PUBLIC UNIVERSITY OF NAVARRA. DEPARTMENT OF HEALTH SCIENCES

JUMPING BIOMECHANICS AND FUNCTION EVALUATION AMONG BOTH ELITE HANDBALL AND RECREATIONAL ATHLETES RECOVERING FROM ACUTE ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION. AN INERTIAL SENSOR UNIT BASED STUDY

Doctoral Thesis

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"Si no levantas los ojos, creerás que eres el punto más alto"

Antonio Porchia

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SUMMARY

Injury of the anterior cruciate ligament (ACL) is one of the most severe and disabling injuries in elite and recreational sport. The ACL reconstruction is performed to restore knee stability and prevent the occurrence of further injuries of adjacent structures over time [1;2].This devastating knee injury have still some concerns that despite previous conscientious scientific efforts made, researchers and clinicians haven't be able yet to clarify. This cornerstones are: the optimums rehabilitation type for successful ACL injury recovery, and the gold standard for an evidence based, objective and clinically feasible criteria for a save and competitive return to play after the suffering of this knee injury.

Studies comparing different types of rehabilitation following ACL reconstruction during the past 25 years have favored the implementation of the so-called accelerated rehabilitation programs (ACCEL)[3;4]. Originally De Carlo et al (1990)[4] and more recently Beynnon et al (2005)[3] evaluated knee joint stability as well as function related aspects among patients with ACL patellar tendon graft ACL reconstruction. More recently, other authors have opted for the implementation of this kind of rehabilitating procedure among patients undergoing a ligament reconstruction with medial hamstring grafts. These protocols are mainly based on early weight bearing and joint mobilization after surgery as well as on a more intense strength and neuromuscular training routines. Early return to full activity levels, lower residual anterior-posterior knee laxity and lower postoperative complication rates have been described among subjects following this kind of rehabilitation routines with both patellar tendon or medial hamstring grafts.

Female athletes have a greater ACL injury risk than do their male counterparts during the same jumping and pivoting tasks[5]. This greater injury risk has been associated with existing neuromuscular, anatomical and hormonal differences between sexes. Handball sport is a good example of a highly strenuous body-contact team sport with a strong emphasis on running speed, jumping, abrupt changes in direction and throwing in which enormous forces are

developed around the knee joint. Due to handball's intrinsic need for abrupt changes in direction and unplanned action management, as well as the high game intensity, anterior cruciate ligament (ACL) rupture is one of the most frequent devastating injuries among handball players. Moreover, an incomplete or insufficient rehabilitation program following an ACL injury may increase the risk of both re-injury and injury of the unaffected contra lateral knee. Thus, the identification of functional, biomechanical and neuromuscular deficits before discharging these patients from rehabilitation appears to be crucial for ACL re-injury prevention in this population. However, for elite handball athletes, the persistence of these potential alterations for several years after the original ACL injury and reconstruction despite a return to the pre-injury activity level remains controversial.

In an effort for identifying potentially risk full athletes for ACL injury, functional performance tests have been proposed as a clinically relevant option for examining functional deficits between extremities after ACL injury rehabilitation. For instance, Noyes et al. (1991) and, more recently, Myer et al. (2011) recommended the utilisation of unilateral functional jump tests after ACL reconstruction to examine deficits between extremities among collegiate recreational athletes. Biomechanical and neuromuscular alterations of trunk, hip and knee joint kinematics as well as net internal joint moments have been widely reported through the literature by using 2- or 3-dimensional motion analysis and inverse mechanics procedures during both the abovementioned functional jumps and other athletics tasks. As a practical limitation, however, the equipment needed to perform the abovementioned studies requires a considerable financial investment and implies the necessity for highly trained staff familiarised with such laboratory-derived procedures.

In order to help in providing further rationale for the commonly reproduced clinical limitations when managing ACL injured patients such as function evaluation and the kind of optimal rehabilitation protocol to follow, the present Doctoral Thesis study aimed to measure jumping performance and thereafter, biomechanics through direct mechanics based procedures by using ISUs among a cohort of professional handball athletes with or without previous ACL injury. With this in mind, we planned three descriptive cross-sectional studies (I, II,III) in which we compared the jumping performance (in terms of jumping height and reached distance) and or biomechanics (at the trunk level supported dimensional accelerations and described angular excursions) between elite handball athletes with or without previous ACL reconstruction. For doing so, we used a previously validated jumping test battery which included vertical bilateral and unilateral drop and countermovement as well as, two horizontal forward jumps. What we found was that previously ACL-reconstructed female athletes demonstrated significant ($p < 0.05$) alterations in relation to the 3 dimensional axis (X-Y-Z-) supported accelerations and differing jump phase durations, including jumping performance values, in both bilateral and unilateral jumping maneuvers several years after ACL reconstruction in comparison to controls healthy counterparts. In contrast, elite male handball athletes with previous ACL reconstruction demonstrated a jumping biomechanical profile similar to control players, including similar jumping performance values in both bilateral and unilateral jumping maneuvers, several years after ACL reconstruction.

Indeed, to evaluate the internal validity and feasibility of the ISU based technology, a validation study of the vertical jumping biomechanical evaluation by using this instrumentation was performed comparing its records to the current gold standard, the force plate (study IV). Three types of Vertical jumping tests were evaluated in order to determine if the data provided by an inertial sensor unit placed at the lumbar spine could reliably assess jumping biomechanics and to examine the validity of the ISU compared to force plate platform recordings. Robust correlation levels of the ISU sensor based jumping biomechanical evaluation with respect to the force plate across the entire analyzed jumping battery were found. In this sense, significant and extremely large correlations were found when raw data of both ISU sensor and force plate derived normalized force-time curves were compared. Furthermore significant mainly moderate correlation levels were also found between both instruments when isolated resultant forces´ peak values of predefined jumping phases of each maneuver were analyzed. However, Bland & Altman graphical representation demonstrated a systematic error in the distribution of the data points within the mean ±1.96 SD intervals.

Lastly, a clinical randomized interventional study was carried out in order to compare the effect of two differentiated rehabilitation protocols on Muscle Cross Sectional Area and Force recovery evolution as well as on knee joint anterior-posterior laxity before and one year after medial hamstrings based ACL reconstruction . Concentric isokinetic knee joint flexo- extension torque assessments at 180º/s and Magnetic Resonance Imaging (MRI) evaluations were performed before and 12 months after ACL reconstruction. Anatomical muscle CSA (mm^2) was assessed, in Quadriceps (Q), Biceps Femoris (BF), Semitendinous, (ST) Semimembranosus (SM) and Gracilis (GR) muscles at 50 and 70% femur length. In that study, (study V) we found that an objective atrophy of Semitendinosus and Gracilis muscles related to surgical ACL reconstruction was found to persist in both rehabilitation groups. In terms of mechanical muscle function, accelerated rehabilitation after ACL reconstruction lead to substantial gains on maximal knee flexor strength and ensured more symmetrical knee joint anterior-posterior laxity levels.

RESUMEN

La lesión del ligamento cruzado anterior (LCA) es una de las lesiones más discapacitante en el ámbito deportivo amateur y profesional. La reconstrucción del LCA, es realizada con el objetivo de dotar a la articulación de la rodilla de la estabilidad pasiva necesaria para evitar probables episodios futuros de inestabilidad produciendo lesiones asociadas en las estructuras articulares colindantes. Esta severa lesión de rodilla, posee todavía ciertas cuestiones que, pese a los esfuerzos científicos realizados, permanecen sin esclarecerse definitivamente. Se trata de cuestiones como el tipo de rehabilitación óptimo a llevar a cabo tras la reparación del ligamento, así como la determinación de un "estándar de oro" para un criterio objetivo y basado en la evidencia científica que permita un retorno seguro y competente a la práctica deportiva tras haber sufrido esta desafortunada lesión de rodilla.

Diversos estudios han comparado el tipo de rehabilitación a llevar a cabo tras la reconstrucción del LCA durante los últimos 25 años. , favoreciendo la implantación de las denominadas rehabilitaciones aceleradas (ACCEL). Originalmente De Carlo y cols, y más recientemente Beynnon y cols evaluaron la laxitud anterior-posterior de la rodilla así como la función de la extremidad en pacientes con reconstrucción previa del LCA utilizando plastias del tendón rotuliano. Más recientemente, otros autores, optaron por la implementación de este tipo de rehabilitaciones en reconstrucciones del LCA realizadas utilizando plastias extraídas de la musculatura isquiotibial medial. Este tipo de rehabilitaciones se fundamentan en una deambulación en carga temprana, una movilización articular intensa inmediatamente después de la cirugía así como en la utilización de rutinas de entrenamiento neuromuscular y de fuerza más intensas. Los resultados obtenidos hasta la fecha por la implantación de este tipo de rehabilitación han arrojado resultados satisfactorios en términos de menor laxitud articular residual y menor tasa de complicaciones postoperatorias, entra otras.

Las atletas femeninas poseen mayor riesgo de lesión del LCA, en comparación con los

hombres, en las mismas acciones de salto y pilotaje. Este aumento en el riesgo de lesión, se ha asociado con diferencias de género en torno a factores neuromusculares, anatómicos y hormonales existentes. El balonmano, es un buen ejemplo de disciplina deportiva en donde existe un gran énfasis en acciones explosivas de salto, cambio de dirección, carrera..etc. En consecuencia, la articulación de la rodilla se ve expuesta a grandes fuerzas mecánicas desarrolladas alrededor y dentro de esta articulación. Debido a estas características intrínsecas al balonmano descritas anteriormente, la lesión del LCA es una de las lesiones más frecuentes y discapacitante en jugadores de balonmano. Además, es conocido que una incorrecta o incompleta rehabilitación tras sufrir la lesión de LCA aumenta el riesgo de recaída e incluso de lesión articular en la rodilla contralateral. Así, la identificación de déficits funcionales, biomecánicos o neuromusculares antes de la determinación del alta médica, resulta crucial para la prevención de la recaída de la lesión del LCA. Sin embargo, en atletas de balonmano de élite, la persistencia o no de las citadas alteraciones funcionales años después del retorno al mas alto nivel de competición tras la reconstrucción y posterior rehabilitación de la lesión del LCA y su relación con un mayor riesgo lesional, permanece sin esclarecer definitivamente.

En un esfuerzo por contribuir a la identificación de atletas en riesgo de lesión del LCA, los test de evaluación funcional del atleta se han venido recomendando en la literatura científica como una opción clínica para la examinación de posibles déficits funcionales entre extremidades tras la rehabilitación consecuente a la lesión del mencionado ligamento. Noyes y cols, así como más recientemente, Myer y cols recomiendan la utilización de test de evaluación funcional unilaterales tras la rehabilitación del LCA; para la evaluación de posibles déficits funcionales persistentes entre extremidades. Asimismo, mediante el análisis de este tipo de maniobras de salto tanto verticales como horizontales, se han detectado alteraciones biomecánicas y neuromusculares a nivel del tronco y cadera, rodilla mediante el análisis de movimiento basado en cámaras Infra-rojo y plataformas de fuerzas utilizando procedimientos de mecánica inversa. Sin embargo, la tecnología y recursos materiales y humanos necesarios para completar este tipo de evaluaciones, convierta a este tipo de metodología para el análisis biomecánico del salto en una opción acotada a centros de investigaciones y universidades especializados.

Con el objetivo de contribuir al conocimiento existente y ayudar en la problemática clínica con respecto a las limitaciones técnicas existentes actualmente en relación a la evaluación funcional así como el estímulo óptimo de rehabilitación a seguir tras la lesión del LCA, la presente Tesis Doctoral se plantea la evaluación en primera instancia de la capacidad de salto y posteriormente del patrón biomecánico del mismo sobre una cohorte de jugadores profesionales de balonmano con o sin reconstrucción previa de LCA. Así, se plantearon tres estudios transversales observacionales (estudios I, II, III) en los cuales se compararon el rendimiento en el salto (en términos de altura o distancia de salto alcanzada) y el patrón biomecánico del mismo (aceleraciones soportadas en los tres ejes del espacio así como las excursiones angulares descritas a nivel del tronco) entre los atletas con reconstrucción previa del LCA, y aquellos que no presentaban dicho antecedente. Para ello, se utilizó una batería de saltos verticales previamente validados, incluyendo maniobras verticales y horizontales como el Drop vertical bilateral y unilateral, el salto contra-movimiento así como dos maniobras de salto horizontal. Los resultados arrojados por este estudió, determinaron que en las jugadoras de balonmano con antecedente previo de lesión, demostraron alteraciones significativas ($p< 0.05$) en relación a la gestión de las aceleraciones soportadas a nivel del tronco, así como diferencias en la duración de las diferentes fases del salto, incluyendo la fase de vuelo en las maniobras de salto vertical unilaterales y bilaterales analizadas, a pesar de haber retomado el deporte de alta competición y llevar varias temporadas en el mismo. Sin embargo, al realizar el mismo análisis en los jugadores masculinos, no se encontraron diferencias significativas en el patrón biomecánico del salto, ni tampoco en el rendimiento demostrado en ellos en términos de duración de la fase del tiempo de vuelo.

Por otro lado, para testar la validez interna y fiabilidad del análisis biomecánico del salto basado en la tecnología de los ISUs, se realizó un estudio de validación mediante la confrontación de los datos obtenidos por medio del ISU en la batería de saltos verticales descrita en las investigaciones previas, a los registrados por medio del estándar de oro actual, la plataforma de fuerzas (estudio IV). Se utilizaron tres tipos de salto vertical (Drop vertical unilateral y bilateral, salto contra-movimiento unilateral) para determinar si los datos reportados por el sensor inercial colocado a nivel de la columna lumbar podrían de manera fiable medir aspectos relacionados con la biomecánica del salto. Paralelamente, se analizó su validez confrontando los mismos a los registros obtenidos mediante la utilización de la plataforma de fuerzas. Los resultados obtenidos arrojaron unos niveles robustos de correlación ($r>0.9$) entre los datos obtenidos por el sensor inercial y los reportados por la plataforma de fuerzas al analizar el patrón de la curva obtenido por ambos instrumentos. Además, se encontraron niveles de correlación moderados, ($r>0.6$) cuando se parearon puntos predefinidos de la curva fuerza tiempo, obtenidos de la curva previamente definida y registrada por el ISU y la plataforma de fuerza. Sin embargo, las ilustraciones de Bland & Altaman examinadas, reportaron la existencia de un error sistemático en la distribución de la nube de puntos en la regresión dentro de los límites de ±1.96 SD, indicando que a mayor magnitud de la fuerza registrada, mayor la magnitud del error.

Por último, se efectuó un ensayo clínico aleatorizado con el objetivo de comparar el efecto de dos tipos de rehabilitación (acelerada vs. convencional), sobre la evolución de la sección transversal de la musculatura del muslo en resonancia magnética, así como de sus valores de fuerza isocinética y laxitud antero posterior de la articulación de la rodilla. Se realizaron evaluaciones antes y un año después de la reconstrucción del LCA mediante plastia obtenida de la musculatura isquiotibial medial. Los resultados obtenidos, señalaron que si bien la reducción de la sección transversal muscular seguía evidenciándose en ambos grupos a nivel de la musculatura isquiotibial con respecto a la extremidad contralateral sana, los niveles de fuerza y la laxitud antero-posterior de la rodilla resultaron significativamente ($p<0.05$) mas favorables (mayores niveles de fuerza tanto de Cuádriceps como de isquiotibiales y menor laxitud articular) en el grupo que siguió una rehabilitación acelerada en comparación con los sujetos que llevaron una rehabilitación convencional.

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LIST OF ABBREVIATIONS

%: Percentage

ACL: Anterior Cruciate Ligament

VBDJ: Vertical Bilateral Drop Jump

VUDJ: Vertical Unilateral Drop Jump

VUCMJ: Vertical Unilateral Counter Movement Jump

ISU: Inertial Sensor Unit

CONV: Conventional Rehabilitation

ACCEL: Accelerated Rehabilitation

VGRF: Vertical Ground Reaction Force

AP Laxity: Anterior-posterior Laxity

1. INTRODUCTION

1.1 Effects of previous ACL reconstruction on jumping performance in elite handball sport

Handball is a highly strenuous body-contact team sport with a strong emphasis on running speed, jumping, abrupt changes in direction and throwing [6]. Due to handball's intrinsic need for abrupt changes in direction and unplanned action management, as well as the high game intensity, anterior cruciate ligament (ACL) rupture is one of the most frequent devastating injuries among handball players [7]. Female athletes have a greater ACL injury risk than do their male counterparts during the same jumping and pivoting tasks [5]. This greater injury risk has been associated with existing neuromuscular, anatomical and hormonal differences between sexes [8]. Moreover, an incomplete or insufficient rehabilitation program following an ACL injury may increase the risk of both re-injury and injury of the unaffected contra lateral knee [9]. Thus, the identification of functional, biomechanical and neuromuscular deficits before discharging these patients from rehabilitation appears to be crucial for ACL re-injury prevention in this population.

Functional performance tests are possibly a clinically relevant option for examining functional deficits between extremities after ACL injury rehabilitation. For instance, Noyes et al. (1991)[10] and, more recently, Myer et al. (2011)[11] recommended the utilisation of unilateral functional jump tests after ACL reconstruction to examine deficits between extremities among collegiate recreational athletes. Biomechanical and neuromuscular alterations of trunk, hip and knee joint kinematics as well as net internal joint moments have been widely reported through the literature by using 2- or 3-dimensional motion analysis and inverse mechanics procedures[12-14], during both the abovementioned functional jumps and other athletics tasks.

In relation to handball sport, Myklebust et al[15] identified functional, strength and anterior-posterior knee joint laxity differences between both ACL injured and uninjured professional and recreational handball players in the long term since ACL injury event. It seems plausible that the available athlete´s surrounding medical staff and material resources could vary depending on the level of competition in which the player is enrolled. This fact could affect injury rehabilitation and return to play outcomes. However, for elite handball athletes, the persistence of these potential alterations for several years after the original ACL injury and reconstruction despite a return to the pre-injury activity level remains controversial.

1.2 Effects of previous ACL reconstruction on jumping biomechanics among elite handball male athletes

Handball is a highly strenuous contact team sport with a strong emphasis on running speed, jumping, abrupt changes in direction and throwing[6]. As a consequence, anterior cruciate ligament (ACL) rupture is one of the most frequent and devastating injuries among handball players[7]. Evidence for neuromuscular or biomechanical risk factors for ACL injuries in male athletes appears to be mainly related to dysfunctions occurring at the trunk and hip joint levels[21]. In this context, video analysis techniques have revealed that athletes with ACL injuries have greater center of mass to base of support distances and lower trunk angles in the sagittal plane relative to the resultant vector of the ground reaction force compared with those in uninjured subjects[22]. Reduced hip range of motion, especially internal rotation, has also been found in male soccer players with previous ACL injuries[23].

It is well known that an incomplete or deficient rehabilitation program after an ACL injury may increase the risks of both re-injury and ACL injury in the contralateral unaffected knee[9]. Thus, the identification and assessment of functional, biomechanical and neuromuscular deficits when discharging athletes with a previously reconstructed ACL from rehabilitation appear to be crucial for preventing ACL re-injury[24].

Functional performance tests are a clinically relevant option for examining functional deficits between extremities after ACL injury rehabilitation. Noyes et al[10], and later Myer et al[11], recommended the utilization of unilateral functional jump tests after ACL reconstruction to examine deficits between extremities among collegiate recreational athletes. Two- or three-dimensional motion analyses and inverse mechanics procedures[12-14] have been used to detect biomechanical and neuromuscular alterations of trunk, hip and knee joint kinematics as well as net internal joint moments during both functional jumps and athletic tasks in athletes with a previous ACL injury.

The development of micro-electromechanical systems has produced inertial sensor unit

(ISU) systems as a new alternative for sports-related movement performance assessment and as a clinical resource in the ACL rehabilitation field[25]. Briefly, ISU systems provide the linear acceleration and angular displacement orientation values in a sensor-fixed Cartesian reference frame (XYZ). Therefore, ISUs offer the possibility of landing outside of a predefined place, as opposed to traditional ground-located force plates. This capability enables a more functional and unplanned movement analysis. Previous studies using ISU-based technologies have highlighted the potential of this measurement technique to identify different persistent movement pattern alterations under conditions of ACL injury[16-18]. However, the aforementioned studies used multiple sensors on body segments. These sensors improved the measurement accuracy but rendered the clinician unable to reproduce this type of movement evaluation in a clinical setting[20]. To simplify the measurement methodology, the present study aimed to measure jumping biomechanics using direct mechanics-based procedures. With these procedures, the body's center of mass behavior during the execution of several vertical jumping tasks could be recorded and further analyzed using the obtained vertical velocity by time curves.

1.3 Effects of previous ACL reconstruction on jumping biomechanics among handball female athletes

Handball is a highly strenuous body-contact team sport with a strong emphasis on running speed, jumping, abrupt changes in direction and throwing [6]. Due to handball's intrinsic need for abrupt changes in direction and unplanned action management, as well as the high game intensity, anterior cruciate ligament (ACL) rupture is one of the most frequent devastating injuries among handball players [7]. Female athletes have a greater ACL injury risk than do their male counterparts during the same jumping and pivoting tasks [5]. This greater injury risk has been associated with existing neuromuscular, anatomical and hormonal differences between sexes [8]. Moreover, an incomplete or insufficient rehabilitation program following an ACL injury may increase the risk of both re-injury and injury of the unaffected contra lateral knee [9]. Thus, the identification of functional, biomechanical and neuromuscular deficits before discharging these patients from rehabilitation appears to be crucial for ACL re-injury prevention in this population.

Functional performance tests are possibly a clinically relevant option for examining functional deficits between extremities after ACL injury rehabilitation. For instance, Noyes et al. (1991)[10] and, more recently, Myer et al. (2011)[11] recommended the utilisation of unilateral functional jump tests after ACL reconstruction to examine deficits between extremities among collegiate recreational athletes. Biomechanical and neuromuscular alterations of trunk, hip and knee joint kinematics as well as net internal joint moments have been widely reported through the literature by using 2- or 3-dimensional motion analysis and inverse mechanics procedures[12-14], during both the abovementioned functional jumps and other athletics tasks.

In relation to handball sport, Myklebust et al[15] identified functional, strength and anterior-posterior knee joint laxity differences between both ACL injured and uninjured professional and recreational handball players in the long term since ACL injury event. It seems plausible that the available athlete´s surrounding medical staff and material resources could vary depending on the level of competition in which the player is enrolled. This fact could affect injury rehabilitation and return to play outcomes. However, for elite handball athletes, the persistence of these potential alterations for several years after the original ACL injury and reconstruction despite a return to the pre-injury activity level remains controversial.

As a practical limitation, however, the equipment needed to perform the abovementioned studies requires a considerable financial investment and implies the necessity for highly trained staff familiarised with such laboratory-derived procedures. These types of measurements have been performed only in laboratories using expensive and complex tools, such as camera motion analysis systems and/or force-plates. The development of micro-electromechanical systems have made inertial sensor units (ISU) new alternative for sports-related movement performance assessments, as well as a clinical resource in ACL rehabilitation[16]. Briefly, ISU systems provide the linear acceleration and angular displacement orientation values in a sensor-fixed Cartesian reference frame (XYZ). In this way, ISUs offer the possibility of landing outside of a predefined place as the traditional ground located force plates do. This fact enables a more functional and unplanned movement analyses .The potential of this measurement techniques to identify movement patterns alterations in relation to ACL injury[16-18] and other orthopedic fields[19] has already been proved in previous studies. However, the above mentioned studies used multiple sensors among body segments. This fact adjusted the measurement accuracy but rendered the clinician unable to reproduce that measurement technique in the clinical setting[20]. In order to simplify measurement methodology, the present study aimed to measure jumping biomechanics through direct mechanics based procedures. By doing so, body´s centre of mass behavior during the execution of several vertical jumping tasks would be recorded and further analyzed by the reported vertical velocity by time curves.

1.4 Validation of an Inertial Sensor Unit- based technology vs Force plate for Vertical Jumping Biomechanical evaluation

Vertical jumping performance is considered a key component of many training routines in numerous sport disciplines and conditioning programs[39-41]. For instance, it has a direct influence on several explosive activities such as jumping and sprinting[42]. Moreover, in the last 30 years, other athletic tasks such as vertical drop jumps have also been studied and implemented by athletic coaches to maximize the performance of explosive activities[43]. In the field of sports biomechanics, vertical jumping maneuvers have been widely studied. The main goal of these studies has been to clarify several concerns related to adaptations of the human body to exercise and to describe basic movement patterns[44]. To do so, direct mechanics-based procedures have been utilized to estimate the center of mass displacement and to detail the biomechanics of jumping[42;44].

However, many other methods and instrumentations have recently been developed to evaluate vertical jumps[45]. Briefly, some such as optical cells and contact mats have been developed to assess jumping performance in terms of the jumping time duration[46;47]. Others, through the description of force and/or vertical velocity by time curves, have estimated the center of mass movement in humans[48;49].

To describe the direct or inverse mechanics-based biomechanics of vertical jumping maneuvers, force plates have become the gold standard during the last decades[50]. As such, numerous research articles related to vertical jumping-related biomechanics focused on both performance enhancement[40;51;52] and injury prevention and rehabilitation[53;54] have been published. In the latest study, Myer et al[11]recommended the utilization of unilateral functional jump tests after ACL reconstructions to examine the deficits between extremities among collegiate recreational athletes.

However, the equipment needed to perform the abovementioned studies requires a considerable financial investment and implies the necessity for highly skilled technicians familiarized with such laboratory-derived procedures. Recently, the latest advances in micro-electromechanical systems have turned inertial sensor units (ISUs) into a suitable tool for sports motion analysis related to both performance-related[45] and injury rehabilitation and prevention -related fields[55]. Briefly, ISU systems provide the linear acceleration and angular displacement orientation values in a sensor-fixed Cartesian reference frame (XYZ). In this way, ISUs offer the possibility of landing outside of a predefined place as opposed to traditional ground located force plates. This fact enables a more functional and unplanned movement analyses at the training field itself[17].

1.5 Muscle morphology and strength evaluation after two different rehabilitation programs following Anterior Cruciate Ligament Reconstruction

Injury of the anterior cruciate ligament (ACL) is one of the most severe and disabling injuries in sport[1;26]. The ACL reconstruction is performed to restore knee stability and prevent the occurrence of further injuries of adjacent structures over time[1;2]. Autologous tendons remain the most frequent graft choice to perform the ligament repair[1]. Medial hamstrings grafts have been increasingly employed along these last years for ACL reconstruction due to its associated lower donor site morbidity[27], good material mechanical properties, minimal impact on the knee extensor mechanism and excellent postoperative outcomes[28-30].However, some limitations have been described for medial hamstring ACL reparative technique. Greater knee laxity[31], persistent knee flexor atrophy in terms of muscle size[1;32] and strength deficits[30] have been reported along with a greater short-term risk for hamstring strain injury after returning to sports[33;34]

Studies comparing different types of rehabilitation following ACL reconstruction during the past 25 years have favoured the implementation of the so-called accelerated rehabilitation programs (ACCEL)[3;4]. Originally De Carlo et al (1990)[4] and more recently Beynnon et al (2005)[3] evaluated knee joint stability as well as function related aspects among patients with ACL patellar tendon graft ACL reconstruction. More recently, other authors[34;35], have opted for the implementation of this kind of rehabilitating procedure among patients undergoing a ligament reconstruction with medial hamstring grafts.

Although many clinical trials have been carried out comparing this methodology to conventional rehabilitation procedures, there is not an accepted single standard for the definition of an accelerated rehabilitation program. These protocols are mainly based on early weight bearing and joint mobilization after surgery as well as on a more intense strength and neuromuscular training routines. Early return to full activity levels, lower residual anterior-posterior knee laxity and lower postoperative complication rates have been described among subjects following this kind of rehabilitation routines with both patellar tendon or medial hamstring grafts[3;4;34].

Isokinetic dynamometry and magnetic resonance imaging (MRI) are the most commonly used methods to evaluate both muscle strength and morphology among the previously ACL reconstructed population. The peak torque for muscle force production and the cross sectional area of thigh muscles have been widely studied in this field[36]. Quadriceps and Hamstring peak torque values represent the highest value of muscle force that the subject produces during the knee motion from 90º to 0º in both extensor and flexor efforts. Although there have been reported several methods for isokinetic hamstring muscle function assessment[37], controversy remains with respect to the influence of previous medial hamstring harvest for ACL reconstruction on successful returning to sports[1]. This fact have favored studies focusing on entire torque-angle curves as well as on the optimum angle for peak torque development among this population[38]. Inconclusive results have been reported, probably due to several factors such as differences in time from evaluation to prior surgery, the biological mechanisms associated with regeneration of the harvested tendon[32], and divergences in the rehabilitation protocols followed that could play a key role in the recovery of hamstring musculature function[28;38]. In this context, to our best knowledge, there are not in the literature investigations focusing on the comparison of accelerated vs. conventional rehabilitation protocols following ipsilateral autologous medial hamstrings ACL reconstruction with regards to muscle strength and morphology recovery rates.

