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Dynamic and static tibial translation in patients with anterior cruciate ligament deficiency initially treated with a structured rehabilitation protocol

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Abstract

Purpose: To compare dynamic and static tibial translation, in patients with anterior cruciate ligament deficiency, at 2 to 5 year follow-up, with the tibial translation after 4 months of rehabilitation initiated early after the injury. Secondary, to compare tibial translation in the injured knee and non-injured knee, and explore correlations between dynamic and static tibial translation.

Methods: Twelve patients with ACL rupture were assessed at 3 to 8 weeks after ACL injury, after 4 months of structured rehabilitation, and 2 to 5 years after ACL injury. Sagittal tibial translation was measured during the Lachman test (static translation) and during gait (dynamic translation) using a CA-4000 electrogoniometer.

Results: 2 to 5 years after ACL injury, static tibial translation was increased bilateral, whereas the dynamic tibial translation was unchanged. Tibial translation was greater in the injured knee compared to the non-injured knee (Lachman test 134 ± 9.1 mm vs. 7.0 ± 1.7 mm, $P = 0.001$, gait 5.6 ± 2.1 mm vs. 4.7 ± 1.8 mm, $P = 0.011$). There were no correlations between dynamic and static tibial translation.

Conclusion: Dynamic tibial translation was unchanged in spite of increased static tibial translation in the ACL deficient knee at 2 to 5 year follow-up compared to directly after rehabilitation. Dynamic tibial translation did not correlate to the static tibial translation. A more normal gait kinematics may be maintained from completion of a rehabilitation program to mid-term follow-up in patients with ACL deficiency treated with rehabilitation only.

Level of evidence: Level IV.

Keywords: ACL, knee laxity, knee kinematics, functional joint stability

INTRODUCTION

The treatment options after anterior cruciate ligament (ACL) injury are structured rehabilitation alone or structured rehabilitation in combination with ACL reconstruction [9,26,28]. It has been advocated that rehabilitation alone can be the primary treatment after ACL injury for many patients [10] and good knee function is reported after non-operative treatment [9,28]. However, the activity level and participation in sports is often reduced [10,28] and the increased risk for osteoarthritis after an ACL injury may lead to impaired knee function in the long term [10,22,23]. Abnormal knee joint biomechanics, in terms of altered kinematics and neuromuscular control [2,6,11,12], have been reported following ACL injury. These changes likely significantly contribute to the development of knee osteoarthritis [3,6,8,14,22,24,29,31]. Increased knowledge of the change of the knee joint kinematics over time is essential. In patients with ACL reconstruction, it has been shown that neither static nor dynamic tibial translation were changed at 5 year follow-up compared to early after surgery [37]. Yet, in patients with ACL deficiency treated with structured rehabilitation, the course in tibial translation over time is unknown.

Individuals with ACL deficiency cope with their knee instability differently, and well-functioning and poor-functioning patients adopt different movement patterns [1,17,33]. A stabilization strategy, characterized by stiffening of the knee joint, has been described among patients who do not cope well with their ACL injury [21,33]. A similar strategy has also been observed in patients early after an ACL injury [35], and in patients with ACL deficiency scheduled for ACL reconstruction [36]. This movement strategy, while reducing dynamic tibial translation, may contribute to excessive joint contact forces [33] and this could increase the risk for osteoarthritis in the long term [3,6]. Though, rehabilitation may normalize the movement pattern [35,43].

It is previously reported that patients early after an ACL injury, who had not completed rehabilitation, used an altered dynamic stabilization strategy. However, in contrast, in those who had completed rehabilitation, the movement pattern was closer to normal [35]. Currently it is unclear whether there is a change of dynamic tibial translation over time after ACL injury. The hypothesis though was that the almost normalized movement pattern gained after the initial structured rehabilitation program would be maintained at a longer follow-up. Better understanding of the change in tibial translation over time in patients with ACL deficiency can contribute to choosing treatment strategy, developing successful rehabilitation programs and reducing the risk of knee osteoarthritis. Therefore, the purpose of the present study was to analyze the knee joint kinematics of patients who had completed structured rehabilitation, at 2 to 5 years after ACL injury. The primary aim was to compare dynamic and static tibial translation measured at 2 to 5 year follow-up with tibial translation measured after 4 months of rehabilitation. The secondary aim was to compare tibial translation between the injured and non-injured knees at the 2 to 5 year follow-up; and explore correlations between dynamic and static tibial translation.

