Copers and Noncopers Use Different Landing Techniques to Limit Anterior Tibial Translation After Anterior Cruciate Ligament Reconstruction

Michèle N.J. Keizer,*† PhD, Egbert Otten,† PhD, Chantal M.I. Beijersbergen,‡ PhD, Reinoud W. Brouwer,§ MD, PhD, and Juha M. Hijmans,‡ PhD

Investigation performed at the Center for Human Movement Sciences, University Medical Center Groningen, Groningen, the Netherlands

Background: At 1 year after anterior cruciate ligament reconstruction (ACLR), two-thirds of patients manage to return to sports (copers), whereas one-third of patients do not return to sports (noncopers). Copers and noncopers have different muscle activation patterns, and noncopers may not be able to control dynamic anterior tibial translation (ATTd) as well as copers.

Purpose/Hypothesis: To investigate whether (1) there is a positive correlation between passive ATT (ATTp; ie, general joint laxity) and ATTd during jump landing, (2) whether ATTd is moderated by muscle activating patterns, and (3) whether there is a difference in moderating ATTd between copers and noncopers. We hypothesized that patients who have undergone ACLR compensate for ATTd by developing muscle strategies that are more effective in copers compared with noncopers.

Study Design: Controlled laboratory study.

Methods: A total of 40 patients who underwent unilateral ACLR performed 10 single-leg hops for distance with both legs. Lower body kinematic and kinetic data were measured using a motion-capture system, and ATTd was determined with an embedded method. Muscle activity was measured using electromyographic signals. Bilateral ATTp was measured using a KT-1000 arthrometer. In addition, the Beighton score was obtained.

Results: There was no significant correlation between ATTp and ATTd in copers; however, there was a positive correlation between ATTp and ATTd in the operated knee of noncopers. There was a positive correlation between the Beighton score and ATTp as well as between the Beighton score and ATTd in both copers and noncopers in the operated knee. Copers showed a negative correlation between ATTd and gastrocnemius activity in their operated leg during landing. Noncopers showed a positive correlation between ATTd and knee flexion moment in their operated knee during landing.

Conclusion: Copers used increased gastrocnemius activity to reduce ATTd, whereas noncopers moderated ATTd by generating a smaller knee flexion moment.

Clinical Relevance: This study showed that copers used different landing techniques than noncopers. Patients who returned to sports after ACLR had sufficient plantar flexor activation to limit ATTd.

Keywords: knee; knee laxity; muscle activity; motor control
showed a small ATTD. These findings suggest that next to the passive resisting force of the ACL and knee ligament properties, other factors, including dynamic muscle activation patterns or landing kinematics and kinetics, are involved for controlling ATTD. One possibility is that patients undergoing ACLR who manage to return to their preinjury sports type and level (copers) are able to modulate muscle activation patterns that limit the strain of the ACL, whereas patients undergoing ACLR who do not manage to return to their preinjury sports (noncopers) rely more on the resisting force from the ACL. Studies have found that noncopers have different dynamic muscle activation patterns than copers during a single-leg stance on a stabilization platform and a hop test.

In line with the suggestion that knee laxity can be mitigated by muscle-activation patterns in a dynamic situation, it has been reported that ACL-injured patients with low muscle strength of the quadriceps or large interleg hamstring muscle strength asymmetry show greater movement asymmetry in the sagittal plane. This may be caused by an imbalance of the quadriceps-to-hamstring ratio, which may result in modified kinematics, kinetics, and ATTD. It has also been found that residual muscle activity of the medial gastrocnemius and hamstring modulates ATTP. Fleming et al found that medial gastrocnemius activity increases ATTP, and computer models have shown that hamstring activity reduces ATTD during gait.

As far as we know, no research has been conducted to study in vivo the relationship between ATTD and muscle-activation patterns. This may be of interest for patients after ACLR, as copers may have a solution to limit knee ATTD that noncopers do not have but may be able to learn. The aims of this study were therefore to investigate whether (1) there is a relationship between ATTP (ie, general joint laxity [Beighton score]) and ATTD during jump landing, (2) whether ATTD can be moderated by muscle-activation patterns during a single-leg hop for distance (SLHD), and (3) whether there is a difference in ATTD between copers and noncopers. We hypothesized that copers compensate for knee laxity in dynamic situations by developing effective muscle-activation strategies, whereas noncopers are not able to actively moderate knee laxity.

METHODS

The study was a collaboration between the Martini Hospital’s Department of Orthopedic Surgery and the University Medical Center Groningen’s Department of Rehabilitation Medicine and was conducted between April 2018 and November 2019. The study design, procedure, and protocol were approved by a medical ethics committee, and all participants provided informed consent.