The relevance of the full functional capacity restoration on both successful clinical outcomes in the short term as well as on the return and maintenance of elite sports activity level (i.e. handball) following previous ACL reconstruction has been widely highlighted. In this context, the potential clinical and performance implications that ISU technology-based methodology would have in the athlete's and or patient's jumping biomechanical evaluation, taken together with the effect two different rehabilitation programs administration following ACL reconstruction would have on patients clinical outcome, lay the foundation of the present doctoral thesis which has the following hypothesis:

2. HYPOTHESIS

H_1: The study hypothesis posited that differences in jumping performance should be present among the previously ACL-reconstructed elite professional handball athletes compared with the control participants, despite several years having passed since the original injury and despite current competition at their preinjury level of sport performance. Due to the higher injury incidence reported among female athletes due to their sex-dependent neuromuscular, biomechanical and physiological characteristics, it was hypothesized that the differences would be greater among female athletes than among their male counterparts. (***Study I***).

H_2: The present study hypothesized that different jump phase durations as well as greater supported peak acceleration in the mediolateral and anterior-posterior axes and trunk angular displacement excursions would be present in male athletes with previous ACL reconstruction compared with control non-ACL reconstructed male athletes; and that these differences would primarily occur during unilateral actions. This assumption was formulated despite the fact that several years had passed since the original injury and that the athletes were currently competing at their pre-injury performance level. (***Study II***).

H_3: The hypothesis of the present research was based on previous research[16-18] and posited that ACL-reconstructed athletes would cope with greater supporting 3-axis peak accelerations, as well as less jumping performance (expressed as the duration in s of the flight time phase of the jump) compared with the control non ACL injured female counterparts. These long term lasting abnormalities would emerge during the execution of a jumping test battery that comprises both bilateral and unilateral maneuvers. (***Study III***).

H_4: The study hypothesis posited that the force by time curves obtained from the ISU during the execution of a vertical jump task would become valid and reliable in terms of correlation robustness and absolute coefficient of variation respectively; in comparison to the force plate (as

the gold standard) recordings. This assumption is based on previous research reporting acceptable levels of concordance between ISUs and force plates for isolated biomechanical analyzed variables of the analyzed force by time curve. (***Study IV***).

H_5: It was hypothesized that better mechanical muscle performance (exerted peak torque) and muscle cross sectional areas would be improved to a greater extent among subjects following an accelerated rehabilitation program. (***Study V***).

In order to test the abovementioned hypothesis, we conducted five experiments with the following objectives:

3. OBJECTIVES

O_1: the objective of the present study was to examine the differences between previously ACL-reconstructed and rehabilitated elite professional handball athletes and sport level, sex and age pairs of uninjured control participants by measuring their jumping performance in a training practice during their regular season. (***Study I***).

O_2: Therefore, the purpose of this study was to examine biomechanical jumping profiles in a cohort of elite male handball players with or without previous ACL reconstruction using a single portable ISU. Published studies on subjects with previous ACL reconstruction have reported increased trunk angular excursion[56] as well as greater supported peak vertical ground reaction force (VGRF)[14].(***Study II***).

O_3: The purpose of this study was therefore to examine the biomechanical jumping differences between previously ACL-reconstructed and returned-to-sport elite professional female handball athletes and sport-level, sex- and age-matched pairs of uninjured control participants. In order to achieve this goal a single Inertial Sensor Unit based simplified analysis was used. (***Study III***)

O_4: In this context, the purposes of the present study were (1) to determine if the data provided by an inertial sensor unit placed at the lumbar spine could reliably assess jumping biomechanics and (2) to examine the validity of the ISU compared to force plate recordings. (***Study IV***).

O_5: The objective of the present study was, therefore, to compare the effect of two differentiated rehabilitation programs (accelerated and conventional) on hamstring muscle strength and size 12 months after ACL reconstruction using a doubled (i.e., four strand) Semitendinosus and Gracilis tendons autograft. (***Study IV***).

4. METHODS

4.1 Study I

4.1.1 Design:

A cross-sectional study with one factor (previous ACL injury) was performed to examine jumping performance differences between previously ACL-reconstructed rehabilitated elite professional handball players and sport level, age and sex-pairs of uninjured controls by sex by measuring jumping performance in a training practice during their regular season.

4.1.2 Participants:

The study population consisted of 43 participants: 22 male (6 ACL-reconstructed and 16 uninjured controls) and 21 female (6 ACL-reconstructed (bilaterally in 2) and 15 uninjured controls) elite handball players. The average time ± standard deviation (SD) since surgical reconstruction was 6.0 ± 3.5 and 6.3 ± 3.4 years in the female and male groups, respectively. All athletes were competing in top-division national leagues. Recruitment was performed through personal interviews with the team managers of each club. The authors used a convenience sample based on available elite level handball players in the region where the research was carried out. Prior injury records were collected by asking players via questionnaire before starting the testing session. These data were corroborated by consulting the medical staff's injury report at each club. All athletes with previous serious lower limb injury (more than 6-week duration and/or surgical treatment required) in the last 3 years, apart from ACL reconstruction procedures, were excluded from participation in the study.

The age and anthropometric characteristics of both the female and the male athletes are shown in Tables 1 and 2, respectively. The dominant leg was defined as the leg that the athletes would use if they were required to jump and then throw a ball. The distribution of the predefined jumping legs in the studied population consisted of 14 left-limb- and 7 right-limb-dominant female participants and 17 left-limb- and 5 right-limb-dominant male participants.

Among the ACL-injured participants, 3 of 4 athletes in the ACL-injured female group with unilateral ACL reconstruction had an ACL injury affecting their dominant limb, whereas only 2 of 6 athletes in the ACL-injured male group had a previous ACL injury compromising their dominant leg. The participants and coaches were informed in detail about the experimental procedures and the possible risks and benefits of the project. The project was approved by the Ethical Committee of the Public University of Navarra and performed according to the Declaration of Helsinki.

4.1.3 Procedures:

The participants performed a previously validated[10;14;57;58] and reliable[53;59] jump test battery for detecting limb asymmetries following ACL injury in athletes. The jump test battery included a vertical bilateral drop jump (VBDJ), a vertical unilateral drop jump (VUDJ), a vertical unilateral countermovement jump (VUCMJ), and two horizontal jumps: the unilateral triple hop for distance (UTHD) and the unilateral cross-over hop for distance (UCHD). For the unilateral jump tests, both the dominant and the non-dominant legs were individually tested in all subjects. Two practice tests were given to each participant to ensure comfort with the task prior to data collection. In all of the tests, the participants were instructed to place their hands on their iliac crest and could not modify that position through the execution of each task. No jumping technique explanation was given in an attempt to avoid execution modification.

The test-retest intraclass correlation coefficients for all anthropometric and jumping variables were greater than 0.95, and the coefficients of variation ranged from 0.94% to 1.5%.

For the VBDJ, the subject was positioned on top of a 50 cm box and instructed to drop off the box, with both feet leaving the box simultaneously and each foot landing on an infrared curtain system (Sport Jump System Pro, DSD Spain, León, Spain), and then immediately execute a maximal-effort vertical jump.

For the VUDJ, the subject was positioned on top of a 20 cm box and instructed to drop off the box with one foot and, after landing on the infrared curtain system, to execute a maximal vertical unilateral jump. For both jumps, the flight and contact times were measured with the aforementioned equipment.

For the VUCMJ, the subject was asked to perform a unilateral countermovement jump from an extended leg position down to approximately 90° of knee flexion, immediately followed by a concentric action in which the subject jumped to a maximal height. The flight times were measured with the abovementioned equipment.

The UTHD and UCHD were performed as reported by Noyes et al.[10]. For the UTHD, the participants stood on one leg, performed three consecutive horizontal hops as far as possible and landed on the same foot, maintaining the last landing position for at least one second. The total distance hopped was measured.

For the UCHD, the subject stood on one leg and hopped three consecutive times on one foot to cross over a 15 cm-wide and 8 m-long center strip marked on the floor. The subject had to successfully land each hop without falling inside the 15 cm-wide strip marked on the floor and to maintain his/her balance after having landed the last jump for at least one second. The subject had to successfully land each hop without stepping on the strip and to maintain the end of the last jump for at least one second. The total distance hopped was measured.

For the unilateral jump tests, intragroup comparisons were performed between the reconstructed legs and the healthy opposite sides of the injured participants and between the dominant and the non-dominant extremities of the control participants. In the case of athletes with bilateral ACL reconstruction, this analysis was not carried out. Furthermore, after having confirmed no dominance effect between the extremities among the healthy control participants by performing a two-tailed paired t-test between the dominant and the non-dominant limbs of control subjects, the reconstructed legs were compared with the dominant lower extremities of the control group for the intergroup comparison. This data analysis concerning the intergroup comparison was conducted to avoid any intra-subject compensation bias that may have existed after ACL injury[57].

All participants performed the test at the beginning of a routine training session that was conducted during the competitive season and at least 48 hours after the last competitive game. For all jumping tests, two trials were performed, interspersed with 10 seconds of rest between repetitions, and the best trial was recorded for further analyses[60]. During the VBDJ, VUDJ and VUCMJ, the flight and contact times (s) were recorded with the infrared curtain system. In the drop maneuvers, the mechanical power $W \cdot kg^{-1}$ output was calculated as previously described in the literature[60]. In the horizontal jump tests, the distance reached (cm) was measured with a standard tape measure.

The lower limb symmetry index (LSI) for the jumping performance of the previously injured athletes was calculated using the following ratio:

$$\frac{\text{Reconstructed limb}}{\text{Contralateral healthy limb}} x100$$

The clinically relevant percentage was set at a more than 15% difference between the achieved intra-subject extremity scores, as previously described in the literature[10].

4.1.4 Statistical Analyses:

Standard statistical methods were used to calculate the means and SDs. The different outcome measures were verified for normal distribution using the Kolmogorov- Smirnov test. A two-tailed unpaired t-test was performed for the mean comparison between the subjects' lower limb scores (dominant control vs. previously ACL-reconstructed legs). A two-tailed paired t-test was used to analyze intragroup between-limb differences. The significance level was set at $p \leq 0.05$.

A prospective calculation of sample size was performed using data previously reported by Schiltz et al.[61] and Myklebust et al.[15] for vertical and horizontal jumps, respectively (PS software for power size biostatistics, version 3.0.43, Vanderbilt University, Tenneesse USA). Assuming a power of 80% and a type I error rate of 0.05, the estimated sample size required to accomplish this study was 57 subjects in each group for the VUCMJ, 60 for the VBDJ and 4 for the UTHD. Previous studies' samples were not specific to elite professional handball players. All elite professional handball players in our region were recruited to determine whether jumping performance deficits could also persist among fully trained, highly supervised handball athletes. The post-hoc power analysis revealed that the power value of the present study (based on the present cohort data) was 0.265 for vertical jumps and 0.203 for horizontal maneuvers.

4.2 Study II

4.2.1 Experimental approach:

A descriptive case series study was performed. The experiment was conducted at the athletes' habitual training court. The participants performed a vertical jump test battery that included a 50 cm vertical bilateral drop jump (VBDJ), 20 cm vertical unilateral drop jump (VUDJ), and vertical unilateral countermovement jump (VUCMJ). The jumping test battery chosen for this study has been considered reliable for measuring limb asymmetries following ACL ligament injury in athletes[57;58;62] **(Figure II-1)**. The test-retest intraclass correlation coefficients for jumping variables were greater than 0.95 in a previous study conducted on ACL-reconstructed subjects[63].

Figure II-1. *VBDJ (top), VUDJ (middle), and VUCMJ (bottom) jumps explaining illustration*

4.2.2 Subjects:

The study population consisted of 22 elite male handball players (6 ACL-reconstructed cases and 16 non-ACL-injured controls). The average and standard deviation of the time since surgical reconstruction was 6.3 ± 3.4 years.

All the athletes were competing in their respective top division national leagues. Athletes were recruited through personal interviews with the team managers of two clubs in our region. Prior injury records were obtained via questionnaires before starting the testing session and were subsequently corroborated by injury reports from the medical staff at each club. Athletes in the control group with a previous lower limb injury that lasted more than 6 weeks were excluded from the study. This decision was made to avoid jumping pattern bias due to potential lasting functional alterations from other severe lower extremity injuries. The participants and coaches were informed in detail about the experimental procedures and the possible risks and benefits of the project. The study was approved by the Ethical Committee of the Public University of Navarra and was performed according to the Declaration of Helsinki.

4.2.3 Equipment:

An inertial orientation tracker (MTx, 3DOF Human Orientation Tracker, Xsens Technologies B.V., Enschede, Netherlands) was attached over the L3 region of the subject's lumbar spine, and this tracker provided kinematic variables at a sampling rate of 100 Hz **(Figure II-2)**. A technical explanation describing the inertial sensor-derived variables has been previously published[64].

Figure II-2. *Inertial sensor placement illustrative picture*

4.2.4 Procedures:

The ages and anthropometric characteristics of the athletes were recorded prior to starting the testing session (**Table II- 1**).

	All participants		**Controls**		**ACL reconstructed**	
Age (years)	25.59	(1.01)	24.81	(1.27)	27.67	(1.26)
Weight (kg)	90.43	(2.01)	89.81	(2.49)	92.08	(3.48)
Height (cm)	188.24	(1.42)	188.23	(1.80)	188.25	(2.31)
*=T – test P value < 0.05 with respect to control group; Kg = Kilograms; cm= centimetres						

Table II- 1. *Anthropometric data. Values expressed as mean and (SEM)*

Leg dominance was defined as the leg the athletes would use if they were required to push off the ground and then throw a ball, as previously described in handball[65]. The distribution of the predefined jumping leg among the studied population included 17 left-limb- and 5 right-limb-dominant male participants. Among the ACL-reconstructed participants, 2 of 6 athletes had a previous ACL injury in their dominant leg.

The ISU provides the linear acceleration and angular displacement orientation values in a sensor-fixed Cartesian reference frame (XYZ). Before beginning the test, the subject stood on the ground with his back in an upright position, and the sensor-fixed reference frame was aligned with an Earth-fixed global reference frame (XYZ), with the Z-axis in the vertical direction pointing upwards, the X-axis in the mediolateral direction and the Y-axis in the anteroposterior direction **(figure II-3)**.

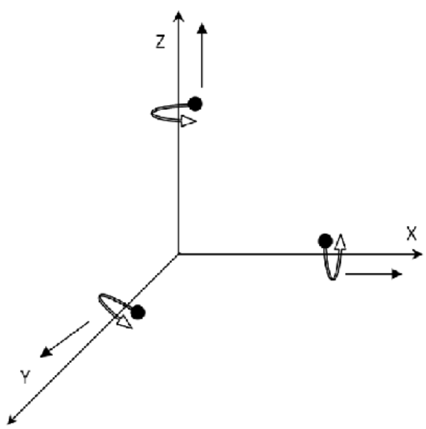


Figure II-3. *Inertial Sensor Unit (ISU) measurement in relation to Cartesian axes alignment explanation. Orientation (white arrows) = Displacements measured turn around the axis(X-) axis = Forward (-) and backward (+) turns; (Y-) axis = Left side (-) and right side directed turns (+) ;(Z-) axis= Clockwise (-) and counter clockwise (+) turns. Acceleration (dark arrows)_= Displacements measured aligned within the axis. (X-) axis = Left side (-) and right (+) side directed accelerations; (Y-) axis = Forward (-) and backward (+) directed accelerations; (Z-) axis= Clockwise (-) and counter clockwise (+) directed accelerations*

All the participants performed the test at the beginning of a routine training session during the competitive season that was at least 48 hours after their last competition. Jumping methodology descriptions have been published elsewhere[66]. Briefly, each participant was allowed to carry out two practice trials to ensure comfort with the task prior to data collection. Two further test trials were performed, with approximately 10 seconds of rest between jumps[66]. The number of repetitions of each jumping task was constant, and the jump battery protocol was fixed. The jump task execution order was from easy to complex execution requirements to avoid possible injury risks associated with the intensity of the jumping tasks.

Direct mechanics-based procedures were utilized to estimate the center of mass displacement and to detail the jumping biomechanics. The direct mechanics procedure is based on the description of the subject as a mechanical system and the estimation of movement and actuation of forces through displacement of the center of mass[50]. The positioning of the ISU at the lumbar spine level, the presumptive location of the human center of gravity[48], and the vertical velocity by time descriptive curves were both based on this approach.

4.2.5 Data processing and analysis:

Each jump was broken down into different phases to enable a more comprehensive biomechanical analysis. Different events were defined based on vertical velocity recordings. Once the different events of the jumping maneuvers were identified, the different phases could be defined, and the peak acceleration and orientation variables of each jump were analyzed by jump phase and jump type.

For the VBDJ and VUDJ, the T1 event was signaled by an abrupt positive change in vertical (Z-axis) velocity, which determined the start of the active negative (eccentric) action of the initial absorption phase, when the center of mass of the athlete was in its lowest position. The T2 event corresponded to the instant that the vertical velocity first passed zero in the transition between the initial absorption and the propulsive phases of the jump. The T3 event corresponded to the instant in which the maximum positive vertical velocity was achieved. Subsequently, the T4 event was documented when the vertical velocity again reached a maximum value, and the final T5 event was noted when the vertical velocity returned to zero after the jump (**Figure II.4 top**).

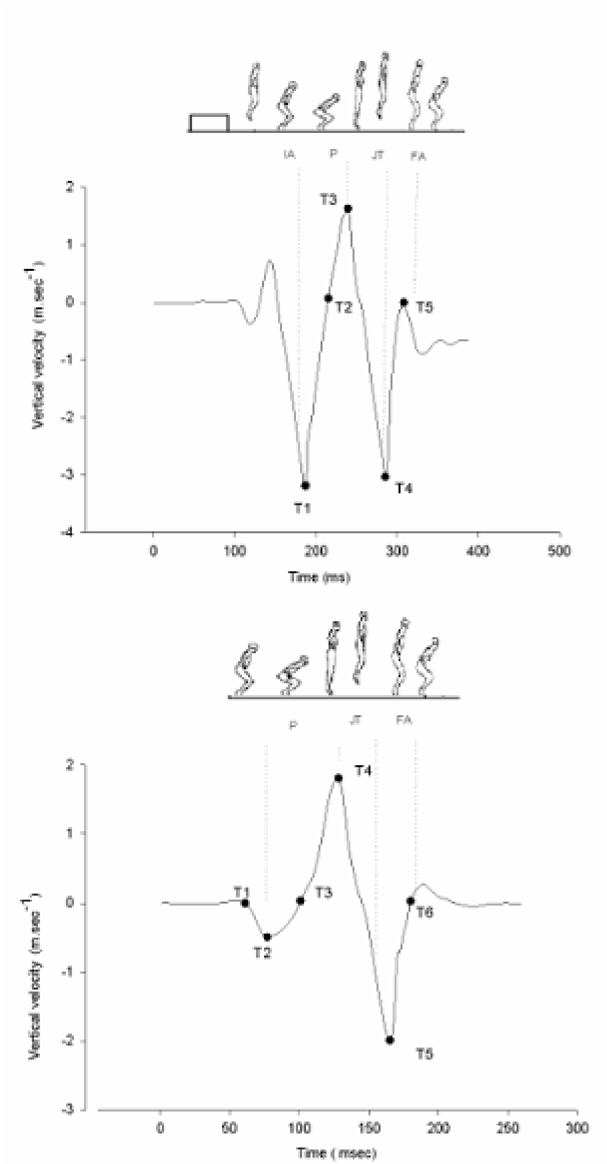


Figure II-4. *(Z-) vertical axis linear velocity descriptive curves. VBDJ Explicative illustration (top) VUCMJ Explicative illustration (bottom). IA = Initial Absorption; P = propulsive phase; JT = Jumping time; FA= Final Absorption*

For the VUCMJ, the action (the T1 event) began when the first negative Z-acceleration was produced. Next, negative passive and active work (pre-stretch) was performed during the "propulsive phase." The subsequent T2 event was determined when the maximum vertical negative velocity was reached (lowest position of the center of mass). T3 was denoted by the instant the vertical velocity first passed through zero in the transition between the initial absorption (countermovement in the case of VUCMJ) and the propulsive phases of the jump. The T4 event corresponded to the instant at which the maximum positive vertical velocity was achieved. Subsequently, the T5 event occurred when the vertical (Z-axis) velocity again reached a maximum value, and the final T6 event was denoted by the point when the vertical velocity reached zero after the jump (**Figure II-4 bottom**).

For every cycle, the Z-velocity signal was used to distinguish the peak from the transition phases of each jump (for example, subject moving upwards = positive Z-velocity at the propulsive phase; subject moving downwards = negative Z-velocity at the landing phase). All of the information was combined to define the boundaries between the different relevant phases: initial absorption, propulsive and final absorption for the drop jumps (bilateral and unilateral) and propulsive and final absorption for the countermovement jumps (**Figure II-4**).

The absorption phase of the jump was defined as the portion of the jump in which the subject endured negative acceleration relative to the instant previous to the initial contact (or active impulse exertion) and the management of the impact against the ground (negative followed by positive vertical axis acceleration corresponding to the vertical axis decomposition of the ground reaction force recorded by the ISU). There were two absorption phases described for the Drop Jumps: initial absorption (IA; T1-T2 events) and final absorption (FA; T4-T5 events). For VUCMJ, an alternative final absorption phase (FA; T5-T6 events) was described (**Figure II-4**).

The propulsive phase of the jump was defined as the portion of the jump in which the subject exerted a positive force, representing an active concentric action against the ground (positive vertical axis acceleration recorded by the ISU) (**Figure II-4**). This phase corresponds to T2-T3 events for drop jumps and T3-T4 events for the VUCMJ.

The flight time of the jump was determined as the portion of the jump in which the subject was not exerting any force against the ground (no positive vertical axis accelerations recorded by the ISU) (**Figure II-4**). This phase corresponds to T3-T4 events for drop jumps and

T4-T5 events for the VUCMJ.

Once the different events were identified based on vertical velocity recordings, the linear acceleration, orientation and jumping phase times were evaluated to obtain the relevant parameters at each phase. This automated data analysis procedure was performed using Matlab 7.11 (MathWorks Inc; Natick, MA, USA).

Descriptive statistical methods were used to calculate the mean and standard error of the mean (SEM). The different outcomes were verified to have normal distributions using Levene's test. In the case of the VBDJ, only a two-tailed unpaired t-test was performed to compare the means between groups (controls vs. previously ACL-reconstructed subjects). For the two unilateral jumping modalities, a one-way analysis of variance (ANOVA) was performed to compare differences between limbs with subsequent Bonferroni post hoc comparisons. When the variance equality was rejected, Tamhane's post hoc test was performed. The significance level was set at $P \leq .05$.

A priori power analysis was not possible to perform due to the lack of previous research using the same jumping methodology. A post hoc power analysis (PS, Power Size Biostatistics version 3.0.43., University of Vanderbilt, USA) revealed a power of 0.551. In terms of reliability, the ISU device in the present study reported CV values that ranged from 1-17% and ICC values that ranged from 0.71-0.93.

4.3 Study III

4.3.1 Experimental approach:

A descriptive case series study design was carried out. The experiment was carried out at the athletes´ habitual training court. The participants performed a vertical jump test battery that included a 50 cm vertical bilateral drop jump (BJ), 20 cm vertical unilateral drop jump (UJ), and vertical unilateral countermovement jump (UCMJ). The jumping test battery chosen for the study has been considered reliable for measuring limb asymmetries following ACL ligament injuries in athletes[57;58;62] **(Figure II-1)**.

4.3.2 Subjects:

The study population consisted of 21 female. There were 6 ACL-reconstructed, two of them bilaterally repaired (*M* ± *SD*; age 26.4 ± 1.4 years; height 169.0±1.6 cm; and weight 61.8±1.4 kg) and 15 uninjured controls (*M* ± *SD*; age 25.1±1.4 years; height 175.0±1.4 cm; and weight 69.5±1.8 kg) elite handball players. All of them were competing in their respective top division national leagues. This cohort of elite athletes was the one available in the region where the study was performed. Recruitment was performed through personal interviews with the team managers of two clubs in our region. Prior injury records were obtained via questionnaires before starting the testing session, which was confirmed with the medical staff's report of injuries in each club. In those athletes with bilateral reconstructions, both legs were recorded as ACL reconstructed limbs. The average and standard deviation of the time since surgical reconstruction was 6.0±3.5 years. All of the athletes were competing in their respective top division national leagues.

All of the athletes were competing in their respective top division national leagues. Recruitment was performed through personal interviews with the team managers of two clubs in our region. Prior injury records were obtained via questionnaires before starting the testing session, which corroborated with the report of injuries by the medical staff of in each club. Athletes in the control group with a lower limb injury in the past lasting more than 6 weeks were excluded from the study in order to avoid jumping patterns bias due to other lower extremity severe injury´s associated potential lasting functional alterations . The participants and coaches were informed in detail about the experimental procedures and the possible risks and benefits of the project, which was approved by the Ethical Committee of the Public University of Navarra and performed according to the Declaration of Helsinki.

4.3.3 Equipment:

An inertial orientation tracker, (MTx, 3DOF Human Orientation Tracker, Xsens Technologies B.V. Enschede, The Netherlands) was attached over the L3 region of the subject's lumbar spine and provided kinematic variables at a sampling rate of 100 Hz. A technical explanation describing the inertial sensor-derived variables has been previously provided [64] (**Figure II-2**).

4.3.4 Procedures:

Leg dominance was defined as the leg the athletes would use if they were required to push off the ground and then throw a ball, as previously described in handball[65]. The ISU provides the linear acceleration and angular displacement orientation values in a sensor-fixed Cartesian reference frame (XYZ). Before the beginning of the test, while the subject was standing on the ground with her back in an upright position, the sensor-fixed reference frame was aligned with an Earth-fixed global reference frame (XYZ), with the (Z-) axis in the vertical direction and pointing upwards, the (X-) axis in the mediolateral direction, taking to the right directed accelerations as positive and the (Y-) axis in the anteroposterior direction, taking posterior directed accelerations as positive (**Figure II-3**).

All of the participants performed the test at the beginning of a routine training session that was conducted during the competitive season and at least 48 hours after their last competition. Jumping methodology descriptions have been published elsewhere[66]. Briefly, each participant was allowed two practice trials to ensure comfort in the task prior to data collection. Two further test trials were performed, interspersed with approximately 10 seconds of rest between the jumps. The number of repetitions within each jumping task was the same. The jump battery protocol was fixed. The elected criteria used for the jump task execution order was from easy to complex execution requirements to avoid possible injury risks associated with the intensity of the jumping tasks. Participants started performing the VBDJ, VUCMJ and finally the VUDJ.

Direct mechanics-based procedures were utilised to estimate the center of mass displacement and to detail the biomechanics of jumping. In that manner, direct mechanics procedure is based on the description of the subject as a mechanical system and the estimation of movement and actuation of forces through the center of mass displacement[50]. Based on this approach, was the positioning of the ISU sensor at the lumbar spine level done where the human´s centre of gravity is considered to be located[48] and hence, were the vertical velocity by time descriptive curves depicted.

4.3.5 Data processing and analysis:

Each jump was broken down into different phases for a more comprehensive biomechanical analysis. The required the definition of different events based on vertical velocity recordings. Once the different events of the jumping maneuvers were identified, the different phases could be defined and the following variables (peak acceleration and orientation) were considered by jump phase and jump type for each of the analysed jumps.

For the VBDJ and VUDJ, the T1 event was signaled by an abrupt positive change in the vertical (Z-axis) velocity, which determined the start of the active negative (eccentric) action of the initial absorption phase, when the center of mass of the athlete was in its lowest position. The T2 event corresponded to the instant that the vertical velocity first passed zero in the transition between the initial absorption and the propulsive phases of the jump. The T3 event corresponded to the instant in which the maximum positive vertical velocity was achieved. Subsequently, the T4 event was set when the vertical z-axis velocity again reached a maximum value, and the final T5 event was noted when the vertical velocity returned to zero after the jump (**Figures II-4**).