MATERIALS AND METHODS

Patients with ACL rupture were assessed at a median 6 weeks after injury, immediately following 4 months of structured rehabilitation and at a median 4 years (range 2 - 5 years) after the injury. In the current study, data are presented from the three assessments, and comparisons made between data collected directly after rehabilitation and at final follow-up. All patients gave written informed consent prior to their participation.

Patients

Participants in the current study had participated in a randomized controlled trial evaluating rehabilitation programs after ACL injury [35]. In the original study participants were recruited from patients attending the orthopedic department after knee trauma. Patients were informed about the study and were asked to participate if they were 15-45 years old and had a unilateral anterior cruciate ligament rupture that was no more than 14 weeks old. Patients were excluded if they had additional injury or previous surgery to the lower extremities, with the exception of partial meniscal injury or minor collateral ligament injury in the injured knee joint or partial meniscectomy in the injured or contralateral knee. All ACL injuries were verified by arthroscopy or magnetic resonance imaging [35]. Forty-two patients completed rehabilitation in the original study [35] and twelve patients were included in the current study (Figure 1). Six participants had an isolated ACL rupture and 6 had an ACL rupture combined with partial meniscectomy.

All patients completed a physical therapist-supervised rehabilitation program, of 4-months duration, directly after the initial evaluation. The rehabilitation program consisted of exercises aiming to improve neuromuscular control, muscle strength and coordination, and functional stability [35].

Excluded patients and drop out analysis

There were no differences in static or dynamic tibial translation, muscle function or objective- or patient-reported knee function between those who participated in the current study and those who did not participate. Compared to those who subsequently underwent ACL reconstruction, participants in the current study were older and had lower mean activity level before injury and more patients returned to their pre-injury activity and activity level.

Moreover, they estimated better effect of the rehabilitation. Characteristics of the included and excluded patients are presented in Table 1.

Assessments

The same assessments were performed at the evaluation completed directly after 4 months of rehabilitation and at the 2 – 5 year follow-up.

Clinical measurements

All testing was performed bilaterally and barefoot. The test procedure lasted approximately 90 minutes. The legs were tested in a randomized order at the assessment in the original study and in the same order in the present study. Two investigators (S.T, J.K.) performed the measurements of tibial translation. All the data were coded during analysis.

Sagittal tibial translation: Sagittal tibial translation was measured during the instrumented Lachman test (static translation) and during gait (dynamic translation), using a computerized goniometer linkage, CA-4000 (OSI Inc., Hayward, CA) [20]. The instrumented Lachman test was performed with the participant strapped to a special seat with the knee flexed to approximately 20°. Tibial translation was measured by pushing and pulling the proximal tibia in a postero-anterior fashion, with a controlled force using a force handle. The total translation at 90 N and 134 N in the sagittal plane is presented as a mean value from 3 repetitions. During gait testing, participants were instructed to walk as normally as possible at a self-chosen speed. Data from a Kistler force plate were used to identify the stance phase. Maximal anterior translation and knee flexion angle during this phase, recorded with the CA-4000, were analyzed (Figure 2).

Data acquisition: The mechanical accuracy of the CA-4000 electrogoniometer is ± 0.7 mm within the normally used sagittal measurement range.[39] The measurement system exhibits satisfactory reproducibility: the mean variation between 3 consecutive dynamic measurements (gait) is 0.03 ± 0.5 mm (95% CI: -0.6 to 0.2). The mean variation throughout a range of motion (a squat on 2 legs, 0° to 90° to 0°) on 2 different days, was 0.73 ± 0.41 mm (95% CI: -0.51 to 1.97) [19]. The system also has satisfactory validity throughout a range of motion when compared to fluoroscopy, as revealed during stair ascent in 10 patients with ACL deficiency and 10 control subjects [40]. The correlation between the electrogoniometric and fluoroscopic measurements was $r > 0.89$ when the patella was used as reference point and $r > 0.94$ when the femur was used as reference point in the fluoroscopic analysis [40].

