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ORIGINAL ARTICLE

Kinetic protocol in torn anterior cruciate ligament

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KEYWORDS
Anterior cruciate ligament;
Biomechanics;
Kinetics;
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Knee

Abstract
Objective: To kinetically evaluate patients with a torn anterior cruciate ligament (ACL) fracture in order to establish a biomechanical assessment and follow-up protocol.
Patients and methods: A total of 45 males, with a mean age of 34 years and an isolated torn ACL or associated with a torn meniscus, were assessed before surgery. Walking, sprinting and jump tests were performed to assess the floor reaction forces, comparing the injured side with the healthy or control side. The force parameters for each of the movements were obtained and analysed.
Results: We obtained differences in the support forces in different tests, particularly in the jumps. The single-legged jump decreased the vertical support strength and increased the support time in the injured leg, and the jump time was half with a torn ACL. In the vertical jump, the vertical propulsion force and also the support time of the injured side decreased. In the drop and push jump, the vertical drop force and the vertical push force decreased.
Conclusions: The torn ACL affects the movement kinetics, particularly in the jump tests. A kinetic protocol would be useful for assessing torn ACL and their outcome after surgery.

PALABRAS CLAVE
Ligamento cruzado anterior;
Biomecánica;
Cinética;
Salto;
Rodilla

Protocolo cinético en la rotura del ligamento cruzado anterior

Resumen
Objetivo: Evaluar cinéticamente pacientes con una rotura del ligamento cruzado anterior (LCA) para establecer un protocolo biomecánico de evaluación y seguimiento.
Pacientes y metodología: Se estudiaron 45 pacientes varones, con una media de 34 años y rotura aislada del LCA o asociado a rotura de menisco, antes de la cirugía. Realizaron pruebas de marcha, "sprint" y salto para valorar las fuerzas de reacción con el suelo,

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comparando el lado lesionado con el sano o control. Se obtuvieron y analizaron los parámetros de fuerza de cada uno de los movimientos.
Resultados: Obtuvimos diferencias en las fuerzas de apoyo en diferentes pruebas, especialmente en los saltos. En el salto monopodal disminuyó la fuerza vertical de apoyo, aumentó el tiempo de apoyo, en la pierna lesionada y el tiempo del salto fue la mitad con una rotura del LCA. En el salto vertical disminuyó la fuerza vertical de impulso y también el tiempo de apoyo del lado lesionado. En el salto con caída e impulso disminuyó la fuerza vertical de caída y la fuerza vertical de impulso.
Conclusiones: La rotura del LCA afecta a la cinética del movimiento, especialmente en las pruebas de salto. Un protocolo cinético puede ser útil para valorar la rotura del LCA y su evolución tras la cirugía.

Introduction

Tearing of the anterior cruciate ligament (ACL) is a frequent lesion in sporting and recreational activities. Practically two thirds of ACL lesions originate in sport, affecting a young, active population with a high prevalence, 3 cases per 10,000 inhabitants and year.[1] This incidence is greater in contact sports and those requiring the knee to be turned, as in football, basketball or skiing.

Knees with a deficient ACL are predisposed to lesions and to the early onset of signs of degeneration so ACL reconstruction techniques not only recover the function of the ACL, they also protect the meniscus and cartilage in the knee. Noyes et al.[2] analyzed the natural history of this lesion, finding that 82% of patients with untreated lesions practised sport again after suffering a torn ACL, although 51% suffered a failure in the joint during the first year, and only 35% continued practising sport five years after the initial lesion. Experience has shown that a torn ACL implies a laxity of the knee, with more or fewer symptoms, as well as a high risk of secondary intra-articular lesions that may even end up, over time, in gonarthrosis.[3]

The ACL is a multifibrillar structure that is not uniform in diameter,[4] between 22 and 41 mm in length[5-10] and 7 to 12 mm wide, with a cross-section between 28 and 57 mm^2.[4,5,10-12] On the other hand, with these dimensions it is normal for them not to offer high resistance, although the forces they have to bear under normal conditions are not high either. Morrison et al.[13] calculated the solicitations acting on the anterior and posterior cruciate ligaments (PCL) while walking on flat surfaces (ACL: 169 N; PCL: 352 N); when climbing up (ACL: 67 N; PCL: 641 N) or down stairs (ACL: 445 N; PCL: 262 N), as well as when tested going up (ACL: 27 N; PCL: 1215 N) and down a 9.5° ramp (ACL: 93 N; PCL: 449 N). These stresses increase in proportion to the speed of their gait.

