Symmetries in muscle torques and landing kinematics are associated with maintenance of sports participation at five to ten years after ACL reconstruction in young men

Abstract

Background: Long-term maintenance of sports participation is important for young adults men undergoing ACL reconstruction. Identifying biomechanical characteristics in patients who achieve this goal can assist in elaborating rehabilitation programs and in identifying successful recovery but this has rarely been investigated.

Purpose: To test the association between maintenance of sports participation at 5-to-10 years after ACL reconstruction and measures of force production and landing biomechanics in adult men.

Study Design: Case series. Level of evidence, 4

Methods: Thirty men with isolated ACL reconstruction were examined. At 5-to-10 year follow-up, associations were tested between reported outcomes of sports maintenance and objective biomechanical measures. The biomechanical tests included isokinetic knee torques and lower limb kinetics and kinematics during landing tasks. Measurements for each limb were conducted separately and side-to-side symmetry indices (SI) were calculated. Subgroups included SI higher than (+)10% (i.e. extreme positive), SI lower than (-)10% (i.e. extreme negative), and SI between -10% and +10% (i.e. symmetric).

Results: At follow-up, concentric knee torques in the operated limb correlated with Tegner and Marx scores (r =0.42 to 0.47, p <0.05). Regarding SI of knee torques, highest Tegner, Marx and KOOS scores were associated with symmetric as opposed to patients with extreme positive or extreme negative SI (p <0.05). As for landing kinematics, Tegner score negatively correlated with knee range of motion (ROM) in the operated limb (r =-0.38, p <0.05). With regard to SI, hip and knee ROM correlated with Tegner, IKDC and KOOS scores (r =0.41 to 0.51, p <0.05). Specifically, highest sports participation levels were associated with achieving symmetric hip and knee ROM but also with extreme positive SI as opposed to patients with extreme negative SI (*p* <0.03) indicating substantially higher ROM in the uninjured limb compared to the operated limb.

Conclusion: At 5-to-10 years after ACL reconstruction, maintenance of sports participation is associated with symmetric side-to-side concentric knee torques and with producing greater attenuation of hip and knee ROM during drop jump landing in the operated limb. Therefore, eccentric load programs which can improve attenuation phase kinematics during landing tasks may be valuable in addition to concentric training and facilitate enhanced long-term outcomes.

Keywords: ACL reconstruction; drop jump test; single-legged landing test; isokinetic strength test; sports participation

What is known about the subject: Previous-researchers have demonstrated the value of identifying asymmetries in hip and knee kinematics during the early phases of rehabilitation after ACL reconstruction. Symmetry indices of knee extensors and flexors torques were also suggested fundamental to guide decision-making during the first and second years after surgery. Focusing on the first two years after surgery is not surprising since return to sports is the primary goal of surgery and therefore the primary interest of many investigators. Less focus is applied in the literature to maintaining sports activities at more than 5 years after surgery. It is unclear whether and which asymmetries in lower limb biomechanics could be identified at this time frame and associated with achieving this target.

What this study adds to existing knowledge: The current study is unique in that it explores knee torques and lower limb biomechanics long after ACL reconstruction in a specific population of young adult men and identifies specific associations between lower limb biomechanical characteristics and level of maintenance of sports participation. The findings provided can potentially assist in decision-making junctions long after surgery.

Introduction

Returning to sport with the ~~re~~establishment of normal knee biomechanics is the primary goal of anterior cruciate ligament (ACL) reconstruction surgery. Following that, maintenance of sports activities throughout the years becomes a second important target, particularly for those who undergo surgery at a relatively young age. This target is related to a multifactorial process involving complex neuromuscular recovery among other factors which evolve over the years [17]. One suggested strategy to improve decision making for young athletes throughout the early recovery and later during the sports maintenance process is by integrating subjective measures (i.e. patient reported outcome scales) with objective biomechanical measures that assess knee function [7]. Until today however, there has been limited evidence to support clear associations between objective measures of knee function in sports-related tasks and the achievement of returning to sports alongside long-term maintenance of sports activities [6]. Further information in this respect can therefore be valuable. In addition, noticeable limitations of study designs related to this subject can be appreciated. These include relying primarily on shorter than 2 years follow-up assessments which miss the time-frame of long-term maintenance of activities and on heterogeneous study populations of mixed graft sources and multiple age groups or combining both sexes for a reported outcome [8, 15, 21]. Because knee function after ACL reconstruction is affected by patient age [16, 18], duration of follow-up, graft source [32, 33, 37, 41], and sex [2, 8, 13, 19, 30, 37, 40], greater specificity of patient demographics and surgical procedure was recommended [21] and longer follow-up is required in order to evaluate function specifically during the maintenance phase after surgery. Furthermore, since ACL reconstruction is particularly justifiable in the young adult age group (i.e. 18-35 years) [36], 5-to-10 year follow-up could represent optimal time frame for assessing maintenance of sports activities beyond the short-term recovery. This is because longer follow-up may further subject the outcomes to changes in life style for other reasons than the knee injury or to potential progression of other health-related problems which may confound the interpretation of maintenance of sports activities in relation to the knee recovery [23, 29, 39]. The purpose of the current study was therefore to test the association between maintenance of sports participation at 5-to-10 years after ACL reconstruction and measures of force production and landing mechanics in young adult men. Based on a meta-analysis that showed altered lower limb kinetics and kinematics at more than 3 years after ACL reconstruction [10], it was hypothesized that at more than 5 years after surgery biomechanical abnormalities through the ankle, knee, and hip joints, could still be identified and that specific associations between objective biomechanical measures and measures of maintaining sports activities could be determined.

