Rehabilitation after anterior cruciate ligament injury influence joint loading during walking but not hopping

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ABSTRACT
Objective: The purposes of this study was to identify changes in clinical outcome and lower extremity biomechanics during walking and hopping in ACL injured subjects before and after a 20 session neuromuscular and strength training program.
Study design: Pre- and post experimental design.
Setting: Out-patient clinic, primary care.
Patients: Thirty-two subjects with unilateral ACL injury, mean 60 days (±35 days) after injury, with a mean age of 26.2 (±5.4) years.
Intervention: The rehabilitation program consisted of neuromuscular and strength exercises.
Main Outcome Measurements: Outcome measurements assessed before and after a 20 session rehabilitation program were; self-assessment questionnaires (KOS-ADL, IKDC2000, Global function), four single leg hop tests, and isokinetic muscle strength tests. Lower extremity kinematics and kinetics were captured during the stance phase of gait and landing after a single leg hop, synchronized with three force plates.
Results: These ACL injured individuals significantly improved their clinical outcome after rehabilitation. Gait analysis disclosed a significantly improved knee extension moment after rehabilitation, but no change in hip or knee excursions. During landing after hop no change in knee excursion or knee moment were recorded.
Conclusion: After rehabilitation the ACL injured subjects showed a significantly improved clinical outcome, but lower extremity biomechanics were still significantly impaired during both walking and hopping. The rehabilitation program influenced knee joint loading during walking, but not during hopping. Longer rehabilitation should be considered before ACL injured individuals return to jumping activities.

INTRODUCTION

Anterior cruciate ligament injury affects lower extremity function and in particular dynamic stability during activities of daily living and sport activities.[1-5] Clinical outcomes improve following rehabilitation after ACL injury. [6] Some lower extremity movement patterns and muscle activation patterns change after injury and after rehabilitation.[7, 8] Knee excursions and knee joint loading are reduced during the stance phase of gait in the ACL injured knee compared to the uninjured knee, and compared to control subjects.[9, 10]

The ultimate goal for rehabilitation after ACL injury is to restore the patients' dynamic knee stability and to enable them to return to their desired activity levels. Strength training and neuromuscular training programs are used in clinical practice to enhance muscle strength and dynamic stability during activities by inducing compensatory biomechanical and neuromuscular responses.[11, 12] In recent years, the re-establishment of neuromuscular control of the lower extremity has been recognized as one of the key factors to restore dynamic joint stability and knee function. Still there is lack of evidence on why and how these rehabilitation techniques affect lower extremity biomechanics and neuromuscular function.

Several studies have examined changes in lower extremity biomechanics before and after neuromuscular exercise programs, but only in healthy athletes.[13-15] Very few studies have examined changes in lower extremity biomechanics after ACL injury and rehabilitation[16], and changes in lower extremity biomechanics and muscle activation patterns have only been examined during gait. However, most ACL injured subjects aim at returning to activities more strenuous than walking, and studies examining movement patterns during more strenuous activities are lacking.[17, 18] Studies examining changes in lower extremity biomechanics and neuromuscular function are sparse[19]. To our knowledge no studies have examined changes in lower extremity biomechanics during hop in ACL injured subjects after a neuromuscular and strength training program.

Therefore, our goal was to identify clinical changes and changes in lower extremity biomechanics (hip, knee and ankle motion and moments) during walking and landing after a single leg hop before and after a 20 session neuromuscular and strength training program. First, we hypothesized that ACL injured subjects would improve their clinical outcome examined by self reported questionnaires, functional performance tests, and muscle strength after a 20 session rehabilitation program. Secondly, we hypothesized that the injured side in ACL injured subjects would have significantly reduced knee extension moment and significantly lower knee excursion during the stance phase of gait and during landing after a single leg hop than the uninjured side. Thirdly, we hypothesized that ACL injured subjects would have significantly more normalized knee excursion and knee extension moment during gait and during landing after a single leg hop after a 20 session neuromuscular and strength training program. Finally, we hypothesized that the total support moment would shift to the hip and ankle prior to rehabilitation and more normalized toward the knee after rehabilitation.