As can be seen, the solicitations on the PCL are, in general, greater than those on the ACL; yet tears are less frequent in the former. The ACL exceeds the PCL only in the activity of walking downstairs. In the rest of the activities studied, the stresses acting on the ACL do not exceed 15 kg, which leads us to think that the ACL is a biologically adapted and mechanically well-designed structure for normal activity, whereas when solicitations increase, as during sports, or when it is subjected to inappropriate positions, it may break very easily.

Proper reconstruction of the anterior cruciate ligament is evaluated clinically through anterior and posterior translation of the tibia and femur. Differences in these displacements between the injured and the healthy knees form a major aspect of the patients' case histories and can be used a clinical criterion for evaluating mechanically deficient knees.[14]

Our hypothesis was that differences in the anterior and posterior translation of a knee with a torn or reconstructed ACL have an impact on the kinetics in the different movements. To this end, our goal has been to analyze the supporting stresses following a protocol of forced homogeneous movements causing a translation and rotation of the tibia on the femur in order to be able to assess the kinetics of the torn ACL based on simple, repeatable movements determining the effect of a torn ACL and prepare objective tests allowing assessment of these patients' functional ability ad progress.

Material and methods

We studied 45 patients with a diagnosis of a torn ACL on the same day they underwent surgery. The mean age of the patients was 34 years, with a standard deviation of 9 years. The mean weight was 843.82 N±20.32 N.

The inclusion criteria were male patients over 20 and under 45 years of age who were about to be operated on for a torn ACL associated with a meniscal lesion. All lesions had occurred between 3 and 6 months prior to the study and all patients had followed the same physiotherapy protocol for 6 weeks.

The exclusion criteria, on the other hand, were female gender and patients with chronic lesions, lasting for more than 6 months, contralateral lesions or prior procedures in either knee, severe chondral lesions and tearing of other ligaments in the knee. Male patients with ACL lesions were also excluded if they had not followed the rehabilitation protocol.

In the clinical biomechanics laboratory, each patient carried out a series of different exercises and movements

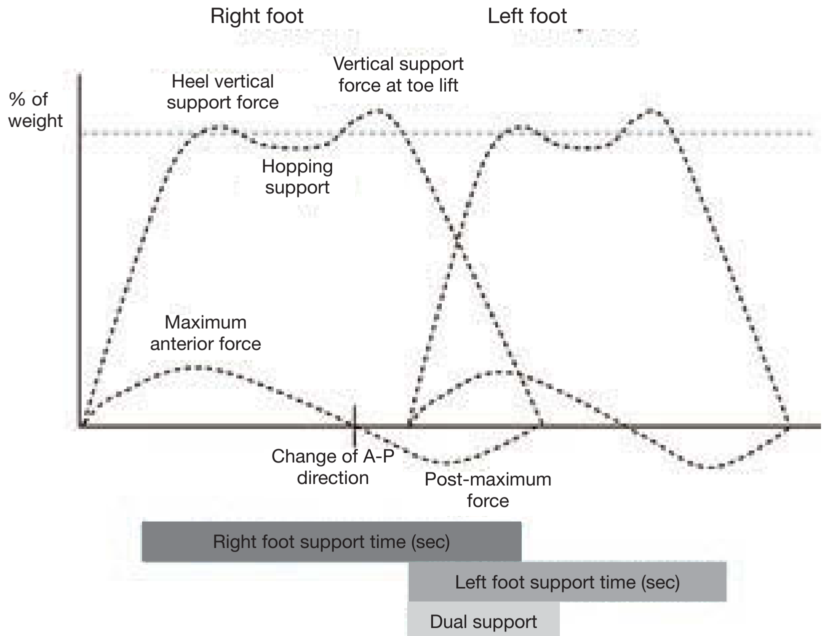

Figure 1 Diagram of the gait kinetics, indicating the parameters studied.

