patients after ACLR.

Conflict of interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Author's contribution

Dr. Fischer participated in the design and conception of the research study, analysis, and interpretation of the data, and drafting of the manuscript. Dr. Erhart-Hledik and Dr. Andriacchi each participated in conceptualization of the research study, interpretation of the data, and drafting of the manuscript. Dr. Chu participated in interpretation of the data and drafting of the manuscript. Ms. Asay and Dr. Erhart-Hledik participated in acquisition and analysis of the data and drafting of the manuscript. Dr. Fischer takes responsibility for the manuscript content. All authors have read and approved the final submitted manuscript.

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