Materials and Methods

Patients who underwent autologous quadrupled Gracilis-Semitendinosus ACL reconstruction between 2004 and 2010 at a single arthroscopy unit were identified. The surgery was performed in all patients using similar principles of trans-tibial femoral tunnel drilling technique. Inclusion criteria for this study were: (1) male sex; (2) ACL tear which occurred during sport activity only; (3) age at surgery 18 to 35 years; (4) isolated ACL reconstruction without concomitant knee ligament reconstruction; and (5) 5-to-10 year follow-up. Exclusion criteria were: (1) contra-lateral ACL tear; (2) revision ACL reconstruction that was performed during the follow-up period or MRI-documented ACL graft tear with functional instability awaiting revision; and (3) other significant lower limb injury, surgery, or deformity which could affect lower limb function. In accordance with these criteria, 55 patients were eligible and available for latest clinical follow-up evaluations and their outcomes and outcomes-associated risk factors were published in a separate manuscript [12]. Of these 55 patients, 30 volunteered to participate in the current study which involved further tests in a biomechanical laboratory set-up. To assess maintenance of sports activities, Tegner [38] and Marx [24] scores were used to indicate level of activity, while the International Knee Documentation Committee (IKDC)-subjective score [3] and the Knee Osteoarthritis and Outcome Sub-scores (KOOS) [35] were used to indicate subjective knee function. Clinical evaluation of knee laxity was performed using side-to-side difference by KT-1000 knee arthrometer device (MEDmetric Corp, San Diego, CA) while the knee was in 25° flexion and under anteriorly-directed 30lbs of force. All KT-1000 measurements were performed by one independent investigator (***) that was not involved in the index surgery. Four objective tests to assess knee biomechanics were performed in a biomechanical laboratory by another independent investigator (***) which was not involved in the index surgery and was blinded to the KT-1000 measurements or the patient reported outcome scores. These included: (1) isokinetic strength tests of knee flexors and extensors, (2) single-legged landing test, (3) double-legged drop jump test, and (4) single-legged hop test for distance.

Biodex system 3 isokinetic dynamometer (Biodex Medical Systems Inc., Shirley, NY, USA) was used to measure knee flexors and extensors maximal torque and work at 180°/sec. The testing was performed in a seated position, with the hip at 110° flexion angle and the knee at 90° flexion angle as a comfortable starting position. The participant was secured to the chair by two straps across the chest and a single strap at the abdomen and distal thigh of the tested limb in order to minimize compensations. Knee range of motion (ROM) was set at 90^0 with 0^0 indicating full extension. Prior to testing, correction for gravity of the tested limb was performed, and several warm-up repetitions were completed. These included 3 sub-maximal repetitions and 2 maximal repetitions at 180°/sec. All participants started the test with the healthy uninjured knee tested before the operated knee. During the test, the participant was encouraged to perform 5 repetitions in maximal torque of knee flexion and extension at 180°/sec. Outcome measure of the test was peak flexors and extensors torque [N*m/Kg].

For the single-legged landing test and double-legged drop jump test the following biomechanical model was used for movement analysis: Twenty one photo-reflective markers were placed at anatomical landmarks on each lower extremity from foot to pelvis level. Location of markers was in accordance with standard plug-in gait protocol (User Manual, Vicon Motion Systems, Ltd., Oxford, UK). A Knee Alignment Device (KAD) was mounted on each knee at the beginning of each examination for the purpose of segments alignment setup at the neutral standing position during a static trial and was then removed prior to beginning the dynamic tests. In both tests the participant landed on a force plate (Kistler Group, Winterthur, Switzerland) sampled at 960 Hz. A six camera optical stereometric system (Vicon Motion Systems, Ltd.,Oxford, UK), sampling at 240 Hz, was used to track lower extremity motions. Data were sampled using NEXUS 1.7.1 program with Woltring filter for filling gaps and Butterworth fourth order filter with cut off frequency of 6 Hz built in the program, and reports were processed with Polygon 3.5.1 software (Vicon Motion Systems, Ltd., Oxford, UK).

The single-legged landing test was performed in accordance with previous investigation [5] as follows: The patient was standing on a 21-cm height step located 6-cm in front of the force plate. The subject's initial position was with both feet on the step facing the force plate. Subjects were instructed to place the hands on the waist. The subject stepped forward with the test leg, and dropped from the step, landing on the force plate on the test leg only. Participants were instructed to stabilize as quickly as possible. After the landing, the subject remained on the force plate for three seconds at the described position. The performance was disqualified and performed again if the opposite leg also touched the ground. Between the performances the patient rested 30 seconds. This test was performed 3 times for each leg. The following measures were extracted from this test: (1) Time to stability [seconds]; and (2) Peak vertical ground reaction forces (GRF)/BW [N/Kg]. The beginning of the landing phase was defined as the time that the force platform signal reached 20N. The moment of stability was defined in accordance with previous investigators [5] as the time from which the moving average signal did not exceed 25% of the average of standard deviation of the whole series mean. Results are reported based on the average of the three trials.