(walking, kicking, vertical jump, hopping and jumping from a height with landing and propulsion), on two force platforms (Kistler, Winterthur, Switzerland) measuring 60 cm by 90 cm. All the exercises were done barefoot and the weight of the patient was obtained on the force platforms themselves prior to the exercise. Patients performed each exercise twice before the definitive measurement was obtained.

We analyzed the different variables comparing the injured knee with the healthy or control knee. All the movements studied reflected the forces and support times for both feet simultaneously, except for hopping, which was measured for one foot and then for the other. The force obtained was, in all cases, the ratio of the force generated by the subject in each of their supports to their body weight, expressed as a percentage.

The forces were expressed as a percentage of bodyweight. The following parameters were calculated for each of the movements:

Kinetic study of gait (fig. 1). Each patient walked on the two force platforms starting always by placing their right foot on the first platform and the left on the second, at a speed that was comfortable for the patient. The parameters obtained were the total support time, from the support of one foot's heel until the lifting of the toes in the contralateral foot (seconds), the support time of the injured foot and the control foot (% of the total support), dual support (seconds), the moment of change in the direction of the forces from anterior to posterior, in both the injured and the control feet (% of support in the corresponding foot). In the gait study, the following weight-normalized forces were obtained and expressed as a percentage of body weight, peak vertical support force by the heel of the injured and control feet (%), the vertical force when hopping of the injured and control feet (%), peak vertical force in the lifting of the toes from the floor in the injured and control feet (%), anterior peak vertical force and posterior peak vertical force in both the injured and control feet (%). We also calculated the ratio of the forces obtained between the injured foot and the control foot (%).

Hopping (Fig. 2). Patients effected two runs, one hopping on the injured leg and the other on the control leg. Each test was done on one leg with support on both force platforms. This is the only test in which it was not possible to obtain the left and right support values simultaneously. Since the first support was unsteady, we only measured the jump times between the first and second support and the data from the second support. We obtained the following parameters: jump time for the injured and control feet

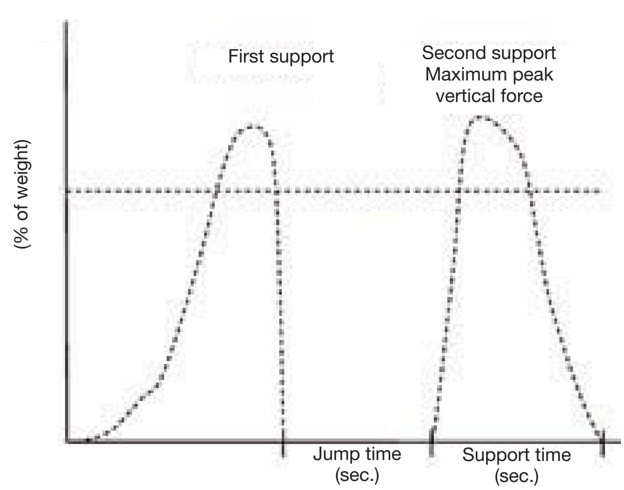

Figure 2 Kinetics of hopping, with indication of the parameters analyzed.