For the VUCMJ, the beginning of the action (T1 event) was set at the time when the first negative Z-acceleration was produced. Next, the negative passive and active work (pre-stretch) was performed during the "propulsive phase." The subsequent T2 event was determined when the maximum vertical negative velocity was reached (lowest position of the center of mass). T3 was denoted by the instant the vertical velocity first passed through zero in the transition between the initial absorption (countermovement in the case of VUCMJ) and the propulsive phases of the jump. The T4 event corresponded to the instant in which the maximum positive vertical velocity was achieved. Subsequently, the T5 event was set when the vertical z-axis velocity again reached a maximum value, and the final T6 event was denoted by the point when the vertical velocity reached zero after the jump (**Figures II-4**).

For every cycle, the Z-velocity signal was used to distinguish the peak from the transition phases of each jump, for example: subject moving upwards – positive Z-velocity at the propulsive phase; subject moving downwards – negative Z-velocity at the landing phase. All of the information was combined to define the boundaries between the different relevant phases: initial absorption, propulsive and final absorption for the drop jumps (bilateral and unilateral) and propulsive and final absorption for the countermovement jump (**Figures II-4 bottom**).

The absorption phase of the jump was determined as the portion of the jump in which the subject endured negative accelerations relative to the instant previous to the initial contact (or active impulse exertion) and the management of the impact against the ground (negative followed by positive vertical-axis accelerations, corresponding to the vertical-axis decomposition of the ground reaction force, recorded by the inertial unit). There were two absorption phases described for the drop jumps. The initial absorption (IA) phase (T1- T2 events) and final absorption phase (FA) (T4-T5 events). Alternatively, for VUCMJ final absorption phase (FA) was described (T5-T6 events) (**Figures II-4**).

The propulsive phase of the jump was defined as the portion of the jump in which the subject exerted a positive force, representing an active concentric action against the ground (positive vertical-axis accelerations recorded by the inertial unit) (Figures 2 A and B). It corresponds to T2-T3 events for the drop jumps and T3-T4 events for the VUCMJ.

The flight time of the jump was determined as the portion of the jump in which the subject was not exerting any force against the ground (no positive vertical-axis accelerations recorded by the inertial unit) (Figures 2 A and B). It corresponds to T3-T4 events for the drop jumps and T4-T5 events for the VUCMJ.

Once the different events were identified (based on vertical velocity recordings), the linear acceleration, orientation and jumping phase times were evaluated to obtain the relevant parameters at each phase. The automated data analysis procedure was implemented with MatLab 7.11 (MathWorks Inc; Natick, MA, USA).

Mean and standard errors of the mean (SEM) were calculated for all the recorded variables. The different outcomes were verified to have normal distributions using Levene's test. In the case of the BJ, two-tailed unpaired t-test was performed for the mean comparison between groups (controls vs. previously ACL reconstructed). For the remaining two unilateral jumps, a 2 X 2 (group by limb) multivariate analysis of variance (ANOVA) was performed to analyse interaction levels between factors. The dominant limb of the control group was matched to the involved limb of the ACLR group and the non-dominant limb was matched to the noninvolved limb of the ACLR group[57]. Thus, if between groups interaction was observed a one way analysis of variance was performed in order to detect with subsequent Bonferroni post hoc comparisons, the existing differences between limbs with only one fixed factor (group; ACL reconstructed vs controls).When the variance equality was rejected, the Tamhane's post hoc test was performed. The significance level was set at $p < 0.05$.

A priori power analysis was not possible to perform due to no availability of previous research using the same methodology of jumping. A post hoc power analysis was performed (PS software, power size biostatistics version 3.0.43. University of Vanderbilt USA.) revealing a power of 0.31 for the vertical bilateral drop jump, 0.99 for the vertical unilateral drop jump and 0.89 for the vertical unilateral counter movement jump. The reliability reported by the ISU device in the present research, reported CV values that ranged from 1 -17% and the ICC values ranged from 0.71 to 0.93.

4.4 Study IV

4.4.1 Experimental approach:

A validation study design was carried out. The experiment was carried out at a biomechanics laboratory. The participants performed a vertical jump test battery that included a 50 cm vertical bilateral drop jump (VBDJ), 20 cm vertical unilateral drop jump (VUDJ), and vertical unilateral countermovement jump (VUCMJ). (**Figure II-1**)

4.4.2 Participants:

The participants were physically active young participants. There were 9 men (mean ± standard deviation; age: 29.33 ± 4.80 years; weight: 74.84 ± 10.38 kg; height: 172.53 ± 5.86 cm) and 8 women (age: 27.50 ± 4.75 years; weight: 57.92 ± 5.40 kg; height: 164.03 ± 3.61 cm). The inclusion criteria for participation in the present study were that the participants performed regular strength and or endurance training a minimum of two times a week at least during the last year. Furthermore, none of the participants were suffering from any articular or muscle pain in the lower legs at the moment of the experimental evaluation. Potential participants with a previous background of any severe injury affecting the lower leg lasting more than six weeks for complete recovery were excluded from the study.

The experimental protocol was approved by the ethics committee of the Public University of Navarra according to the ethical principles of the Declaration of Helsinki. All participants gave their consent to the experiment after having been informed of the aims and the risks of the testing procedures.

4.4.3 Procedures:

The testing procedure comprised the execution of three vertical jump maneuvers: the vertical bilateral drop jump (VBDJ), the vertical unilateral drop jump (VUDJ) and the vertical unilateral counter movement jump (VUCMJ) (**Figure II-1**). Each examination was composed by five repetitions of each of the three vertical jumps mentioned above. The participants performed 5 min of resistance free stationary cycling as a warm up to start activity and reduce chondral and soft tissue viscosity. Participants were asked to define which leg they would employ to jump as high as possible in order to jump with their dominant leg. None of the participants were involved in any jumping-based activity.

The resting period was 30 seconds between two consecutive jump trials within a set and 1minute between each of the three vertical jump maneuvers examined. To avoid possible injury risks associated with the intensity of the jumping tasks, the order of execution was fixed; the jumps were performed from easiest to most complex execution requirements. A detailed explanation of the selected jumping maneuvers has been described elsewhere[67;68]. For the entire jump repetitions performed, the subject was instructed to perform a maximal effort task immediately following an acoustic signal.

The participants were equipped with an inertial sensor unit (ISU) (MTx, 3DOF Human Orientation Tracker, Xsens Technologies B.V. Enschede, Netherlands). The ISU was attached over the L4- L5 region of the subject's lumbar spine, which is considered to be the center of mass (CM) of the human body (Linthorne, 2001) (**Figure II-2**). A technical explanation describing the ISU-derived analyzed variables has been previously provided[67;68] and it is detailed below (*kinematic data* sub-section).

The trials were simultaneously recorded by the ISU at a sampling rate of 100 Hz and the force plate (AMTI net force v.2.4.0 2006 Advanced Mechanical technology. Inc. ISU sensor based jumping biomechanical evaluation USA) at a sampling rate of 1000 Hz.

In order to reduce the error due to the integration process, the highest sampling rate for data recording was selected for both instruments[69]. Therefore, both devices were calibrated on the highest possible value: 1000 Hz for the force platform, and 100 Hz for the ISU. Before each trial, the participants were asked to assume a vertical posture as well as to keep their hands over their waists during the three jumps to avoid upper body interference caused by arm swinging[70].

Direct mechanics-based procedures were utilized to estimate the center of mass displacement and to detail the biomechanics of jumping. In this manner direct mechanics procedure is based on the description of the subject as a mechanical system and the estimation of movement and actuation of forces through the center of mass displacement[50]. Based on this approach, was the positioning of the ISU sensor at the lumbar spine level where the human´s centre of gravity is considered to be located (Linthorne, 2001) and hence were the vertical velocity by time descriptive curves depicted.

4.4.4 Kinematic data:

The ISU provides the linear acceleration and rate of turn in a sensor-fixed Cartesian reference frame (XYZ). The MTx sensor combines nine individual MEMS sensors to provide drift-free 3D orientation, as well as kinematic data: 3D acceleration, 3D rate of turn (rate gyro) and 3D magnetometry (**Figure II-3**).

Before the beginning of the test, while the subject was standing on the ground with her back in an upright position, the sensor-fixed reference frame was aligned to an Earth-fixed global reference frame (XYZ), for which the Z-axis was vertical and pointing upwards, the X-axis was in the medio-lateral direction and the Y-axis was in the anterior-posterior direction. The same reset procedure was performed with the force plate according to the manufacturer's instructions.

Each jump was assessed in different phases for a more comprehensive biomechanical analysis. This required the definition of different events that were determined using vertical accelerations provided by the ISU and vertical forces obtained from the force plate. Once the different events of the jumping tasks were identified, the different phases could be defined. Finally, the peak acceleration (expressed in $m{\cdot}s^2$) and peak ground reaction force (expressed in *N*) variables, were considered for each of the analyzed jumping tasks. For every cycle, the (Z-) acceleration signal from the ISU sensor and the (Z-) force signal for the force plate were used to distinguish the peaks from the transition phases of each jump (i.e., subject moving upwards – positive Z-acceleration or force at the propulsive phase; subject moving downwards – negative

Z-acceleration or force at the landing phase). All of the information was combined to define the boundaries between the different relevant phases; the initial attenuation (IA), propulsive (P) and final attenuation (FA) phases were defined for the drop jumps (bilateral and unilateral), and the propulsive (P) and final attenuation (FA) phases were determined for the countermovement jump. (**Figure II-4**)

The attenuation phase (A) of the jump was determined as the fraction of the jump in which the subject was negatively accelerating relative to the instant prior to the initial contact (or active impulse exertion) and to the management of the impact against the ground (negative followed by positive vertical-axis accelerations or forces, corresponding to the vertical-axis decomposition of the ground reaction force, simultaneously recorded by both the inertial unit and the force plate). There were two absorption phases described for the Drop Jumps. The initial attenuation (IA) phase (T1- T2 events) and final attenuation phase (FA) (T4-T5 events). Alternatively, for VUCMJ final absorption phase (FA) was described (T5-T6 events) (**Figures II-4**).

The propulsive phase (P) of the jump was defined as the fraction of the jump in which the subject exerted a positive force, or an active concentric action against the ground (positive vertical-axis accelerations or forces simultaneously recorded by both the inertial unit and the force plate). The jumping time (JT) of the jump was determined as the fraction of the jump in which the subject was not exerting any force against the ground (no positive vertical-axis accelerations or forces recorded by neither the inertial unit nor the force plate) (**Figure II-4**). It corresponds to T2-T3 events for the Drop jumps and T3-T4 events for the VUCMJ.

4.4.5 Data processing and statistical analysis:

Peak maximal vertical accelerations (obtained in $m \cdot s^{-2}$) and forces (N) occurring at the propulsive and final attenuation phases of the studied jumping tasks were recorded. To analyze the reliability and agreement between the force plate and the ISU sensor recordings in the same magnitude, the acceleration values were transformed into N by using the following formulae based on the Newton´s third law:

$$F = m \cdot a$$

F = Force (N)

m= subject´s mass expressed in Kg

a= peak acceleration (resultant) at each jump phase analyzed ($m \cdot s^{-2}$)

Subsequently, the (X-) and (Y-) axis values corresponding to the vertical (Z-) peak predefined times were obtained for each analyzed phase in order to calculate the resultant forces (RF). This calculation was performed by using the root-mean-square quadratic equation of the 3 dimensional peak forces registered:

$$RF\ (N) = \sqrt{[\text{peak (X-) axis force}^2\ (N) + \text{peak (Y-) axis force}^2\ (N) + \text{peak (Z-) axis force}^2\ (N)]}$$

Finally, graphical representations of the vertical force (Z-force) provided by the force plate and calculated from the ISU data, respectively, were performed. In order to avoid jumping height -related variability and sampling frequency-related deviations in the data acquired from the ISU and the force plate, the Z-force curve representations were normalized to the mean and time. Additionally, root-mean-square quadratic errors and correlation coefficients were calculated for each of the obtained point pairs to assess the concordance between sensor- and force plate-derived data acquisition

All of the descriptive statistics were utilized to assess the normality assumption of all of the studied variables. The Kolmogorov -Smirnov test revealed no abnormal data patterns ($p>0.05$).

The reliability of the ISU with respect to the force plate was assessed with Pearson´s correlation coefficient (r) and 95% Confidence intervals (95%CI). Correlations between global force-time curves (raw data) and isolated previously defined IA and FA peak ground reaction resultant force values obtained from both devices were analyzed for the VBDJ, VUDJ and VUCMJ. Correlations were separately carried out across all activities for each individual (intra-subject, intra-task and repetition). The correlation coefficients (r) were interpreted in accordance with the scale of magnitude proposed by Hopkins (Hopkins, Marshall, Batterham, & Hanin, 2009): $r \leq 0.1$, trivial; $r > 0.1\text{-}0.3$, small; $r > 0.3\text{-}0.5$, moderate; $r > 0.5\text{-}0.7$, large; $r > 0.7\text{-}0.9$, very large; and $r > 0.9\text{-}1$, extremely large.

Coefficients of variation (CV %) were also calculated in order to measure the dispersion of the scores for each subject and jump task performed for both the ISU and the force plate. Furthermore, paired sample T-test were used for mean comparisons across the CVs obtained from both instrumentations. The level of significance was set at $P < 0.05$. SPSS® statistical software (V. 20.0, Chicago, IL, USA) was used for the abovementioned statistical calculations.

Bland & Altman graphical representations were performed to increase the understanding of the data with respect to the agreement and the existence of a standard bias between the values obtained from the force plate and ISU sensor.

4.5 Study V

4.5.1 Patients

A longitudinal clinical double blinded (patients and evaluator) level 1 of evidence-randomized trial was performed with 40 (30 male, 10 female) recreationally active athletes (Tegner activity scale 7) in order to analyse the effect of two different rehabilitation programs following ACL reconstruction.

Table V-1 depicts patient demographics. All patients were operated by the same orthopaedic surgeon (JAA) following identical surgical technique. Antero-medial portal cam was used in all cases to perform an anatomical ACL reconstruction. Autologous double bundle hamstring grafts were used for all patients. Tension was applied to all grafts for 10¨at 20pounds prior to implantation in order to reduce residual graft laxity (Retrobutton TightRope RT, & Bio-Interference screw, Arthrex®, Naples, USA). Subjects were evaluated before, and twelve months after ACL reconstruction. All patients were discharged from hospital within 24 hours from surgery. Criotherapy and rutine analgesia were prescribed for all patients as pain control. Elastic compressive stockings were prescribed for deep thromboembolism prophilaxis

Patients with chondral injuries grade ≥ II or suffering from other knee ligament complete disruptions other than ACL were excluded from the study. Time from injury to surgery was consistent between groups (mean ± standard deviation; 199.5 ± 166.5 and 146.3 ± 147.4 days for both accelerated and conventional groups respectively).

All participants were informed in detail about the experimental procedures and the possible risks and benefits of the project. The study was approved by the Ethical Committee of the Public University of Navarra and performed according to the Declaration of Helsinki. Informed consent was obtained from all individual participants included in the study.

4.5.2 Rehabilitation protocols

The patients were consecutively, divided in two different rehabilitation groups after the operation. Group 1 (n=20) followed a conventional rehabilitation protocol (CON) and patients in Group 2 (n=20) were enrolled in an accelerated rehabilitation protocol (ACCEL). The allocation procedure was block randomized prospectively; the 20 first participants were enrolled to conventional rehabilitation protocol and the subsequent 20 to an accelerated rehabilitation protocol. The two different rehabilitation programs were conducted in two different rehabilitation centers. This decision with respect to treatment allocation was made to ensure appropriate patient blinding. Neither the patients, nor the evaluators were aware of the group allocation nor follow-up examination results during the time course of the investigation.

The CON group followed a traditional ACL reconstruction rehabilitation procedure,[71] *(***Appendix V-1***)*. The main features of this protocol are two to four weeks of immobilization prior to free gait, delayed onset of strength training, and restricted return to sports activity up to six months postoperatively.

The ACCEL group followed a standardized accelerated rehabilitation program based on that previously described by Myer et al (2006)[72] *(***Appendix V- 2***)*. The main features of this rehabilitation protocol include early full range of motion restoration, free gait, and specific strength training and agility drills introduced progressively as the patients achieved certain pre-set rehabilitation algorithm progression criteria.

No knee braces were used after the surgical ligament reconstruction, during the rehabilitation program, or during the knee performance tests at the follow-up examinations. Patients who developed pain, swelling, or range of motion deficits during the rehabilitation programs underwent symptomatic treatments until the impairments were resolved. There were not statistically significant ($p<.05$) differences between groups with respect to the number of rehabilitation sessions administered (58.8 ± 22.0 and 67.6 ± 22.6 sessions in CON and ACCEL groups respectively)

4.5.3 Isokinetic strength testing

The dynamic concentric knee extensor/flexor strength (concentric/concentric muscle action) was measured with each subject seated on an isokinetic dynamometer (Humac norm®, CSMi solutions, Stoughton. Ma. USA) with their trunk perpendicular to the floor, and the hip and knee joints flexed to 90 degrees. Subject posture was secured with straps. Before each data collection set, a warm-up set consisting of 5 submaximal knee flexion/extensions for each leg at 180 degrees/s was performed. The test session consisted of 8 knee isokinetic extension/flexion (90 to 0 degree range of motion, 0º = to full extension) repetitions for each leg at 180 degrees/s. Gravity corrected flexor and extensor peak torques (PT) (Nm) were recorded for the testing leg. Isokinetic concentric strength evaluations of the hamstring and quadriceps muscle groups have previously demonstrated excellent reliability [25]. An automated data analysis procedure was implemented using Matlab 7.11 (MathWorks Inc®; Natick, MA, USA) to determine the angle of Peak Torque for the hamstring muscles in each testing repetition. In addition, the area under the torque-angle curve was also calculated (i.e., mechanical work in J)

4.5.4 Muscle Imaging

MRI scans of the thigh were performed with a 1.5 T whole body image with surface phased-array coils (Magnetom Avanto; Siemens-Erlangen®, Germany). For the magnetic resonance scans, subjects were positioned supine with their knee extended. MRI of the subjects' thighs was performed before and 12 months after surgery. The length of the right femur (Lf) was measured by the distance from the intercondylar notch to the superior border of the femoral head measured in the coronal plane. Subsequently, 15 axial scans of the thigh interspaced by a distance of 1 / 15 Lf were obtained from the level of 1/15 Lf to 15/15 Lf. Every image obtained was labeled with its location (i.e. slice 1 being closer to the coxofemoral joint and slice 15 closer to the knee). Great care was taken to reproduce the same individual Lf each time by using the appropriate anatomical landmarks as previously described[73].

For the final calculation of the CSA of each muscle, slices corresponding to 8/15 and 12/15 of the total femur length levels (50% and 70% of the bone axial length) were used for all muscles examinations *(***Figure V-1***)*. Then T2-weighted transverse spin-echo MR axial images [repetition time (RT) = 3,250 ms, echo time (ET) = 32, 64, and 96 ms were collected using a 256 x 256 image matrix, with a 320 mm field of view and 10-mm slice thickness] were analyzed. This data was used to obtain the anatomical cross sectional area (CSA) of each Quadriceps (Q), Biceps Femoris (BF), Semitendinosus (ST), Semimembranosus (SM), and Gracilis (GR) muscles (Fig 1). The MRI files obtained were converted to a Digital Imaging and Communications in Medicine (DICOM®) format and analyzed with image manipulation and analysis software (Slice Omatic, Tomovision®, Canada). The same examiner (EBL) performed all muscle perimeter measurements. The anatomical muscle CSA was calculated by drawing a region of interest an tracing the outline of the muscles on the previously prepared proton-density images (ET:32) as previously described[74].

4.5.5 Knee joint laxity assessment

Knee joint laxity was evaluated with the KT-1000 arthrometer (MEDmetric Corporation®, San Diego, CA) at 20 lbs (89N) with anterior-posterior (AP)- directed loads. The measurement continued until the value was reproduced. KT-1000 instrumented examination of knee laxity in the ACL injured leg shows high intratester reliability[75].

4.5.6 Statistical analysis

Descriptive statistics were calculated. In order to check out the normality assumption of the analyzed variables, the Kolmogorov-Smirnov testing was applied revealing no abnormal data patterns. The number of patients enrolled in the present investigation was based on a power analysis calculated previously by Lindstom et al (2011)[76] in a similar study. They determined that the number of patients needed to detect a 4% change in hamstring muscle cross-sectional area with 80% statistical power was 37 subjects.

Paired T-tests were used to detect significant differences between a subject's lower limbs at each time point. Two way analysis of variance (group by time) ANOVA was used to compare between groups´ mean comparisons with subsequent Bonferroni post hoc corrections. When the variance equality was rejected, the Tamhane's post hoc test was performed. The level of significance was set at $p< 0.05$ for all statistical tests. SPSS® statistical software (V. 20.0, Chicago, IL, USA) was used for all statistical calculations.

5. RESULTS AND DISCUSSION

5.1 Study I

The main findings of this study revealed that previously ACL-injured female athletes were on average 8.2 kg lighter and 5.8 cm smaller than uninjured players (Table 1). Regarding function-related variables, previously ACL- injured athletes showed lower VBDJ contact times and less reached distance in the UTHD (Figures 1 and 2). Although no significant differences were reached, there was a trend toward worse performance in the UCHD and VUCMJ among previously ACL-reconstructed elite female athletes (**Table I-1**).

		Controls (n=15)		ACL reconstructed (n=6)	
		Dominant	Non dominant	Injured	Non injured
Age (years)		25 ± 5.1		26 ± 4.0	
Weight (Kg)		70.2 ± 5.1		61.8 ± 3.9*	
Height (cm)		174.8 ± 6.1		169.0 ± 4.4*	
Vertical Bilateral Drop Jump [a]	Flight time (ms)	484.4 ± 27.7		451.7 ± 40.6	
	Contact (time)	429.4 ± 179.9		349.4 ± 151.1*	
	Mechanical Power Output ($W \cdot Kg^{-1}$)	27.5 ± 3.1		25.9 ± 5.8	
Vertical Unilateral Drop Jump	Flight time (ms)	346.5 ± 26.1	337.3 ± 26.6	330.3 ± 45.2	334.7 ± 43.8
	Contact (time)	403.9 ± 184.1	412.8 ± 193.7	357.9 ± 174.3	283.01 ± 206.2
	Mechanical Power Output ($W \cdot Kg^{-1}$)	9.1 ± 5.2	8.7 ± 5.2	9.9 ± 6.6	12.2 ± 6.1
Verttical Unilateral Counter Movement Jump	Flight time (ms)	345.3 ± 21.9	357.5 ± 53.4	320.6 ± 41.7	350.3 ± 25.1
Unilateral Tripe Hop for Distance	Distance (cm)	442.9 ± 44.7	430.3 ± 47.9	382.0 ± 54.6*	398.3 ± 87.8
Unilateral Cross Over Hop for Distance	Distance (cm)	326.1 ± 44.8	330.9 ± 58.5	289.6 ± 58.2	310.5 ± 70.1
Lower Symmetry Index (LSI)	%			100.63 ± 8.06	

Table I-1. *Descriptive data of jump test battery variables among female athletes.*

		Controls (n=16)		ACL reconstructed (n=16)	
		Dominant	Non dominant	Injured	Non injured
Age (years)		24 ± 5.1		27 ± 3.1	
Weight (Kg)		89.8 ± 9.9		92.1 ± 8.5	
Height (cm)		188.2 ± 7.0		188.3 ± 5.7	
Vertical Bilateral Drop Jump[a]	Flight time (ms)	541.5 ± 40.1		543.3 ± 52.8	
	Contact (time)	308.5 ± 7.3		328.7 ± 81.0	
	Mechanical Power Output ($W \cdot Kg^{-1}$)	25.4 ± 6.3		30.6 ± 5.4	
Vertical Unilateral Drop Jump	Flight time (ms)	422.4 ± 44.6	405.8 ± 41.5	403.1 ± 34.8	416.0 ± 38.1
	Contact (time)	322.7 ± 19	319.7 ± 114.0	358.7 ± 157.9	354.5 ± 136.4
	Mechanical Power Output ($W \cdot Kg^{-1}$)	15.1 ± 6.5	14.0 ± 5.6	12.3 ± 4.0	13.2 ± 4.9
Vertical Unilateral Counter Movement Jump	Flight time (ms)	406.2 ± 44.7	392.3 ± 38.9	389.9 ± 40.4	395.5 ± 59.7
Unilateral Tripe Hop for Distance	Distance (cm)	489.4 ± 126.3	452.0 ± 73.1	540.3 ± 101.0	563 ± 53.1
Unilateral Cross Over Hop for Distance	Distance (cm)	445.5 ± 72.0	442.7 ± 86.6	444 ± 81.3	473.7 ± 67.0
Lower Symmetry Index (LSI)	%			97.4 ± 2.6	

Abbreviations: Kgs. kilograms; cm. centimeters; ms. miliseconds; $W \cdot kg^{-1}$. $Watts \cdot kilograms^{-1}$.
*Denotes statistically significant differences between groups.
LSI were only calculated among previously reconstructed athletes

Table I-2. *Descriptive data of jump test battery variables among male athletes.*

No significant differences (P>0.05) were observed between ACL-reconstructed and non-ACL-injured male participants regarding anthropometric data or jumping performance-related variables (**Table I-2**).

A comparison between the injured and the uninjured legs revealed no significant differences in the LSI (expressed as the mean LSI score during the entire test battery, resulting from the between-extremity ratio in each test for reconstructed athletes) for either female (100.6 ± 8.1) or male (97.4 ± 2.57%) athletes (**Tables I-1 and I-2**).

female (100.6 ± 8.1) or male (97.4 ± 2.57%) athletes (**Tables I-1 and I-2**).

Although many articles have reported both functional and biomechanical dysfunctions after ACL injury [9;11;77], to the best of our knowledge, this study is the first to report a decrease in jumping performance among previously ACL-reconstructed elite female handball players who have returned to a high athletic competition level.

The reason why jumping-related differences were found in the present study among female but not male athletes could be controversial. Lower contact times could be the result of a knee joint stiffening strategy, and the attenuated horizontal jumping capacity may be explained by both muscular activation pattern modification and by persistent strength deficits, which have been previously described in the literature[9;14;57;78]. Several authors have concluded that the reported weakness may be attributable to activation failure at maximal force output[79;80]. This statement is based on the assumption that following traumatic and degenerative joint damage, inhibition of quadriceps muscle full activation may occur. Indeed, the extent of the reduction in the quadriceps' activation appears to be related to the sustained joint damage[81]. This maximal force output attenuation after serious knee injury[81] could be accentuated in females compared with males because of different muscle activation strategies and internal developed moments around the knee joint that were previously described in the literature[54;82]. Thus, females appear to be more susceptible to incomplete functional recovery after ACL reconstruction compared with males[54;83-85]. The results of our study could be linked to the movement pattern adaptation shown in the literature after ACL injury, leading the injured female athlete to adopt non-conscious reinjury avoidance via a function-limiting strategy.

Previous studies have reported functional deficits in a wide but generally mixed group of athletes following ACL reconstruction[10;77]. Due to evident methodological difficulties, the literature focusing on ACL injury-related functional alterations in elite professional handball athletes is limited. In agreement with our results, Mycklebust et al.[15] reported functional alterations among elite and recreational female and male handball players 6 to 11 years after

ACL injury. The authors reported compromised knee function in approximately half of the previously ACL-injured players who were treated surgically or non-operatively based on knee functional jumping test results, radiologic findings, strength measurements and function-related knee questionnaires. However, in contrast to the present study, the previous study examined a heterogeneous group of elite and recreational athletes and did not analyze outcome variables separately for different sport activity levels or sexes. In addition, the authors did not indicate the proportion of players who returned to their preinjury level. The fact that all players in our study had resumed their previous elite sport level makes the sample in the present study potentially relevant for team physicians who manage the functional status of previously ACL-reconstructed professional athletes in the field.

Regarding the anthropometric differences between previously reconstructed female athletes and non-ACL-injured female controls, in our opinion, this difference may due to a possible playing position effect. Outside players may be more exposed to ACL injury risk due to more demanding plant and cut-type movement requirements, which have been previously described as a cause of ACL injury[86]. We suggest that this issue should be addressed in the future by properly designed descriptive studies with larger sample sizes.