The drop jump test was performed in accordance with previous investigations [25, 31] as follows: The patient was standing on a 21-cm height step located 6-cm in front of the force plate. The subject's initial position was with both feet on the step facing the force plate. Subjects were instructed to place the hands on the waist. The patient dropped off the box, landed with each foot onto a separate force platform and immediately executed a maximal effort vertical jump. The eccentric phase of the drop landing was defined as the duration from time that the force platform signal reached 20N to the lowest vertical height of the line connecting the right and left anterior superior iliac spine markers. The following measures were extracted for each limb during the eccentric phase of the drop jump test: (1) Peak support moment [42], computed as the momentary highest summation of sagittal torques of hip extension, knee extension, and ankle plantar flexion [N*m/Kg]; and (2) ROM in the sagittal plane at the ankle, knee and hip joints [°]. ROM was defined as the difference between maximal flexion and maximal extension during the eccentric phase. Total ROM of the lower limb during the eccentric phase of the drop jump was computed as the summation of the ankle, knee and hip ROMs. Results are reported as average of all trials.

The Single-legged hop test for distance was performed with take-off and landing on the same limb as described [28]. The distance was measured bilaterally. The longest hop of three trials was selected for analysis.

The symmetry index (SI) for all biomechanical measures was calculated in accordance with accepted formula used to indicate asymmetries between the limbs in different variables of gait [34] as follows: $SI[\%] = 2*(Xn-Xi)/(Xn+Xi)*100$, where "Xn" indicates the value of variable in the uninjured side, and "Xi" indicates the value of variable in the injured side. Perfect symmetry is achieved when "SI" equals zero.

The study was approved by the institutional review board and each participant signed informed consent.

Statistical analysis

The study sample size was in accordance with previous investigations that evaluated hip and knee landing kinetics and kinematics after ACL reconstruction. These referred to sample sizes of between 11 and 35 patients [21]. Intraclass correlation coefficients (ICCs) were computed to estimate the reliability of the biomechanical measures. Associations between the subjective measures of ongoing sports participation at 5-to-10 year follow-up and the objective measures of muscle strength and landing biomechanics were analyzed by means of Pearson's product-moment correlations. In addition, due to large standard deviations observed in most biomechanical measures among the participants despite symmetric mean values, subgroup analysis was added to assess whether extreme asymmetry in any of the objective biomechanical variables was associated with reported outcome scores of sports participation. For this purpose, 3 subgroups were defined in relation to the symmetry indices (SI) of the biomechanical variable as follows: (1) subgroup of patients with extreme positive SI, i.e. SI higher than (+)10% (uninjured limb was characterized by substantial higher value of the biomechanical variable compared to operated limb); (2) subgroup of patients with extreme negative SI, i.e. SI lower than (-)10% (operated limb was characterized by substantial higher value of the biomechanical variable compared to uninjured limb); and (3) subgroup of patients with almost perfect side-to-side symmetry, i.e. SI between (-10%) and (+10%). With each sports participation outcome score as a dependent variable, a series of one-way ANOVAs were applied for each biomechanical variable in order to compare the means among the three subgroups. In case of a significant main effect a Tukey HSD procedure was used for post hoc comparisons among the means. Level of significance was set at 0.05. SPSS Software version 25 was used for data analysis.

Results

Mean Tegner activity level before the injury was 8.0±1.4 (range 7-10), supportive that the studied sample represented ACL reconstruction in active population in terms of cutting-pivoting sports. Table 1 presents the patient reported outcome scores at 5-to-10 years after surgery.

Table 1: Descriptive statistics of the patient activity reported outcomes

Reported outcome scale	Mean ± SD
Tegner activity level	6.0 ± 2.3
Marx activity level	6.4 ± 5.4
IKDC-subjective	83.3 ± 13.2
KOOS-Knee symptoms	82.9 ± 11.3
KOOS-Pain	87.8 ± 12.7
KOOS-ADL	94.5 ± 9.3
KOOS-Sports	76.8 ± 20.8
KOOS-QOL	62.0 ± 22.2

Mean activity level scores indicated that patients were still maintaining moderately intense sports activities. Among the reported functional outcomes scales, the lowest scores were represented by KOOS-sports and KOOS-QOL sub-scores which also displayed the largest score variability.

Table 2 presents descriptive statistics of all biomechanical measures in the operated limb and in the contralateral uninjured limb.