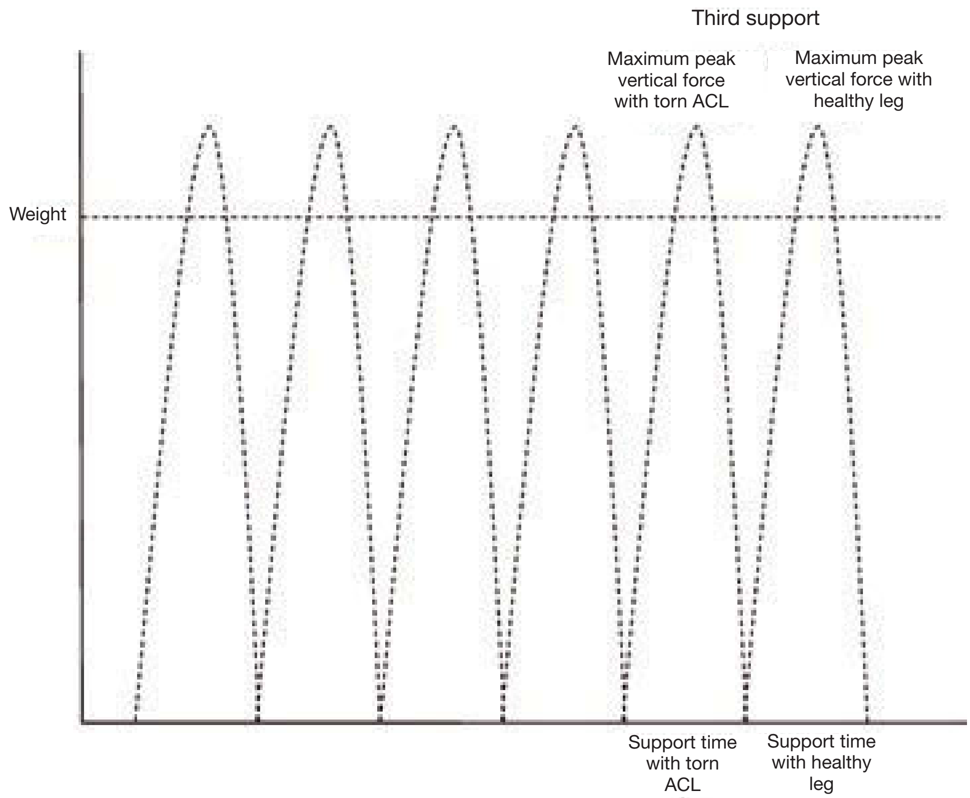

Figure 3 Kinetics for kicking. We studied the maximum peak vertical force and the support times during the third kick for both the healthy foot and that corresponding to the torn ACL.

(seconds), support time for the injured and control feet (seconds) and the maximum vertical support force for the injured and control feet, normalized by the weight of each patient and expressed as a percentage.

Kicking on platforms (fig. 3). Standing on the platforms, patients kicked with the maximum intensity for 5 seconds and the force and number of the kicks effected in that time were measured; we collected the data from the third kick,

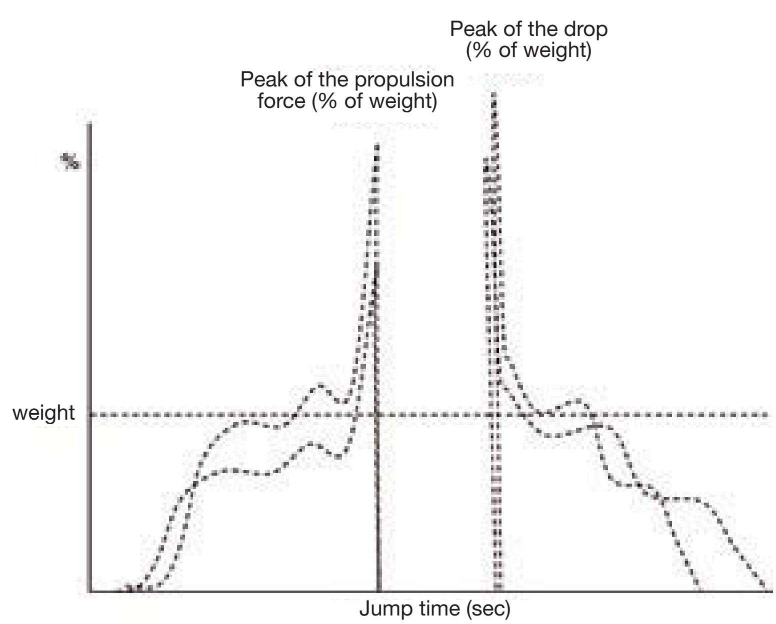

Figure 4 Kinetics of the vertical jump with both feet, specifying the parameters analyzed.