Participants

The correlation between ATTD and ATTP was used for an a priori power analysis (R² = 0.47). Based on an effect size of 0.69, alpha of ≤0.05, and power of 80% to detect statistically significant differences, 12 participants were needed. We included 40 patients (15 women and 25 men; age range, 18–42 years). Inclusion criteria were patients who were followed up 12 to 24 months after ACLR and had undergone ACLR using hamstring tendon autografts. Exclusion criteria were patients with cartilage abnormalities that needed concomitant surgical treatment, those who underwent revision ACLR, those who underwent osteotomy, or those with contralateral ACL injuries.

ACLR for all patients was performed with an ipsilateral gracilis and semitendinous tendon autograft, which was fixed using an endobutton (Endobutton CL Ultra; Smith & Nephew) in the femoral socket. For graft fixation in the tibial tunnel, a screw and sheath of polyether ether ketone (PEEK) material were used. This sheath has 4 wings that separate and compress graft strands against the bone tunnel as the PEEK screw is fixed into the sheath.

Study Parameters

The primary outcome measures were ATTD during an SLHD, ATTP measured using a KT-1000 arthrometer (MEDmetric), and muscle-activation patterns during both ATTD and ATTP measurements for both the operated and contralateral legs. The coefficient of variation for this procedure for determining ATTD across 16 healthy knees was 5.2% ± 1.2%, and excellent reproducibility was observed (intraclass correlation coefficient [ICC] (3,1) = 0.92). Moreover, Keizer and Otten showed that ATTD >2.32 mm is reliable in terms of wobbling masses and the Vicon position error. Previous studies have found a smaller variability with the KT-1000 arthrometer compared with other devices to measure ATTP. The mean variability of the KT-1000 arthrometer has been reported as 1.8 mm (intrarater ICC = 0.79).

The secondary study parameters during the SLHD were the knee flexion angle, external knee flexion moment, and vertical ground-reaction force in both the operated and the contralateral legs. The Beighton score (range, 0–9 points),
a scoring system for joint laxity and hypermobility, was also used as a secondary study parameter.

**Procedure**

Each participant was measured in a single session. Participants completed a questionnaire about sports participation and anxiety (see Appendix), and the Beighton score was calculated. The questionnaire was then used to categorize patients as copers (those who are returned to their preinjury type of sports) or noncopers (those who did not return to their preinjury type of sports) for the subsequent data analysis. After this, ATTp (KT-1000 arthrometer; condition 1) and ATTd (SLHD test; condition 2) were calculated. The order of the conditions was randomized to reduce the effect of fatigue on knee laxity.9

Surface electromyographic (EMG) electrodes (Wave Plus wireless EMG system; Cometa Systems) were attached according to SENIAM (surface EMG for noninvasive assessment of muscles) guidelines.32 For condition 2, we recorded the EMG signals for the medial hamstring, lateral hamstring, rectus femoris, vastus medialis, vastus lateralis, gastrocnemius medialis, and gastrocnemius lateralis. For condition 1, the EMG signals were recorded for the medial hamstring, lateral hamstring, rectus femoris, vastus medialis, and vastus lateralis. Gastrocnemius activity was not measured in condition 1 because the location of the EMG electrodes interfered with the attachment of the KT-1000 arthrometer. The same researcher (M.N.J.K.) placed all the electrodes.

During condition 1 (passive test), ATTp was measured using a KT-1000 arthrometer with the knee at 30° of flexion under a force of 67, 89, and 133 N.33 The participants lay supine and were instructed to relax their leg, which was verified by observing the surface EMG recordings. This test was repeated 3 times for both legs.

During condition 2 (dynamic test), 10 SLHDs were performed on both the operated and contralateral legs, and ATTd, muscle activation patterns, knee flexion angle, and external knee flexion moment were determined. Using a 10-camera, 3-dimensional (3D) motion capture system (Vero; Vicon), 3D marker positions were measured at a frequency of 200 Hz. Markers were attached as adapted from Boeth et al14 (Figure 1). Markers were placed by the same researcher (M.N.J.K.) for each participant. After attaching the markers, calibration frames of a flexion-extension movement and a star-arc movement, as prescribed by the manufacturer’s instructions, were taken to be able to identify the hip and knee joint centers and axis of rotation of the knees.16,17 See Keizer and Otten25 for details on the entire procedure.