METHODS

Subjects

Thirty-two consecutive subjects referred to our institution between the age of 15 to 40 years were included if they had a verified ACL rupture by Lachman test, KT-1000 manual max test of more than 3 mm difference between knees[21, 22], MRI, and no more than 6 months since the

injury. They were included if they had meniscal injury that were asymptomatic at the time of inclusion. Criteria for inclusion and participation in the clinical examination and motion analysis testing were; resolved knee impairments, including full knee range of motion, no or subtle pain or joint effusion, and ability to hop on the injured limb. If subjects did not meet all criteria for the clinical examination (resolved impairments) they were enrolled in a rehabilitation program to address these impairments. Subjects were excluded if they had posterior cruciate ligament injury, fractures, meniscus injury that required repair, or major cartilage injury, or any injury to the other leg.
The investigation was approved the Regional Committee for Medical Research Ethics, and all patients signed informed consent form before participation.

Clinical outcome measurements

The functional outcome measurements consisted of four single leg hop tests (one leg hop, triple hop, cross-over hop, and 6 meter timed hop)[23-25], a self-report of knee function survey (KOS-ADLS)[26], a Global Rating of knee function, assessed by a visual analogue scale (VAS), and the IKDC2000.[27] The single leg hop index were calculated using the length of the best hop on the injured leg, divided by the best hop on the uninjured leg and multiplied by 100. The VAS from 0-100 was related to the patient's subjective evaluation of their knee function related to their preinjury activity level, with 100 being normal knee function.

Isokinetic muscle strength testing (Cybex 6000) was used to evaluate the quadriceps and hamstrings muscle performance[28-32] at 60°/sec. Total work was used as parameter and calculated as follows: (injured/ uninjured) x100.

Activity level was recorded using an activity scale from 0-100 categorized into four levels; level 1 being physical active 4-7 times per week, level 2 1-3 times per week, level 3 1-3 times per month, and level 4 no regularly physical activities.[33]

Motion Analysis - kinematics and kinetics

Kinematic data were collected using Qualisys pro-reflex (Qualisys Inc, Gotheburg, Sweden), with eight cameras at a sampling frequency of 240 Hz. Kinetic data were collected with three AMTI force plates embedded in the walkway. Force data were synchronized and collected at a rate of 960Hz (AMTI Model LG6).

Reflective passive anatomical markers defining the joint centers was placed over the medial and lateral malleolus, the medial and lateral femoral condyle, bilaterally over the greater trochanter, and bilaterally on the top iliac crest. Clusters of three markers attached to rigid thermoplastic shells were located at the sacrum, and bilaterally at the thigh and shank. Both feet were defined by two markers attached to the heel of the shoe and one marker at the 5th metatarsal head. After a standing calibration the anatomical markers were removed, and the dynamic trials were collected.

Subjects were instructed to walk along a 17m walkway in which three force plates were embedded. The subjects walked at their self-selected pace and practice trials was performed until the subjects walking speed was consistent and force platform contact could be achieved with only one foot (without targeting). Speed was measured by photoelectric beams located 3.06m apart, midway along the walkway and only trials in which speed did not vary by ±5% from the average speed were accepted.

For gait, eight to ten walking trials were averaged for each subject. Joint motions and internal moments data were normalized for each subject as from the initial contact, zero, to toe-off, 100%, for the stance phase of gait. Four events during gait were analyzed; initial contact (ic), peak knee flexion (pkf), peak knee extension (pke), and toe-off (to). For hopping, three trials were averaged for each subject. Two events for the landing phase were included for landing; ic and pkf. Joint motions and internal moments were normalized for each subject as from pkf to toe-off for the push-off phase, and from ic to pkf for the landing phase. Knee excursion was calculated as the difference between knee flexion angle at pkf and ic during the stance phase of gait, and the difference between knee flexion angle at ic and pkf at landing after hop. Similarly, hip excursion was calculated both during the stance phase of gait and during the landing phase after hop.