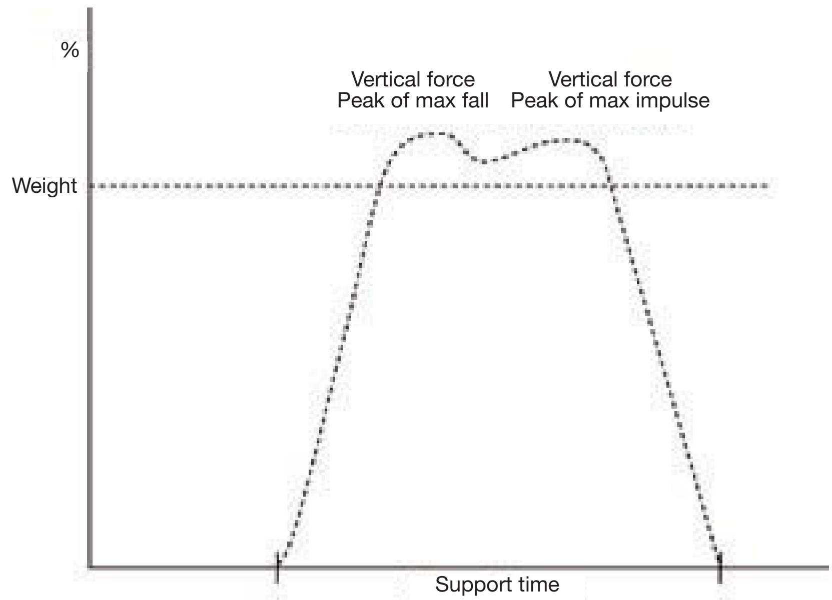

Figure 5 Kinetics of the jump from a height and jumping to another height located in front, indicating the parameters analyzed for the injured and the control feet.

normalizing the forces with the patient's body weight. We obtained the following parameters, the maximum vertical force of the injured and the control feet (%) and the support time for the kick with the injured and the control feet (second). In addition, we calculated the ratio between the maximum vertical forces in the injured and the control feet and the ratio of the support times for the injured and control feet.

Maximum vertical jump with propulsion and landing (Fig. 4). The patients placed each foot on one platform. They jumped upwards with propulsion and the help of their arms and landed with one foot on each of the platforms. Thus, we calculated the force in the propulsion and on landing and the jump time. The parameters analyzed were the maximum vertical force of the propulsion from the injured and the control feet (%), the maximum vertical force of the landing in the injured and the control feet, normalized with the weight of the patient and expressed as a percentage, the jump time from the injured and the control feet (seconds). We calculated the index between the jump times for the injured foot and the control foot.

Box test or jump with landing and propulsion (Fig. 5). Patients effected a jump, dropping from a height of 30 cm, landing with each foot on a force platform, and then propelled themselves forward, without stopping, to another box 30 cm high placed opposite them. The parameters measured were maximum vertical force of the landing on the injured and the control foot, normalized for the patient's weight and the maximum vertical force of the propulsion from the injured and the control feet expressed as a percentage, support time for the injured and the control feet (seconds). We calculated the ratio of the vertical drop force between the injured and the control feet, the ratio of the vertical propulsion force between the injured and the control feet and the ratio of the support time between the between the injured and the control feet.

Statistical tests used

The data obtained for each patient in each test were exported into a database (Excel, Microsoft Office 2008) in

Table 1 Kinetic gait parameters

	ACL	Control foot	p
Support time (%)	55.72±0.45	55.85±0.39	—
Anteroposterior change of direction (%)	55.42±2.2	50.33±2.09	0.003
Vertical force heel/weight (%)	95.51±1.01	99.81±1.58	0.001
Vertical force in monopodal support (%)	82.17±1.3	80.15±1.28	0.002
Vertical force in propulsion (%)	96.93±1.57	100.39±1.58	0.001
Maximum anterior force (%)	12.39±4.25	14.36±4.25	0.01
Maximum posterior force (%)	16.95±0.63	17.71±0.52	—

Table 2 Kinetic parameters obtained with the kicking action

	ACL	Control
Vertical force (N)	1502.38±46.72	1.557.50±49.58
Support time (s)	0.24±0.02	0.24±0.02
Vertical force/ weight (%)	178.95±5.77	185.34±5.9

N = Newton; s = seconds.

which they were analyzed and filtered, eliminating the non-support times. Following review of the tables, the data of interest were then placed in another table containing all of the patients to obtain the calculations indicated. Comparisons were made between the injured side and the control side using Wilcoxon's test for non-parametric monopodal support ($p \leq 0.002$), toe lift-off ($p \leq 0.001$) and maximum anterior force ($p \leq 0.01$) all diminished significantly in the injured foot. That is to say, the support forces were slightly lower, 96%, in the operated leg than in the control leg (table 1).