The participants subsequently performed 3 practice SLHDs with both legs, starting with the uninjured leg. The participants started by standing still on their tested leg and hopped forward as far as possible. Participants were instructed to stand still for at least 3 seconds after landing to ensure a controlled landing. For each leg, the median of the distance of the 3 practice jumps was used for the starting distance from the middle of a 40 × 60–cm force platform (AMTI). Overall, 10 successful jumps were recorded with both legs. The starting leg was randomized.

**Data Analysis**

Data were processed and analyzed using the Statistics Toolbox in MATLAB (Version 9.7; MathWorks). All kinematic and kinetic data and muscle activity during each jump were determined between 1 second before and 1.5 seconds after initial contact (IC), defined as the moment at which the vertical ground-reaction force was >5% of the body weight. The zero point of ATTd was calibrated using the frames captured during a flexion-extension task. Raw 3D marker position data were filtered using a low-pass frequency convolution filter of 10 Hz with zero lag. Gaps smaller than 20 frames were filled using quadratic spline
interpolation with zero lag. Trials with larger gaps were excluded.

The knee flexion moment was calculated from the ground-reaction force vector and its lever arm to the center of the knee of the stance leg. For the quantification of \( \text{ATTd} \) and knee angles, 2 coordinate systems were reconstructed in the tested knee using a customized MATLAB script based on the method of Boeth et al.\(^{14} \) One system was reconstructed in the femoral segment (parent system) and 1 in the tibial segment (child system). See Keizer and Otten\(^ {25} \) for the details of this procedure. The motion of each coordinate system was consistent with the movement of the respective segment. \( \text{ATTd} \) was quantified in millimeters using the relative movement of the origin of the coordinate system of the tibia relative to that of the femoral coordinate system. The knee flexion angles and rotations between both coordinate systems (tibial and femoral) were calculated. Rotations were obtained using scalar products as in the equations by Robertson et al.\(^ {35} \)

The surface EMG signals were recorded at a sampling frequency of 1000 Hz. Muscle activity around the point of first ground contact, taking into account an electromechanical delay of 49.7 milliseconds,\(^ {10} \) was rectified and filtered using a fourth-order, low-pass frequency Butterworth filter at 6 Hz with zero lag. To minimize the influence of body fat and skin conductivity, we scaled the EMG signals to the mean muscle activity from 1 second before IC to 1.5 seconds after IC of the SLHD for each participant. Because of large variations in peak activation between and within participants, especially of the semitendinosus muscle, during a maximal isometric contraction task, we did not scale to this maximal isometric contraction task, we did not scale to this

\[ \text{ATTd, mm} \]

and skin conductivity, we scaled the EMG signals to the mean muscle activity from 1 second before IC to 1.5 seconds after IC of the SLHD for each participant. Because of large variations in peak activation between and within participants, especially of the semitendinosus muscle, during a maximal isometric contraction task, we did not scale to this

\[ \text{ATTd, mm} \]

attained a post hoc regression analysis was performed for each independent muscle activity and kinetic variables as independent variables. This procedure was performed for the whole cohort, for only the copers, and for only the noncopers.

\[ P \text{ values were considered to be significant with an alpha of } < .05. \]

If a correlation was significant, a correlation coefficient of 0.20-0.49, 0.50-0.79, and 0.80-1.00 were considered to represent a weak, moderate, and strong association, respectively.\(^ {15} \)

**RESULTS**

The baseline characteristics of the study participants are displayed in Table 1. Figure 2 shows the results between copers and noncopers of the kinetic and kinematic data over the 10 trials in the operated leg, and Figure 3 shows similar data for the contralateral leg.

### General Joint Laxity and ATT

There was a weak but significant positive correlation between the Beighton score and \( \text{ATTp} \) of the operated leg \((r = 0.42; P = .007)\). The SPM(\( t \)) regression analysis (Figure 4) showed a significant positive correlation between the Beighton score and \( \text{ATTd} \) of the operated leg between 0.08 and 0.19 seconds before IC \((P = .003)\).