Lastly, no differences were observed in the jumping performance-related variables among the male handball players. The encountered absence of differences between the previously ACL-injured athletes and the uninjured sex, age and sport level-pairs of control participants could be related to a less predominant ACL injury-facilitating motion pattern among male athletes than among their female counterparts[8;53]. Accordingly, a return to the previous activity level after an ACL injury has been demonstrated to be more frequent among elite male athletes than among their female counterparts[87]. It should be also highlighted that both the small sample size and the fact that only athletes able to resume previous sport level were included. This fact could have affected between groups differences identification. In the author´s opinion this point is crucial in the present investigation since the aim of the present study was precisely to target this issue, if athletes competing at the top level after having suffered and ACL reconstruction, would still exhibit some jumping related alterations that could affect either their performance or their reinjury chances.

One potential limitation of the current study is that despite the time passed since the original injury was not registered, nor the postoperative rehabilitation protocols among those athletes with a previous ACL injury neither the graft choice for ligament reconstruction was controlled.

The clinical relevance of this measurement technique should be considered due to its low cost and high applicability. More research is needed to assess whether a correlation exists between functional performance tests and biomechanical, strength and proprioceptive disorders that seem to coexist during the function restoration process after ACL injury reconstruction.

5.2 Study II

The results of the present study supports the notion that clinicians can utilize a single ISU to perform a biomechanical examination of several vertical jumping tests to measure supported acceleration in 3 dimensions and jumping performance (jump phase duration) in previously ACL-reconstructed male athletes, even if several years have passed since the original injury. There were no significant ($P \leq .05$) differences between previously ACL reconstructed and control groups with regard to any of the anthropometric-related registered variables (**Table II-1**).

VBDJ

That control participants demonstrated the ability to support greater X-axis peak acceleration at the FA phase of the VBDJ compared with athletes with a previously reconstructed ACL (**Figure II-5**).

Peak acceleration values

The control athletes showed significantly greater X-axis peak acceleration in the FA phase of the VBDJ compared with the athletes with a previously reconstructed ACL ($P = 0.008$; 95% CI = 4.91-30.63; (**Figure II.5**). No other significant differences were found for any of the other axes for any of the described jump phases (**Table II-2**).

Jumping phases	Peak Aceleration ($m \cdot s^{-2}$) and angular Excursion (º)	Non-ACL injured Control (n=32)		ACL reconstructed (n= 12)		T-Test 95%Confidence interval for mean difference
IA phase	Med-lat axis (X) ($m \cdot s^{-2}$)	-1.09	(2.64)	3.18	(4.79)	(-14.79) - 6.26
	Ant-post axis (Y) ($m \cdot s^{-2}$)	-20.64	(2.62)	19.42	(1.76)	(-10.19) - 7.75
	Vertical axis (Z) ($m \cdot s^{-2}$)	42.85	(1.13)	44.46	(1.59)	(-5.82) - 2.60
	Med-lat axis (X) (º)	-17.88	(2.08)	-17.59	(3.14)	(-8.19) - 7.60
	Ant-post axis (Y) (º)	-0.26	(0.62)	-0.10	(0.89)	(-2.47) - 2.16
	Vertical axis (Z) (º)	0.12	(0.83)	-1.76	(1.06)	(-1.16) - 4.91
P phase	Med-lat axis (X) ($m \cdot s^{-2}$)	2.28	(1.41)	5.64	(3.07)	(-9.35) - 2.62
	Ant-post axis (Y) ($m \cdot s^{-2}$)	-20.98	(3.29)	-19.84	(6.27)	(-10.19) - 7.75
	Vertical axis (Z) ($m \cdot s^{-2}$)	16.51	(1.87)	18.56	(1.69)	(-5.82) - 2.60
	Med-lat axis (X) (º)	23.89	(1.81)	26.23	(2.75)	(-9.21) - 4.52
	Ant-post axis (Y) (º)	1.73	(0.93)	1.06	(0.86)	(-2.61) - 3.96
	Vertical axis (Z) (º)	0.30	(0.97)	2.57	(1.52)	(-6.03) - 1.49
FA phase	Med-lat axis (X) ($m \cdot s^{-2}$)	10.41	(3.37)	-7.36	(5.22)*	4.91 - 30.63
	Ant-post axis (Y) ($m \cdot s^{-2}$)	-19.06	(3.61)	-15.56	(4.80)	(-16.81) - (9.83)
	Vertical axis (Z) ($m \cdot s^{-2}$)	47.02	(1.49)	45.61	(2.07)	(-4.16) - 6.97
	Med-lat axis (X) (º)	-12.41	(1.66)	-17.28	(3.86)	(-2.36) - 12.11
	Ant-post axis (Y) (º)	-0.61	(0.71)	1.24	(0.84)	(-4.41) - 0.72
	Vertical axis (Z) (º)	-0.77	(0.56)	0.51	(1.05)	(-3.55) - 0.97

*=T – test P value < 0.05 with respect to control group ;IA = Initial absorption ;P = Propulsive ;FA = Final Absorption; med-lat = medio-lateral ;ant-post = anterior-posterior

Table II-2. *Vertical Bilateral Drop jump (VBDJ) inertial orientation tracker derived descriptive values. Values expressed as mean and (SEM).*

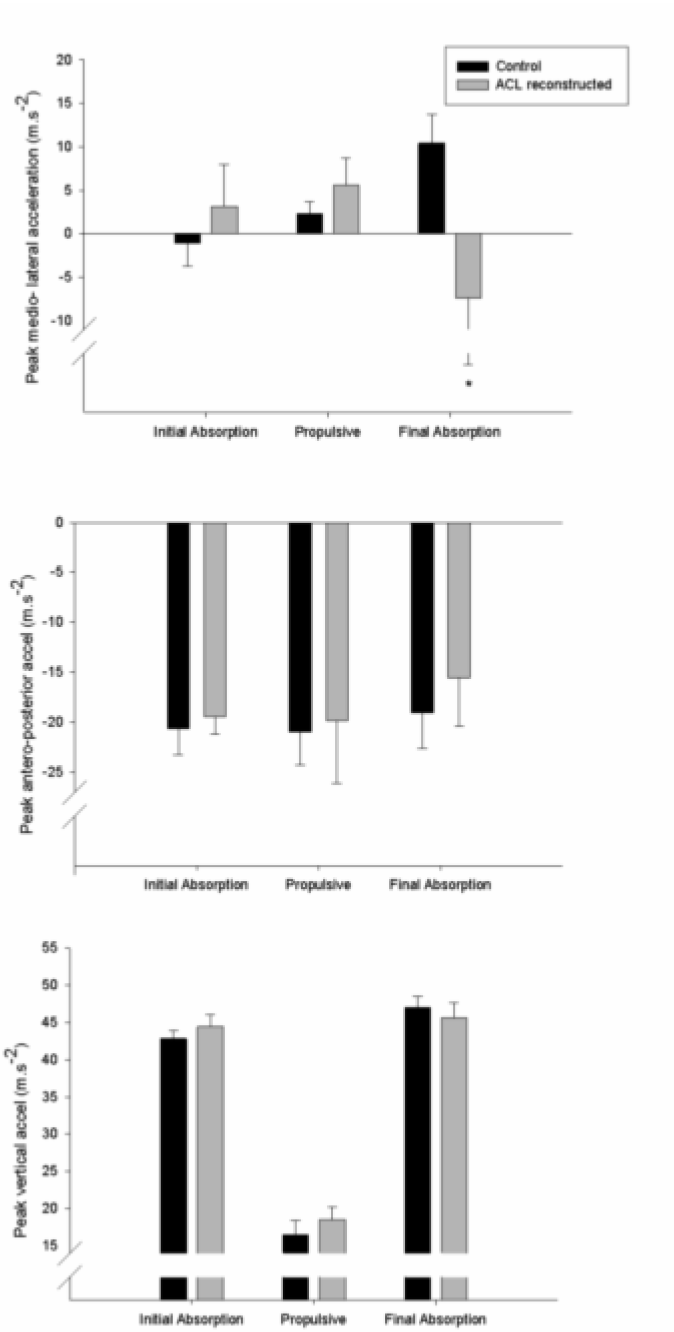


Figure II.5. *VBDJ Peak Acceleration. (X) mediolateral axis (A). (Y) anterior-posterior axis (B). (Z) vertical axis (C). * denotes P value < 0.05 with respect to control group at VDBJ; s = seconds; med-lat= mediolateral; ant-post = anterior-posterior*

Duration of jumping phases

There were no significant ($P \geq .05$) differences between the groups with regard to any of the recorded variables for the VBDJ jump phase durations (**Figure V-6 top**).

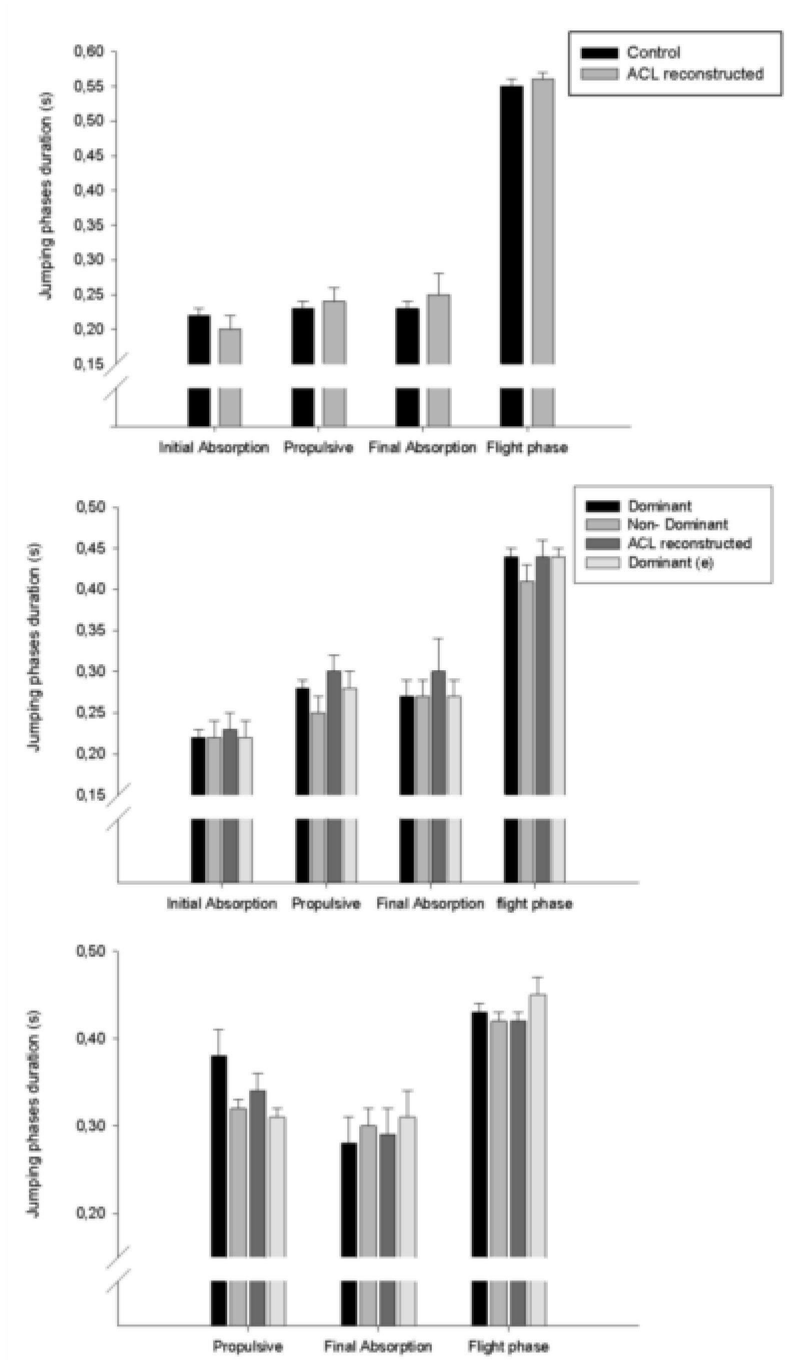


Figure II-6. *Time phases duration. Vertical Bilateral Drop Jump (VBDJ) (Top) Vertical unilateral Drop Jump (VUDJ) (Center) Vertical unilateral counter movement jump (Bottom). * denotes P value < 0.05 with respect to control group at VDBJ and to control dominant limbs at VUDJ and VUCMJ. ^ denotes P value < 0.05 with respect to control non-dominant limbs; s = seconds*

Mean orientation values

There were no significant ($P \geq .05$) differences for the absolute angular excursion within the jump phases between the extremities in the X-, Y- or Z-axis (**Table II-3**).

Jumping phases	**Peak Aceleration ($m \cdot s^{-2}$) and angular Excursion (º)**	**Dominant (controls; n=28)**		**Non dominant (controls; n=28)**		**ACL recons (cases. n= 16)**		**Non ACL recons (cases;,n=8)**	
IA phase	Med-lat axis (X) ($m \cdot s^{-2}$)	7.32	(3.41)	-10.35	2.81*	7.39	7.72	-6.89	7.01
	Ant-post axis (Y) ($m \cdot s^{-2}$)	-9.70	2.06	-13.06	2.77	0.25	6.10	-14.36	3.64
	Vertical axis (Z) ($m \cdot s^{-2}$)	29.03	2.42	27.86	2.22	31.78	3.21	30.22	3.18
	Med-lat axis (X) (º)	-9.41	1.43	-11.35	1.36	-12.58	1.62	-14.17	2.05
	Ant-post axis (Y) (º)	-0.31	0.57	-0.89	0.64	2.39	1.07	0.48	1.80
	Vertical axis (Z) (º)	1.69	1.35	-4.73	1.10*	-2.83	2.76	-0.91	2.20
P phase	Med-lat axis (X) ($m \cdot s^{-2}$)	2.23	3.33	-7.57	2.25	5.14	5.28	5.44	4.65
	Ant-post axis (Y) ($m \cdot s^{-2}$)	-10.92	2.23	-11.83	2.18	-14.68	4.35	-11.95	4.65
	Vertical axis (Z) ($m \cdot s^{-2}$)	16.61	1.59	15.47	1.43	14.96	1.52	15.71	1.60
	Med-lat axis (X) (º)	17.09	2.01	16.20	1.65	15.87	2.28	17.50	2.25
	Ant-post axis (Y) (º)	-0.11	1.81	5.52	1.38	-3.39	2.95	1.36	2.79
	Vertical axis (Z) (º)	-4.64	2.52	7.28	1.39*	-1.80	3.85	2.59	3.19
FA phase	Med-lat axis (X) ($m \cdot s^{-2}$)	1.66	5.39	-2.75	5.70	9.93	7.51	-2.27	8.46
	Ant-post axis (Y) ($m \cdot s^{-2}$)	-12.47	3.90	-16.72	3.11	-2.58	6.78	-7.16	6.58
	Vertical axis (Z) ($m \cdot s^{-2}$)	47.33	1.80	44.45	1.91*	43.23	2.18	46.05	2.90
	Med-lat axis (X) (º)	-11.21	1.33	-11.55	1.58	-14.12	2.38	-11.76	2.33
	Ant-post axis (Y) (º)	-0.41	1.42	-2.87	0.98	1.61	2.71	0.82	1.95
	Vertical axis (Z) (º)	1.00	1.21	-3.80	1.32*	0.83	1.55	-2.21	1.89

* =ANOVA test P value < 0.05 with respect to control dominant limb; ^ = ANOVA test P value < 0.05 with respect to control non- dominant ;IA = Initial absorption ;P = Propulsive ;FA = Final Absorption ;med-lat = medio-lateral ;ant-post = anterior-posterior

Table II-3. *Vertical Unilateral Drop jump (VUDJ) inertial orientation tracker derived descriptive values. Values expressed as mean and (SEM).*

Several authors have studied sagittal and frontal plane lower limb kinematics during Drop Jumps and compared the results by gender, ACL injury, and age[17;88-90]. However, multi-plane kinetic and kinematic examinations of these jumps in previously ACL-reconstructed subjects based on direct mechanics procedures have not been conducted. Non-ACL-reconstructed athletes in the present study demonstrated greater X-axis peak acceleration compared with

ACL-reconstructed participants during the FA phase of the VBDJ (**Table II-3**). These results could indicate a better capacity of non-ACL-reconstructed athletes to dissipate the VGRF into the other spatial axes, although this assumption could not be verified because the vertical accelerations were not different between groups.

VUDJ

Furthermore, the non-dominant leg of non-ACL-reconstructed participants displayed greater angular excursions around the Z-axis while performing a VUDJ during all three pre-defined jumping phases (**Table II-4**). Surprisingly, this dominance effect was not observed in participants with a previously reconstructed ACL.

Peak acceleration values

In the controls, the dominant leg displayed significantly ($P < .05$) greater peak acceleration in the X-axis compared with the contralateral leg ($P = 0.005$; 95% CI = 3.83-31.50) during the IA phase of the VUDJ. This pattern of laterality dependence between the different limbs was not observed in the limbs of athletes with a previously reconstructed ACL (**Figure II-7 top**).

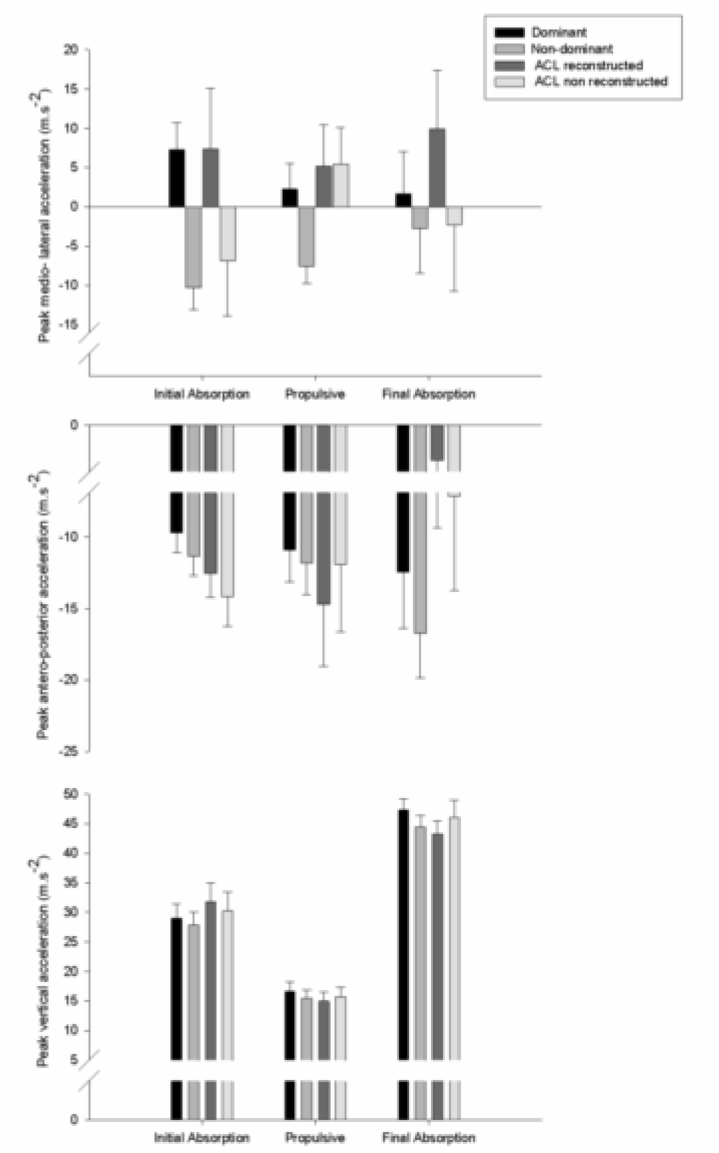


Figure II-7. *VUDJ Peak Acceleration. (X) mediolateral axis (top). (Y) anterior-posterior axis (middle). (Z) vertical axis (bottom). * denotes P value < 0.05 with respect to control dominant limbs group at VUDJ. ^ denotes P value < 0.05 with respect to control non-dominant limbs; s = seconds; med-lat= mediolateral; ant-post = anterior-posterior.*

Duration of jumping phases

No significant (*P* ≥.05) differences were found between the extremities for any of the recorded variables for the VUDJ jump phase durations (**Figure II-6 middle**).

Mean orientation values

The non-dominant legs of the control athletes showed significantly greater angular excursions around the Z-axis (rotational transversal plane movement at the L3-L4 lumbar vertebrae level) compared with their contralateral limbs in the IA phase (*P* = 0.006; 95% CI = 1.30-11.55), the P phase (*P* = 0.001; 95% CI = 4.00-19.84) and the FA phase [*P* = 0.006; 95% CI = (-10.83)-1.56] compared with the contralateral dominant limbs.

This pattern of laterality dependence between different limbs was not observed in previously ACL-reconstructed limbs (**Table II-4**).

Jumping phases	**Peak Aceleration ($m \cdot s^{-2}$) and angular Excursion (º)**	**Dominant (controls; n=28)**		**Non dominant (controls; n=28)**		**ACL recons (cases. n= 16)**		**Non ACL recons (cases;,n=8)**	
IA phase	Med-lat axis (X) ($m \cdot s^{-2}$)	7.32	(3.41)	-10.35	2.81*	7.39	7.72	-6.89	7.01
	Ant-post axis (Y) ($m \cdot s^{-2}$)	-9.70	2.06	-13.06	2.77	0.25	6.10	-14.36	3.64
	Vertical axis (Z) ($m \cdot s^{-2}$)	29.03	2.42	27.86	2.22	31.78	3.21	30.22	3.18
	Med-lat axis (X) (º)	-9.41	1.43	-11.35	1.36	-12.58	1.62	-14.17	2.05
	Ant-post axis (Y) (º)	-0.31	0.57	-0.89	0.64	2.39	1.07	0.48	1.80
	Vertical axis (Z) (º)	1.69	1.35	-4.73	1.10*	-2.83	2.76	-0.91	2.20
P phase	Med-lat axis (X) ($m \cdot s^{-2}$)	2.23	3.33	-7.57	2.25	5.14	5.28	5.44	4.65
	Ant-post axis (Y) ($m \cdot s^{-2}$)	-10.92	2.23	-11.83	2.18	-14.68	4.35	-11.95	4.65
	Vertical axis (Z) ($m \cdot s^{-2}$)	16.61	1.59	15.47	1.43	14.96	1.52	15.71	1.60
	Med-lat axis (X) (º)	17.09	2.01	16.20	1.65	15.87	2.28	17.50	2.25
	Ant-post axis (Y) (º)	-0.11	1.81	5.52	1.38	-3.39	2.95	1.36	2.79
	Vertical axis (Z) (º)	-4.64	2.52	7.28	1.39*	-1.80	3.85	2.59	3.19
FA phase	Med-lat axis (X) ($m \cdot s^{-2}$)	1.66	5.39	-2.75	5.70	9.93	7.51	-2.27	8.46
	Ant-post axis (Y) ($m \cdot s^{-2}$)	-12.47	3.90	-16.72	3.11	-2.58	6.78	-7.16	6.58
	Vertical axis (Z) ($m \cdot s^{-2}$)	47.33	1.80	44.45	1.91*	43.23	2.18	46.05	2.90
	Med-lat axis (X) (º)	-11.21	1.33	-11.55	1.58	-14.12	2.38	-11.76	2.33
	Ant-post axis (Y) (º)	-0.41	1.42	-2.87	0.98	1.61	2.71	0.82	1.95
	Vertical axis (Z) (º)	1.00	1.21	-3.80	1.32*	0.83	1.55	-2.21	1.89

* =ANOVA test P value < 0.05 with respect to control dominant limb; ^ = ANOVA test P value < 0.05 with respect to control non- dominant ;IA = Initial absorption ;P = Propulsive ;FA = Final Absorption ;med-lat = medio-lateral ;ant-post = anterior-posterior

Table II-4. *Vertical Unilateral Drop jump (VUDJ) inertial orientation tracker derived descriptive values. Values expressed as mean and (SEM).*

Interestingly, non-ACL-reconstructed athletes demonstrated an exacerbated laterality-dependent Z-axis orientation asymmetry when jumping with either the dominant or non-dominant limb; this was not observed in ACL-reconstructed cases during the execution of a VUDJ (**Table II-4**). Thus, the non-dominant legs of the control athletes showed significantly greater angular excursions around the Z-axis (rotational transversal plane movement described at the trunk level) compared with the contralateral limbs in the IA, P and FA phases of the VUDJ. Some controversy exists in the literature regarding the biomechanical evidence for a dominance effect during single unilateral vertical jumping tasks in healthy and/or previously ACL-reconstructed individuals. Some authors have argued that rehabilitation[91] or training effects[92] could attenuate asymmetry in extremities in healthy individuals, whereas others have reported no dominance effects[93].

VUCMJ

The VUCMJ did not reveal any meaningful discriminative capacity between groups (**Figure II-8, table II-4**). It has been widely reported[94] that in drop jumps, the height from which the drop is performed directly affects the magnitude of the resultant ground reaction force. Because this force is often the triggering event in an ACL injury, perhaps more physically demanding activities (such as drop rather than countermovement jumps) should be used to challenge the lower limb absorption capacity and thereby make potential deficits among different cohorts more evident.

Peak acceleration values

No significant differences ($P \geq .05$) were found between limbs for any of the analyzed axes (**Figure II-8**).

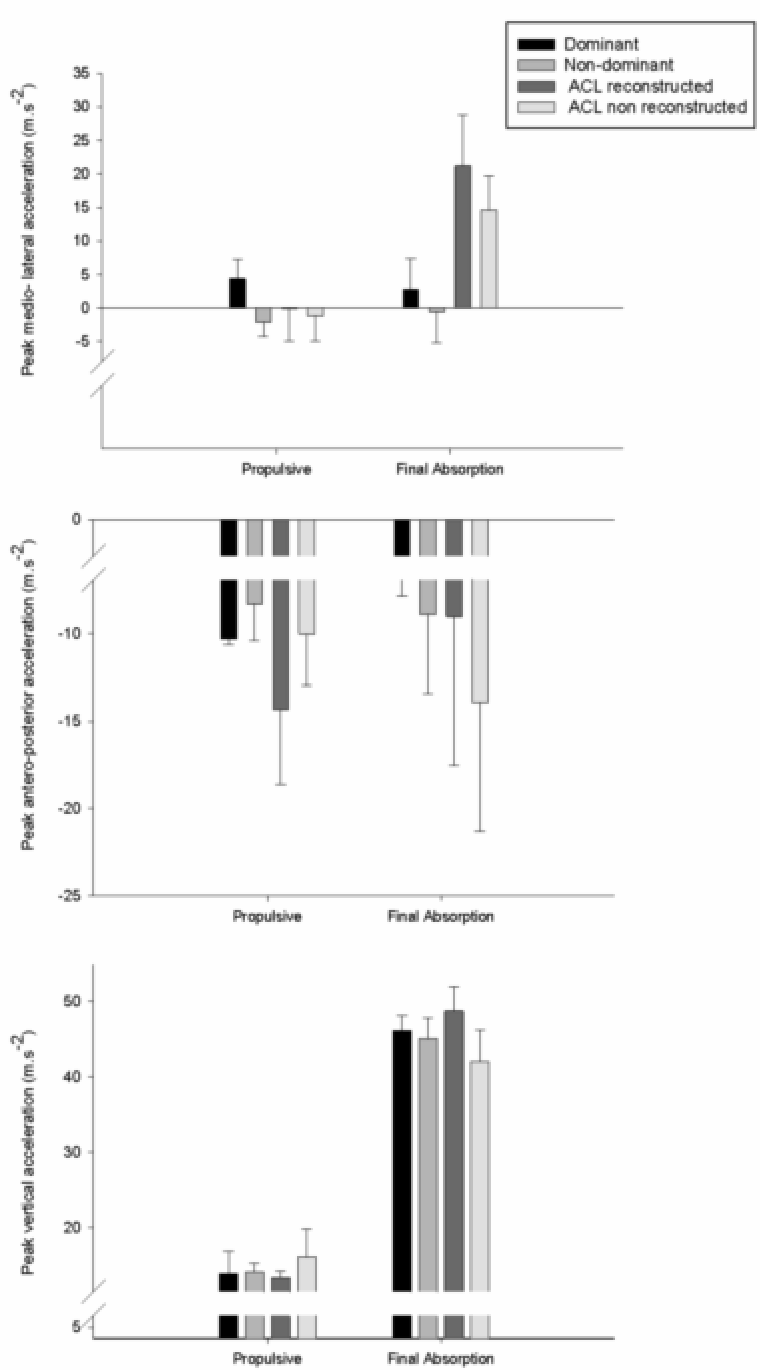


Figure II-8. *VUCMJ Peak Acceleration. (X) mediolateral axis (Top). (Y) anterior-posterior axis (middle). (Z) vertical axis (bottom). * denotes P value < 0.05 with respect to control dominant limb at VUCMJ. ^ denotes P value < 0.05 with respect to control non-dominant limbs; s = seconds; med-lat= mediolateral; ant-post = anteroposterior.*

Duration of jumping phases

There were no significant ($P \geq .05$) differences between groups with respect to any of the recorded variables for the VUCMJ jump phase durations (**Figure II-6 bottom**).