Table 2: Descriptive statistics of the biomechanical measures (mean ± SD)

Variable	ACLR limb	Contralateral limb	Symmetry Index (%)
Knee extension isokinetic peak torque (N*m/kg)	1.73 ± 0.4	1.85 ± 0.4	6.8 ± 21.5
Knee flexion isokinetic peak torque (N*m/kg)	0.88 ± 0.2	0.90 ± 0.2	2.4 ± 18.8
Single-legged landing time to stability (sec)	1.25 ± 0.1	1.25 ± 0.1	0.3 ± 6.3
Single-legged landing peak GRF/BW (N/kg)	39.3 ± 8.4	40.1 ± 9.8	1.7 ± 11.5
Drop jump - peak support moment/BW (N*m/kg)	4.75 ± 1.5	4.69 ± 1.6	-1.6 ± 22.7
Drop jump – hip torque at peak support moment (N*m/kg)	1.78 ± 0.52	1.45 ± 0.61	-16.9 ± 47.1
Drop jump – knee torque at peak support moment (N*m/kg)	1.59 ± 0.80	1.67 ± 0.83	5.1 ± 42.3
Drop jump – ankle torque at peak support moment (N*m/kg)	1.38 ± 0.55	1.57 ± 0.71	5.9 ± 24.5
Drop jump - sagittal hip ROM (°)	31.3 ± 14.5	30.7 ± 13.7	-3.3 ± 18.0
Drop jump - sagittal knee ROM (°)	47.5 ± 13.3	49.1 ± 13.7	3.6 ± 19.4
Drop jump - sagittal ankle ROM (°)	39.2 ± 18.6	41.9 ± 16.7	9.1 ± 42.8
Drop jump - sagittal total ROM (hip + knee + ankle) (°)	118.0 ± 32.4	121.7 ± 35.5	2.6 ± 24.7
Single-legged hop for distance (m)	1.79 ± 0.3	1.84 ± 0.2	1.6 ± 6.9

Positive symmetry index indicates a higher value of the measured variable in the contralateral uninjured limb and negative symmetry index indicates a higher value of the measured variable in the operated limb. In all measures, except hip torque component of the overall peak support moment (defined as hip torque at peak support moment) during drop jump landing, mean side-to-side symmetry indices were within ±10% but large standard deviations suggested high variability among subjects in almost all biomechanical measures tested.

Tables 3 and 4 present bi-variate correlation coefficients between Tegner, Marx, IKDC and KOOS scores and each biomechanical measure.

Table 3: Bi-variate correlation coefficients relating to the contralateral uninjured limb (CL), the operated limb (ACLR), and the symmetry index between the limbs (SI) for the Tegner, Marx, and IKDC scores

Variable	Tegner preinjury [CL; ACLR; SI]	Tegner FU [CL; ACLR; SI]	Marx FU [CL; ACLR; SI]	IKDC [CL; ACLR; SI]
Peak knee extensors torque at 180°*sec^{-1}	0.44**; 0.54**; -0.15	0.33; 0.46*; -0.21	0.44*; 0.47**; -0.09	-0.06; 0.15; -0.29
Peak knee flexors torque at 180°*sec^{-1}	0.52**; 0.53**; 0.03	0.31; 0.42*; -0.13	0.29; 0.42*; -0.15	-0.03; 0.14; -0.21
Single-legged landing - time to stability	0.05; 0.11; 0.05	0.13; -0.12; -0.31	0.17; -0.12; -0.37*	0.17; 0.05; -0.18
Single-legged landing - peak GRF/BW	0.35; 0.26; 0.23	0.33; 0.45*; -0.17	0.14; 0.31; -0.17	0.13; 0.05; 0.18
DJ - peak support moment/BW	0.63**; 0.57**; 0.14	0.37; 0.38; -0.03	0.34; 0.37; -0.06	-0.20; -0.11; -0.24
DJ - hip torque at peak support moment	0.34; 0.32; -0.05	0.46*, 0.47*; -0.09	0.47*; 0.51*; -0.09	0.10; -0.03; -0.13
DJ - knee torque at peak support moment	0.64**; 0,54**; -0.08	0.17; 0.25; 0.14	0.14; 0.20; 0.15	-0.17; -0.02; 0.34
DJ - ankle torque at peak support moment	0.37; 0.44*; 0.07	0.19; 0.20; -0.01	0.15; 0.22; 0.07	-0.41*; -0.23; 0.29
DJ – hip sagittal ROM	-0.26;-0.41*; 0.34	0.06; -0.12; 0.43*	0.11; -0.01; 0.27	0.40*; 0.23; 0.51*
DJ – knee sagittal ROM	-0.33;-0.56**; 0.39*	-0.17; -0.38*; 0.33	-0.09; -0.25; 0.23	0.38*; 0.06; 0.46*
DJ – ankle sagittal ROM	-0.24;-0.45*; 0.25	-0.05; -0.32; 0.27	0.07; -0.25; 0.24	-0.05; -0.26; 0.24
DJ - total sagittal ROM¥	-0.35;-0.64**; 0.33	-0.06; -0.38*; 0.33	0.05; -0.24; 0.28	0.28; -0.01; 0.37
Single-legged hop test for distance	0.50**;0.65**; 0.31	0.29; 0.33; -0.06	0.20; 0.31; 0.02	-0.09; 0.07; 0.34

Table 4: Bi-variate correlation coefficients relating to the contralateral uninjured limb (CL), the operated limb (ACLR), and the symmetry index between the limbs (SI) for the KOOS scores