Data analysis

Kinematic and kinetic data were calculated with Visual 3D software (C- motion Inc, Crabbs Branch Way Rockville MD), a movement analysis program designed for the consolidation of 3D trajectories and of analog signals into kinematics and inverse dynamics report. Kinetic data were given as internal moments. Data were normalized to subjects bodyweight x height. Knee, hip and ankle moments are also given in percent of the total support moment for all three joints as described by Winter et al[20].

Rehabilitation program

The rehabilitation program consisted of balance exercises, dynamic knee stabilization exercises, jump exercises, and strength exercises. Each session lasted for 60 to 90 minutes and was performed 2-3 times per week. Jump exercises included drop-jump, side-hop, and crossover-hop. The strength exercises included hamstring-, quadriceps-, and calf exercises; one-legged leg press, eccentric leg press (two legs knee extension followed by one-legged eccentric knee flexion), squats, one-legged squats on balance mat, one-legged leg curls, nordic hamstring, one-legged toe-raises, and launch exercises. Patients were instructed to perform 3 series of 10 repetitions for all exercises. Resistance strength training was individualized, and load was increased when the individual was able to perform three extra repetitions at the third set of each exercise. Each subject was required to fill out weekly log sheets that document their compliance with the rehabilitation program. At least 18 of the 20 session exercise program had to be completed. The information in the weekly log sheets was reviewed by the physical therapist on a weekly basis.

Statistical analysis

Statistical analyses were performed using NCSS (Number Crunches Statistical System, NCSS, Kaysville, Utha, USA) For comparison between injured and uninjured side parametric statistics using paired t-test for comparisons between lower limbs were used when normality distribution were presumed. Similarly, were normality distribution was rejected Wilcoxon Rank-Sum Test for difference in medians were used. A probability level of $p<0.05$ was used.

RESULTS

The ACL injured patients were on average 26.2 years (±5.4 years), 9 females (28%) and 23 males (72%), with a mean time of 60 days (±35 days) since injury at the time of baseline examination (Table 1). The pre injury activity level[34] was all Level 1 and 2 the with a mean activity score of 92.4 (75-100) (Table 1). The KT-1000 knee arthrometer manual maximum test revealed an average difference in knee joint laxity between injured and uninjured side of 6.9mm (±3.3) (Table 1). Three individuals did not complete the rehabilitation program and post test; one due to illness, and two to not willing to complete the rehabilitation program or the post test. The isokinetic muscle strength tests were performed at another location, and another four did not perform the strength tests (n=25).

Table 1. Subject characteristics at baseline (n=32)

	Mean (SD)
Age (years)	26.2 (5.4)
Female/male (%)	28/72
Days since injury (days)	60 (35)
KT 1000 manual maximum test (mm difference between injured and uninjured knee)	6.9 (3.3)
Activity score pre injury (0-100)	92.4 (8.4)
Activity score pre rehab (0-100)	75.8 (3.2)

Clinical outcome

All clinical outcome measurements showed that the patients significantly improved their knee function from before to after the 20 session rehabilitation program (Table 2). The functional scores (IKDC2000, KOS-ADLS, Global function), the single leg hop tests (one leg hop test, triple hop test, cross over hop test, and the 6 meter timed hop test), and the knee extension and flexion muscle strength tests showed significant improvements from baseline to retest after the 20 session rehabilitation program ($p<0.01$).

TABLE 2. Functional scores, single leg hop tests, and isokinetic muscle strength tests; injured side in percent of uninjured side at baseline and after the rehabilitation program; mean (standard deviation).