The CA-4000 was zeroed at the beginning of each test with the participant positioned supine on the examination table, and the knee relaxed and fully extended. The alignment of the CA-4000 was checked repeatedly during the assessment. Dynamic anterior tibia translation was calculated by subtracting the tibial position recorded at each flexion angle during the passive extension, from the tibial position recorded at the same flexion angle during dynamic extension [20]. For the Lachman test, the total anterior-posterior translation in the sagittal plane was recorded. For each test, the maximal translation was derived from each repetition, and the mean of the 3 repetitions was calculated. Data were sampled from the potentiometers by a computer at a rate of 2000 Hz.

Isokinetic testing: Participants performed 3 repetitions of maximal isokinetic $60^\circ/\text{s}$ knee extension and flexion using a Biodex machine (Biodex Medical Systems Inc., Ronkonkoma, NY). Peak torque during the flexion and extension phases was derived from the maximum

torque for any of the 3 repetitions. Before recording, some submaximal familiarization repetitions were performed.

Jump tests: *Unilateral vertical jump:* Patients were assessed for their ability to perform a unilateral vertical jump with hands free to move. Each patient stood on 1 leg on a Kistler force plate (Kistler, Switzerland) and performed 1 jump as high as possible, landing on the same foot. The time from takeoff to landing was determined.

Unilateral horizontal jump: Each patient performed a unilateral horizontal jump for distance (cm) with hands kept behind the back to prevent their use in generating momentum.

Side jump: The side jump test was performed with the subjects standing on the test leg, keeping their hands behind their back. They jumped from side to side between two parallel strips of tape, placed 40 cm apart on the floor. Participants were instructed to jump as many times as possible in a 30-second period. The total number of jumps completed was counted; a jump was not counted if the foot touched any of the lines. The number of correct jumps was analysed [13]. The side jump test was only evaluated at the 2 – 5 year follow-up.

For calculation of muscle strength and jump performance, limb symmetry index (LSI; injured leg divided by uninjured leg and multiplied by 100) was used.

Questionnaires evaluating patient reported knee function and activity level

The Lysholm score [38] and the Knee Injury and Osteoarthritis Outcome Score (KOOS) [32] were used to evaluate patient-reported knee function. The Tegner score [38] was used to determine physical activity level. At the 2-5 year follow-up, the ACL Quality of Life questionnaire (ACL QoL) [27] was also completed.

Ethical approval was granted by the Ethical Review Board at Linköping University (Dnr 02-374).

Statistical analysis

Analyses were performed using IBM SPSS Statistics version 21 (SPSS Inc., Chicago, IL, USA). A significance level of $P < 0.05$ was used for all variables. A priori sample-size calculation showed that 10 participants would be required to detect a 1.5-mm difference in translation as significant ($\alpha = 0.05$, $\beta = 0.20$). A paired samples t -test was used to compare tibial translation between legs and tibial translation, patient-reported knee function, muscle strength, and jump performance between assessment sessions. Pearson correlation was used to calculate correlations between dynamic and static tibial translation.

RESULTS

Patient-reported knee function, muscle strength, and jump performance after 4 months of rehabilitation and at the 2-5 year follow-up are reported in Table 2.

In both the injured and the non-injured knees, the total static tibial translation during Lachman test increased from the assessment immediately after rehabilitation to 2-5 year follow-up (Table 3). The mean increase in the injured knee was 0.9 ± 1.5 mm at Lachman test 90 N and 1.2 ± 2.0 mm at 134N ($P < 0.05$). The mean increase in the non-injured knee was 0.8 ± 1.2 mm at 90 N and 1.1 ± 1.4 mm at 134N ($P < 0.05$). The maximal anterior tibial translation measured during gait did not differ between assessments in either knee (Table 3 and Figure 3).