Variable	KOOS KS [CL; ACLR; SI]	KOOS Pain [CL; ACLR; SI]	KOOS ADL [CL; ACLR; SI]	KOOS Sports [CL; ACLR; SI]	KOOS QOL [CL; ACLR; SI]
Peak knee extensors torque at 180°*sec^{-1}	-0.07; 0.09; -0.20	-0.15; -0.11; -0.07	-0.05; 0.02; -0.11	0.02; 0.22; -0.27	0.10; 0.27; -0.24
Peak knee flexors torque at 180°*sec^{-1}	-0.12; 0.03; -0.18	-0.21; 0.00; -0.29	-0.15; -0.09; -0.07	0.02; 0.20; -0.21	0.05; 0.28; -0.30
Single-legged landing - time to stability	0.13; 0.07; -0.07	0.09; 0.02; -0.11	0.23; 0.21; -0.05	0.19; 0.13; -0.10	-0.03; -0.12; -0.13
Single-legged landing - peak GRF/BW	-0.10; -0.10; -0.02	0.07; -0.06; 0.23	0.06; -0.06; 0.21	-0.01; -0.04; 0.02	0.04; 0.03; 0.07
DJ - peak support moment/BW	-0.26; -0.19; -0.24	-0.30; -0.23; -0.08	-0.18; -0.02; -0.26	-0.18; -0.08; -0.25	0.01; 0.00; -0.01
DJ - hip torque at peak support moment	-0.11; -0.25; -0.06	0.00; -0.15; -0.11	-0.19; -0.26; 0.02	0.04; 0.00; -0.03	0.26; 0.02; -0.29
DJ - knee torque at peak support moment	-0.25; -0.10; 0.35	-0.25; -0.10; 0.31	-0.01; 0.19; 0.38	-0.11; -0.05; 0.15	-0.05; 0.00; 0.14
DJ - ankle torque at peak support moment	-0.21; -0.12; 0.14	-0.45*; -0.32; 0.13	-0.25; -0.08; 0.22	-0.36; -0.14; 0.33	-0.22; -0.03; 0.29
DJ – hip sagittal ROM	0.43*; 0.35; 0.24	0.33; 0.27; 0.21	0.08; 0.01; 0.15	0.48**; 0.33; 0.50**	0.36; 0.21; 0.48**
DJ – knee sagittal ROM	0.35; 0.19; 0.18	0.35; 0.14; 0.28	0.05; -0.10; 0.22	0.48*; 0.19; 0.41*	0.44*; 0.13; 0.46*
DJ – ankle sagittal ROM	0.20; -0.01; 0.15	-0.05; -0.25; 0.16	-0.03; -0.08; 0.06	0.11; -0.22; 0.29	0.04; -0.26; 0.29

DJ - total sagittal ROM¥	**0.41***; 0.23; 0.19	0.24; 0.05; 0.21	0.10; -0.08; 0.12	**0.43***; 0.10; **0.40***	**0.40***; 0.01; **0.43***
Single-legged hop test for distance	-0.13; -0.07; 0.09	-0.23; -0.01; 0.33	-0.07; 0.13; **0.40***	0.01; 0.14; 0.28	0.02; 0.15; 0.23

At follow-up, Tegner and Marx activity level scores were positively correlated with concentric knee flexors and extensors peak torques and with hip torque at peak support moment in the operated limb during drop jump landing. Tegner scores were also positively correlated with single-legged peak GRF and negatively correlated with knee and total sagittal ROM in the operated limb during drop jump landing. In relation to symmetry indices, hip sagittal ROM symmetry index during drop jump landing positively correlated with Tegner score, and with IKDC, KOOS-Sports and KOOS-QOL sub-scores at follow-up, while knee sagittal ROM symmetry index during drop jump landing positively correlated with the latter three measures of sports maintenance. Preinjury Tegner scores significantly correlated with most unilateral biomechanical measures tested in the operated limb.

Table 5 presents subgroup comparisons of the 3 symmetry indices categories of biomechanical measures that showed significant associations with ongoing sports participation scores. These included knee isokinetic muscle torques and hip and knee ROM during drop jump landing.

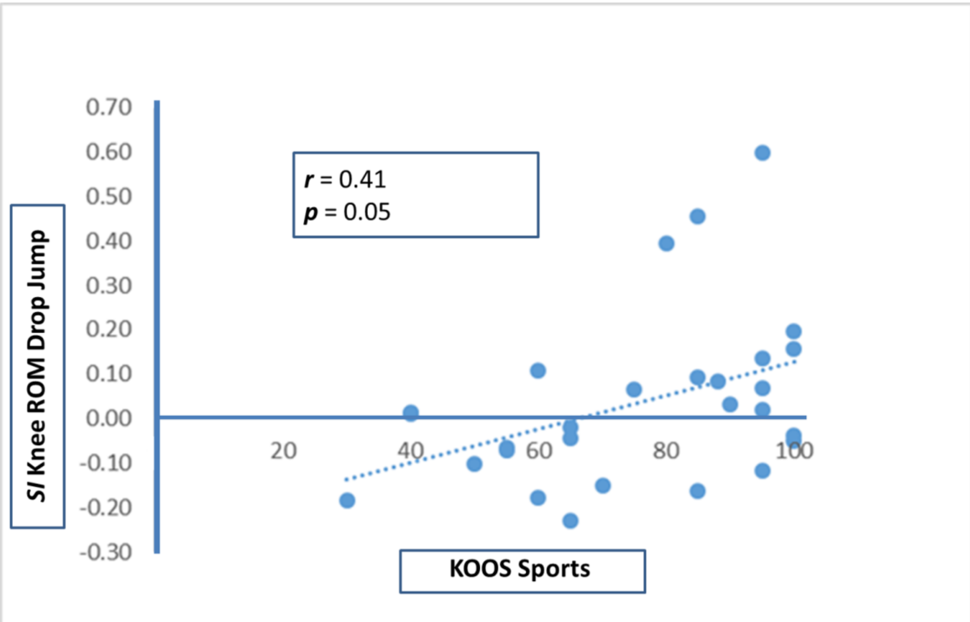
<u>Table 5: Comparisons of the activity outcome scores between subgroups of symmetry indices (SI) of knee torques and drop jump kinematics showing significant inter-relationships</u>