	Baseline (n=32)	After rehabilitation (n=29)	p-value
Functional scores			
IKDC2000	64.5 (13.5)	79.7 (9.9)	<0.0001
KOS-ADLS	86.2 (12.3)	92.3 (7.3)	0.009
Global function (VAS)	54.6 (24.4)	77.6 (16.3)	0.0001
	85.6 (10.0)	94.1 (7.9)	<0.0001

Single leg hop tests			
One-leg hop (%)	85.6 (9.9)	94.1 (7.9)	<0.0001
Triple hop (%)	85.1 (10.6)	92.8 (7.2)	0.002
Cross over hop (%)	86.2 (9.6)	93.8 (7.4)	0.0001
6 meter timed hop (%)	90.5 (11.8)	96.5 (5.4)	0.011
Quadriceps muscle strength tests			
ETW60†	83.3 (12.3)	92.8 (15.0)	0.003
Hamstring muscle strength test:			
FTW60§	81.4 (14.0)	97.4 (14.1)	0.0001

†ETW60=Extension total work at 60 degrees per second

§FTW60=Flexion total work at 60 degrees per second

Kinematic and kinetic data for gait and hop

Baseline

There was a significantly reduced knee flexion excursion and a significantly increased hip flexion excursion from ic to pkf on the injured side compared to the uninjured side at baseline ($p<0.01$) (Table 3). Similarly, there was a significantly reduced knee flexion excursion during landing after hop on the injured as compared to the uninjured side ($p= 0.002$) (Table 4).

There was a significantly lower knee extension moment at pkf on the injured compared to the uninjured side during walking ($p=0.01$) (Table 3), and even more evident during landing after hop ($p<0.001$)(Table 3 and 4). There were no significant differences between the injured and the uninjured side for the hip extension moment during walking, but during hopping the hip extension moment was higher at pkf during landing after hop on the injured side compared to the uninjured side ($p=0.067$). The plantar flexion moment in the ankle was significantly higher during landing after hop ($p=0.016$), but no other significant differences were found between the injured and the uninjured side (Table 3 and 4).

After rehabilitation

After rehabilitation there were still significantly lower knee flexion excursion and significantly higher hip flexion excursion on the injured compared to the uninjured side during walking, and still significantly reduced knee flexion excursion during landing after hop. Both the injured and the uninjured hip flexion angle at pkf significantly increased during landing after hop compared to baseline (Table 4). For the joint loading, there was no longer a significant reduced knee extension moment on the injured side compared to the uninjured side during gait. However, there were still significantly reduced knee extension moment on the injured compared to the uninjured side during landing after hop ($p=0.004$) and a significantly increased hip extension moment on the injured side compared to the uninjured side ($p=0.03$). The ankle plantar flexion moment on the injured side compared to the uninjured side had normalized compared to baseline.

TABLE 3. Hip, knee and ankle joints kinematics and kinetics during the stance phase of gait for the injured side versus the uninjured side at baseline and after rehabilitation. Support moment is total support moment as described by Winter et al[20] . Mean and (standard deviation).

Variables	Baseline (n=32)					After rehabilitation (n=29)				
	Injured (I)	*Support moment (I)*	*Uninjured (UI)*	*Support moment (UI)*	*p-value UI/I*	*Injured (I)*	*Support moment(I)*	*Uninjured (UI)*	*Support moment (UI)*	*p-value UI/I*
Knee flexion at pkf[†]	17.3 (4.1)		18.1 (5.2)		0.21	16.5 (4.4)		17.5 (4.4)		0.04
Knee excursion[§]	15.4 (3.9)		17.8 (3.6)		<0.0001	15.4 (3.8)		17.3 (3.3)		<0.0001
Hip flexion at pkf[†]	15.4 (8.6)		15.4 (10.0)		0.96	17.0 (5.3)		16.9 (5.3)		0.92
Hip excursion[§]	9.9 (2.6)		8.8 (2.3)		0.002	9.8 (2.6)		8.8 (2.9)		0.01
Hip moment[¥] at pkf[1]	0.40 (0.13)	56%	0.39 (0.17)	52%	0.73	0.40 (0.16)	56%	0.40 (0.16)	52%	0.83
Knee moment[¥] at pkf[1]	0.20 (0.15)	28%	0.27 (0.17)	36%	0.01	0.24 (0.14)	34%	0.27 (0.10)	35%	0.20
Ankle moment[¥] at pkf[1]	0.12 (0.12)	16%	0.09 (0.10)	12%	0.17	0.07 (0.08)	10%	0.10 (0.06)	13%	0.19