Total static tibial translation measured during the Lachman test at 90 N and 134 N, and maximal anterior tibial translation during gait was greater in the injured knee compared to the non-injured knee at the 2-5 year assessment (Table 3). The mean difference between legs was 1.7 ± 1.1 mm for the Lachman test at 90 N, 2.2 ± 1.5 mm at 134 N, and 1.0 ± 1.1 mm during gait ($P \leq 0.01$). There were no differences between the knees in maximum or minimum knee flexion angle during stance phase in gait (Table 3 and Figure 3).

There were no significant correlations between maximal anterior tibial translation and total static tibial translation in either knee after 4 months of rehabilitation or at the 2-5 year follow-up (Figure 4).

DISCUSSION

The main finding in the present study was that in the ACL-deficient knee, dynamic tibial translation was unchanged from the assessment directly after 4 months of rehabilitation to the 2-5 year follow-up. However, in contrast, static tibial translation increased. The same pattern, i.e. unchanged dynamic tibial translation despite of increased static tibial translation, was also found in the uninjured knee. We have previously reported that dynamic tibial translation increased after rehabilitation compared with before rehabilitation, in the ACL deficient knee [35]. The present study shows that this increased dynamic tibial translation persists at 2-5 years after the injury.

When assessed before rehabilitation, participants used a joint stiffening strategy to control knee movement, resulting in reduced peak knee extension angle during gait compared to the uninjured knee and increased hamstring activation. This altered neuromuscular control reduced the dynamic tibial translation. Directly after rehabilitation knee range of motion and

muscle activation was normalized, and dynamic tibial translation was increased [35]. The clinical interpretation of these results could be that a supervised rehabilitation program can normalize the knee joint movement pattern in patients with ACL deficiency, and this corrected movement pattern can be maintained over time. It has been advocated that rehabilitation alone, without ACL-reconstruction, can be the primary treatment option after ACL injury for many patients [10]. Therefore, increased knowledge of the change in knee joint kinematics over time in individuals with ACL deficiency, treated with structured rehabilitation, is of great importance. In addition, the dynamic tibial translation is an interesting factor to highlight since it has shown to be of importance for good function after ACL injury [17].

The finding that static tibial translation had increased in the ACL deficient knee joint 2-5 years after the injury could suggest that the secondary restraints in the injured knee joint may have been further strained during this follow-up period. With the loss of the primary restraint to anterior tibial translation [5], secondary restraints, such as the posterior joint capsule, the collateral ligaments, and the menisci [5,25], in the injured knee joint could be exposed to increased strain. It is possible that the knee joint has been exposed to excessive forces for example during demanding sporting activities. Whether the increased static tibial translation is harmful to the knee joint in the long term is unclear. In addition to the effect of the loss of the ACL, strained secondary restraints in the knee joint and increased static tibial translation may further impact on the knee joint kinematics. Altered kinematics after an ACL injury has been described as a risk factor for the development of knee osteoarthritis [3,6,8,14,22,24,29,31]. However, the fact that the dynamic tibial translation did not further increase with time after the ACL injury, in spite of the increased static tibial translation, suggests that participants were able to stabilize their ACL deficient knee joint during gait.

Hence, the unchanged dynamic tibial translation from after rehabilitation to follow-up is an essential finding, as it suggests that the kinematics were not further altered. Thus, neither should this risk factor for knee osteoarthritis be further increased.

The finding that static tibial translation in the uninjured knee was increased at final follow-up means that the static tibial translation had changed towards the amount of static tibial translation in the injured knee. This is in line with earlier research that has shown that the uninjured knee in individuals with ACL deficiency or ACL reconstruction adapts toward an ACL injured kinematic pattern and is not comparable to the knees of uninjured individuals [4,15,19,41]. Despite the fact that static tibial translation in the uninjured knee was increased at follow-up, yet, as expected, both static and dynamic tibial translation was greater in the injured knee compared to the uninjured knee. Thus, a unilateral ACL injury affects the kinematics in both knees, and that might contribute to the increased risk for a subsequent ACL injury.