### \( \text{ATT} \) of Copers Versus Noncopers

There was no significant correlation between \( \text{ATTp} \) and maximal \( \text{ATTd} \) of the operated leg for copers \((r = 0.05; P = .82)\), and there was a moderate significant positive correlation for noncopers \((r = 0.55; P = .04)\). There was no statistically significant difference between \( \text{ATTp} \) and maximal \( \text{ATTd} \) for copers or noncopers in the contralateral knee \((r = 0.05, P = .82; \text{and } r = 0.38, P = .18, \text{respectively})\).

| Variable                  | Copers | Noncopers | P Value |
|---------------------------|--------|-----------|---------|
| Sex, male/female, n       | 17/9   | 8/6       | .60     |
| Age, y                    | 26.5 (19 to 39) | 26.1 (18 to 42) | .97     |
| Height, cm                | 181 (161 to 198) | 181 (163 to 196) | .81     |
| Weight, kg                | 79 (61 to 112) | 76 (52 to 107) | .66     |
| Follow-up, mo             | 16.5 (12 to 24) | 17.0 (12 to 24) | .82     |
| Beighton score            | 2.2 (0 to 7)  | 1.9 (0 to 6)  | .75     |
| \( \text{ATTp, mm} \)     |         |           |         |
| Operated                  | 5.2 (1.1 to 9.5) | 4.8 (1.7 to 8.5) | .69     |
| Contralateral             | 4.3 (1.6 to 8.7) | 3.5 (0.8 to 7.7) | .24     |
| \( \text{ATTd, mm} \)     |         |           |         |
| Operated                  | 12.5 (–0.1 to 22.3) | 11.1 (1.5 to 19.4) | .51     |
| Contralateral             | 12.5 (4.5 to 20.0) | 11.3 (5.5 to 16.6) | .42     |
| Anxiety, yes/no           | 9/17   | 10/4      | .03     |

*Data are reported as mean (range) unless otherwise indicated. Bolded P value indicates a statistically significant difference between groups \((P < .05)\). \( \text{ATTd} \), dynamic anterior tibial translation; \( \text{ATTp} \), passive anterior tibial translation.*
The correlation of ATTp between the operated and contralateral legs was moderately significant for both the copers and noncopers (copers: $r = 0.56; P = .003$) (noncopers: $r = 0.68; P = .008$) (Figure 5A). The correlation of ATTd between the operated and contralateral legs was weak for copers ($r = 0.39; P = .047$) and moderately significant for noncopers ($r = 0.76; P = .002$) (Figure 5B).

Control of ATTd

Table 2 shows the results of the SPM($\chi^2$) CCA in the operated and contralateral legs for the whole cohort, copers, and noncopers. Also shown are the variables with a significant correlation of ATTd according to the post hoc SPM($t$) analysis.

For the whole cohort, the SPM($\chi^2$) CCA of the operated leg showed a significance between 2 and 3 milliseconds after IC ($P = .049$) and between 11 and 17 milliseconds after IC ($P = .028$). The post hoc SPM($t$) regression analysis showed significant correlations of vastus lateralis, gastrocnemius medialis, and gastrocnemius lateralis muscle activity and knee flexion angle with ATTd over some time points (Table 2).

For copers, the SPM($\chi^2$) CCA of the operated leg showed a significance between 0 and 3 milliseconds after IC ($P =$...
The post hoc SPM[t] regression analysis showed significant correlations between gastrocnemius medialis and lateralis muscle activity and ATTd over some time points (Table 2).

For noncopers, the SPM[x^2] CCA showed a significance between 12 and 15 milliseconds after IC (P = .049) in the operated leg and between 4 and 6 milliseconds after IC (P = .049) and between 16 and 19 milliseconds after IC (P = .048) in the contralateral leg. The post hoc SPM[t] regression analysis for the contralateral leg showed significant correlations between gastrocnemius medialis and lateralis activity and ATTd over some time points (Table 2).

**DISCUSSION**

This research shows that after ACLR, patients who were able to return to sports and who had larger activation of the gastrocnemius muscles just after IC during a unilateral landing with the operated leg had less ATTd. Moreover,
patients who were not able to return to sports had a larger knee flexion moment during a unilateral landing with the operated leg and had greater ATTd. ATTd of the operated knee was less in noncopers who had less ATTp, but there was no significant association present in copers.

Correlation of ATT Between Legs

In the current study, we found a positive association between ATTp of the operated and contralateral leg. We also found a positive association between maximal ATTd of the operated and contralateral leg. This may suggest that surgeons are able to reconstruct the ACL at a comparable length as that of the native ACL in the contralateral knee or that, during rehabilitation, the length of the reconstructed ACL adapts to its use. Miura et al.30 also found that ACLR could reduce knee laxity close to the level of that of the contralateral knee. However, there is also a study that found higher ATTp in the operated leg compared with the contralateral leg.29