[†]pkf= peak knee flexion angle
[§]excursion= joint angle from initial contact (ic) to peak knee flexion (pkf) during the stance phase of gait
[¥]Nm/(body weight x height)

TABLE 4. Hip, knee, and ankle joints kinematics and kinetics during landing after hop at baseline and after rehabilitation for the injured side versus the uninjured side. Support moment is total support moment as described by Winter et al[20] . Mean and (standard deviation)

	Baseline (n=32)					After rehabilitation (n=29)				
Landing	*Injured (I)*	*Support moment (I)*	*Uninjured (UI)*	*Support moment (UI)*	*p-value UI/I*	*Injured (I)*	*Support moment (I)*	*Uninjured (UI)*	*Support moment (UI)*	*p-value UI/I*
Knee flexion at pkf†	52.4 (9.2)		54.4 (8.9)		0.26	53.7 (8.8)		56.4 (8.4)		0.12
Knee excursion§	39.8 (8.7)		43.4 (7.5)		0.002	39.8 (8.4)		43.6 (6.5)		0.02
Hip flexion at pkf†	45.7 (12.0)		46.3 (11.5)		0.71	50.9 (12.4)**		51.0 (11.2)**		0.93
Hip excursion§	9.9 (8.1)		12.0 (7.0)		0.14	12.0 (7.4)*		13.4 (6.5)		0.80
Hip moment¥ at pkf†	0.64 (0.37)	32%	0.53 (0.35)	26%	*0.067*	0.61 (0.41)	32%	0.50 (0.37)	26%	0.03
Knee moment¥ at pkf†	0.84 (0.30)	41%	1.10 (0.40)	54%	0.0003	0.92 (0.35)	47%	1.08 (0.36)	55%	0.004
Ankle moment¥at pkf†	0.56 (0.26)	27%	0.42 (0.22)	20%	0.016	0.42 (0.23)*	21%	0.38 (0.28)	19%	0.42

†pfk=peak knee flexion angle
§excursion= joint angle from initial contact (ic) to peak knee flexion (pkf)
¥Nm/(body weight x height)
*significant change from baseline to after rehabilitation on injured side, p<0.05
**significant change from baseline to after rehabilitation on injured side, p=<0.01

DISCUSSION

Our first hypothesis was confirmed for all variables as the ACL injured subjects significantly improved their clinical outcome after the 20 session rehabilitation program. Our second hypothesis was also confirmed as the knee excursion and the knee extension moment were significantly reduced on the injured compared to the uninjured side during both during the stance phase of gait and during landing after hop. During walking, the ACL injured subjects' significantly increased their hip excursion on the injured side compared to the uninjured side. During landing after hop no significantly increased hip excursion was seen on the injured side, and this was probably due to the larger variation in hip flexion excursion during landing (larger standard deviation for hop compared to walk). During walking the expected significantly reduced knee extension moment was present, but there were no other significant changes in hip or ankle moments. For landing after hop, a much more complex movement pattern emerged. The significantly reduced knee extension moment on the injured side was compensated by an increased hip extension moment and a significantly increased plantar flexion moment. This indicated a hip-ankle strategy to compensate for the significantly lower knee extension moment during landing after hop. None of these mechanisms were evident during the less strenuous task gait. But despite the compensating strategy, these individuals' hop lengths were significantly lower in the injured compared to the uninjured side (Table 2). Our third hypothesis was only partly confirmed. There was still significantly less knee excursion and more hip excursion on the injured side compared to the uninjured side after rehabilitation during walking, and similarly there was still a significantly less knee excursion during landing after hop. Hip flexion angle at pkf during landing after hop was significantly increased on both the injured and uninjured side after the rehabilitation program. Furthermore, the knee extension moment during walking was normalized after rehabilitation as hypothesized, but this was not the case for the knee extension moment during landing after hop. The rehabilitation program seemed to have affected the less strenuous activity, walking, but not the more strenuous activity, hopping.