Self-reported knee function and performance tests showed that the patients had maintained their knee function over time. Moreover, dynamic tibial translation was unchanged to final follow-up, despite increased static tibial translation. In addition, dynamic tibial translation did not correlate to static tibial translation at any of the assessments in the current study. These results are in line with previous work [18,37]. Dynamic tibial translation is a measure of the dynamic knee stability that depends on the integration of articular geometry, soft-tissue restraints, and the loads applied to the joint through weight bearing and muscle activation [42]. Dynamic tibial translation is likely important for the knee-related functional outcome [17]. On the contrary, static tibial translation has been found to correlate with knee function [7,16,30,34].

The present study had certain limitations. First, the study sample was small, including only 12 participants in the follow-up. However, sample size calculation estimated that 10 patients would be sufficient to detect a clinically significant difference in tibial translation. Second, only movements in the sagittal plane were assessed. Registrations of movements in all planes would have provided additional information on knee joint movement. While in the current study we assessed dynamic tibial translation during gait, it is also possible that participants may have impaired knee joint stability during more demanding sporting activities. Moreover, electromyographic registration was not performed at follow-up. Data on muscle activation would have added further information about the dynamic knee stability. The measurements were performed by two investigators. However, these investigators are both experienced with the measurement equipment and have been working extensively with this measurement together to ensure that the measurements were performed identically.

The clinical recommendation from this study is that a more normal gait kinematics may be maintained from completion of a rehabilitation program to mid-term follow-up in patients with ACL deficiency treated non surgically with a comprehensive rehabilitation supervised by a physiotherapist. A stiffening strategy, which leads to excessive joint compression, may be present in the acute phase after ACL injury. This movement pattern is probably disadvantageous in the long term for return to activity and sports and to avoid subsequent injuries and osteoarthritis. However, the movement pattern can be changed after structured rehabilitation and the corrected movement pattern can be maintained for years. The current study showed that for some patients with ACL deficiency a structured rehabilitation program can be used in order to maintain dynamic knee joint stability over time. Though, the optimal movement pattern for patients with ACL deficiency is unknown. Further research is needed to

evaluate the importance of dynamic knee stability in the long term and its relation to the development of knee osteoarthritis.

CONCLUSION

The dynamic tibial translation was unchanged in spite of increased static tibial translation in the ACL-deficient knee at 2-5 years follow-up compared to directly after 4 months of rehabilitation. Dynamic tibial translation did not correlate to the static tibial translation.

FIGURE LEGENDS

Figure 1 Patient flowchart.

Figure 2 Schematic presentation of the tibial translation and flexion angle during gait and the tibial translation during the Lachman test. A posterior directed force with the force handle is reported by negative values on the y-axis while an anterior directed force is reported by positive values on the y-axis.

Figure 3 Static tibial translation during the Lachman test and maximal anterior tibial translation during gait (mean values in box plots and ± 1 SD in error bars).

Figure 4. Correlations between static tibial translation during Lachman test 134N and maximal anterior tibial translation during gait at assessment immediately after 4 months of rehabilitation and at 2 to 5 year follow-up. Pearson correlations: at assessment after rehabilitation: injured knee $r = 0.48$ ($P = 0.117$), non-injured knee $r = 0.25$ ($P = 0.436$); at follow-up: injured knee $r = -0.34$ ($P = 0.287$), non-injured knee $r = 0.43$ ($P = 0.161$).

CONFLICT OF INTEREST STATEMENT

The authors declare that they do not have any financial or personal relationships with other people or organizations that could inappropriately influence (bias) this work.

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Table 1. Patient characteristics and drop out analysis.

Variable		Included in follow up n = 12	Excluded due to ACL rec n = 20	Excluded due to other reasons n = 10
Sex, male/female		9/3	11/9	4/6
Age at injury, years, median (range)		30 (16-41)	20 (15-36)	32 (17-44)
Injured leg, right/left		6/6	14/6	5/5
Tegner score, median (range)	before injury ^a	7 (4-9)	7 (4-10)	5 (4-9)
	after 4 months rehab	4 (4-5)	4 (4-7)	4 (4-7)
	at 2-5 year follow up	4 (3-7)		

^aRetrospective estimation at the assessment 6 weeks after the injury.