General Joint Laxity and ATT

It has been shown that general joint laxity is associated with a higher risk of ACL injuries and an increased risk of graft failure after ACLR and is more common in patients with an ACL injury.3,43 We found an association between the Beighton score and ATTp for the entire cohort, showing that patients with larger general joint laxity also had larger amounts of specific ATTp. In addition, our analysis showed that just before a unilateral landing with the operated leg, patients who had a higher Beighton score also had a larger amount of ATTd. These results imply that in passive situations, ATTp (or in dynamic situations with no external forces, ATTd) is associated with general joint laxity. After IC, there was no association between general joint laxity and ATTd for copers or noncopers, and this suggests that during a jump landing, ATTd is limited by joint kinetics and/or muscle activation. In girls with large general joint laxity, a different muscle activation pattern was shown during a static balance task, which supports our suggestion.21

Relationship Between ATTp and ATTd

Previous studies showed no correlation between ATTp and ATTd during gait, active extension, heel raises, cycling, single-leg squats, and chair squats in ACL-deficient, ACL-reconstructed, and healthy knees.27,41 One previous study, using the same technique as the present study, showed a weak negative correlation between ATTp and ATTd in healthy participants.23 Contrarily, the present study showed a positive association between ATTp and ATTd of the operated leg for noncopers but not for copers. This difference may be because of the injury. Noncopers with larger

Figure 4. SPM(t) regression analysis between the Beighton score and dynamic anterior tibial translation (ATTd). IC, initial contact; SPM, statistical parametric mapping.

Figure 5. Correlation between the operated and contralateral legs in copers and noncopers for (A) passive anterior tibial translation (ATTp) and (B) maximal dynamic anterior tibial translation (ATTd).
amounts of ATTp also had larger amounts of ATTd during unilateral landing in the operated leg, and this suggests that noncopers rely more on the strain of the ACL during impact than copers. The absence of a significant association in copers supports the hypothesis that those who are able to return to sports are able to control ATTd and develop an effective strategy during their rehabilitation to reduce ATTd during landing. Consequently, copers rely less on the strain of the ACL to limit ATTd. This was also shown in healthy participants who amended their knee flexion moment to reduce their ATTd.23

In the following subsections, we discuss the underlying mechanisms of how joint kinematics, kinetics, and/or muscle activation can contribute to an effective strategy that reduces ATTd during a unilateral jump landing in patients after ACLR.

Kinematics, Kinetics, and ATTd

We can divide a unilateral jump landing into different phases: preparation, loading response, and stabilization. The preparation phase is during flight, and the knee is extending to prepare for IC. Our analysis showed that during this preparation phase, there were no crucial differences in kinematics, kinetics, or muscle activation between the operated and nonoperated legs and/or between copers and noncopers. The second phase, loading response, is characterized by a rapid knee flexion movement that enables shock absorption and deceleration of the body’s center of mass. We found larger knee flexion angles during the loading response phase and more ATTd. This finding is in line with previous findings in healthy participants using the same measurement methods.23 Previous cadaveric studies using a strain transducer on the anteromedial bundle of the ACL showed that the ACL is most strained when the knee is flexed between 0° and 30° and that the strain becomes less by larger amounts of knee flexion.7,34 Similar results were shown in healthy knees using magnetic resonance imaging– and fluoroscopy-based modeled jump landings.42 These studies showed that when the knee is flexed more than 30°, the ACL is less strained. Consequently, there is more room for ATT, and this is thus in line with our findings on ATTd.

More knee flexion during jump landing results in less strain on the ACL,7,34 and physical therapists usually instruct their patients to land with a more flexed knee to prevent reruptures.12,46 However, when the ACL is slack (at high knee flexion angles), greater translational acceleration can occur in the tibia relative to the femur, which subsequently is decelerated by the ACL, resulting in greater peak stress of the ACL in uncontrolled sudden movements. Only the noncopers, with their operated leg, decreased their knee flexion moment and showed less ATTd. A decreased knee flexion moment is possible because of less knee flexion, which limits energy absorption around the knee joint during landing. Future studies should focus on the combination of knee flexion during landing and mechanical properties of the ACL to obtain more insight into the optimal and patient-specific landing technique that lowers the strain on the ACL.

Muscle Activation and ATTd

Gastrocnemius activity limits ATTp,8,19,26 and we, for the first time, showed that increased gastrocnemius activity also limited ATT during a dynamic hopping task. The
reason for this may be the tibial plateau angle, posteriorly lower than anteriorly, which favors ATT. Fleming et al showed that the gastrocnemius is an antagonist for the ACL. This seems contrary to our results. That study measured ACL strain, which is related to ATT, but its authors evoked isolated muscle activity by electrical stimulation, which is different from muscle group activation in the task used in the present study. A future study could investigate the influence of the anatomy of the knee on ATTd. In healthy participants, in contrast with the findings of the present study, there is no significant association between muscle activation and ATTd also during a unilateral jump landing. This difference may be explained by the injury. After ACLR, patients may learn to limit their ATTd in different ways than healthy participants. Another possible explanation is that the significant correlation that we found between gastrocnemius activity and ATTd is caused by the pattern of activation of all muscles together during landing.