Mean orientation values

No consistent differences were identified between the groups with respect to registered variables related to the VUCMJ orientation (**Table II-4**).

Jumping phases	**Peak Acceleration ($m \cdot s^{-2}$) and angular Excursion (º)**	**Dominant (controls; n=28)**		**Non dominant (controls; n=28)**		**ACL recons (cases. n= 16)**		**Non ACL recons (cases;,n=8)**	
P phase	Med-lat axis (X) ($m \cdot s^{-2}$)	4.35	(2.95)	-2.12	(2.13)	-0.12	(4.83)	-1.21	(3.70)
	Ant-post axis (Y) ($m \cdot s^{-2}$)	-10.32	(3.01)	-8.32	(2.09)	-14.32	(4.27)	-10.03	(2.92)
	Vertical axis (Z) ($m \cdot s^{-2}$)	13.90	(0.68)	14.05	(1.20)	13.37	(0.84)	16.13	(2.80)
	Med-lat axis (X) (º)	28.54	(2.35)	22.95	(1.85)	23.29	(3.63)	25.28	(1.41)
	Ant-post axis (Y) (º)	-2.42	(2.21)	4.41	(1.76)	-5.00	(4.37)	2.54	(3.21)
	Vertical axis (Z) (º)	-7.89	(2.83)	1.36	(2.75)	4.00	(5.40)	-0.89	(-10.24)
FA phase	Med-lat axis (X) ($m \cdot s^{-2}$)	2.81	(4.62)	-0.55	(4.64)	21.19	(7.59)	14.65	(-5.01)
	Ant-post axis (Y) ($m \cdot s^{-2}$)	-3.60	(4.26)	-8.89	(4.51)	-9.02	(8.48)	-13.90	(7.40)
	Vertical axis (Z) ($m \cdot s^{-2}$)	46.18	(1.92)	45.07	(2.79)	48.75	(3.18)	42.03	(4.17)
	Med-lat axis (X) (º)	-12.35	(2.33)	-10.10	(1.57)	-13.52	(2.70)	-13.11	(3.45)
	Ant-post axis (Y) (º)	1.00	(1.67)	-2.95	(0.98)	5.16	(2.11)^	-0.83	(2.45)
	Vertical axis (Z) (º)	1.98	(1.62)	-0.04	(1.59)	1.34	(2.24)	-1.34	(2.73)

* =ANOVA test P value < 0.05with respect to control dominant limb ; ^ = ANOVA test P value < 0.05 with respect to control non- dominant ;IA = Initial absorption ;P = Propulsive ;FA = Final Absorption ;med-lat = medio-lateral ;ant-post = anterior-posterior

TABLE II-4. *Vertical Unilateral Counter Movement jump (VUCMJ) inertial orientation tracker derived descriptive values. Values expressed as mean and (SEM).*

Trunk-supported accelerations have been shown to positively correlate with the VGRF produced at initial contact during walking[95]. The results of the present study are in contrast with previous research based on inverse mechanics, which stated that several VGRF asymmetries exist among previously ACL-reconstructed subjects once having returned back to sports in both the short and long term[57;96]. Moreover, some evidence argues that increased trunk flexion and contralateral leg swing exist in previously ACL-reconstructed subjects for a maximum of 12 months after surgery[56;77]. This strategy reflects an attempt to attenuate the knee extension internal moment by transferring the acting moments to the adjacent joints (hip and ankle) to protect the integrity of the ACL graft[56;77]. This exacerbated forward trunk displacement while landing was not observed in our cohort of previously ACL-reconstructed elite male handball players.

With respect to biomechanical jumping alterations once resuming a non- restricted activity level resumed after ACL surgical reconstruction, the discrepancies with the available scientific literature could be explained by the lack of available studies focusing on cohorts stratified by sex, activity level and time since the original injury and reconstruction[97;98]. All the athletes with previous ACL reconstruction in the present investigation were top-level professional handball players that had resumed their previous activity level after ACL reconstruction. This point together with the fact that several years had passed since the original injury event, could have favored the lack of differences between the groups. In agreement with the results of the present investigation, Buesfield et al[99] showed non-significant differences in playing-related abilities among elite professional male basketball players, and Brophy et al demonstrated similar results in male soccer players[100]. Thus, the restoration of full jumping capacity appears to be common among high performance male athletes after ACL reconstruction.

One potential limitation of the current study could be that although the ISU devices were positioned at the trunk level, they obviously cannot replace higher-precision 3-dimensional motion analysis and inverse dynamics technology-based models in describing body segment movement. ISUs could alternatively be utilized in the clinical setting to measure gross whole body-supported 3-dimensional acceleration, orientation, and jump phase duration based on center of gravity behavior recorded during the jumping tasks. Despite the time since the original injury, neither the postoperative rehabilitation protocol for athletes with previous ACL reconstruction nor the graft choice for ligament repair was controlled. Furthermore, the unique placement of the ISU at the trunk level could limit the quality of information obtained regarding knee joint biomechanics. Nevertheless, this technique was used to facilitate the methodology in an attempt to provide clinicians with a simple new method capable of detecting gross VGRF attenuation strategy disruptions relative to at trunk level ACL-related pathobiomechanics. The limited post hoc power size for the study cohort could limit the interpretation of the results. Nevertheless, elite professional handball players, such as those evaluated in the present study, may constitute a population of interest for sports medicine professionals.

5.3 Study III

The purpose of this study was to examine if biomechanical jumping differences persist among a cohort of elite female handball players with previous ACL reconstruction several years after return to top-level competition. In order to achieve this goal, an ISU- utilization based simplified analysis was used. Results show that previously ACL-reconstructed elite female handball athletes may cope with persisting jumping biomechanics alterations (i.e. greater (X-), (Y-) and or (Z-) axis supporting accelerations and differing pre-defined jump phases´ duration values) during the execution of the vertical bilateral drop jump (VBDJ). Furthermore, significant group by limb interaction was present across the unilateral jumping tasks analysed. This result would indicate that both dominant and ACL reconstructed legs of controls of cases respectively functioned overall in a better way than non-dominant leg of cases and non ACL reconstructed legs of cases. However, several between groups significant differences were found in the subsequent one way (group factor fixed) ANOVA. This group of subjects (cases), showed altered angular excursion values around the (X-), (Y-) and or (Z-) axes as well as an attenuated jumping capacity than their non-ACL reconstructed counterparts during the execution of Unilateral Vertical Drop (VUDJ) and countermovement (VUCMJ) jumps. Finally limb dependent peak accelerations and angular excursion trunk displacements around the (X-), (Y-) and or (Z-) axes were detected among controls but not in previously ACL reconstructed elite female players. Previously ACL reconstructed players showed to be significantly ($p < 0.05$) lighter and smaller than their non- ACL injured counterparts (**table III-1**).

These results partially agree with the study hypothesis, which posited that ACL-reconstructed athletes would cope with greater supporting 3-axis peak accelerations, as well as less jumping performance (expressed as the duration in s of the flight time phase of the jump) compared with the control non-ACL injured counterparts.

VBDJ

Peak acceleration values

Previously ACL reconstructed athletes showed significantly greater peak acceleration values for the (X-) and (Y-) axis ($p < 0.001$ (i.e., toward the posterior direction) and (Z-) axis (p = 0.008) in comparison to those observed in the control athletes pairs during the IA and P phase of the VBDJ (Table 1). Furthermore, ACL reconstructed athletes, also displayed greater (X-) (p = 0.002) and (Y-) ($p < 0.001$) peak accelerations at FA phase of the jump in comparison to the non-ACL injured group (**Table III-1**).

Jumping phases m/s^2) (º)	**Peak Acceleration (and angular excursion**	**Non-ACL injured Control (n=15)**		**ACL reconstructed (n= 6)**		**T-Test 95%Confidence interval for mean difference**
IA phase	Med-lat axis (X) (m/s^2)	0.13	±2.25	13.16	±1.81*	(-18.89) – (-7.16)
	Ant-post axis (Y) (m/s^2)	-6.18	±4.27	14.67	±2.16*	(-30.55) – (-11.14)
	Vertical axis (Z) (m/s^2)	39.84	±2.09	49.86	±2.44*	(-17.28) – (-2.75)
	Med-lat axis (X) (º)	-20.82	±2.11	-15.42	±2.63	(-12.81) – (-2.02)
	Ant-post axis (Y) (º)	-0.56	±0.52	-1.48	±0.97	(-0.01) – (4.10)
	Vertical axis (Z) (º)	-0.93	±0.71	1.15	±0.95	(-4.69) – (0.50)
P phase	Med-lat axis (X) (m/s^2)	-0.48	±0.67	2.71	±0.32*	(-4.70) – (-1.68)
	Ant-post axis (Y) (m/s^2)	-4.91	±2.54	6.27	±0.55*	(-16.51) – (-5.86)
	Vertical axis (Z) (m/s^2)	12.39	±1.05	16.68	±1.78*	(-8.32) – (-0.28)
	Med-lat axis (X) (º)	23.16	±1.73	17.41	±2.76	(-0.75) – (12.22)
	Ant-post axis (Y) (º)	0.71	±0.6	2.19	±0.88	(-3.68) – (0.71)
	Vertical axis (Z) (º)	-1.02	±0.66	-0.75	±1.46	(-3.09) – (2.53)
FA phase	Med-lat axis (X) (m/s^2)	-0.71	±2.16	8.54	±1.75*	(-14.92) – (-3.61)
	Ant-post axis (Y) (m/s^2)	-9.43	±3.56	9.31	±0.93*	(-26.25) – (-11.23)
	Vertical axis (Z) (m/s^2)	38.29	±2.17	32.21	±3.74	(-2.28) – (14.43)
	Med-lat axis (X) (º)	-7.82	±1.64	-10.02	±2.67	(-3.98) – (8.38)
	Ant-post axis (Y) (º)	-9.43	±3.56	9.31	±0.93	(-1.49) – (4.06)
	Vertical axis (Z) (º)	38.29	±2.18	32.22	±3.75	(-3.09) – (2.53)

*=T – test p value < 0.05 with respect to control group ;IA = Initial absorption ;P = Propulsive ;FA = Final Absorption; med-lat = medio-lateral ;ant-post = anterior-posterior

Table III-1. *Vertical Bilateral Drop jump (VJ) inertial orientation tracker derived descriptive values. Values expressed as mean ± SEM*

Duration of jumping phases

With respect to vertical bilateral drop jump (VBDJ) previously ACL reconstructed athletes displayed significantly shorter P-phase times (0.20 s; 95% CI = 0.01-0.09; $p = 0.006$) and greater FA-phase time durations (0.28 s; 95% CI = 0.01-0.12; p = 0.014) in comparison to the non-ACL injured group (0.25 s and 0.21 s for the P and FA phases, respectively) (**Figure III-1 top**).

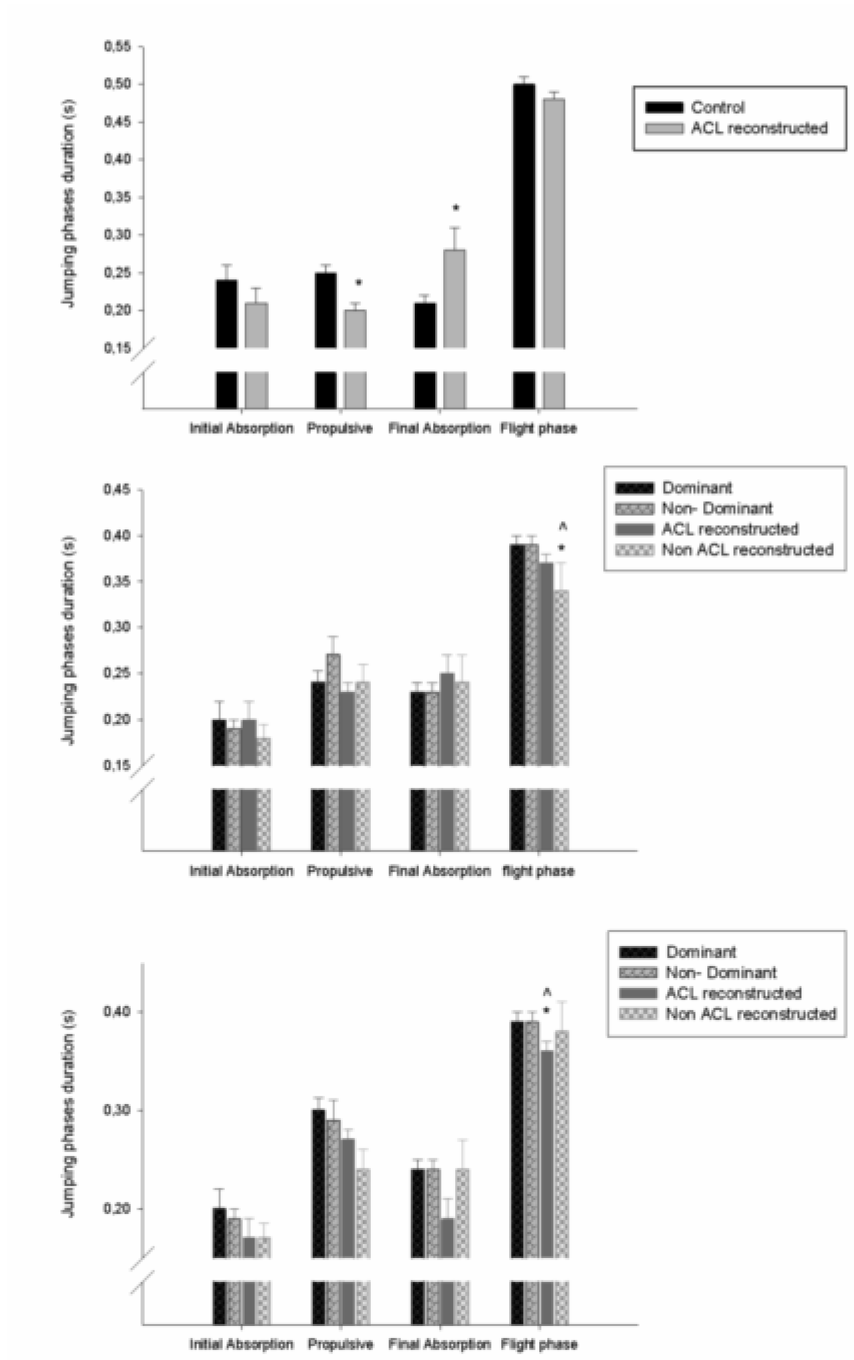


Figure III-1. *Time phases duration. Vertical bilateral drop jump (VBDJ) (Top). Vertical unilateral drop jump (VUDJ) (Middle). Vertical unilateral counter movement jump (Bottom). * denotes p value < 0.05 with respect to control group at VBDJ and to control dominant limbs at UJ and VUCMJ. ^ denotes p value < 0.05 with respect to control non-dominant limbs; s = seconds.*

Mean orientation values

No significant differences were found when analyzing mean orientation values (**Table III-1**).

The magnified trunk supported accelerations during jumping task executions have been shown to positively correlate with VGRF effects on the whole body produced at initial contact with the ground[95]. Those reported in the present research among the previously ACL reconstructed subjects in the VBDJ, may be explained by a previously reported trunk stiffening strategy[90] which could influence proper VGRF attenuation and kinetic energy re-utilization through the countermovement phase of the maneuver affecting both joint resultant reaction forces and jumping performance. It could be assumed that force production was compensated by the contralateral non-ACL reconstructed leg in this bilateral task, leading to no differences in jump performance[57]. Furthermore, this fact may be explained by the elite profile of this study cohort in which exhaustive strength training routines are frequent.

VUDJ

Peak acceleration values

Furthermore, the dominant leg of controls showed significantly differing peak accelerations in the (X-) axis vs. those observed on their contralateral non-dominant leg during the IA ($p < 0.001$; 95% CI = 9.05-34.56) and P phases ($p = 0.032$; 95% CI = 0.46-15.51) of the jump (**Table III-2**).

Jumping phases	Peak Acceleration (m/s^2) and angular excursion (º)	Dominant (controls; n=15)		Non dominant (controls; n=15)		ACL recons (cases; n= 8)		Non ACL recons (cases; n=4)	
IA phase	Med-lat axis (X) (m/s^2)	11.83	±2.32	-9.17	±3.76*	-1.82	±4.23	1.68	±3.50
	Ant-post axis (Y) (m/s^2)	-11.20	±1.28	-13.57	±2.04	-15.67	±1.91	-11.10	±2.43
	Vertical axis (Z) (m/s^2)	23.65	±2.44	26.71	±2.40	23.54	±3.10	23.15	±3.04
	Med-lat axis (X) (º)	-5.86	±1.57	-7.95	±1.32*	-10.19	±1.59	-10.12	±2.77
	Ant-post axis (Y) (º)	0.49	±0.89	-1.05	±0.63	-0.89	±1.26	-1.23	±1.21
	Vertical axis (Z) (º)	2.71	±1.33	-2.38	±1.25*	-0.14	±1.97	-1.91	±1.48
P phase	Med-lat axis (X) (m/s^2)	4.73	±1.69	-3.24	±1.74	-0.99	±3.25	3.33	±3.70
	Ant-post axis (Y) (m/s^2)	-2.01	±1.50	-5.44	±1.10	-5.79	±1.83*^	-4.81	±4.50
	Vertical axis (Z) (m/s^2)	13.35	±0.77	12.95	±0.49	13.80	±0.77	14.92	±3.14
	Med-lat axis (X) (º)	9.79	±1.22	10.04	±1.63	9.53	±1.03	10.73	±2.20
	Ant-post axis (Y) (º)	-3.58	±2.01	7.53	±1.73*	2.30	±3.35	0.97	±3.37
	Vertical axis (Z) (º)	-5.65	±1.71	1.63	±1.88*	-0.46	±2.50	2.68	±3.75
FA phase	Med-lat axis (X) (m/s^2)	4.38	±3.61	-7.42	±4.15	1.81	±6.03	-2.40	±7.53
	Ant-post axis (Y) (m/s^2)	-5.96	±2.97	-12.02	±2.71	-9.39	±3.50*^	-5.36	±6.87
	Vertical axis (Z) (m/s^2)	37.57	±1.83	37.75	±2.20	43.38	±3.10	38.17	±3.07
	Med-lat axis (X) (º)	-8.35	±1.33	-8.23	±1.22	-7.96	±1.93	-10.03	±3.09
	Ant-post axis (Y) (º)	3.33	±1.17	-5.97	1.34*	-1.33	±2.78	0.08	±3.03
	Vertical axis (Z) (º)	0.84	±0.97	-2.71	±1.09	0.73	±1.31	-2.82	±2.64

* = One way ANOVA test p value < 0.05 with respect to control dominant limb; ^ =One way ANOVA test P value < 0.05 with respect to control non-dominant ;IA = Initial absorption ;P = Propulsive ;FA = Final Absorption ;med-lat = medio-lateral ;ant-post = anterior-posterior

Table III-2. *Vertical Unilateral Drop jump (VUDJ) inertial orientation tracker derived descriptive values. Values expressed as mean ± SEM.*

Duration of jumping phases

In the vertical unilateral drop jump (VUDJ) significant group by limb interaction was found in the multivariate test for between factors' interaction (f = 2.05; p = 0.019). Subsequent one way Anova revealed that the non-injured leg of the previously ACL reconstructed athletes, displayed significantly lesser flight time values than those reported by both dominant and non dominant limbs of controls (*p* = 0.003; 95% CI= 0.01-0.09 and *p* = 0.005; 95% CI= 0.01-0.08).

Mean orientation values

Finally, regarding mean orientation reported values, significant differences around the (Y-) and (Z-) axes were found between the dominant and the non-dominant sides of controls (Table II) that were not found between the limbs of previously ACL reconstructed athletes.

Regarding unilateral actions, (VUDJ) and (VUCMJ) maneuvers demonstrated significantly ($p < 0.05$) lower trunk angular excursions around the (Y-) and or (X-) axes as well as lesser flight times in ACL reconstructed cases compared to controls. During UJ in particular, greater trunk angular displacements excursions around the (Y-) and (X-) axes, were observed among previously ACL reconstructed athletes. In these case not the accelerations but the trunk displacements showed to be decreased among ACL reconstructed cases. This fact could be explained by the more challenging demands with respect to balance and performance that the unilateral actions impose to the body, in order to maintain the center of mass within the balance margins. In that way, ACL reconstructed athletes could have adapted their movement pattern trough central motor control reprogramming during the unilateral jumping tasks into a more balance ensuring action, thereby attenuating the imposed accelerations to the center of mass limiting in that way, the jumping performance[56;77]. This fact could partially explain the observed jumping performance attenuation observed during the VUDJ and VUCMJ among both previously ACL reconstructed and healthy contralateral limbs of cases. Previous research has demonstrated residual long-term functional imbalances between affected and unaffected limbs among previously ACL reconstructed female handball players[15]. However the results of the present research did not support these findings. It could be plausible that previously ACL reconstructed athletes have adapted their jumping capabilities to the weaker side (ACL reconstructed). In this manner, they did not exhibit between extremities significant differences with respect to jumping performance but did exhibit differing whole body motion patterns (altered supporting accelerations´ dissipation capacity as well as the magnitude of trunk displacement) during vertical jumping evaluations compared to their healthy counterparts as it has been reported in the present research. Other fact that could have influenced these results is the professional profile of subjects in the present research compared to those of the study of Myklebust et al[15]. In that study both recreational and professional players were enrolled. In this sense, more exhaustive training routines as well as personalised injury prevention training programs habitually carried out in professional teams (such as those analysed in the present research) could have mitigated between extremities differences in previously ACL reconstructed athletes.

VUCMJ

Peak acceleration values

Lastly, regarding vertical unilateral counter movement jump (VUCMJ), significant group by limb interaction was found in the multivariate test for between factors interaction (f = 3.37; p < 0.001). Subsequent one way Anova revealed that the dominant leg of controls showed significantly differing peak accelerations in the (X-) axis vs. those observed on their contralateral non-dominant leg at both P (p <0.001; 95% CI =2.21-17.50) and FA (p <0.001; 95% CI =7.23-33.84) phases of the jumping task. Indeed during this latest phase of the jump, the peak (X-) axis accelerations recorded among the non-dominant leg of cases demonstrated to be significantly greater than those observed among their contralateral dominant [p <0.001; 95% CI =(-33.84)-(-7.23)], and the ACL reconstructed [p = 0.004; 95% CI =(-35.51)-(-4.63)], as well as non ACL injured legs of cases [p = 0.033; 95% CI =(-40.10)-(-1.04)] (**Table III-3**).

Duration of jumping phases

Previously ACL reconstructed legs of cases presented significantly shorter flight time phase durations in comparison to the dominant (p = 0.001; 95% CI = 0.01-0.06) and non-dominant side of controls (p = 0.001; 95% CI = 0.01-0.06) (**Figure III-1 Bottom**).

Mean orientation values

Finally, significant differences around the (Y-) and (Z-) axes were observed between groups and the dominant and the non-dominant side of controls. Mainly, controls displayed significantly greater trunk angular excursion values around the (X-) axis when jumping with their non-dominant legs than cases acting with their ACL reconstructed limb (p = 0.03; 95% CI =15.81-0.39). Indeed non ACL injured athletes exhibited greater trunk angular excursion values around the (Y-) axis when jumping with their dominant leg than cases (p = 0.04; 95% CI =14.85-0.25) (Table III).Finally, significant differences around the (Y-) and (Z-) axes were found between the dominant and the non-dominant sides of controls (**Table III- 3**) that were not found between the limbs of previously ACL reconstructed athletes.

Jumping phases	**Peak Acceleration (m/s^2) and angular excursion (º)**	**Dominant (controls; n=15)**		**Non dominant (controls; n=15)**		**ACL recons (cases; n=8)**		**Non ACL recons (cases; n=4)**	
P phase	Med-lat axis (X) (m/s^2)	5.58	±2.12	-4.27	±1.72*	0.41	±2.70	3.73	±3.29
	Ant-post axis (Y) (m/s^2)	-0.11	±1.32	-0.22	±1.56	-2.52	±2.49	-6.52	±3.66
	Vertical axis (Z) (m/s^2)	12.89	±0.49	11.94	±0.35	12.25	±0.68	14.31	±1.68
	Med-lat axis (X) (º)	19.54	±1.69	21.24	±2.02	13.14	±1.92^	15.85	±2.18
	Ant-post axis (Y) (º)	-6.10	±1.92	7.46	±2.11*	1.37	±3.43	-1.15	±3.27
	Vertical axis (Z) (º)	-5.25	±2.36	4.61	±2.70*	-2.66	±-9.90	2.16	±3.09
FA phase	Med-lat axis (X) (m/s^2)	5.47	±2.87^	-15.06	±3.67	5.00	±5.51^	5.50	±5.05^
	Ant-post axis (Y) (m/s^2)	0.25	±2.76	-5.27	±3.66*	-9.81	±4.07*	-4.48	±8.10
	Vertical axis (Z) (m/s^2)	40.61	±1.39	39.92	±2.18	40.40	±2.43	35.05	±5.77
	Med-lat axis (X) (º)	-7.49	±1.25	-8.17	±1.59	-7.34	±2.27	-8.80	±2.68
	Ant-post axis (Y) (º)	7.26	±1.24	-6.08	±2.06*	0.29	±3.64*	-1.25	±3.27
	Vertical axis (Z) (º)	0.54	±1.04	-0.94	±0.93*	3.04	±1.61	-3.22	±2.19

* =One way ANOVA test p value < 0.05with respect to control dominant limb ; ^ = One way ANOVA test P value < 0.05 with respect to control non-dominant ;IA = Initial absorption ;P = Propulsive ;FA = Final Absorption ;med-lat = medio-lateral ;ant-post = anterior-posterior

Table III-3.*Vertical Unilateral Counter Movement jump (UCMJ) inertial orientation tracker derived descriptive values. Values expressed as mean ± SEM.*

In the present study we did not found any performance (i.e. jumping flight time) differences between limbs in controls but several trunk displacement differences were found around the (Y-) and (Z-) axes that were not evident among cases. Furthermore there were no difference in the mentioned trunk displacements around the cited axes among left or right limbs of ACL reconstructed cases. The absence of those limb dominance effects on trunk specific displacements during the unilateral jumps could be due to a lasting adaptation to original ACL injury. In that manner, some controversy exists in the literature regarding the biomechanical evidence of a dominance effect among single unilateral vertical jumping tasks in healthy and/or previously ACL reconstructed individuals. Some authors argue that the rehabilitation[91] or training effects[92] could attenuate asymmetries between extremities identified among healthy individuals, whereas others report no dominance effect[93].

One potential limitation of the current study is that there is a lack of control of the postoperative rehabilitation protocol and also of the graft choice for the ligament repair. However, the aim of the present research was to determine if lasting biomechanical alterations persist several years after having suffered an ACL injury and reconstruction event. Previous researches have reported that no difference exists between different grafts choices based reconstructions in relation to function of the knee in the long term. Furthermore, the use of a single ISU placed at the trunk level does limit the quality of the information perceived regarding to knee joint biomechanics. This strategy was used because the aim of the study was to analyze the jumping biomechanics though the use of direct mechanics based procedures. In that way we studied the centre of mass behavior during the different jumping tasks executed and thus, whole body as a single system of mass and inertia. Thus, specific joint net moment of force calculations were out of the scope of the present study.

5.4 Study IV

The aims of this validation study were (1) to determine if the data provided by an inertial sensor unit placed at the lumbar spine could reliably assess jumping biomechanics and (2) to examine the validity of these data compared to force plate platform recordings.

The primary finding of this study corroborated the study hypothesis. Thus, a robust level of agreement was found between the force curve patterns obtained from ISU data and those provided by a force plate for the direct mechanics based vertical jumping biomechanical evaluation. Accordingly, both instruments demonstrated significant (P <0.01) and extremely large correlation levels across the analyzed resultant patterns of the whole force-time curves. Furthermore, significant (P <0.01) and mainly moderate correlation levels were also found between both instruments upon analyzing the isolated peak values of the acting resultant forces of the initial and final attenuation phases of each jumping task. However a considerable systematic bias was found between both instrument recordings when the magnitude of the acting forces increased. Greater the force magnitude, greater the disagreement between ISU and force plate recordings.

ISU sensor demonstrated to exhibit a robust correlation level with respect to the force plate across the entire analyzed jumping battery; the VBDJ, VUDJ and VUCMJ (**Figure IV-1**).