Table 2. Patient reported knee function, muscle strength, and jump performance^a. *P*-values for comparisons between the assessment after rehabilitation and the assessment at the 2 to 5 year follow up are displayed.

Variable/score		After rehabilitation ^b	Follow up ^c	<i>P</i> -value
Lysholm score		92 (58-100)	95 (66-100)	0.518
KOOS ^d ;	Pain	89 (50-100)	96 (72-100)	0.148
	Symptoms	81 (32-100)	90 (57-100)	0.133
	Function in Daily Living	97 (63-100)	100 (82-100)	0.124
	Function in Sport and Recreation	70 (15-95)	83 (35-100)	0.154
	Knee-related Quality of Life	47 (25-81)	63 (38-100)	0.095
ACL QoL ^e	Symptom		89 (66-98)	
	Work		84 (34-96)	
	Participation		32 (12-91)	
	Lifestyle		71 (34-96)	
	Social and Emotional		74 (41-98)	
Isokinetic quadriceps strength ^f		87±17	94±9	0.017
Isokinetic hamstring strength ^f		97±20	93±20	0.293
Unilateral vertical jump ^f		91±10	97±11	0.250
Unilateral horizontal jump for distance ^f		90±11	93±10	0.606
Unilateral side jump ^f			81±20	

^a Values are expressed as median (range) and mean ± standard deviation

^b Assessment directly after 4 months of rehabilitation

^c Assessment 2 to 5 years after the injury

^d Knee Injury and Osteoarthritis Outcome Score

Table 3. Static tibial translation during the Lachman test and maximal anterior tibial translation (mm) and knee flexion angle (degrees) during gait (mean $\pm$ standard deviation) in the injured and non-injured knee^a. *P*-values for comparisons between the assessment after rehabilitation and the assessment at the 2 to 5 year follow up are displayed.

	Before rehabilitation		After rehabilitation ^b		Follow up ^c		<i>P</i> -value ^{b-c}	<i>P</i> -value ^{b-c}	<i>P</i> -value
							Non- injured knee	Injured knee	Non- injured vs. injured knee at follow up ^c
Measurement	Non- injured knee	Injured knee	Non- injured knee	Injured knee	Non- injured knee	Injured knee			
Lachman 90N	5.1 $\pm$ 1.0	5.6 $\pm$ 1.7	5.0 $\pm$ 1.2	6.3 $\pm$ 1.4	5.7 $\pm$ 1.7	7.3 $\pm$ 1.2	0.049	0.038	0.001
Lachman 134N	6.1 $\pm$ 1.2	7.0 $\pm$ 2.0	5.9 $\pm$ 1.6	7.5 $\pm$ 1.4	7.0 $\pm$ 1.7	9.1 $\pm$ 1.0	0.020	0.043	0.001
Gait translation	4.6 $\pm$ 1.7	4.6 $\pm$ 1.2	4.4 $\pm$ 1.6	5.3 $\pm$ 1.7	4.7 $\pm$ 1.8	5.6 $\pm$ 2.1	n.s.	n.s.	0.011
Gait max flexion ^d	38 $\pm$ 8	35 $\pm$ 10	39 $\pm$ 5	39 $\pm$ 5	31 $\pm$ 10	33 $\pm$ 6	0.004	0.030	n.s.
Gait min flexion ^e	-1 $\pm$ 6	6 $\pm$ 4	0 $\pm$ 5	3 $\pm$ 4	-1 $\pm$ 9	-1 $\pm$ 6	n.s.	n.s.	n.s.

^a Values are mean $\pm$ standard deviation; translation is reported in millimetres and flexion angle in degrees.

^b Assessment directly after 4 months of rehabilitation

^c Assessment 2 to 5 years after the injury

^d Max flexion= maximum knee flexion during stance phase

^e Min flexion = minimum knee flexion during stance phase

^c ACL Quality of Life questionnaire (response format VAS 1-100)

^f Performance of the ACL-deficient leg expressed as a percentage of the performance of the uninjured leg

Figure 1

Figure 2

Figure 3

Tibial translation

Figure 4