		SI subgroup I	II	III		
Biomechanical measure	**Activity reported outcome measure**	**SI <-10%**	**SI ±10%**	**SI >+10%**	**post hoc comparisons**	***p***
Quad peak torque/BW	Marx latest FU	1.5 ± 1.9	9.0 ± 4.9	5.3 ± 5.3	I<II	0.025
	KOOS-knee symptoms	76.8 ± 9.6	89.1 ± 9.6	78.5 ±10.8	I,III<II	0.024
Hams peak torque/BW	Tegner latest FU	6.0 ± 2.1	7.0 ± 2.2	4.7 ± 1.8	III<II	0.041

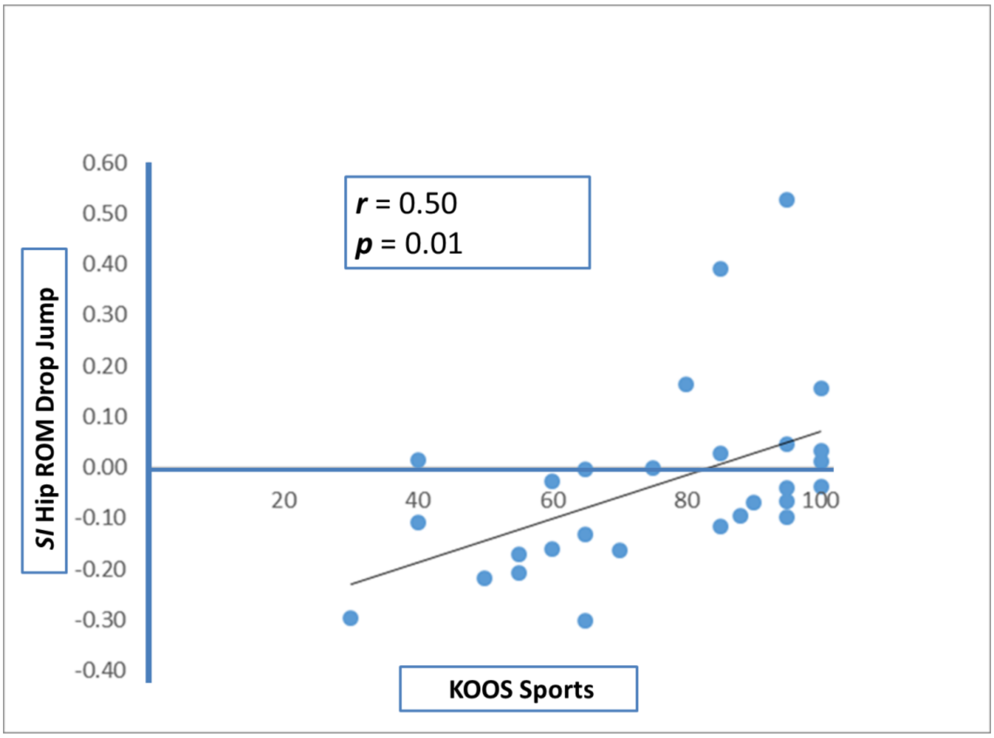
	Marx latest FU	6.7 ± 6.0	8.64 ± 5.3	3.1 ± 3.3	III<II	0.037
DJ hip sagittal ROM	IKDC-subjective	73.3 ± 10.5	85.5 ± 12.6	94.8 ± 5.1	I<II,III	0.006
	KOOS-knee symptoms	75.8 ± 7.8	84.5 ± 11.9	88.3 ±10.0	I<II,III	0.073
	KOOS-sports	57.5 ± 15.5	84.5 ± 18.1	90.0 ± 9.1	I<II,III	0.001
	KOOS-QOL	41.5 ± 14.9	70.6 ± 18.4	72.0 ± 16.6	I<II,III	0.001
DJ knee sagittal ROM	KOOS-QOL	43.1 ± 17.5	63.1 ± 22.9	72.4 ± 12.4	I<III	0.027

For isokinetic extensors and flexors knee torques, patients who reported the highest ongoing sports participation belonged to the mid-range subgroup of SI. These patients had close to perfect symmetry of extensors and flexors knee torque values. For hip and knee ROM during drop jump landing, patients who reported the highest ongoing sports participation belonged to the symmetric SI subgroup but also to the extreme positive SI subgroup (SI > +10%) which refers to patients with substantially higher hip and knee ROM in the uninjured limb compared to the operated limb during the drop jump landing.

Figures 1 and 2 show on individual basis the correlations between knee and hip side-to-side SIs of ROM during drop jump landing and maintenance of sports participation as represented by KOOS-Sports sub-score.