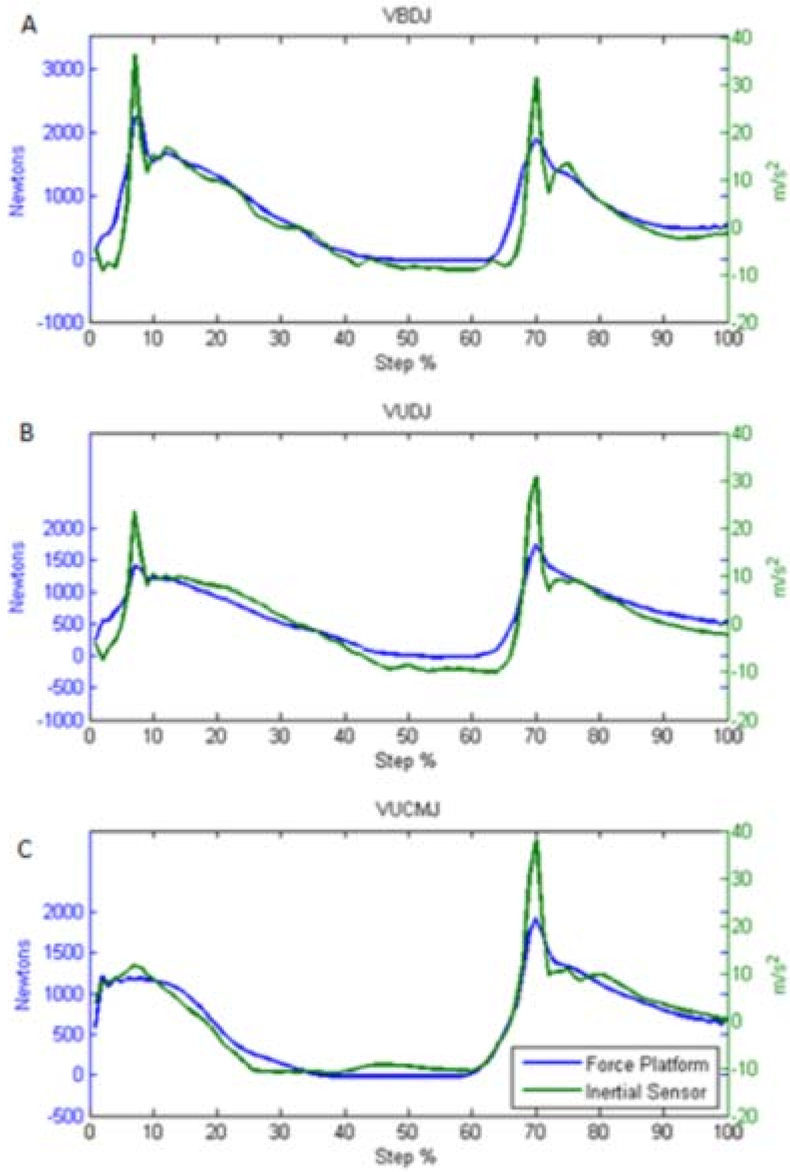


Figure IV-1. *Z vertical force by time ISU and Force Plate curves. Vertical Bilateral Drop Jump (A). Vertical Unilateral Drop Jump (B). Vertical Unilateral Counter Movement Jump (C).*

In this sense, significant ($P< 0.001$) and extremely large correlations were found when raw data of both ISU sensor and force plate derived normalized force-time curves were compared. Furthermore significant ($P < 0.001$) and moderate to very large correlation levels were also found between both instruments when isolated resultant forces´ peak values of defined IA and FA phases´ of each maneuver were analyzed (**Table IV-1**).

				VBDJ	VUDJ	VUCMJ
ISU-Force plate Pearson´s Correlation product		Raw Data (Whole curve)	r value (95%CI)	0.93 (0.81-0.97)	0.93 (0.810.97)	0.96 (0.89-0.99)
			p value	<0.001*	<0.001*	<0.001*
		IA pre-defined instant	r value (95%CI)	0.48 (-0.01-0.78)	0.44 (-0.015-0.76)	0.48 (-0.01-0.78)
			p value	<0.001*	<0.005*	<0.001*
		FA pre-defined instant	r value (95%CI)	0.52 (0.05-0.80)	0.62 (0.20-0.85)	0.71 (0.35-0.89)
			p value	<0.001*	<0.001*	<0.001*
Coefficient of Variation	IA phase	ISU	mean	10.74	19.74	12.81
			range (max-min)	1.43 -25.48	3.84-39.25	3.97-32.09
		Force plate	mean	14.25	10.10	4.71
			range (max-min)	6.73-26.02	3.85-33.15	1.58-8.61
	FA phase	ISU	mean	16.04	17.05	10.45
			range (max-min)	3.15-40.9	2.76-33.50	4.29-29.91
		Force plate	mean	12.14	13.14	10.84
			range (max-min)	2.89-25.75	6.40-34.21	2.55-42.93

*Denotes statistical significance *P* <0.005.

Table IV-1. ISU and Force plate related data correlation and variability report

Both ISU sensor and force plate recorded force- time curves, reported acceptable levels of variability (**Figure IV-2 A and B**).

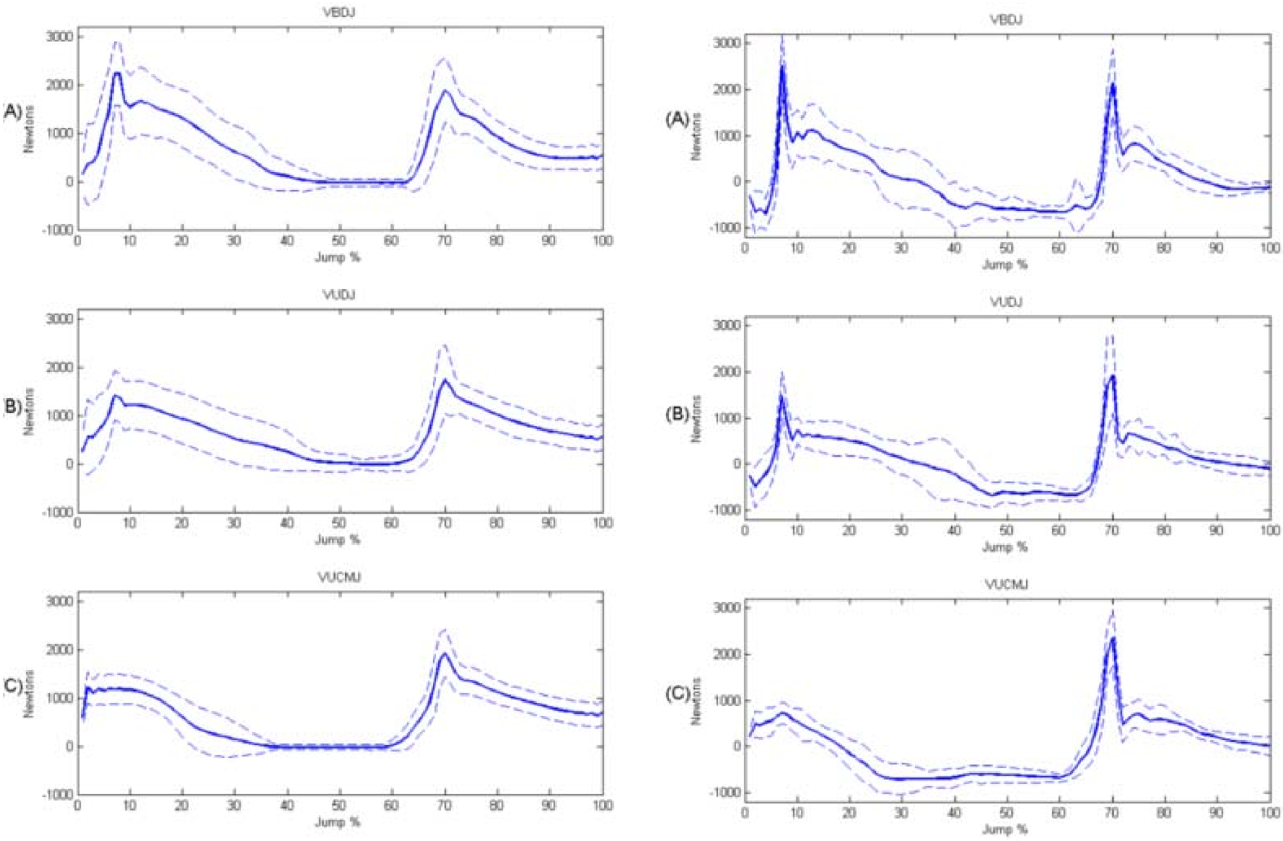


Figure IV-2. *Z vertical force by time Force Plate curves. Mean (solid line) and SD (dotted line) (left). Z vertical force by time ISU curves. Mean (solid line) and SD (dotted lined) (right)*

Furthermore, the mean Coefficients of variation (CV) displayed by each subject across the entire jumping task performed reported by ISU and force plate ranged from 10 to 19 and from 4-14% respectively (**Table IV-1**).

Lastly, Bland & Altman graphical representation were used in order to display the agreement of both ISU sensor and force plate for measuring Resultant Ground Reaction Force (RGRF) across the IA and FA phases of each jump analyzed. They showed that the vast majority of points were enclosed within the mean ±1.96 SD. The mean difference (estimated bias) was calculated and plotted in the representations. The significant ($p<0.05$) correlations encountered in the mean of between pairs differences (Y-) axis and the mean of the measured data from both ISU and force plate (X- axis), revealed a non random distribution of the data points within the confidence intervals which indicates the existence of a systematic bias . Thus, the assumption that no relation existed between the measurement differences (errors) and their mean could not be accepted. It was demonstrated, in consequence, that greater the force, greater the disagreement between ISU and force plate recordings (**Figure IV-3**).

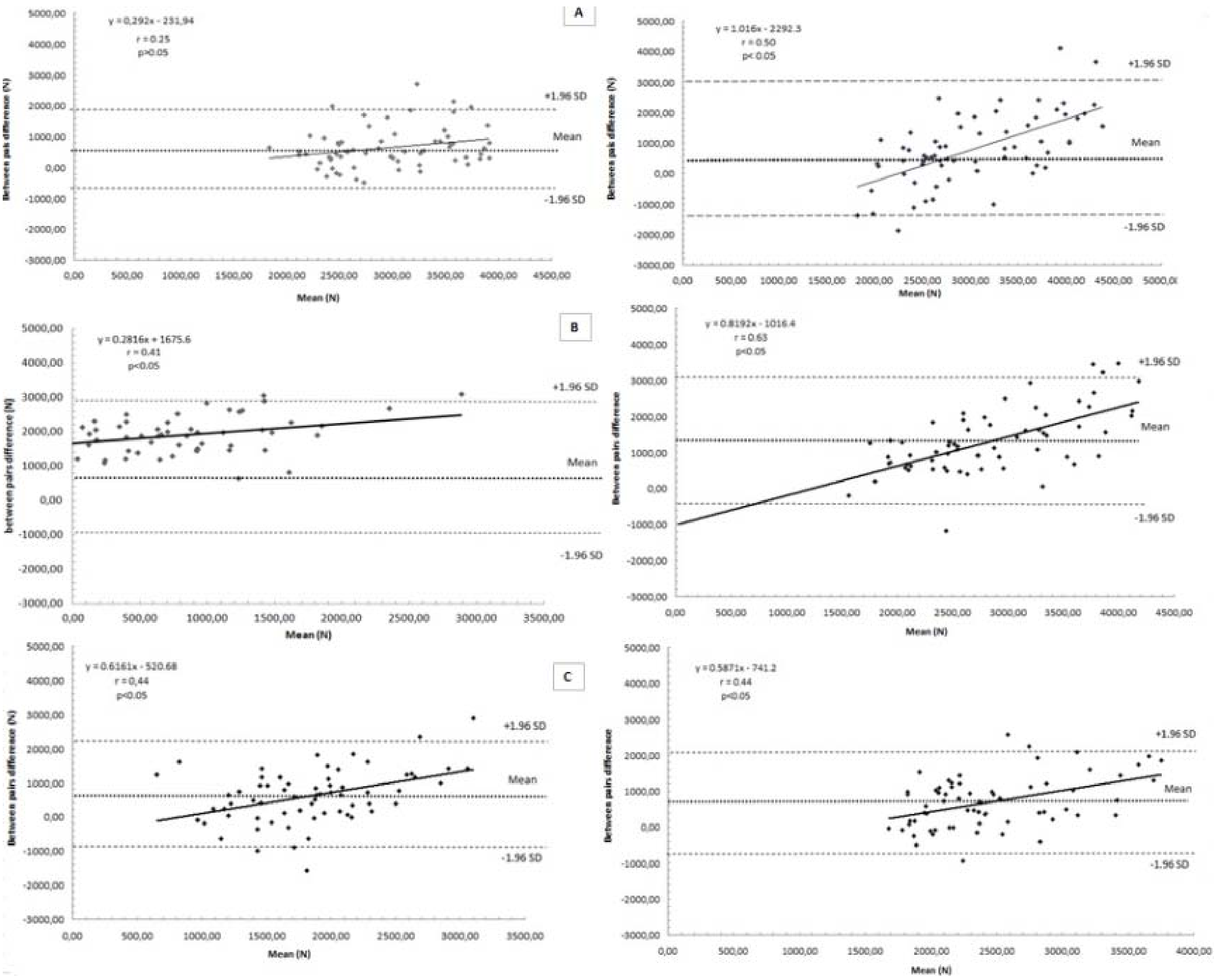


Figure IV-3. *Bland and Altman Representations comparing the differences between ISU and Force plate registered data. See text for details. The dotted horizontal lines represent the mean bias between the measurements made from each instrumentations. The dashed horizontal lines represent the 95% limits of agreement between the two variables. The solid lines correspond to the regression lines. Vertical Bilateral Drop Jump; IA left; FA right (A). Vertical Unilateral Drop Jump; IA left ; FA right (B). Vertical Unilateral Counter Movement Jump; IA left; FA right (C)*

The accuracy of a new assessment tool is usually studied by comparing the new device and its methodology with the current gold standard [45]. Force plate instruments have become the gold standard for jumping-related biomechanical research during the last decades[50]. As such, numerous research articles have been published related to the biomechanical evaluation of vertical jumps by utilizing a force platform for both performance enhancement[40;51;52] and injury prevention and rehabilitation concerns[53;54]. Briefly, as previously stated by Hatze et al.[50], two different methodologies for the biomechanical evaluation of vertical jumps have been described: the direct or inverse dynamics methods. The present research utilized the direct dynamic method approach based on a point mass body model: the center of mass (CM), estimated at the L4-L5 spine level to estimate the actuating forces generated when executing the analyzed vertical jumping tasks[48;101].

The utilization of several ISU sensor devices to assess different biomechanical variables of vertical jumping has been widely reported in the literature, demonstrating its internal validity and agreement with the gold standard[45;95;102]. Furthermore, using a similar methodology with respect to placing the ISU sensor at the mid lumbar spine level of the body, previous studies have also found significant correlations between the biomechanical parameters of jumping measured by ISUs and force plates[45;69;95]. In this sense, Choukou et al.2014[69], demonstrated high interclass reliability of an accelerometric system placed at the lumbar spine level for several jumping performance parameters, as well as good agreement with respect to the force platform in measuring vertical jumping-related biomechanical variables. The jump height, contact time, leg stiffness and reactivity indices were assessed and shown to positively correlated to the gold standard. Furthermore, Rowlands et al. 2012[95], reported significant moderate to large correlations between the ISU sensor and the force plate recordings for the average resultant force and peak loading rate during different functional activities, including walking and vertical jumping maneuvers. All of these previous studies agree with the findings of the present investigation. Even positioned at the trunk level, ISU devices cannot replace the higher-precision 3D motion analysis trough inverse dynamics technology-based models, but regarding previous[69;95;102] and the present research, they could feasibly record CM-supporting 3-dimensional axis forces as well as measure jump phases´ duration of several vertical jumping tasks performed at the training court itself.

Significant differences with respect to the CV values from both the force plate and the

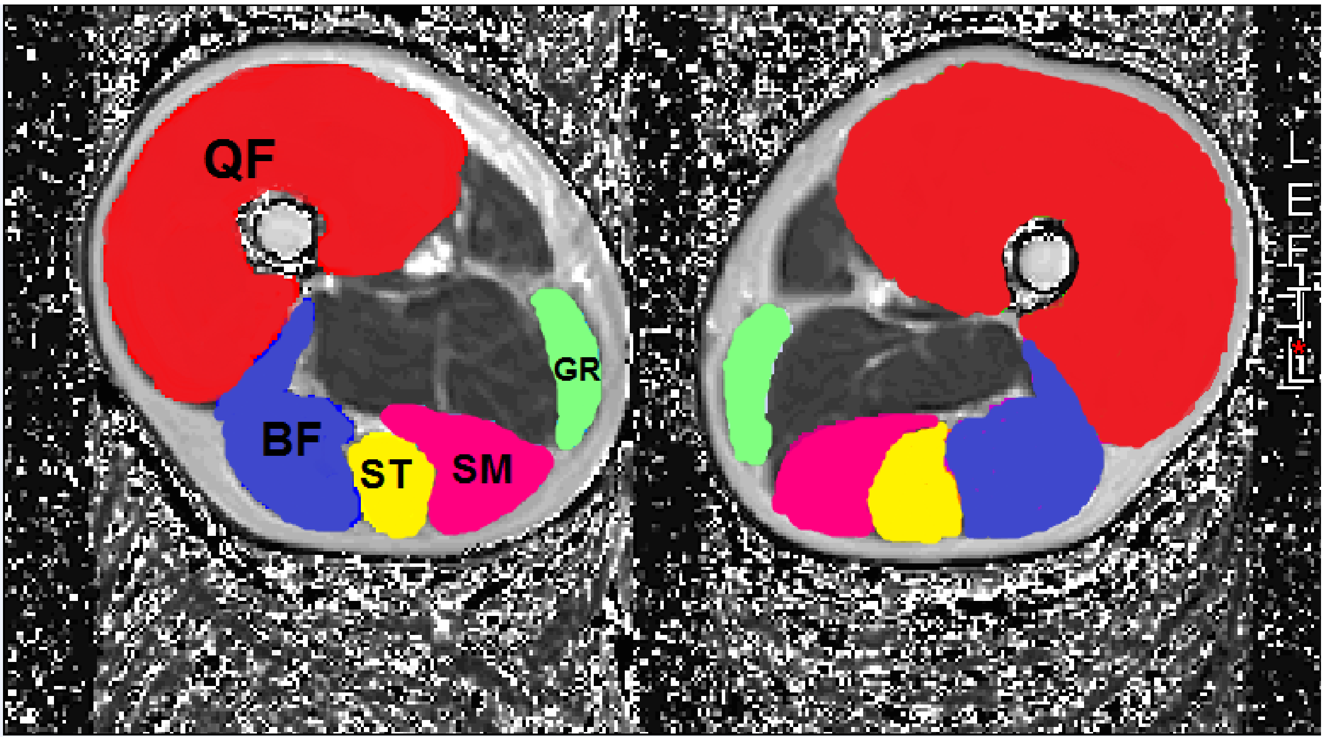
ISU were observed when isolated IA and FA points from the force by time curve were analyzed. Furthermore, a considerable mean bias as well a systematic error between the measurements from both instrumentations was detected through the Bland and Altman scatter plots. Greater the force magnitude measured, greater the disagreement between ISU and force plate recordings (**Figure IV-3**). This fact should make the clinician interpret the results of the present investigation with caution. In the authors´ opinion the encountered differences between ISU and force plate recording would arise from a sensor location related issue. In this context, the traditionally accepted assumption, that the vertical translational motion of the center of mass of the body represents the total body motion when assessing jumping biomechanics by using a force platform through direct mechanics procedures could be controversial[48;101]. This potential controversy is justified by the assumptions that all body segments execute rotational and translational motions relative to the CM and that the CM itself also executes non-vertical motions in the sagittal and lateral directions. This implies that an additional amount of forces acting at the trunk level could not be registered when analyzing jumping biomechanics through a direct method based on force plate recordings. In the authors´ opinion, the placement of the ISU at the L4- L5 lumbar spine level, which is considered to be the center of mass in humans[48;101], could allow for more comprehensive monitoring of the CM´s mechanical behavior during the execution of vertical jumping tasks.

Potential limitations from the present research could arise from technical differences between the alignments of the 3 orthogonal axes of the ISU and force plate instruments. Thus, alignment problems could arise because of the positioning of the ISU at the lumbar spine level. This fact could provide confusing data compared with those obtained from the force plate due to intrinsic movement of the trunk while executing the analyzed jumping tasks with respect to the force plate recordings, taken at ground level. To mitigate this problem, the accelerations registered by the ISU were expressed with respect to an aligned Earth-fixed global reference frame (XYZ). Afterwards, the obtained accelerometric values were transformed into force values and were finally expressed as the resultant force of both instruments to coincide with the highest level of concordance between the registered measurements.

The present study provides further evidence about the suitability of the ISUs to measure jumping biomechanical parameters. Using ISUs, several biomechanical variables such as the resultant force-time curve patterns as well as the peak resultant acting forces during the initial and final attenuation phases of the three different vertical jumps analyzed could be directly measured. However some considerations are warranted when attempting to compare isolated IA or FA data points between both ISU and force plate devices.

5.5 Study V

The present study aimed to compare the effect of two differentiated rehabilitation protocols (ACCEL vs. CON) on dynamic hamstring muscle strength and size 12 months after ACL reconstruction. Doubled ST and GR tendons autograft was used in all cases. A novel finding of the present study was that thigh musculature strength was recovered to a greater extent in subjects undergoing an accelerated rehabilitation program compared to that observed after a conventional intervention. In contrast, the muscle size in terms of CSA was not significantly (p<. 05) different between the two groups (**Figure V-1**).



FigureV-1. *Middle-thigh (50% length of the femur) cross sectional area of a subject enrolled in ACCEL group 12 months post reconstruction (Left side ACL reconstructed). Muscular structure fragmentation with fat suppression of knee flexors and extensors: Quadriceps femoris (Q); Biceps Femoris (BF); Stemitendinous (ST); Semimbranous (SM); Gracilis (GR).*

At the same time, subjects in the ACCEL group recovered symmetrical values of KT1000 AP knee joint laxity 12 months after ACL reconstruction, while subjects in the CON group did not. These results partially confirm our initial study hypothesis, which stated that greater improvements in mechanical muscle performance and muscle CSA would be found in subjects undergoing an ACCEL protocol. To the best of our knowledge, this is the first study that has analyzed thigh muscle function and morphology among subjects undergoing 4 strand medial hamstring tendon ACLRs and were subsequently exposed to two contrasting rehabilitation regimens.

No significant differences were found regarding anthropometrics between the ACCEL and the CON group *(***Table V-1***).*Before the operation, no significant differences were found either in HT or Quadriceps PT between both groups. This statement was valid for both limbs: the ACL injured and the healthy contralateral one.

One year after the operation, subjects allocated in the ACCEL group showed significant greater both Quadriceps and HT PT in the ACLR limb when compared to the PT measured before ACLR. Again, this measurement is true for both reconstructed and healthy limbs. However, one year after the reconstruction, there were no significant differences found in any of both limbs for Quadriceps or HT PT in the CON group.

When the ACCEL rehabilitation group is compared to the CON group of patients one year after surgery, significant differences were found in both Quadriceps and HT peak torques. The ACLR limb of subjects in the ACCEL group displayed greater ($p < 0.5$) Quadriceps PT values 12 months after surgery than those in the CON group (259.8 ± 52.7 Nm; 95 % CI: 233.6 – 286.0 Nm vs. 189.6 ± 52.9 Nm; 95 % CI: 164.1 – 215.1 Nm) *(Fig 2A and B)*. With respect to hamstring muscles force evaluation, subjects in the ACCEL rehabilitation group demonstrated significantly ($p < .05$) greater knee flexion peak torques 12 months after ACL reconstruction, which were not present before surgical repair *(***Figure V-2A***),* in both reconstructed and healthy limbs in comparison to conventionally rehabilitated subjects *(***Figure V- 2B***).*

Group	Time	Limb		Age (Y)	Body weight(kg)	Height (cm)	knee AP laxity (mm)	Hamstring Peak Torque º	Hamstring Work (J)
ACCEL Group	Before ACL reconstruction	Healthy	Mean (SD)	24.53(6.99)	74.06(11.72)	176.75(5.85)	6.11(2.75)	35.99(8.24)	9355.7(3265.0)^{a}
			95%CI				4.92-7.30	30.22-38.48	7615.9-11095.5
		ACL injured	Mean (SD)				8.59(2.79)	36.29(14.69)	7512.3(3205.3)
			95%CI				7.35-9.82	30.22-41.74	5804.3-9220.3^{+}
	12 months After ACL reconstruction	Healthy	Mean (SD)				6.17(1.78)	35.34(7.93)	11840.7(2542.3)
			95%CI				5.26-7.09	32.20-38.48	10486.0-13195.4
		ACL injured	Mean (SD)				7.32(2.82)	35.25(7.81)	10871.4(2352.3)*
			95%CI				5.87-8.77	33.75-36.46	9618.0(12124.9)
CON Group	Before ACL reconstruction	Healthy	Mean (SD)	23.54(6.98)	73.16(12.99)	176.44(7.46)	7,50(2.67)	35.54(8.15)	7474.4(2488.8)$^{a+}$
			95%CI				6.25-8.75	32.18-38.91	5970.4-8978.3
		ACL injured	Mean (SD)				9.5(3.33)	35.89(8.24)	7340.9(3054.3)$^{a+}$
			95%CI				7.84-11.16)	32.49-39.30	5495.2-9186.6
	12 months After ACL reconstruction	Healthy	Mean (SD)				5.52(2.66)	33.41(7,04)	9100.9(2529.5)
			95%CI				4.22-6.83	30.50(36.32)	7572.3-10629.4
		ACL injured	Mean (SD)				7.00(3.05)	32.94(7.18)	9440.3(2695.0)
			95%CI				5.53-8.47	29.97-35.90	7811.7-11068.9

ACLR. Anterior Cruciate Ligament Reconstruction. * Denotes statistical difference ($p<.05$) with respect to ACLR limb of ACCEL group pre surgery. ^Denotes statistical difference ($p<.05$) with respect to ACLR limb of CON group pre surgery. ^{a} Denotes statistical difference ($p<.05$) with respect to ACLR limb of ACCEL group 12 months post surgery.$^{+}$ Denotes statistical difference ($p<.05$) with respect to Healthy limb of ACCEL group post surgery

Table V-1. *Anthropometric, knee joint laxity and optimum angle for Peak Torque*

Indeed, 12 months after reconstruction, subjects in the ACCEL group displayed greater hamstring PT in their reconstructed limb compared with both preoperative limbs [185.5 ± 37.0 Nm; 95% confidence interval (CI): 167.1 – 203.9 Nm vs. 143.0 ± 37.7 Nm; 95 % CI: 126.2 – 159.7 Nm and 142.4 ± 38.5 Nm; 95 % CI: 124.8 - 160.0 Nm for the postoperative ACL injured, preoperative ACL injured and healthy limbs, respectively].