Vastus lateralis activity was negatively associated with ATTd. Indeed, patients with greater activation of the vastus lateralis just after IC showed less ATTd. This negative correlation is not expected, as a previous study showed that the quadriceps causes an increase in ACL loading. A previous study in healthy participants also found a negative weight coefficient between the vastus lateralis and ATTd; however, the findings were not statistically significant. Increased vastus activity reduces further knee flexion, and we found that the knee flexion angle was positively correlated with ATTd. The knee flexion angle may make a larger contribution to ATTd than vastus activity, which may explain that at the moment that vastus lateralis activity is increased (and the knee flexion angle is smaller), ATTd is smaller than with less vastus lateralis activity.

Because of the harvest of the medial hamstring tendon, it is a self-evident hypothesis that the activity of the hamstring is reduced, shifting the balance toward the quadriceps. However, we did not find a difference in hamstring activity of the injured leg compared with the uninjured leg. This is in line with a previous study that showed that the medial hamstring tendon regenerates and strength returns. Consequently, harvesting of that tendon may not have been the cause of the observed differences.

Summary of Copers Versus Noncopers

We found that copers and noncopers, in their operated and contralateral legs, showed differences in the association between muscle activity and ATTd and between kinetics and ATTd. Copers increased their gastrocnemius activity to reduce ATTd of the knee in the operated leg. Noncopers amended their knee flexion moment in their operated leg to reduce ATTd. Moreover, in their contralateral leg, noncopers also used muscle activation of the gastrocnemius to reduce ATTd. These results may imply that copers use muscle activation of the gastrocnemius to limit ATTd, whereas noncopers fail to do this. Instead, noncopers limited their knee flexion moment to limit ATTd. Figure 6 summarizes the results of this study. Only the significant variables on ATTd are depicted.

**Figure 6.** Relationship between significant variables and dynamic anterior tibial translation (ATTd). Dashed line: whole cohort. Dotted line: only the copers. Continuous line: only the noncopers. ATTp, passive anterior tibial translation.

**Limitations**

A limitation of this study may be that as we have no information on the unstrained length of the ACL, we have no way to determine clinical benchmark values of ATTd in particular patients. A second limitation is that the measured ATTd is influenced by wobbling masses. In another experiment in which we identified the sensitivity of the method used to quantify ATTd on marker placement (wobbling masses) and the Vicon position error, we found an error in the measured ATTd of 2.32 mm. All differences between patients on 1 SLHD of less than 2.32 mm should be interpreted with caution. This limitation is used to interpret the results of the current study. Thereby, previous studies showed comparable ATTd ranges with our study. A third limitation is the method of normalization of muscle activity. We chose to normalize muscle activity to the percentage of the mean muscle activity during the SLHD. This normalized muscle activity might be more comparable between participants than non-normalized electrical muscle activity because the influence of variables such as conductance and body fat is bypassed. We used muscle activation over a longer time window in the same task for normalization, which forms a background to detect peaks at certain moments in time. Because of large variations in peak activation in maximal isometric contractions between and within patients, especially of the semitendinosus muscle, we did not scale to this muscle activity. Maximal isometric contraction tasks are notorious for these kinds of large variations. Another limitation is that we measured the absolute ATTp using the KT-1000 arthrometer, which may have introduced effects of the weight of the lower legs on ATTp, thus yielding different net loads in different limbs of varying masses. A future study may analyze the effect of lower leg mass using the KT-1000 arthrometer.

**CONCLUSION**

The study findings indicated that ATT during a unilateral jump landing was limited by knee flexion moment and gastrocnemius muscle activation but differed between copers and noncopers. Copers used increased gastrocnemius
activity to limit ATTD in their operated leg, whereas non-copers limited their knee flexion moment to reduce ATTD.

REFERENCES

1. Abourezk MN, Ithurburn MP, McNally MP, et al. Hamstring strength asymmetry at 3 years after anterior cruciate ligament reconstruction alters knee mechanics during gait and jogging. *Am J Sports Med*. 2017;45(1):97-105.

2. Ahmad CS, Clark AM, Seiler C, et al. Anterior cruciate ligament-reconstructed knee and contralateral stable knee using navicular comparison of knee laxity between anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2016;24(11):2821-2829.

