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

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ABSTRACT

Objective: The purpose 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 programme.

Study design: Pre and post experimental design.

Setting: Outpatient clinic, primary care.

Patients: 32 subjects with unilateral ACL injury, mean 60 (SD 35) days after injury, with a mean age of 26.2 (5.4) years.

Intervention: The rehabilitation programme consisted of neuromuscular and strength exercises.

Main outcome measurements: Outcome measurements assessed before and after a 20-session rehabilitation programme 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, synchronised 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 was 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 programme influenced knee joint loading during walking, but not during hopping. Longer rehabilitation should be considered before ACL-injured individuals return to jumping activities.

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 with the uninjured knee, and compared with control subjects.[2 9]

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 programmes are used in clinical practice to enhance muscle strength and dynamic stability during activities by inducing compensatory biomechanical and neuromuscular responses.[10 11] In recent years, the re-establishment of neuromuscular control of the lower extremity has been recognised 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 programmes, but only in healthy athletes.[12–14] Very few studies have examined changes in lower extremity biomechanics after ACL injury and rehabilitation,[7] 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.[15 16] Studies examining changes in lower extremity biomechanics and neuromuscular function are sparse.[7] To our knowledge no studies have examined changes in lower extremity biomechanics during hop in ACL-injured subjects after a neuromuscular and strength training programme.

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 programme. First, we hypothesised 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 programme. Secondly, we hypothesised 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 hypothesised that ACL-injured subjects would have significantly more normalised knee excursion and knee extension moment during gait and during landing after a single-leg hop after a 20-session neuromuscular and strength training programme. Finally, we hypothesised that the total support moment would shift to the hip and ankle prior to rehabilitation and be more normalised toward the knee after rehabilitation.

METHODS

Subjects

Thirty-two consecutive subjects referred to our institution between the ages of 15 and 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,[17 18] MRI, and no more than 6 months since the injury. They were included if they had meniscal injury that was 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 programme to address these impairments. Subjects were excluded if they had posterior cruciate ligament injury, fractures, meniscus injury that required repair, major cartilage injury, or any injury to the other leg.

The investigation was approved by the Regional Committee for Medical Research Ethics, and all patients signed an 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 metre timed hop),[19–21] a self-report of knee function survey (KOS-ADLS),[22] a Global Rating of knee function, assessed by a visual analogue scale (VAS), and the IKDC2000.[23] The single-leg hop index was 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 knee function related to the 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[24–28] at 60°/sec. Total work was used as parameter and calculated as follows: (injured/uninjured) ×100.

Activity level was recorded using an activity scale from 0–100 categorised into four levels: level 1 being physically active 4–7 times per week, level 2 1–3 times per week, level 3 1–3 times per month, and level 4 no regular physical activities.[29]

Motion analysis — kinematics and kinetics

Kinematic data were collected using Qualisys pro-reflex (Qualisys Inc, Gothenburg, 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 synchronised and collected at a rate of 960 Hz (AMTI Model LG6).

Reflective passive anatomical markers defining the joint centres were 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 fifth metatarsal head. After a standing calibration the anatomical markers were removed, and the dynamic trials were collected.

Subjects were instructed to walk along a 17 m walkway in which three force plates were embedded. The subjects walked at their self-selected pace and practice trials were 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 3.06 m apart, midway along the walkway, and only trials in which speed did not vary by ±5% from the average speed were accepted.