Analyzing the kinetic parameters of the kicking action, we also observe a reduction in the vertical support force without showing any changes in support time (table 2).

Jumps presented greater differences and so jumps with monopodal support presented lower forces and a greater support time in the injured leg. In addition, the jump time in the leg with a torn ACL was half that in the control leg ($p \leq 0.044$) whereas, on the other hand, the ratio of the support time (120%) between the two legs increased ($p \leq 0.000$) (table 3).

In the vertical jump with propulsion by the upper limbs, the vertical propulsion force diminished ($p \leq 0.000$) without any changes being observed in the landing force between the two legs and with the support time falling slightly. We did not observe any difference in the jump time between

Table 3 Kinetic parameters obtained with a monopodal jump

	ACL	Control	p
Jump time (s)	0.18±0.11	0.18±0.09	—
Vertical support forces (N)	1881.43±478.46	2045±374.88	—
Support times (s)	0.44±0.19	0.38±0.14	—
Vertical forces/weight (%)	228.40±66.94	245.75±45.11	—
Support time/jump time	0.56±0.9	0.54±0.4	0.044
Jump time on injured foot/jump time on control foot (%)	51.44±26.71	—	—
Support time on injured foot/support time on control foot (%)	119.41±44.91	—	0.000

N = Newton; s = seconds.

Table 4 Kinetic parameters of the vertical jump with propulsion by the upper limbs

	ACL	Control	p
Vertical propulsion force (N)	947.30±166.59	1.155.42±339.65	0.000
Support time (s)	0.42±0.11	0.41±0.11	—
Vertical landing force (N)	1.949.35±670.99	1.950.5±464.00	—
Vertical force propulsion/weight (%)	113.45±25.8	136.6±36.37	0.000
Vertical landing force/weight (%)	233.5±88.98	234.07±67.6	—
Vertical propulsion force/vertical landing force (%)	59.93±48.36	64.09±30.69	0.035

N = Newton; s = seconds.

Table 5 Kinetic parameters obtained with jump, landing and propulsion

	ACL	Control	p
Vertical landing force (N)	1.336±46.41	1.554±55.90	—
Vertical propulsion forces (N)	1.015.12±41.32	1.233.46±42.38	—
Support times for each foot (s)	0.63±0.06	0.62±0.05	—
Ratio of landing force to weight (%)	160.1±6.31	184.66±6.50	0.003
Ratio of propulsion force to weight (%)	121.46±5.36	146.61±5.14	0.001

patients operated on for torn ACLs. Therefore it is no surprise that a number of instruments have been designed to measure it, even though this assessment is still effected subjectively. Noyes et al.[5] introduced the monopodal jump test and in the 1980s the first instruments appeared that were capable of assessing the tibial-femoral displacement and, somehow, of evaluating joint instability. Thus, with the KT-1000® or KT-2000® (MEDmetric Corp, San Diego, CA USA), the Genucom Knee Analysis System® (FARO Medical Tech Inc, Montreal, Canada), the Stryker Knee Laxity Tester® (Stryker, Kalamazoo, MI, USA), the UCLA - Instrumented Clinical Testing Apparatus® (University of California - Los Angeles, CA, USA), the Acufex Knee Signature System (KSS) ® (Acufex Microsurgical, Norwood, MA, USA) and their more evolved CA-4000 Electrogoniometer® (OSI Inc, Hayward, CA, USA), the Dyonics Dynamic Cruciate Tester® (DCT) (Dyonics, Andover, MA, USA), el Vermont Knee Laxity Device® (VKLD) (University of Vermont, Burlington, VT, USA), the Rolimeter® (Aircast Europe, Neubeuern, Germany) or the TELOS® functional radiography system (Telos Gmbh, Laubscher, Hölstein, Switzerland) are all more or less straightforward or complicated systems measuring the degree of joint instability in one or more directions and, according to Pugh et al.,[14] the KT-1000® and the Rolimeter® offer the best guarantees for measuring anterior laxity although the Rolimeter® is easier to integrate into clinical practice. These authors recommend TELOS® functional radiographies as the best way to measure posterior laxity.