3. Akhter MA, Bhattacharya R, Keating JF. Generalised ligamentous laxity and revision ACL surgery: is there a relation? *Knee*. 2016;23(8):1148-1153.

4. Akhtar MA, Bhattacharya R, Keating JF. Generalised ligamentous laxity and revision ACL surgery: is there a relation? *Knee*. 2016;23(8):1148-1153.

5. Alkjaer T, Henriksen M, Simonsen EB. Different knee joint loading patterns in ACL deficient copers and non-copers during walking. *Knee Surg Sports Traumatol Arthrosc*. 2011;19(4):615-621.

6. Anderson W, Zauel R, Bishop J, Demp E, Tashman S. Validation of three-dimensional model-based tibio-femoral tracking during running. *Med Eng Phys*. 2009;31(1):10-16.

7. Arden CL, Webster KE, Taylor NF, Feller JA. Return to sport following anterior cruciate ligament reconstruction surgery: a systematic review and meta-analysis of the state of play. *Br J Sports Med*. 2011;45(7):596-606.

8. Bakker R, Tomescu S, Brennan E, Hangarul G, Laing A, Chandra-skhar N. Effect of sagittal plane mechanics on ACL strain during jump landing. *J Orthop Res*. 2016;34(9):1636-1644.

9. Barcellona MG, Morrissey MC, Milligan P, Amis AA. The effect of thigh muscle activity on anterior knee laxity in the uninjured and anterior cruciate ligament-injured knee. *Knee Surg Sports Traumatol Arthrosc*. 2014;22(11):2821-2829.

10. Baumgart C, Gokeler A, Donath L, Hoppe MW, Freiwald J. Effects of static stretching and playing soccer on knee laxity. *Clin J Sport Med*. 2015;25(6):541-545.

11. Benoigov H, Zhou G-Q, Li T, Wang Y, Zheng Y-P. Detection of the electromechanical delay and its components during voluntary isometric contraction of the quadriceps femoris muscle. *Front Physiol*. 2014;5:494.

12. Beighton P, Solomon L, Sokolotn CL. Articular mobility in an African population. *Ann Rheum Dis*. 1973;32(5):413-418.

13. Benjamais A, Gokeler A, Dowling AV, et al. Optimization of the anterior cruciate ligament injury prevention paradigm: novel feedback techniques to enhance motor learning and reduce injury risk. *J Orthop Sports Phys Ther*. 2015;45(3):170-182.

14. Berry J, Kramer K, Binkley J, et al. Error estimates in novice and expert raters for the KT-1000 arthrometer. *J Orthop Sports Phys Ther*. 1999;29(1):49-55.

15. Boeth H, Duda GN, Heller MO, et al. Anterior cruciate ligament-deficient patients with passive knee joint laxity have a decreased range of anterior-posterior motion during active movements. *Am J Sports Med*. 2013;41(5):1051-1057.

16. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. Academic Press; 1969.

17. Ehrg RM, Taylor WR, Duda GN, Heller MO. A survey of formal methods for determining functional joint axes. *J Biomech*. 2007;40(10): 2150-2157.

18. Ehrg RM, Taylor WR, Duda GN, Heller MO. A survey of formal methods for determining the centre of rotation of ball joints. *J Biomech*. 2006;39(15):2798-2809.

19. Eltzen I, Eltzen TJ, Holm I, Snyder-McMkker L, Risberg MA. Anterior cruciate ligament-deficient potential copers and nocopers reveal different isokinetic quadriceps strength profiles in the early stage after injury. *Am J Sports Med*. 2010;38(3):586-593.

20. Fleming BC, Renstrom PA, Ohlen G, et al. The gastrocnemius muscle is an antagonist of the anterior cruciate ligament. *J Orthop Res*. 2001;19(6):1178-1184.

21. Gardinier ES, Di Stasi S, Manal K, Buchanan TS, Snyder-McKeller 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.

22. Juul-Kristensen B, Johansen KL, Hendriksen P, Melcher P, Sandfeld J, Jensen BR. Girls with generalized joint hypermobility display changed muscle activity and postural sway during static balance tasks. *Scand J Rheumatol*. 2016;45(1):57-65.

23. Kacmaz IE, Topkaya Y, Basa CD, et al. Posterior tibial slope of the knee measured on X-rays in a Turkish population. *Surg Radiol Anat*. 2020;42(6):673-679.

24. Keizer MN, Hetjans GM, Gokeler A, Benjaminse A, Otten E. Healthy subjects with lax knees use less knee flexion rather than muscle control to limit anterior tibia translation during landing. *J Exp Orthop*. 2020;7(1):32.