<u>Figure 1: Correlations between knee side-to-side SIs of ROM during drop jump landing and maintenance of sports participation as represented by KOOS-Sports sub-score</u>



<u>Figure 2: Correlations between hip side-to-side SIs of ROM during drop jump landing and maintenance of sports participation as represented by KOOS-Sports sub-score</u>

Patients with higher scores (KOOS-Sports > 80) were characterized by positive SIs as opposed to patients with lower scores (KOOS-Sports < 80) which were characterized by negative SIs. This means greater attenuation of hip and knee ROM in the operated limb relative to the uninjured limb in more active patients.

BMI was within normal range (mean 24.1±2.2). KT side-to-side difference was 3.1±2.2 mm, and in 26 (87%) cases, the difference was ≤ 5 mm, which is considered "normal" or "nearly normal" [11]. This also supports the generalizability of the studied group in terms of surgical outcome and in accordance with others who evaluated similar graft source for ACL reconstruction at 7 years follow-up [22].

The ICCs were fair for the time to stability (ICC = 0.66 and 0.77 for the injured and uninjured limb, respectively) and high for all other variables (ICC = 0.86-0.99).

Discussion

The present study was designed to test correlations between objective biomechanical measures of force production and landing biomechanics versus maintenance of sports participation at 5-to-10 years after ACL reconstruction. The most pronounced biomechanical characteristics observed in patients who reported higher maintenance of sports participation included: (1) symmetric concentric knee extensors and flexors torques, (2) symmetric hip and knee ROM during drop jump landing, and (3) positive side-to-side symmetry indices of hip and knee ROM indicating higher ROM in the uninjured limb during drop jump landing. Inferior maintenance of sports participation was observed in patients with inverse side-to-side relationships of hip and knee ROM where higher sagittal motion appeared in the operated limb compared to the uninjured limb. In other words, patients who reported higher activity scores have not only reestablished symmetric side-to-side concentric knee extensors and flexors torques, but also showed improved hip and knee sagittal plane motion attenuation immediately following ground contact which was accompanied by higher GRFs and higher moments in the operated limb. Previous investigators indicated the value of identifying asymmetries in hip and knee kinematics during the early phases of the rehabilitation process after ACL reconstruction [25, 31]. The current study shows that these asymmetries still remain valuable to distinguish between an optimal and a suboptimal functional recovery and thus potentially guide decision-making junctions long after surgery. These results are also consistent with previous investigators who emphasized that the best functional outcome scores were observed in patients who achieved symmetric knee range of motion during the rehabilitation phase after ACL reconstruction [4]. Symmetry indices of isokinetic knee extensors and flexors torques were also suggested fundamental to guide decision-making during the first and second years after surgery [1, 9, 14]. The current results support the value of this measure during the maintenance phase at 5 or more years after surgery. In this regard, although previous investigators suggested nearly full recovery of knee muscle strength to deficits of within 10% at 5 or more years after surgery [20, 26], a finding supported by the current study when looking at the group means, this did not undermine the value of measuring concentric force production around the knee during such a relatively long follow-up. This is because large inter-individual variabilities in the ability to produce powerful knee extension and flexion torques characterized this population. Thus, close to perfect side-to-side symmetry of concentric knee flexors and extensors torque was still associated with maintenance of higher activity levels as opposed to subjects with either higher than (+)10% or lower than (-)10% side-to-side symmetry indices. Altogether, it could be summarized that in order to maintain higher activity levels at the maintenance phase after ACL reconstruction, patients would benefit from reestablishment of concentric knee force production which is important during jumping or changing directions, in addition to optimizing eccentric muscle torque around the knee and hip which is important for the reestablishment of stable and effective landing. Of note, drop jump landing kinematics in this study were reported through sagittal plane motions at the hip, knee, and ankle although motion in this plane is inter-related with coronal and transverse plane motions [25, 31]. Transverse plane kinematics involves smaller range of motion and asymmetries and thus are harder to quantify compared to sagittal plane kinematics [25]. Furthermore, accuracy of measuring coronal plane kinematics has been previously questioned [27]. Therefore, the focus in this study was on sagittal plane kinematics, which is also consistent with previous investigations [15].

Among the biomechanical measures tested, all showed side-to-side symmetry indices means of within +/- 10% except hip torque at peak support moment which showed substantial asymmetry with 17% higher values at the operated side. This may imply that patients compensate for suboptimal knee function by generating higher torques at the hip region of the involved side to dissipate the external loads during the drop jump landing. The clinical significance of the hip role during this task is substantiated by the correlations between hip torque levels at peak support moment during drop jump landing and both Tegner and Marx scores at follow-up. It is also important to note that the clinical benefit of achieving symmetry in this study should be viewed in light of the fact that the contralateral limb in this group represented healthy uninjured limb with normal values of strength and kinematics. Symmetry by itself may not be a desired goal in cases where the contralateral limb is poorly functioning for whatever reason.