This is the first study to report changes in lower extremity biomechanics during landing after hop after a supervised rehabilitation program for ACL injured subjects. Our findings that the knee extension moment during the stance phase of gait was normalized after rehabilitation is supported by previous studies.[35] But the significantly reduced knee extension moment after rehabilitation during landing after hop in injured compared to uninjured knee, has not previously been reported. Despite highly significant clinical changes in these ACL injured individuals, common sports activity such as hopping showed that the dynamic stabilization strategies were not normalized. A much more detailed picture of the changes in lower extremity kinematics and kinetics were revealed during landing after hopping compared to gait analysis. Most of these ACL injured subjects returned to sport activities including jumping and pivoting activities with these lower extremity dysfunctions (66%). The rehabilitation programs should be reconsidered both regarding duration and types of exercises, to enable ACL injured subjects to normalize joint loading during hopping before returning to sport activities including jumping and pivoting. Only 11 (34%) subjects went through surgery immediately after the end of the rehabilitation program.

The rehabilitation program significantly increased the quadriceps muscle strength thereby improving the ability to absorb the deceleration forces during landing after hop. Knee joint loading during landing is controlled by several factors; the ability of the ankle, knee and hip extensors to absorb the deceleration forces (impact forces), in addition to the excursions of the hip, knee, and ankle joints. Our data showed that the knee moment increased (however, not significantly) during landing after hop and that the total support moment distribution was higher at the knee (from 41% to 47%) and lower at the ankle, but still a significant reduced knee extension moment on the injured compared to the uninjured side during hopping after rehabilitation. As long as knee excursion did not change, these individuals still have a significant impairment that could affect the load on the cartilage during landing after hop, and thereby a possible degeneration of the knee joint over time. Furthermore, if the knee joint loading was not normalized after rehabilitation after an ACL injury, these individuals should probably not perform sport activities including hopping. Prolonged rehabilitation and exercise programs should probably be performed to see if these joint dysfunctions can be resolved. No studies have examined if reconstruction of the ACL with subsequent rehabilitation could resolve these biomechanical dysfunctions.

The question is whether these ACL injured subjects need prolonged rehabilitation, or are there other rehabilitation exercises that could affect lower extremity biomechanics better during strenuous activities (such as landing after hop). Perturbation exercises have previously shown to facilitate significant changes in lower extremity kinematics and muscle activation patterns.[36] Further elucidation of whether perturbation exercises or other exercises may influence lower extremity biomechanics need to be performed.

The future question would be if these movement patterns are compensating strategies that are necessary for the individuals to cope with their injury and that one should not expected them to normalize as long as the ACL is not intact, or if ACL injured individuals should aim at normalizing these movement patterns due to the fact that we think they are dysfunctions that could lead to joint degeneration.

We recognize the inherent limitations of the present study. First and foremost, the study was a non-randomized prospective study design. We do not know if the clinical changes and biomechanical changes observed were due to time since injury or due to the actual intervention (the rehabilitation program) or both. As this is the first study to identify significant changes in lower extremity during hopping after a standardized neuromuscular and strength training program these mechanisms need to be further studied, and randomized controlled trials should be carried out. Further limitations of this study could be the sample size, due to some border line significant differences. However, this study has a sample size that is larger than most other studies on ACL injured subjects examining lower extremity biomechanics. [18, 37] The only hop study that has identified differences in lower extremity biomechanics between the ACL injured and uninjured knee included 21 individuals[17].

In summary, this study is the first to identify changes in lower extremity biomechanics during landing after hop after a 20 session neuromuscular and strength training program. These ACL injured individuals significantly improved their clinical knee function. After the rehabilitation program, the lower extremity kinematics were more or less unchanged, the knee joint loading was normalized during walking but not during hopping. Both the duration of the rehabilitation programs and types of exercises should be reconsidered before ACL injured individuals return to sport activities including jumping activities since knee joint loading during landing after hop was still impaired.

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Conflict of Interest

Financial Disclosure and Conflict of Interest: I affirm that I have no financial affiliation or involvement with any commercial organization that has a direct financial interest in any matter including this manuscript (see author agreement and publication rights form).

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