Nonetheless, numerous studies have been published to understand the biomechanics of movement in patients with a torn ACL. Most studies make use of kinematics to evaluate movement angles, observing the impact on knees with torn or operated ACLs of differences in gait, running or climbing up or down stairs.[15-17] These differences are attributed to the elimination of the anterior shearing solicitations on the tibia. A reduction in flexion has been seen in patients with torn ACLs,[18,19] but has also been demonstrated in other pathologies such as gonarthrosis,[20,21] total knee prosthesis[22] or partial arthroscopic meniscectomy.[23] The sagittal plane has always been seen to be more affected than the frontal plane.

DeVita et al.[18] proved that patients with ACL reconstruction recovered normal mobility 6 months after surgery although the flexion moments remained significantly diminished for much longer.

Many of the kinematic studies of gait are based on the atrophy of the quadriceps muscle and the improvement of the contraction force in the quadriceps muscle has been correlated with good evolution following ACL reconstruction.[24] Thus, when the knee is almost in extension, during the support phase,[25] the contraction of the quadriceps muscle produces an anterior displacement force in the tibia.[26] Therefore, the reduction in the contraction of the quadriceps muscle reduces anterior translation of the tibia and prevents the sensation of joint instability.[27] For this reason, the muscle atrophy of the quadriceps muscle appearing after the tearing of ACLs[2,15,25,27] has been understood as a subconscious protection mechanism to avoid excessive forward displacement of the tibia in a knee without any ACL while walking.[15,27,28] Although Ferber et al.,[29] in ten chronic cases of torn ACL, pointed out that the lack of strength in the quadriceps muscle is not as frequent as is indicated in the literature.

Kinematic alterations have also been shown after the repair of the ACL[6,30-34] and Mikkelsen et al.[35] have proved that subjects with good quadriceps muscle after ACL reconstruction are capable of performing again the same activities as prior to the lesion.

Torry et al.[25] found two different gait patterns in patients with a torn ACL. Some people apply what is called the "hip strategy", i.e. they increase the extension of the hip and reduce the extension of the knee to maintain normal kinematics in the knee, while others use the so-called "knee strategy", i.e. walking with the knee in flexion.

It has also been established that the taking of grafts from goose legs has a residual action on joint kinematics[36-39] and reduces the muscle strength in flexion and weakens internal rotation. Beard et al.,[31] in patients operated on two years earlier, saw that they walked with a greater knee flexion angle and presented greater activity of the hamstrings during the monopodal support phase while the duration of the activity of the quadriceps muscle was similar to the control group.

Nor is it clear how much time is needed after surgery in order to return to normal. Andriacchi et al.[15] saw that patients with a chronic ACL lesion, some many years after the injury, showed no differences in the kinetics and kinematics of gait when compared with control subjects, although they presented differences in muscle activity. For their part, Wexler et al.[39] found that, 7 and a half years after the lesion, subjects with a deficient ACL walk with a greater knee extension angle during the final phase of the support period as this requires less activity by the quadriceps muscle and reduces the forward translation of the tibia. However, there are other studies that have not obtained this kind of result.