Preinjury Tegner activity level was associated with several biomechanical characteristics at 5 to 10 years after the operation. These variables accounted for 17% to 42% of the variance of the Tegner preinjury scores in spite of the prolonged follow-up period. Five of the variables were associated with preinjury activity for both the operated and the uninjured limbs namely, isokinetic knee flexors and extensors torques, peak drop jump support moment, knee torque during peak drop jump support moment and the single-legged hop distance. These results may well exemplify a general association between preinjury activity level and higher ability for force production, even in the long run. This also provides a biomechanical explanation for the association observed previously [12] between preinjury- and long-term follow-up Tegner levels after ACL reconstruction, beyond the mere "wish" of any athlete to maintain activity levels throughout the years after an injury. Furthermore, in the operated limb, the preinjury activity level was also associated with lower sagittal ROMs during force absorption in all three lower extremity joints. Since knee sagittal ROM during force attenuation was significantly related to Tegner score during follow-up as well, together these results point again to a potential benefit of inclusion of an eccentric strengthening of the lower musculature through a limited ROM in the adaptation process, particularly with respect to the knee muscles. This perspective is in accordance with recent meta-analyses that showed reductions in knee extension moments in ACL reconstructed knees during single and double-legged landing tasks [15, 21], a finding which supports addressing such deficits after surgery.

The significant relationships between Tegner activity level scores and long term movement characteristics signify the relevancy of motion variables in the evaluation of the adaptation process. Most strength measures of the operated limb as well as knee ROM correlated with both preinjury and follow-up activity outcome measures. However, at follow-up, peak support moment and hip and ankle ROM during drop jump, and single-legged hop distance did not reach significance. On the other hand, hip torque during drop jump landing significantly correlated with Tegner score at follow-up. The differences between the preinjury and follow-up associations of activity level with movement variables can be, at least in part, attributed to the span of the follow-up period. That is, at more than 5 years after the operation, maintenance of activities is subjected to multiple factors that determine whether athletes remain active and at which level. For example, factors that can affect Tegner level at follow-up besides biomechanical constraints per-se may include changes in life style for other reasons than the knee injury, accumulation of other health-related problems, and other intervening factors [23, 29, 39]. With longer follow-up after surgery it likely becomes even more challenging to isolate specific common biomechanical measures which correlate with maintenance of active life style. This supports the rational to limit this type of a study, which focuses on biomechanical aspects of sport-related elements of movement, to 5-to-10 years of follow-up, as opposed to studies which focus on the development of specific long-term knee morbidity such as arthritis where longer follow-up after ACL reconstruction is desired.

Limitations of this study include the retrospective design and using the uninjured leg after an ACL injury as a reference for measuring neuromuscular deficits in the injured leg. This is nevertheless in accordance with a recent study showing that neuromuscular functions which included peak torque of knee extensors and flexors contractions measured on a Biodex dynamometer, knee joint proprioception, one-leg standing balance test, and the single-legged hop test for distance, were not impaired in the uninjured leg at more than six months after an ACL injury despite the reduction in physical activity following an injury [43] supporting that the contralateral limb can serve as adequate reference to examine recovery of the injured leg's neuromuscular function during the rehabilitation process following an injury [43]. In addition, the relatively limited follow-up rate of only 55% resulted from the nature of this study which was a voluntary-based study requiring from the participants a thorough time-consuming biomechanical evaluation in a biomechanical laboratory. In these circumstances, 25 of the 55 patients, which were all young men from the workers class, were unwilling to volunteer for personal reasons unrelated to the surgery. Despite this limitation however, the study sample size was in accordance with previous investigations that reported about hip and knee kinetics and kinematics after ACL reconstruction and referred to sample sizes of between 11 and 35 patients [21].

Conclusion

At 5-to-10 years after ACL reconstruction, maintenance of sports participation is associated with symmetric side-to-side concentric knee torques and with producing greater attenuation of hip and knee ROM during drop jump landing in the operated limb. Therefore, eccentric load programs which can improve attenuation phase kinematics during landing tasks may be valuable in addition to traditional concentric training and facilitate enhanced long-term outcomes.

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Legends

Table 1: Descriptive statistics of the patient activity reported outcomes

Table 2: Descriptive statistics of the biomechanical measures (mean ± SD)

- Positive symmetry index indicates a higher value of the measured variable in the contralateral uninjured limb and negative symmetry index indicates a higher value of the measured variable in the operated limb

Table 3: Bi-variate correlation coefficients relating to the contralateral uninjured limb (CL), the operated limb (ACLR), and the symmetry index between the limbs (SI) for the Tegner, Marx, and IKDC scores

Table 4: Table 4: Bi-variate correlation coefficients relating to the contralateral uninjured limb (CL), the operated limb (ACLR), and the symmetry index between the limbs (SI) for the KOOS scores

*****, $p \leq 0.05$; ******, $p \leq 0.01$

[¥], total sagittal ROM = [hip ROM + knee ROM + ankle ROM]

GRF = Ground Reaction Force; BW = Body Weight; DJ = Drop Jump

- Significant correlations in bold

Table 5: Comparisons of the activity outcome scores between subgroups of symmetry indices (SI) of knee torques and drop jump kinematics showing significant inter-relationships

- The SI subgroup with the highest activity outcome score for each biomechanical measure is indicated in bold

Figure 1: Correlations between knee side-to-side SIs of ROM during drop jump landing and maintenance of sports participation as represented by KOOS-Sports sub-score

Figure 2: Correlations between hip side-to-side SIs of ROM during drop jump landing and maintenance of sports participation as represented by KOOS-Sports sub-score