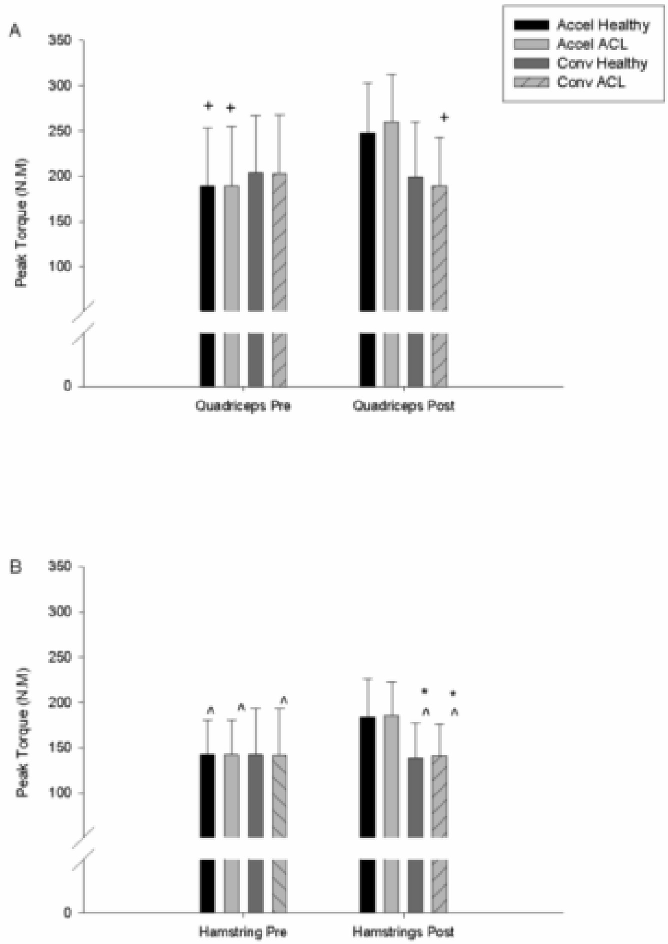


Figure V-2. . *Isokinetic muscle strength evaluation. Nm = Newtons per Meter.* $^{+}$ *represents statistical significance (p< .05) with respect to Accel RACL Quadriceps 12 months post (A).* * *represents statistical significance (p< .05) with respect to Accel Healthy Hamstrings 12 months post .* ^ *represents statistical significance (p< .05) with respect to Accel RACL Hamstrings 12 months post(B).*

Muscle force evaluation

In addition, ACL reconstructed limb of subjects undergoing an accelerated rehabilitation displayed greater hamstring muscle peak torque values 12 months after reconstruction than baseline values of ACL injured leg of subjects in the CON group (185.5 ± 37.0 Nm; 95 % CI: 167.1 – 203.9 Nm vs. 142.0 ± 52. 0 Nm; 95 % CI: 117.6 – 166.3 Nm for the reconstructed leg of subjects in the ACCEL group and the injured leg of CR group before ACL reconstruction, respectively). *(***Figure V-2.A and B***)*

ACCEL subjects also showed greater Quadriceps PT values in their ACL reconstructed leg 12 months postoperatively ($p < .05$) than those reported for both their ACL injured and healthy limbs before undergoing the reparative surgery (259.78 ± 52.71 Nm; 95 % CI: 233.57 – 285.99 Nm vs. 189.29 ± 65.59 Nm; 95 % CI: 159.43 – 219.14 Nm and 189.31 ± 64.01 Nm; 95 % CI: 160.94 – 217.70 Nm for the postoperative ACL injured, preoperative ACL injured, and healthy limbs, respectively). In fact, ACL reconstructed legs of subjects in the ACCEL group showed greater ($p < .05$) Quadriceps muscle PT than ACL reconstructed legs of subjects in the CON group at 12 months post surgical reconstruction (259.8 ± 52.7 Nm; 95 % CI: 233.6 – 286.0 Nm vs. 189.6 ± 52.9 Nm; 95 % CI: 164.1 – 215.1 Nm, respectively). *(***Figure V-2.A and B***)*

Subjects enrolled in the ACCEL group, exhibited greater ($p < .001$) mechanical work than their CON group counterparts in their ACL reconstructed limb compared to ipsilateral baseline values *(***Table V-1***)*. Certainly, at the 12-month follow up, subjects in the ACCEL group exhibited significantly ($p < .05$) greater total mechanical work in their limbs compared with both legs of the subjects in the CON group *(***Table V-1***)*.

Regarding the thigh strength recovery process, previous studies have reported varied results when assessing hamstring muscle strength after using ST and GR tendon harvesting for ACL repair[32]. The discrepancies in the results may be due to several factors such as the time from surgery, muscle size, hamstring strength evaluation methodology, proximal shifts of the newly formed muscle tendinous junction (MTJ) and/or medial HT tendon regeneration[1;103]. Previous investigations have documented long-lasting (up to two years from ACLR) strength deficits in hamstrings with respect to the contralateral healthy limb while assessing the torque generated at deep flexion values (more than 75º knee flexion)[32;37]. However, other authors have found no differences in HT muscle strength between the ACLR limbs and the contralateral healthy extremities when measuring the absolute peak torque, which is produced at lower flexion angles (15-30º)[104;105]. The differing results obtained between these methodologies could arise from the joint position in which the optimum mechanical advantage for the medial hamstrings is produced[32]. In the present study, it was found that subjects in the ACCEL group recovered both QT and HT muscle peak torque values to a greater extent than their CON group counterparts. In the authors´ opinion, these differences may be related to the more exhaustive muscle strength program performed by the subjects enrolled in the ACCEL group that in fact started on day 1 postop. Another proposed limiting factor for full recovery of the HT strength after medial hamstring graft based ACLR is the ability of the previously harvested tendon to regenerate. Recently, Papalia et al (2015)[1] concluded in a systematic review including up to 400 subjects of both sexes, that tendon regeneration after harvesting occurs in the 85% of patients. However, they also reported persistent strength deficits mainly at deep knee flexion angles despite successful tendon regeneration had occurred. Jenssen et al. (2013)[106], found no correlation between tendon regeneration and isokinetic hamstring muscles performance.

Group	Time	Limb	Muscle CSA (mm^2) / %Femur lenght	Quadriceps 50	Quadriceps 70	Biceps Femoris 50	Biceps Femoris 70	Semitendinosus 50	Semitendinosus 70	Semimenbranosus 50	Semimenbranosus 70	Gracilis 50	Gracilis 70
ACCEL Group	Before surgery	Healthy	Mean (SD)	6827.0(937.3)	4278.1(1735.3)	1379.0(307.9)	1076.5(367.1)	806.6(237.1)*^	301.5(324.0)	661.7(106.4)	1143.5(242.3)	434.6(132.4)	171.1(127.5)*^
			95%CI	6285.8-7368.2	3276.2-5280.1	1192.9-1565.1	864.5-1288.5	669.7-943.5	83.8-465.4	597.4-726.0	1003.6-1283.4	358.1-511.0	90.1-252.2
		ACL injured	Mean (SD)	6112.3(969.1)	3910.6(1918.6)	1422.5(358.8)	1063.5(366.6)	807.6(178.1)*^	274.6(284.0)	718.9(164.7)	1120.2(246.9)	401.0(115.1)	165.2(130.9)*
			95%CI	5552.7-7368.2	2802.8-5018.3	1205.6-1639.4	851.9-1275.2	704.8-910.4	83.8-465.4	619.3-818.4	977.7-1262.8	334.5-467.4	86.1-244.4
	12 months Follow up	Healthy	Mean (SD)	7412.6(1300.4)	4362.7(994.3)	1414.8(345.8)	1117.6(349.4)	879.0(213.6)*^	204.4(139.5)	737.6(196.1)	1385.5(431.9)	434.2(182.0)	155.1(48.2)^
			95%CI	6661.9-8163.4	3788.6-4936.8	1215.1-1614.5	915.8-1319.3	749.9-1008.1	104.6-304.2	624.3-850.8	1136.1-1634.9	329.2-539.3	124.5-185.7
		ACLR	Mean (SD)	6848.9(1178.1)	4075.9(888.7)	1423.6(413.8)	1220.5(340.3)	630.6(158.2)	170.6(247.8)	718.7(204.6)	1378.8(514.4)	347.1(175.6)	76.7(58.6)
			95%CI	6168.7-7529.1	3562.8-4589.1	1184.7-1662.5	1024.1-1417.0	539.2-721.9	(-83.5)-430.6	595.1-842.3	1081.8-1675.8	245.6-448.5	31.7-121.8
CON Group	Before surgery	Healthy	Mean (SD)	7203.8(1589.9)	4046.9(1482.9)	1307.0(476.3)	1149.0(535.7)	840.8(246.1)*^	276.2(197.1)	668.1(302.5)	1169.7(357.9)	415.0(115.7)	163.2(96.4)*^
			95%CI	6323.4-8084.2	3190.7-4903.1	1043.2-1570.7	839.6-1458.3	704.5-977.1	157.1-395.3	500.5(835.6)	971.5-1367.8	351.0-479.1	107.6-218.9
		ACL injured	Mean (SD)	6855.5(1425.1)	3831.6(1211.6)	1349.9(432.3)	1145.9(478.2)	861.9(279.0)*^	234.7(155.6)	701.1(268.6)	1208.4(337.7)	397.2(147.3)	140.9(82.9)^
			95%CI	6066.4-7644.7	3160.6-4502.6	1110.5-1589.3	881.1-1410.7	707.4-1016.4	140.7-328.6	546.1-856.1	1021.4-1395.4	315.7-478.6	93.0-188.7
	12 months Follow up	Healthy	Mean (SD)	7194.3(1610.6)	4318.2(1320.0)	1339.6(453.6)	1331.3(497.3)	858.4(304.7)*^	426.3(482.4)	757.8(427.9)	1113.6(562.8)	410.0(129.2)	155.6(85.9)^
			95%CI	6302.3-8086.2	3587.2-5049.2	1088.5-1590.8	1044.2-1618.4	689.7-1027.2	102.3-750.4	510.74-1004.8	801.9-1425.2	335.4-484.6	103.7-207.5
		ACLR	Mean (SD)	6850.0(1508.0)	4024.5(1044.6)	1358.0(488.8)	1327.5(393.3)	625.8(208.4)	147.4(166.5)	778.9(397.5)	1260.0(320.1)	348.3(155.1)	63.4(85.1)
			95%CI	6285.8-7368.2	3446.0-4603.0	1087.3-1628.7	1109.7-1545.3	510.4-741.2	28.3-266.5	558.75-999.0	1082.7-1437.2	262.4-434.2	9.3-117.5

ACLR. Anterior Cruciate Ligament Reconstructed.* Denotes statistical difference ($p<.05$) with respect to ACLR limb of ACCEL group 12 months post surgery. ^Denotes statistical difference ($p<.05$) with respect to ACLR limb of CON group 12 months post surgery

Table V-2. Muscle Cross Sectional Areas (mm^2) (CSA) before and after ACL reconstruction. Accelerated (ACCEL) and Conventional (CON) rehabilitation groups.

Muscle CSA

Both the ACCEL and CON rehabilitation groups displayed GR muscle CSA reduction at 70% of the femur length level vs. their uninjured limb before and 12 months after the ACLR ($p < .05$) *(***Table V-2***)*. GR muscle sizes at this level were also diminished ($p < .05$) with respect to their baseline measurements on reconstructed limbs *(***Table V-2***)*.ST muscle CSAs at the 50% femur length level were also diminished with respect to the contralateral uninjured limb in both the ACCEL and CON groups. Moreover, the ACL reconstructed limb of both groups showed lasting ST muscle size reductions with respect to baseline measurements (**Table V-2**).

In the present study both groups showed similar changes in medial HT CSA which has been shown to be directly correlated to tendon regeneration rates[28]. With respect to thigh muscle radiological examinations, it has been widely reported that short and long-term medial HT muscle size reductions occur after ACLR with autologous ST and GR tendon grafts[28;107;108]. These are similar to the results of our investigation. However, little is known regarding the functional recovery of this muscle group according to the rehabilitation process[28]. In this sense, previous studies have shown that an ACCEL rehabilitation following ACLR with ST and GR tendons could lead to earlier improvements in muscle strength without affecting knee joint residual laxity[35;109]. These results are consistent with those reported in the present investigation. Furthermore, the study contributes with original data with respect to muscle morphology adaptations with regards to the effect of the implementation of two different rehabilitation programs following ACLR. A similar tendency was observed in the Quadriceps muscles, where better isokinetic muscle strength performance was found in the ACCEL group at 12 months post-reconstruction despite a lack of significant improvement in muscle CSA.

However, the greater muscle peak torque values exhibited by the ACCEL group indicate that perhaps the type of physical training received after surgery could play a determining role in the neuro-mechanical HT function recovery.

Anterior-posterior Knee laxity

Regarding AP laxity, ACLR limbs of subjects enrolled in the CON rehabilitation group displayed greater knee AP laxity with respect to their contralateral healthy limb 12 months after surgical reconstruction ($p<.05$). That difference was not observed among subjects in the ACCEL rehabilitation group *(***Table V-1***)*.

This study has a number of potential limitations that should be addressed. The first one is related to the body positioning for HT strength evaluation. Tadokoro et al [18] found that strength deficits vs. the contralateral healthy limb varied depending on the position in which the subjects were placed for evaluation. They found 14%, 45%, and 51% deficits when assessing HT isokinetic function in a sitting position at 90º of knee flexion and in a prone position at 90º and 110º of flexion, respectively. With this in mind, we decided to measure the absolute peak torque for HT muscle strength, which was not restricted to deeper knee joint flexion angles. We did this way because the hamstring muscles strain at near full extension knee joint positions[110]. It is also known that ACL integrity is most challenged in this position but in closed kinetic chain efforts[26] . Secondly, we cannot asseverate that neural factors derived strength gains were observed following and ACCEL rehabilitation, since no neuromuscular examination was performed in the present research.

6. CONCLUSIONS

1. Previously ACL-reconstructed elite female handball athletes demonstrated lower VBDJ contact times and lower UTHD scores in their injured leg several years after the injury occurred, thereby potentially increasing their ACL reinjury risk. The restoration of these deficits following an ACL injury prior to returning to a high athletic competition level would help to decrease the reinjury rates in this population. The identification of ACL injury-facilitating motion patterns in this population seems to be crucial for the implementation of effective and deficit-based on-the-field ACL prevention training programs. More research is needed to develop clinical rehabilitation algorithms that objectively guide the patient in the improvement of all of the identified deficits prior to returning to sport participation. Thus, several Inertial Units (ISU) based studies were performed in order to analyze jumping biomechanics among professional handball athletes in order to check out for lasting biomechanical alterations apart from jumping performance measurements that could provide more precise information with regard to the athletes' readiness for non restricted sport participation. Furthermore, a clinical interventional study comparing two different rehabilitation protocols was also carried out, to contribute to the knowledge in the sparse scientific field of optimal recovery strategies to follow after the frequent and devastating ACL injury and subsequent reconstruction.

2. Among male elite handball athletes, Previously ACL-reconstructed subjects demonstrated similar jumping biomechanical profile, including jumping performance values in both bilateral and unilateral jumping maneuvers, several years after ACL reconstruction. These findings are in agreement with previous research showing full functional restoration capacity of male top-level athletes after ACL reconstruction, rehabilitation and later return to previous activity level sports.

3. With respect to their female counterparts, previously ACL-reconstructed elite female handball athletes demonstrated different (Y-) (X-) and (Z-) spatial axis peak acceleration and displacement distribution strategies at their estimated center of mass level, and worse unilateral jumping performance in comparison to non-ACL reconstructed controls.

4. By means of the utilization of the described Inertial sensors- based methodology for jumping biomechanics examination, several biomechanical variables such as the resultant force-time curve patterns as well as the peak resultant acting forces during the initial and final attenuation phases of the three different vertical jumps analyzed could be directly measured. However some considerations are warranted when attempting to compare isolated IA or FA data points between both ISU and force plate devices. Having assessed its validity and reliability, the purposed ISU technology-based methodology could provide athletic trainers, sport clinicians and scientists with a portable and cost-effective tool for the direct mechanics based biomechanical evaluation of vertical jumping.

5. On the other hand, the optimal rehabilitation stimulus to restore muscle function after ACL reconstruction and muscle harvesting for graft conformation was evaluated. Objective atrophy of the implicated musculature (ST and GR) related to the surgical reconstruction persisted in the reconstructed limb one year after medial hamstring ACL reconstruction, regardless of whether ACCEL or CON rehabilitation protocols were used. Surprisingly, subjects following the accelerated rehabilitation protocol demonstrated greater muscle strength gains despite persisting reductions in muscle size. At the same time no differences were found with respect to the optimum angle for peak torque production between groups. However, larger flexion mechanical work values were found in the

harvested musculature among ACCEL participants. Selective retraining of the hamstring musculature (ACCEL group) after ACL reconstruction seems necessary to counteract the persisting knee flexor strength deficits and restore anterior-posterior knee laxity to normal levels.

6. In summary, ISU systems could aid the implementation of real-time simple biomechanical jumping examinations by sports medicine professionals in the clinical setting to reduce the residual uncertainty that often accompanies the clinician during the process of ACL rehabilitation and return to sports.

7. A unique potential clinical implication of the present Doctoral Thesis, is that by means of a biomechanical examination of several vertical jumping tests through the utilization of a single ISU, clinicians can measure 3-axes supported accelerations as well as jumping performance in terms of jump phase duration among previously ACL-reconstructed male and female athletes, even if several years have passed since the original injury. At the time of the deposit of this Doctoral Thesis, the utilization of ISU based jumping biomechanical analysis among patients undergoing the rehabilitation process subsequent to the ACL reconstruction was under data analysis process. The utilization of such methodology for patient functional status assessment through the rehabilitation process seems encouraging ad would provide clinicians with a feasible and economic tool to improve their clinical practice quality standards.

Appendix V-1

CONVENTIONAL REHABILITATION PROTOCOL FOLLOWING ACL-PTG RECONSTRUCTION

<u>WEEK 1-3:</u>

- Quadriceps electrical muscle stimulation (Compex).
- Quadriceps isometric setting. 3x10.
- Range of motion work. Flexion/extension. 5 minutes.
- Quadriceps, gluteus and adductor strengthening work. 2x10. Firs week without weight and then adding 1 Kg.
- Hamstrings work in both closed and open kinetic chain 3x10.

.

- Strengthening exercises using an elastic band focused on gastrocnemISUs, anterior tibialis and peroneus muscles 3x10.
- Restore independent ambulation.
- Manual therapy: scar tissue restoring; diminish swelling; hamstring, quadriceps and gastrocnemISUs muscle massage.
- Patellar mobilization.
- Progress to a one-crutch ambulation.

<u>WEEK 3-6:</u>

- Bicycle. Flexion 100º.
- Walking.
- Weight-bearing exercises, soft proprioception work: double-leg drills, single-leg drills with ball/eyes closed 3x10.

<u>WEEK 7-12</u>

- Strengthening work of injured leg including Quadriceps, Hamstring and calf muscles: 1x12/14.
- Increase level of proprioception work.
- Bilateral squats. 1x12/14.
- Step up-down with injured limb 1x12/14.
- Weight-bearing exercises achieving last extension degrees using an elastic band 1x12/14.

<u>WEEK 13-24:</u>

- Begin with soft running 3x10.
- Double-leg jump 3x10.
- Functional activities as the patient could tolerate feeling confident

**Since first phases of the rehabilitation we suggested exercises at the swimming pool, increasing difficulty and intensity progressively.*

***During the rehabilitation, we should pay attention to the overload of patellar tendon and muscles that form part of the pes anserineus in order to avoid an undesirable tendinopathic process. The treatment of Trigger Points in pes anserinus and vastus medialis would be advisable.*

Appendix V-2

ACCELERATED REHABILATION FOLLOWING DOUBLE BUNDLE SEMITENDINOUS-GRACILIS RECONSTRUCTION

Phase 1.1: Immediate Post-operative Period (Week 1):

Progression Requirements:

- Reduced swelling and pain.
- Restore total range of motion. Symmetrical extension
- Restore quadriceps voluntary contraction.
- Restore patellar mobility (in distal-proximal and medial-lateral directions).
- Start independent ambulation and proper gait technique.

Exercises:

1. *ROM:*

- Tighten a pad with the heel, Quadriceps maximum recruitment. 3x12
- Active assisted manual knee hiperextension 3x12
- Using webbing placed on the foot, provoke a knee hyperextension while the heel lifts and the quadriceps is recruited maximally. 3x12
- Seated in the edge of the stretcher, provoke knee flexion and extension as far as possible, helping with the healthy leg or by the PT. 3x12
- Deep flexion exercises as the patient tolerates 3x12

2. *CORE STABILITY (CE) EXERCISES:*

- Lying on the stretcher in supine decubitus, active straight leg rises after quadriceps voluntary maximum contraction. 45º of hip flexion and knee extension. 3x8
- Transversus Abdominal voluntary contraction keeping the abdominal wall stiff.
- Lying on the stretcher in lateral decubitus with the affected leg up. Elevate the pelvis with the hip and the knee completely extended with abduction of the affected limb. 3x8

3. *GAIT TECHNIQUE RETRAINING:*

- Normalization of patterns (symmetry in the foot support; progression from partial load to the total weight-bearing; correct forefoot-heel cycle; avoid ipsilateral pelvis tilt).
- Leg-to-leg dynamic weight transfer. 3x12

Phase 1.2: Early Rehabilitation Period (Weeks 2-4):

Progression Requirements:

- Independent ambulation with correct gait cycle in different directions and planes of movement.
- Strength improvement in Quadriceps, Hamstrings, hip proximal musculature and core musculature.
- Correct performance of the bilateral squat till 90º.

.

Exercises:

- Addition of more difficult and intense exercises on each working aspect:

1. *ROM:*

- Femur backward pushing in closed kinetic chain. 3x12
- Leg-to-leg weight transfer with more weight using a barbell in the Multipower machine. 3x12

1. *CE EXERCISES:*

- Lying in supine decubitus with the elastic band placed above the knees, tense it and lifts the pelvis contracting the gluteus muscles and abdomen. 3x10

1. *WEIGHT-BEARING EXERCISES:*

- Gait cycle improvement adding obstacles in all directions (frontal, lateral and backward).

2. *STRENGHTENING EXERCISES (GYM):*

- Quadriceps-hamstring isometric co-contractions, pushing a fit ball against a wall.3x8
- Hamstring low isometric contractions 3x12.
- Standing on the healthy leg, injured leg hip extension against resistance (open kinetic chain) 3x12
- Standing on the healthy leg, injured leg hip abduction against resistance (open kinetic chain) 3x12
- Bilateral squat with the elastic band placed around the knees t. Progress adding more weight.3x10

Phase 1.3 (Weeks 4-7)

<u>Progression Requirements:</u>

- Neuro-muscular control: qualitative assess of valgus control and lateral plane stability of the knee through the Counter Movement Jump test (CMJ) and Tuck Jump test (TJ). Patient is fit to start with running training in the next phase (2.1).

<u>Exercises:</u>

1. *ROM:*

- Maintain same exercises as phase 1.1 and 1.2, focusing on individual deficits, if necessary.

2. *CE EXERCISES:*

- Maintain same exercises as phase 1.1 and 1.2.
- "Bridge" position. Maintain the posture. Increase intensity adding hip abduction and extension with the limb totally extended. 3x10

3. *STRENGHTENING EXERCISES:*

- Progress in hip extension and hip abduction exercises standing on the injured leg. 3x10
- Unilateral squat tensing the elastic band placed above the knees, progressing in intensity 3x12
- Step Ups: sagittal and frontal plane, tensing the band placed around the knees 3x12
- Pelvis tilts by contracting t the lateral hip musculature 3x12.

Phase 2.1 (Weeks 7-10)

<u>Exercises:</u>

1. *ROM:*

- Maintain same exercises as phase 1.1 and 1.2, focusing on individual deficits, if necessary.

2. *CE EXERCISES:*

- Maintain same exercises as phase 1.2 and 1.3.

3. *STRENGHTENING EXERCISES:*

- Maintain same exercises as phase 1.2 and 1.3, focusing on individual deficits, if necessary.
- Dynamic lunge 3x12.
- Squat: progress to unilateral performance with the injured leg 3x12
-

4. *PROPRIOCEPTION TRAINNING:*

- **STATIC:**

- Standing on the injured leg at 30º of knee flexion (stability position), tense the elastic band placed above the knees 3x10.
- Same position, move the free leg in different directions, enduring the posture and the created perturbation 3x10.

- **DYNAMIC:**

- Step to a pad and receipt the drop enduring the stability position. 3x6
- Increase difficulty and intensity varying the surface type and height of the drop. 3x6

RUNNING:

- 5 minutes, 9 km/h on the treadmill.

Phase 2.2 (Weeks 10-12)

Progression Requirements:

- Isokinetic test: less than 15% deficit in knee flexo-extension torque versus contralateral leg.
- Correct performance of the TJ test (qualitative assess).
- Correct running performance (VGRF absorption, correct impulse and force generation).
- Correct (less than 15% deficit) impulse and force generation capability in CMJ with the injured leg.

Exercises:

1. *ROM:*

- Maintain same exercises as phase 1.1 and 1.2, focusing on individual deficits, if necessary.

2. *CE EXERCISES:*

- Maintain same exercises as phase 1.2 and 1.3.

3. *PROPRIOCEPTION TRAINNING:*

- Integrate frontal plane exercises.
- Jump to a pad enduring the stability position and tensing the elastic band placed above the knees.3x6.
- Between two pads, displace laterally and jump on each pad maintaining stability position and tensing the elastic band placed above the knees 3x6.

4. *JUMPS:*

- Horizontal Bilateral Jump (HBJ): tensing the elastic band placed above the knees. Increase difficulty landing on unstable surfaces 3x6
- Vertical Jump (VJ): increasing the height progressively 3x12.
- Drop Jump (DJ): increase the drop height progressively as the surface instability.

Phase 3.1 (Weeks 10-13):

Progression Requirements:

- Normalize lower extremity strength.
- Enhance muscular power and endurance.
- Improve neuromuscular control.
- Perform selected sport-specific drills.

Exercises:

1. *CE EXERCISES:*

- Maintain same exercises as phase 1.2 and 1.3.

2. *DJS – PROPRIOCEPTION TRAINNING:*

- Same as phase 2.2 exercises. Increase difficulty landing on more unstable surfaces and adding weight using a barbell.

3. *JUMPS:*

- Same as phase 2.2 exercises. Increase difficulty landing on more unstable surfaces and adding weight using a barbell

4. *PLYOMETRIC TRAINNING DRILLS:*

- Plyometric leg press: jump 3x5

- Double-leg plyometric jumping drills, tensing the elastic band placed above the knees. 3x6
- Side-to-side single-leg jumps, 3x6
- **Phase 3.2 (Weeks 12-15)**

Progression Requirements:

- Maximal strength and endurance achievement on the injured leg.
- Normalize neuromuscular control.

Exercises:

1. *CE EXERCISES:*

- Maintain same exercises as phase 1.2 and 1.3.

2. *DJS – PROPRIOCEPTION TRAINNING:*

Increase difficulty. Reception with multiplane and rotational movements:

- Bosu V drill (multiplane). 3x5
- Bosu-to-bosu displacement in frontal plane. 3x5

3. *PLYOMETRIC TRAINNING DRILLS:*

- Double-leg lateral jump from side to side of a step in frontal plane.3x5
- Double-leg plyometric forward jumping during 10 meters.3x5
- Single-leg drop jump into matt and vertical/forward jump. 3x5

4. *AGILITY TRAINNING:*

- Clock exercise 3x5
- Multi-direction sprinting 3x3

.

Phase 3.3 (Weeks 15-16):

Progression requirements:

- Gradual return to full unrestricted sports.
- Achieve maximal strength and endurance.
- Normalize neuromuscular control.
- Progress skill training.

Exercises:

- Maintain same exercises as phase 1.2 and 1.3.

2. *DJS – PROPRIOCEPTION TRAINNING:*

- Maintain same progression as in phase 3.2

3. *PLYOMETRIC TRAINNING DRILLS:*

- Single-leg jump length. 3x5
- Tuck Jumps:
    - Sagittal plane: jump to a step forward using resistance bands as described before. 3x15
    - Frontal plane: jump from side to side a step moving forward. 3x15
- Drop Jump: Single-leg 3x5

5. *AGILITY TRAINNING DRILLS*

- Clock exercise 3x5
- Multi-direction sprinting 3x3.

5. *SPORT SPECIFIC TRAINNING*

- Shooting. 3x12
- Direction and speed changes.
- Lateral race with changes of direction.
- Abrupt braking actions.