25. Keizer MN, Otten E. Passive anterior tibia translation in anterior cruciate ligament-injured, anterior cruciate ligament-reconstructed and healthy knees: a systematic review. *Musculoskelet Surg*. 2018;103(2):121-130.

26. Keizer MN, Otten E. Technical note: sensitivity analysis of the SCFORE and SARA methods for determining rotational axes during tibiofemoral movements using optical motion capture. *J Exp Orthop*. 2020;7(1):6.

27. Klyne DM, Keays SL, Bullock-Saxton JE, Newcombe PA. The effect of anterior cruciate ligament rupture on the timing and amplitude of gastrocnemius muscle activation: a study of alterations in EMG measures and their relationship to knee joint stability. *J Electromyogr Kinesiol*. 2012;22(3):446-455.

28. Kvist J. Sagittal tibial translation during exercises in the anterior cruciate ligament-deficient knee. *Scand J Med Sci Sports*. 2005;15(3):148-158.

29. Lin C-C, Li J-D, Lu T-W, Kuo M-Y, Kuo C-C, Hsu H-C. A model-based tracking method for measuring 3D dynamic joint motion using an alternating biplane X-ray imaging system. *Med Phys*. 2018;45(8):3637-3649.

30. Meyer CAG, Gette P, Mouton C, Sell R, Theisen D. Side-to-side asymmetries in landing mechanics from a drop vertical jump test are not related to asymmetries in knee joint laxity following anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2018;26(3):381-390.

31. Miura K, Ishibashi Y, Tsuda E, Fukuda A, Tsukada H, Toh S. Intraoperative comparison of knee laxity between anterior cruciate ligament-reconstructed knee and contralateral stable knee using navigation system. *Arthroscopy*. 2010;26(9):1203-1211.

32. Palmieri-Smith RM, Lepley NK. Quadriceps strength asymmetry after anterior cruciate ligament reconstruction alters knee joint biomechanics and functional performance at time of return to activity. *Am J Sports Med*. 2015;43(7):1662-1669.

33. Project TS. Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles. SENIAM guidelines. 2016. Accessed May 2020. http://www.seniam.org/.

34. Rangger C, Daniel DM, Stone ML, Kaufman K. Diagnosis of an ACL disruption with KT-1000 arthrometer measurements. *Knee Surg Sports Traumatol Arthrosc*. 1993;1(1):60-66.

35. Renstrom P, Arms SW, Stanwyck TS, Johnson RJ, Pope MH. Strain within the anterior cruciate ligament during hamstring and quadriceps activity. *Am J Sports Med*. 1986;14(1):83-87.

36. Robertson G, Caldwell G, Hamil J, Kamen G, Whittlesey S. Research Methods in Biomechanics. 2nd ed. Human Kinetics; 2013.

37. Rogowski I, Vigne G, Blache Y, et al. Does the graft used for ACL reconstruction affect the knee flexion moment in their operated leg, whereas non-copers limited their knee flexion moment to reduce ATTD.

38. Rongger C, Daniel DM, Stone ML, Kaufman K. Diagnosis of an ACL disruption with KT-1000 arthrometer measurements. *Knee Surg Sports Traumatol Arthrosc*. 1993;1(1):60-66.

39. Shelburne KB, Torry MR, Pandy MG. Effect of muscle compensation on knee instability during ACL-deficient gait. *Med Sci Sports Exerc*. 2005;37(4):642-648.

40. Steiner ME, Brown C, Zarins B, Brownstein B, Koval PS, Stone P. Measurement of anterior-posterior displacement of the knee: a comparison of the results with instrumented devices and with clinical examination. *J Bone Joint Surg Am*. 1990;72(9):1307-1315.
APPENDIX

Questionnaire About Sports Participation (Translated From Dutch)

Date of measurement: _______________________   Birthdate: ______________________________
Male/female: ________________________________   Dominant leg (soccer): ___________________

Have you (had) any other injuries to one of your legs?   Yes/no
If you answered yes to the previous question, what kind of injury did you have and how long ago?

What sport(s) did you practice before you tore your anterior cruciate ligament?

At what level did you practice the sport(s)? (recreational, competition, regional, national, international)

Did you participate in same sport(s) after your anterior cruciate ligament reconstruction? Yes/no
If so, at what level? _________________________
If not, do you plan to resume same sport(s)? Why not? _____________________________

If you have not returned to sports after anterior cruciate ligament reconstruction, what was the reason for this? (pain, unstable, anxiety, other interests, etc)

Are you anxious about performing certain actions because of your knee? Yes/no
If so, what actions?