Kinetic studies such as that carried out in this paper are less frequent. Lindström et al.[40] found that patients with a chronicity in excess of 20 months in their ACL lesion had a reduction in the two support peaks in the stride, accompanied by an increase in the lateral forces and the anterior forces, results that coincide with several publications.[19,25,40-42] On the other hand, Rudolph et al.[19] maintain, in co-operative patients, that a chronic lesion of the ACL does not produce any biomechanical alteration in the gait and they require very demanding tests to find biomechanical alterations. For that reason, in addition to studying gait, we have analyzed other simple tests, easy to conduct and repeat, in order to establish those that produce modifications with a torn ACL, always comparing with the uninjured contralateral side. Comparing the parameters between both limbs seems to us to be more correct than comparing with a control group that, in these cases, usually shows much greater differences. Although it has been pointed out that, in some movements, the control foot adapted to the conditions of the injured limb.[43]

In our study, the kinetic gait analysis has shown differences in the vertical reaction forces with the floor on heel support and the lift-off of the toes and, in particular, in the change of direction of the anterior forces to posterior forces, the instant when the foot finishes monopodal support and begins the lift-off of the toes. The vertical forces are also reduced in the kicking activity, although this test is left up to the individual patient and there is great variability from one patient to another, depending on technique and physical preparation.

In activities such as jumping and landing, the forces are applied on the foot to decelerate the centre of gravity in a very short distance[44] and the knee has a more demanding function than while walking.

Studies analyzing jumps have great variability among the subjects as each one has his or her own style or technique and most of the published studies analyze differences with age and gender or assess the physical fitness of athletes. Ford et al.[45] conducted a kinetic and cinematic analysis of vertical jumps in young sports people, focusing on the impact of the landing as a repeatable and reliable factor for detecting the risk factor for lesions to the ligaments. Nonetheless, in jumps it is necessary to bear in mind technique and patients' physical condition, so both sides must always be compared, both the side with the injury and the healthy one, against each other. Padua et al.[46] effected a study of jump and propulsion, in which patients jumped from a height but jumped up again on landing, a similar test to our box test. They studied 2,691 individuals and collected kinematic and kinetic data. Subjects with a low score, due to poor technique, obtained very different results from those who had an appropriate technique and women had worse results than men.

The box tests in our study have shown significant differences in many of the parameters as the forces were significantly lower on the injured side without any variation in times. Jumping down from a box with propulsion to jump onto another box placed in front has revealed differences in the vertical landing forces and propulsion forces, without presenting any differences in the support times. Jumping with vertical propulsion has found differences in the propulsion force in the foot on the injured side compared to the control side, but not in the landing force.

The monopodal jump, according to the recommendations of the International Knee Documentation Committee (IKDC) is a dynamic functional test of muscular co-activation[47] and it has been shown that there is a relationship with the muscle force of the lower limb in patients with a reconstructed ACL.[47-49] This test has a very direct relationship with ACL[50] as the monopodal jump test can be performed without costly equipment, is related to the tests of isokinetics and reports on the stability of the knee with activity. However, Sekiya et al.[47] did not find any link between the monopodal jump and residual anterior laxity in the reconstructed knee as the extensor and flexor muscles in the knee compensate anterior laxity during this kind of jump. In our study, despite not finding differences in the jump times, we obtained a reduction in the vertical support forces and an increase in the support times. Yet it has been seen in monopodal umps that patients with a chronic ACL lesion have the same or better functional development than uninjured control subjects.[51]

The vertical jump test is one of the most explosive tests possible as it is short-lasting and requires high intensity in connection with peak power.[52] Paterno et al.[53] saw that the vertical jump with propulsion and landing on two force platforms, in young females and athletes with an ACL injury, showed biomechanical differences between both limbs and that these persisted two years after surgery, both in the jump propulsion and in the landing. In our study, we have seen that the propulsion force is greater on the healthy side while we did not see any differences in the landing reaction forces.

The reaction force on the floor is a risk factor for injuries to the lower limbs[54] and it is necessary to take into account that, by raising the height of the fall, the peak for the floor reaction forces increases and this aggravates the risk of injury. However, a protocol based on different types of jump allows us to assess patients prior to surgery and to monitor their subsequent progress in order to enable them to return to their working and sporting lives. These tests are real and objective, and preferable to the use of equipment to assess passive anterior translation or rotation of the knee. The differences between both genders must be studied, as must the relationship with age, in both healthy individuals and people with a torn ACL, and the time to progress needed after surgery to achieve normal function must also be determined before bringing them into the clinic.

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Level of evidence

Comparative prospective study. Level of evidence II.

Conflict of interest

The authors have declared they have no conflict of interest.

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