- Turns. & Pivoting tasks

7. LISTA DE ARTÍCULOS CIENTÍFICOS

Study I. *Jumping performance differences among elite professional handball players with or without previous ACL reconstruction.* **Journal of Sports Medicine and Physical Fitness. Accepted.**

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Jumping performance differences among elite professional handball players with or without previous ACL reconstruction

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Study II. *Acceleration and orientation jumping performance differences among elite professional male handball players with or without previous ACL reconstruction: An inertial sensor unit based study.* **Physical Medicine and Rehabilitation Journal. Accepted.**

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Original Research

Acceleration and Orientation Jumping Performance Differences Among Elite Professional Male Handball Players With or Without Previous ACL Reconstruction: An Inertial Sensor Unit-Based Study

Igor Setuain, PT MS, Miriam González-Izal, PhD, Jesús Alfaro, MD, PhD, Esteban Gorostiaga, MD, PhD, Mikel Izquierdo, PhD

Abstract

Background: Handball is one of the most challenging sports for the knee joint. Persistent biomechanical and jumping capacity alterations can be observed in athletes with an anterior cruciate ligament (ACL) injury. Commonly identified jumping biomechanical alterations have been described by the use of laboratory technologies. However, portable and easy-to-handle technologies that enable an evaluation of jumping biomechanics at the training field are lacking.
Objective: To analyze unilateral/bilateral acceleration and orientation jumping performance differences among elite male handball athletes with or without previous ACL reconstruction via a single inertial sensor unit device.
Design: Case control descriptive study.
Setting: At the athletes' usual training court.
Participants: Twenty-two elite male (6 ACL-reconstructed and 16 uninjured control players) handball players were evaluated.
Methods: The participants performed a vertical jump test battery that included a 50-cm vertical bilateral drop jump, a 20-cm vertical unilateral drop jump, and vertical unilateral countermovement jump maneuvers.
Main outcome measurements: Peak 3-dimensional (X, Y, Z) acceleration ($m \cdot s^{-2}$), jump phase duration and 3-dimensional orientation values (°) were obtained from the inertial sensor unit device. Two-tailed *t*-tests and a one-way analysis of variance were performed to compare means. The *P* value cut-off for significance was set at $P < .05$.
Results: The ACL-reconstructed male athletes did not show any significant ($P < .05$) residual jumping biomechanical deficits regarding the measured variables compared with players who had not suffered this knee injury. A dominance effect was observed among non-ACL reconstructed controls but not among their ACL-reconstructed counterparts ($P < .05$).
Conclusions: Elite male handball athletes with previous ACL reconstruction demonstrated a jumping biomechanical profile similar to control players, including similar jumping performance values in both bilateral and unilateral jumping maneuvers, several years after ACL reconstruction. These findings are in agreement with previous research showing full functional restoration of abilities in top-level male athletes after ACL reconstruction, rehabilitation and subsequent return to sports at the previous level.

Introduction

Handball is a highly strenuous contact team sport with a strong emphasis on running speed, jumping, abrupt changes in direction, and throwing [1]. As a consequence, anterior cruciate ligament (ACL) rupture is one of the most frequent and devastating injuries among handball players [2]. Female athletes have a greater risk of ACL injury than their male counterparts during the same jumping and pivoting tasks [3], which has been associated with neuromuscular, anatomical, and hormonal differences between genders [4].

In contrast, evidence for neuromuscular or biomechanical risk factors for ACL injuries in male athletes appears to be mainly related to dysfunctions occurring at the trunk and hip joint levels [5]. In this context, video analysis techniques have revealed that athletes with ACL injuries have greater center of mass to base of support distances and lower trunk angles in the sagittal plane relative to the resultant vector of the ground reaction force compared with those in uninjured

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Study III. *Biomechanical jumping differences among elite female handball players with and without previous ACL reconstruction: a novel inertial sensor unit study.* **Sports Biomechanics. Accepted.**

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Biomechanical jumping differences among elite female handball players with and without previous anterior cruciate ligament reconstruction: a novel inertial sensor unit study*

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Abstract
Persistent biomechanical and jumping capacity alterations have been observed among female athletes who have sustained anterior cruciate ligament (ACL) injuries. The purpose of this study was to examine if biomechanical jumping differences persist among a cohort of elite female handball players with previous ACL reconstruction several years after return to top-level competition. In order to achieve this goal, a direct mechanics simplified analysis by using a single Inertial Sensor Unit (IU) was used. Twenty-one elite female (6 anterior cruciate ligament reconstructed and 15 uninjured control players) handball players were recruited and evaluated 6.0 ± 3.5 years after surgical anterior cruciate ligament reconstruction. Bilateral and unilateral vertical jumps were performed to evaluate the functional performance and a single inertial sensor unit was employed in order to collect 3D acceleration and 3D orientation data. Previously ACL-reconstructed analysed athletes demonstrated significant ($p < 0.05$) alterations in relation to the three-dimensional axis (X–Y–Z) supported accelerations and differing jump phase durations, including jumping performance values, in both bilateral and unilateral jumping manoeuvres several years after ACL reconstruction. Identification of the encountered deficits through the use of an IU devise could provide clinicians with a new reliable tool for movement analysis in a clinical setting.

Keywords: *Knee, injury, functional evaluation, accelerometry*

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*The study protocol was approved by the by the Institutional Review Committee of the Public University of Navarra, Spain.

Study IV. *Vertical jumping biomechanical evaluation through the use of inertial sensor- based technology.* **Journal of Sports Sciences.**

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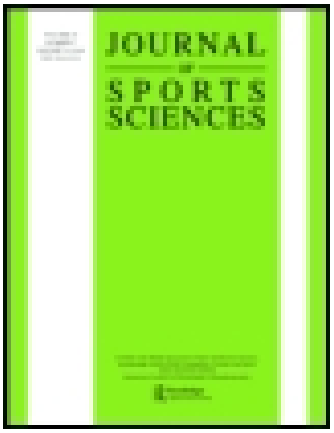

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Vertical jumping biomechanical evaluation through the use of an inertial sensor-based technology

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Study V. *Muscle morphology and strength evaluation after two different rehabilitation programs following Anterior Cruciate Ligament Reconstruction*. **American Journal of sports Medicine. Submitted**

Muscle morphology and strength evaluation after two different rehabilitation programs following Anterior Cruciate Ligament Reconstruction.

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Abstract

Controversy remains regarding the effects of the type of physical rehabilitation followed after ACL reconstruction using autologous Semitendinosus and Gracilis tendons graft on thigh muscles strength and cross sectional area (CSA) recovery.

Porpuse: To analyze the cross sectional area (CSA) and dynamic strength of Quadriceps and Hamstring muscles in a sample of 40 recreational athletes following either accelerated or conventional rehabilitation programs, before and one year after undergoing an ACL reconstruction.

Methods: Concentric isokinetic knee joint flexo- extension torque assessments at 180º/s and Magnetic Resonance Imaging (MRI) evaluations were performed before and 12 months after ACL reconstruction. Anatomical muscle CSA (mm^2) was assessed, in Quadriceps (Q), Biceps femoris (BF), Semitendinous, (ST) Semimembranosus (SM) and Gracilis (GR) muscles at 50 and 70% femur length. Within and inter groups comparison were made (healthy and operated limbs of both groups before and after surgical procedure), using a significance level of $p < .05$.

Results: Reduced muscle CSA was observed in both treatment groups for ST and GR one year after ACL reconstruction. At one year follow up, subjects allocated to the accelerated rehabilitation, demonstrated greater knee flexor peak torque in their reconstructed limbs in comparison to conventionally treated subjects ($p<.05$).

Conclusions: Objective atrophy of ST and GR muscles related to surgical ACL reconstruction was found to persist in both rehabilitation groups. In terms of mechanical muscle function, accelerated rehabilitation after ACL reconstruction lead to substantial gains on maximal knee flexor strength and ensured more symmetrical anterior-posterior laxity levels at the knee joint.

Keywords: *ACL; MRI; muscle strength; accelerated rehabilitation*

Introduction

Injury of the anterior cruciate ligament (ACL) is one of the most severe and disabling injuries in sport [13, 26]. The ACL reconstruction is performed to restore knee stability and prevent the occurrence of further injuries of adjacent structures over time [17, 26]. Autologous tendons remain the most frequent graft choice to perform the ligament repair [26]. Medial hamstrings grafts have been increasingly employed along these last years for ACL reconstruction due to its associated lower donor site morbidity [22], good material mechanical properties, minimal impact on the knee extensor mechanism and excellent postoperative outcomes [1, 27, 32].However, some limitations have been described for medial hamstring ACL reparative technique. Greater knee laxity [12], persistent knee flexor atrophy in terms of muscle size [2, 26] and strength deficits [1] have been reported along with a greater short-term risk for hamstring strain injury after returning to sports [9, 31]

Studies comparing different types of rehabilitation following ACL reconstruction during the past 25 years have favoured the implementation of the so-called accelerated rehabilitation programs (ACCEL) [4, 10]. Originally De Carlo et al (1990) [10] and more recently Beynnon et al (2005) [4] evaluated knee joint stability as well as function related aspects among patients with ACL patellar tendon graft ACL reconstruction. More recently, other authors [31, 34], have opted for the implementation of this kind of rehabilitating procedure among patients undergoing a ligament reconstruction with medial hamstring grafts.

Although many clinical trials have been carried out comparing this methodology to conventional rehabilitation procedures, there is not an accepted single standard for the definition of an accelerated rehabilitation program. These protocols are mainly based on early weight bearing and joint mobilization after surgery as well as on a more intense strength and neuromuscular training routines. Early return to full activity levels, lower residual anterior-posterior knee laxity and lower postoperative complication rates have been described among subjects following this kind of rehabilitation routines with both patellar tendon or medial hamstring grafts [4, 10, 31].

Isokinetic dynamometry and magnetic resonance imaging (MRI) are the most commonly used methods to evaluate both muscle strength and morphology among the previously ACL reconstructed population. The peak torque for muscle force production and the cross sectional area of thigh muscles have been widely studied in this field [24]. Quadriceps and Hamstring peak torque values represent the highest value of muscle force that the subject produces during the knee motion from 90º to 0º in both extensor and flexor efforts. Although there have been reported several methods for isokinetic hamstring muscle function assessment [30], controversy remains with respect to the influence of previous medial hamstring harvest for ACL reconstruction on successful returning to sports [26]. This fact have favored studies focusing on entire torque-angle curves as well as on the optimum angle for peak torque development among this population [8]. Inconclusive results have been reported, probably due to several factors such as differences in time from evaluation to prior surgery, the biological mechanisms associated with regeneration of the harvested tendon [2], and divergences in the rehabilitation protocols followed that could play a key role in the recovery of hamstring musculature function [8, 32]. In this context, to our best knowledge, there are not in the literature investigations focusing on the comparison of accelerated vs. conventional rehabilitation protocols following ipsilateral autologous medial hamstrings ACL reconstruction with regards to muscle strength and morphology recovery rates.

The objective of the present study was, therefore, to compare the effect of two differentiated rehabilitation programs (accelerated and conventional) on hamstring muscle strength and size 12 months after ACL reconstruction using a doubled (i.e., four strand) Semitendinosus and Gracilis tendons autograft. It was hypothesized that better mechanical muscle performance (exerted peak torque) and muscle cross sectional areas would be improved to a greater extent among subjects following an accelerated rehabilitation program.

Methods

Patients

A longitudinal clinical double blinded (patients and evaluator) level 1 of evidence- randomized trial was performed with 40 (30 male, 10 female) recreationally active athletes (Tegner activity scale 7) in order to analyse the effect of two different rehabilitation programs following ACL reconstruction.

Table 1 depicts patient demographics. All patients were operated by the same orthopaedic surgeon (JAA) following identical surgical technique. Antero-medial portal cam was used in all cases to perform an anatomical ACL reconstruction. Autologous double bundle hamstring grafts were used for all patients. Tension was applied to all grafts for 10¨at 20pounds prior to implantation in order to reduce residual graft laxity (Retrobutton TightRope RT, & Bio-Interference screw, Arthrex®, Naples, USA). Subjects were evaluated before, and twelve months after ACL reconstruction. All patients were discharged from hospital within 24 hours from surgery. Criotherapy and rutine analgesia were prescribed for all patients as pain control. Elastic compressive stockings were prescribed for deep thromboembolism prophilaxis

Patients with chondral injuries grade ≥ II or suffering from other knee ligament complete disruptions other than ACL were excluded from the study. Time from injury to surgery was consistent between groups (mean ± standard deviation; 199.5 ± 166.5 and 146.3 ± 147.4 days for both accelerated and conventional groups respectively).

All participants were informed in detail about the experimental procedures and the possible risks and benefits of the project. The study was approved by the Ethical Committee of the Public University of Navarra and performed according to the Declaration of Helsinki. Informed consent was obtained from all individual participants included in the study.

Rehabilitation protocols

The patients were consecutively, divided in two different rehabilitation groups after the operation. Group 1 (n=20) followed a conventional rehabilitation protocol (CON) and patients in Group 2 (n=20) were enrolled in an accelerated rehabilitation protocol (ACCEL). The allocation procedure was block randomized prospectively; the 20 first participants were enrolled to conventional rehabilitation protocol and the subsequent 20 to an accelerated rehabilitation protocol. The two different rehabilitation programs were conducted in two different rehabilitation centers. This decision with respect to treatment allocation was made to ensure appropriate patient blinding. Neither the patients, nor the evaluators were aware of the group allocation nor follow-up examination results during the time course of the investigation.

The CON group followed a traditional ACL reconstruction rehabilitation procedure, [7] *(Appendix 1)*. The main features of this protocol are two to four weeks of immobilization prior to free gait, delayed onset of strength training, and restricted return to sports activity up to six months postoperatively.

The ACCEL group followed a standardized accelerated rehabilitation program based on that previously described by Myer et al (2006) [23] *(Appendix 2)*. The main features of this rehabilitation protocol include early full range of motion restoration, free gait, and specific strength training and agility drills introduced progressively as the patients achieved certain pre-set rehabilitation algorithm progression criteria.

No knee braces were used after the surgical ligament reconstruction, during the rehabilitation program, or during the knee performance tests at the follow-up examinations. Patients who developed pain, swelling, or range of motion deficits during the rehabilitation programs underwent symptomatic treatments until the impairments were resolved. There were not statistically significant ($p<.05$) differences between groups with respect to the number of rehabilitation sessions administered (58.8 ± 22.0 and 67.6 ± 22.6 sessions in CON and ACCEL groups respectively)

Isokinetic strength testing

The dynamic concentric knee extensor/flexor strength (concentric/concentric muscle action) was measured with each subject seated on an isokinetic dynamometer (Humac norm®, CSMi solutions, Stoughton. Ma. USA) with their trunk perpendicular to the floor, and the hip and knee joints flexed to 90 degrees. Subject posture was secured with straps. Before each data collection set, a warm-up set consisting of 5 submaximal knee flexion/extensions for each leg at 180 degrees/s was performed. The test session consisted of 8 knee isokinetic extension/flexion (90 to 0 degree range of motion, 0º = to full extension) repetitions for each leg at 180 degrees/s. Gravity corrected flexor and extensor peak torques (PT) (Nm) were recorded for the testing leg. Isokinetic concentric strength evaluations of the hamstring and quadriceps muscle groups have previously demonstrated excellent reliability [25]. An automated data analysis procedure was implemented using Matlab 7.11 (MathWorks Inc®; Natick, MA, USA) to determine the angle of Peak Torque for the hamstring muscles in each testing repetition. In addition, the area under the torque-angle curve was also calculated (i.e., mechanical work in J)

Muscle Imaging

MRI scans of the thigh were performed with a 1.5 T whole body image with surface phased-array coils (Magnetom Avanto; Siemens-Erlangen®, Germany). For the magnetic resonance scans, subjects were positioned supine with their knee extended. MRI of the subjects' thighs was performed before and 12 months after surgery. The length of the right femur (Lf) was measured by the distance from the intercondylar notch to the superior border of the femoral head measured in the coronal plane. Subsequently, 15 axial scans of the thigh interspaced by a distance of 1 / 15 Lf were obtained from the level of 1/15 Lf to 15/15 Lf. Every image obtained was labeled with its location (i.e. slice 1 being closer to the coxofemoral joint and slice 15 closer to the knee). Great care was taken to reproduce the same individual Lf each time by using the appropriate anatomical landmarks as previously described. [20].

For the final calculation of the CSA of each muscle, slices corresponding to 8/15 and 12/15 of the total femur length levels (50% and 70% of the bone axial length) were used for all muscles examinations *(Fig 1)*. Then T2-weighted transverse spin-echo MR axial images [repetition time (RT) = 3,250 ms, echo time (ET) = 32, 64, and 96 ms were collected using a 256 x 256 image matrix, with a 320 mm field of view and 10-mm slice thickness] were analyzed. This data was used to obtain the anatomical cross sectional area (CSA) of each Quadriceps (Q), Biceps Femoris (BF), Semitendinosus (ST), Semimembranosus (SM), and Gracilis (GR) muscles (Fig 1). The MRI files obtained were converted to a Digital Imaging and Communications in Medicine (DICOM®) format and analyzed with image manipulation and analysis software (Slice Omatic, Tomovision®, Canada). The same examiner (EBL) performed all muscle perimeter measurements. The anatomical muscle CSA was calculated by drawing a region of interest an tracing the outline of the muscles on the previously prepared proton-density images (ET:32) as previously described [20]

Knee joint laxity assessment

Knee joint laxity was evaluated with the KT-1000 arthrometer (MEDmetric Corporation®, San Diego, CA) at 20 lbs (89N) with anterior-posterior (AP)- directed loads. The measurement continued until the value was reproduced. KT-1000 instrumented examination of knee laxity in the ACL injured leg shows high intratester reliability [14]

Statistical analysis

Descriptive statistics were calculated. In order to check out the normality assumption of the analyzed variables, the Kolmogorov-Smirnov testing was applied revealing no abnormal data patterns. The number of patients enrolled in the present investigation was based on a power analysis calculated previously by Lindstom et al (2011) [18] in a similar study. They determined that the number of patients needed to detect a 4% change in hamstring muscle cross-sectional area with 80% statistical power was 37 subjects.

Paired T-tests were used to detect significant differences between a subject's lower limbs at each time point. Two way analysis of variance (group by time) ANOVA was used to compare between groups´ mean comparisons with subsequent Bonferroni post hoc corrections. When the variance equality was rejected, the Tamhane’s post hoc test was performed. The level of significance was set at $p < 0.05$ for all statistical tests. SPSS® statistical software (V. 20.0, Chicago, IL, USA) was used for all statistical calculations.

Results

No significant ($p < .05$) differences were found with respect to subjects´ anthropometrics in both the ACCEL and CON groups. *(Table 1)*

Subjects in the ACCEL rehabilitation group demonstrated significantly ($p < .05$) greater knee flexion peak torques 12 months after ACL reconstruction, which were not present before surgical repair *(Fig 2A),* in both reconstructed and healthy limbs in comparison to conventionally rehabilitated subjects *(Fig 2B).* Indeed, 12 months after reconstruction, subjects in the ACCEL group displayed greater hamstring PT in their reconstructed limb compared with both preoperative limbs [185.5 ± 37.0 Nm; 95% confidence interval (CI): 167.1 – 203.9 Nm vs. 143.0 ± 37.7 Nm; 95 % CI: 126.2 – 159.7 Nm and 142.4 ± 38.5 Nm; 95 % CI: 124.8 - 160.0 Nm for the postoperative ACL injured, preoperative ACL injured and healthy limbs, respectively].

In addition, ACL reconstructed limb of subjects undergoing an accelerated rehabilitation displayed greater hamstring muscle peak torque values 12 months after reconstruction than baseline values of ACL injured leg of subjects in the CON group (185.5 ± 37.0 Nm; 95 % CI: 167.1 – 203.9 Nm vs. 142.0 ± 52. 0 Nm; 95 % CI: 117.6 – 166.3 Nm for the reconstructed leg of subjects in the ACCEL group and the injured leg of CR group before ACL reconstruction, respectively). *(Fig 2.A and B)*

ACCEL subjects also showed greater Quadriceps PT values in their ACL reconstructed leg 12 months postoperatively ($p < .05$) than those reported for both their ACL injured and healthy limbs before undergoing the reparative surgery (259.78 ± 52.71 Nm; 95 % CI: 233.57 – 285.99 Nm vs. 189.29 ± 65.59 Nm; 95 % CI: 159.43 – 219.14 Nm and 189.31 ± 64.01 Nm; 95 % CI: 160.94 – 217.70 Nm for the postoperative ACL injured, preoperative ACL injured, and healthy limbs, respectively). In fact, ACL reconstructed legs of subjects in the ACCEL group showed greater ($p<.05$) Quadriceps muscle PT than ACL reconstructed legs of subjects in the CON group at 12 months post surgical reconstruction (259.8 ± 52.7 Nm; 95 % CI: 233.6 – 286.0 Nm vs. 189.6 ± 52.9 Nm; 95 % CI: 164.1 – 215.1 Nm, respectively). *(Fig 2.A and B)*

Subjects enrolled in the ACCEL group, exhibited greater ($p<.001$) mechanical work than their CON group counterparts, in their ACL reconstructed limb compared to ipsilateral baseline values *(Table1).* Certainly, at the 12-month follow up, subjects in the ACCEL group exhibited significantly ($p<.05$) greater total mechanical work in their limbs compared with both legs of conventionally treated subjects before surgical ligament repair *(Table1).*

ACL reconstructed limbs of subjects enrolled in the CON rehabilitation group displayed greater knee AP laxity with respect to their contralateral healthy limb 12 months after surgical reconstruction ($p<.05$). That difference was not observed among subjects in the ACCEL rehabilitation group *(Table 1).*

Both the ACCEL and CON rehabilitation groups displayed GR muscle CSA reduction at 70% of the femur length level vs. their uninjured limb before and 12 months after the ACL reconstruction ($p<.05$) *(Table 2)*. GR muscle sizes at this level were also diminished ($p< .05$) with their baseline measurements on reconstructed limbs *(Table 2).*

ST muscle CSAs at the 50% femur length level were also diminished with respect to the contralateral uninjured limb in both the ACCEL and CON groups. Moreover, the ACL reconstructed limb of both groups showed lasting ST muscle size reductions with respect to baseline measurements *(Table 2).*

Discussion

The present study aimed to compare the effect of two differentiated rehabilitation protocols (ACCEL vs. CON) on dynamic hamstring muscle strength and size 12 months after ACL reconstruction. Doubled ST and GR tendons autograft was used in all cases. A novel finding of the present study was that thigh musculature strength was recovered to a greater extent in subjects undergoing an accelerated rehabilitation program compared to that observed after a conventional intervention. In contrast, the muscle size in terms of CSA was not significantly ($p<.05$) different between the two groups. At the same time, subjects in the ACCEL group recovered symmetrical values of KT1000 AP knee joint laxity 12 months after ACL reconstruction, while subjects in the CON group did not. These results partially confirm our initial study hypothesis, which stated that greater improvements in mechanical muscle performance and muscle cross-sectional area would be found in subjects undergoing an accelerated rehabilitation protocol. To the best of our knowledge, this is the first study that has analyzed thigh muscle function and morphology among subjects who underwent 4 strand medial hamstring tendon ACL reconstructions and were subsequently exposed to two contrasting rehabilitation regimens.

Regarding the thigh strength recovery process, previous studies have reported varied results when assessing hamstring muscle strength after using ST and GR tendon harvesting for ACL repair [2]. The discrepancies in the results may be due to several factors such as the time from surgery, muscle size, hamstring strength evaluation methodology, proximal shifts of the newly formed muscle tendinous junction (MTJ) and/or medial hamstring tendon regeneration [6, 26]

Previous investigations have documented long-lasting (up to two years from ACL reconstruction) strength deficits in hamstrings with respect to the contralateral healthy limb while assessing the torque generated at deep flexion values (more than 75º knee flexion) [2, 30]. However, other authors have found no differences in hamstring muscle strength between 4-band hamstring graft ACL reconstructed limbs and the contralateral healthy extremities when measuring the absolute peak torque, which is produced at lower flexion angles (15-30º) [28, 33]. The differing results obtained between these methodologies could arise from the joint position in which the optimum mechanical advantage for the medial hamstrings is produced [2]. In the present study, it was found that subjects in the ACCEL group recovered both Quadriceps and Hamstring muscle peak torque values to a greater extent than their CON group counterparts. In the authors´ opinion, these differences may be related to the earlier and more exhaustive muscle strength training program performed by the subjects enrolled in the ACCEL group. These results agree with previous researches focusing on the comparison of the strength recovery rates among accelerated and conventionally rehabilitated patients following prior ACL reconstruction [10, 31].

Another proposed limiting factor for full recovery of the hamstring strength after medial hamstring graft based ACL reconstruction is the ability of the previously harvested tendon to regenerate. Recently Papalia et al (2015) [26] concluded in a systematic review including up to 400 subjects of both sexes, that tendon regeneration after harvesting occurs in the 85% of patients. However, they also reported persistent strength deficits among this muscle group mainly at deep knee flexion angles despite successful tendon regeneration had occurred. Jenssen et al. (2013) [16], found no correlation between tendon regeneration and isokinetic hamstring muscles performance. In the present study both groups showed similar changes in medial hamstring CSA which has been shown to be directly correlated to tendon regeneration rates [32]. However, the greater muscle peak torque values exhibited by the ACCEL group indicate that perhaps the type of physical training received after surgery could play a determining role in the neuromechanical hamstring function recovery.

The time from original ACL reconstruction has also been observed to be a significant contributor to medial hamstrings strength imbalances. Studies analyzing muscle short-term function up to one year after ACL surgical repair [6, 16] have found greater strength deficits than those targeting this issue after longer follow-up periods [2, 30]. Our study results showed that the lasting muscle strength deficits were more evident among the CON group. These results are also in agreement with previous investigations targeting this issue [10, 31].

Lastly, muscle retraction after tendon harvesting have also been postulated as a limiting factor for full hamstring strength recovery rates [26]. This notion was based on potential medial hamstring moment arm reduction due to the MTJ retraction process [8]. Carofino et al (2005) [8] argued that the muscle torque curve would be affected after medial hamstring tendon harvesting. Other authors have stated that the total area under the torque- angle curve, but most likely not the peak torque, would be decreased due to medial hamstring tendon harvesting [25] Our results partially supports this statement. The optimum angle for peak flexor torque was not altered but increases in total mechanical work (area under the torque-angle curve) and peak torque were found in the affected limb of ACCEL subjects 12 months after ACL reconstruction. At the same time, the CON group participants did not show any such response. Thus, it seems that accelerated rehabilitation regimens have an important influence in the successful final hamstring functional recovery despite of medial hamstring-based ACL reconstructions.

With respect to thigh muscle radiological examinations after ACL reconstruction, several authors have reported similar results to those from the present investigation. It has been widely reported that short- and long-term [29] medial hamstring muscle size reductions occur after ACL reconstruction with autologous ST and GR tendon grafts [3, 15, 32]. However, little is known regarding the functional recovery of this muscle group with regard to the rehabilitation process [32]. In this sense, previous studies have shown that an accelerated rehabilitation following ACL reconstruction with ST and GR tendons could lead to earlier improvements in muscle strength without affecting knee joint residual laxity [19, 34]. These results are consistent with those reported in the present investigation. Furthermore, they contribute original data with respect to muscle morphology adaptations with regards to the effect of the implementation of two different rehabilitation programs following ACL reconstruction. A similar tendency was observed in the Quadriceps muscles, where better isokinetic muscle strength performance was found in the ACCEL group at 12 months post-reconstruction despite a lack of significant improvement in muscle CSA.

The observed strength-related gains through non-hypertrophy-derived pathways could have been achieved by a neural drive optimization effect in subjects undergoing the accelerated rehabilitation program. Abundant evidence exists with respect to neural factor-derived strength gains when no objective hypertrophy is observed [11]. In this sense, the present study could be the first to report neural but not hypertrophy- derived muscle strength gains among previously ACL-reconstructed patients following an accelerated rehabilitation program in both the harvested and antagonist musculature. This hypothesis should be further corroborated by electromyography recordings and/ or rate of force development assessments to address this issue.

This study has a number of potential limitations that should be addressed. The first one is related to the body positioning for hamstring strength evaluation. Tadokoro et al [18] found that strength deficits vs. the contralateral healthy limb varied depending on the position in which the subjects were placed for evaluation. They found 14%, 45%, and 51% deficits when assessing hamstring isokinetic function in a sitting position at 90º knee flexion and in a prone position at 90º and 110º of flexion, respectively. With this in mind, we decided to measure the absolute peak torque for hamstring muscle strength, which was not restricted to deeper knee joint flexion angles. We did this way because the hamstring muscles strain at near full extension knee joint positions [5]. It is also known that ACL integrity is most challenged in this position but in closed kinetic chain efforts [13] . Secondly, we cannot asseverate that neural factors derived strength gains were observed among ACL reconstructed patients following and accelerated rehabilitation, since no neuromuscular examination was performed in the present research.

In summary, objective atrophy of the implicated musculature (ST and GR) related to the surgical reconstruction persisted in the reconstructed limb one year after medial hamstring ACL reconstruction, regardless of whether ACCEL or CON rehabilitation protocols were used. Surprisingly, subjects following the accelerated rehabilitation protocol demonstrated greater muscle strength gains despite persisting reductions in muscle size. At the same time no differences were found with respect to the optimum angle for peak torque production between groups. However, larger flexion mechanical work values were found in the harvested musculature among ACCEL participants. Selective retraining of the hamstring musculature (ACCEL group) after ACL reconstruction seems necessary to counteract the persisting knee flexor strength deficits and restore anterior-posterior knee laxity to normal levels.

Conflict of interest Disclosure: None

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