Table 1 Subject characteristics at baseline (n = 32)

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

For gait, eight to ten walking trials were averaged for each subject. Joint motions and internal moments data were normalised for each subject as from the initial contact, zero, to toe-off, 100%, for the stance phase of gait. Four events during gait were analysed: 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 normalised 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 analogue signals into kinematics and inverse dynamics report. Kinetic data were given as internal moments. Data were normalised to subjects' bodyweight × height. Knee, hip and ankle moments are also given in per cent of the total support moment for all three joints as described by Winter *et al*.[30]

Table 2 Functional scores, single-leg hop tests, and isokinetic muscle strength tests; injured side as percentage of uninjured side at baseline and after the rehabilitation programme

	Baseline (n = 32)	After rehabilitation (n = 29)	p Value
Functional scores			
IKDC2000	64.5 (13.5)	79.7 (9.9)	<0.001
KOS-ADLS	86.2 (12.3)	92.3 (7.3)	0.009
Global function (VAS)	54.6 (24.4)	77.6 (16.3)	0.001
Single-leg hop tests			
One-leg hop (%)	85.6 (9.9)	94.1 (7.9)	<0.001
Triple hop (%)	85.1 (10.6)	92.8 (7.2)	0.002
Cross-over hop (%)	86.2 (9.6)	93.8 (7.4)	<0.001
6 metre timed hop (%)	90.5 (11.8)	96.5 (5.4)	0.011
Quadriceps muscle strength test			
ETW60*	83.3 (12.3)	92.8 (15.0)	0.003
Hamstring muscle strength test			
FTW60†	81.4 (14.0)	97.4 (14.1)	<0.001

*ETW60, extension total work at 60 degrees per second
†FTW60, flexion total work at 60 degrees per second
Values expressed as mean (SD)

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Rehabilitation programme

The rehabilitation programme consisted of balance exercises, dynamic knee stabilisation 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 cross-over 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 three series of 10 repetitions for all exercises. Resistance strength training was individualised, 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 documented compliance with the rehabilitation programme. At least 18 of the 20 sessions in the exercise programme 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 sides, parametric statistics using paired t test for comparisons between lower limbs were used when a normal distribution was assumed. Similarly, where a normal distribution was rejected, Wilcoxon rank-sum test for difference in medians was used. A probability level of $p<0.05$ was used.

RESULTS

The ACL-injured patients were on average 26.2 (SD 5.4) years old, nine women (28%) and 23 men (72%), with a mean time of 60 (35) days since injury at the time of baseline examination (table 1). The preinjury activity level[29] was all Level 1 and 2, 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 sides of 6.9 (SD 3.3) mm (table 1). Three individuals did not complete the rehabilitation programme and post test; one was ill, and two were 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).

Clinical outcome

All clinical outcome measurements showed that the patients significantly improved their knee function from before to after the 20-session rehabilitation programme (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 metre timed hop test), and the knee extension and flexion muscle strength tests showed significant improvements from baseline to retest after the 20-session rehabilitation programme ($p<0.01$).

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 with 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 with the uninjured side ($p = 0.002$) (table 4).

There was a significantly lower knee extension moment at pkf on the injured side than on the uninjured side during walking ($p = 0.01$) (table 3), and this was even more evident during landing after hop ($p<0.001$) (tables 3 and 4). There were no significant differences between the injured and the uninjured sides 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 than on 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 sides (tables 3 and 4).

After rehabilitation

After rehabilitation there were still significantly lower knee flexion excursion and significantly higher hip flexion excursion on the injured than on the uninjured side during walking, and still significantly reduced knee flexion excursion during landing after hop. Both the injured and the uninjured hip flexion angles at pkf significantly increased during landing after hop compared with baseline (table 4). For the joint loading, there was no longer a significantly reduced knee extension moment on the injured side compared with the uninjured side during gait. However, there was still significantly reduced knee extension moment on the injured compared with the uninjured side during landing after hop ($p = 0.004$) and a significantly increased hip extension moment on the injured side compared

Table 3 Hip, knee and ankle joint kinematics and kinetics during the stance phase of gait for the injured side versus the uninjured side at baseline and after rehabilitation

	Baseline (n = 32)					After rehabilitation (n = 29)				
Variables	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)		<0.001	15.4 (3.8)		17.3 (3.3)		<0.001
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*	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*	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*	0.12 (0.12)	16%	0.09 (0.10)	12%	0.17	0.07 (0.08)	10%	0.10 (0.06)	13%	0.19

Support moment is total support moment as described by Winter *et al*.[30] Values expressed as mean (SD)
*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 × height)

Table 4 Hip, knee, and ankle joint kinematics and kinetics during landing after hop at baseline and after rehabilitation for the injured side versus the uninjured side

	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

Support moment is total support moment as described by Winter *et al*.[30] Mean SD.
*significant change from baseline to after rehabilitation on injured side, $p<0.05$
**significant change from baseline to after rehabilitation on injured side, $p<0.01$
†pkf, peak knee flexion angle
‡excursion = joint angle from initial contact (ic) to peak knee flexion (pkf)
§Nm/(body weight × height)

with the uninjured side ($p = 0.03$). The ankle plantar flexion moment on the injured side compared with the uninjured side had normalised compared with baseline.

DISCUSSION

Our first hypothesis was confirmed for all variables, as the ACL-injured subjects significantly improved their clinical outcome after the 20-session rehabilitation programme. Our second hypothesis was also confirmed, as the knee excursion and the knee extension moment were significantly reduced on the injured compared with the uninjured side 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 with 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 than for 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 than in 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 than on the uninjured side after rehabilitation during walking, and similarly there was still 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 sides after the rehabilitation programme. Furthermore, the knee extension moment during walking was normalised after rehabilitation as hypothesised, but this was not the case for the knee extension moment during landing after hop. The rehabilitation programme 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 programme for ACL-injured subjects. Our finding that the knee extension moment during the stance phase of gait was normalised after rehabilitation is supported by previous studies.[2] But the significantly reduced knee extension moment after rehabilitation during landing after hop in injured compared with uninjured knee has not previously been reported. Despite highly significant clinical changes in these ACL-injured individuals, a common sports activity such as hopping showed that the dynamic stabilisation strategies were not normalised. A much more detailed picture of the changes in lower extremity kinematics and kinetics were revealed during landing after hopping than by 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 programmes should be reconsidered regarding both duration and types of exercises, to enable ACL-injured subjects to normalise 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 programme.

The rehabilitation programme 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 there was still a significantly reduced knee extension moment on the injured than on 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 normalised after rehabilitation after an ACL injury, these individuals should probably not perform sport activities including hopping. Prolonged rehabilitation and exercise programmes should probably be performed to see whether these joint dysfunctions can be resolved. No studies have examined whether reconstruction of the ACL with subsequent rehabilitation could resolve these biomechanical dysfunctions.

The question is whether these ACL-injured subjects need prolonged rehabilitation, or whether there are other rehabilitation exercises that could affect lower extremity biomechanics better during strenuous activities (such as landing after hop). Perturbation exercises have previously been shown to facilitate significant changes in lower extremity kinematics and muscle activation patterns.[7] Further elucidation of whether perturbation exercises or other exercises may influence lower extremity biomechanics needs to be performed.

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

We recognise the inherent limitations of the present study. First and foremost, the study was a non-randomised prospective study design. We do not know whether the clinical changes and biomechanical changes observed were due to time since injury or due to the actual intervention (the rehabilitation programme) or both. As this is the first study to identify significant changes in lower extremity during hopping after a standardised neuromuscular and strength training programme, these mechanisms need to be further studied, and randomised controlled trials should be carried out. A further limitation of this study could be the sample size, due to some borderline significant differences. However, this study has a sample size that is larger than most other studies on ACL-injured subjects examining lower extremity biomechanics.[7 16] The only hop study that has identified differences in lower extremity biomechanics between the ACL-injured and uninjured knee included 21 individuals.[16]

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 programme. These ACL-injured individuals significantly improved their clinical knee function. After the rehabilitation programme, the lower extremity kinematics were more or less unchanged and the knee joint loading was normalised during walking but not during hopping. Both the duration of the rehabilitation programmes and types of exercises should be reconsidered before ACL-injured individuals return to sporting activities including jumping activities, since knee joint loading during landing after hop was still impaired.

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