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Biomechanical evaluation of horizontal jumping after Anterior Cruciate Ligament (ACL) Reconstruction in elite Handball Players: An Inertial Sensor Unit (ISU)-Based Study

DOCTORAL THESIS

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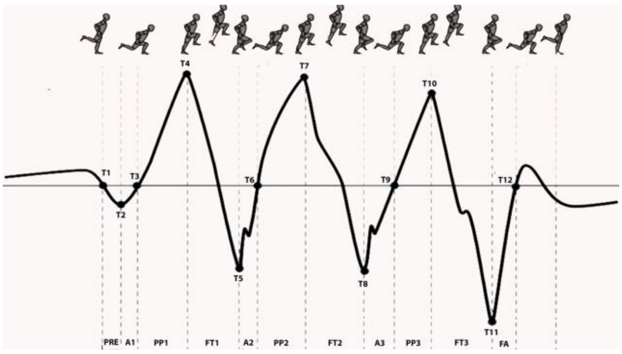

Ph.D Thesis

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List of abbreviations

ACL: Anterior Cruciate Ligament

ACL-R: ACL-Reconstructed

BPTB: Bone-Patellar Tendon-Bone

COHD: Cross-Over Hop for Distance ISU: Inertial Sensor Unit

GRF: Ground Reaction Force

LESS: Landing Error Scoring System

ME: Mechanical Efficiency ratio

RTS: Return to Sport

UTHD: Unilateral Triple Hop for Distance

VBDJ: Vertical Bilateral Drop Jump

VUCMJ: Vertical Unilateral Countermovement Jump

VUDJ: Vertical Unilateral Drop Jump

Summary

(Inglés-Español)

Summary

The current Ph.D. dissertation revolves around the Biomechanical jumping evaluation after ACL reconstruction in elite Handball Players and its possible effect on ground reaction force (GRF) management several years after competition resumption. The most common knee injury is of the Anterior Cruciate Ligament (ACL) in terms of long absence from or termination of sport carrier and early osteoarthritis, ACL tears occur without any contact with another player (non-contact) due to the knee is most commonly in/or close to full extension; and the lower limbs in "dynamic knee valgus," a position characterized by hip internal rotation and adduction, tibial external rotation, and foot eversion. Return to sports after ACL reparative surgery is one of the main expectations for athletic patients after suffering this devastating knee injury, several functional evaluation routines prior to return to sport participation has been proposed during the last years after ACL injury but there is no standardized protocol to evaluate return to sport after ligament reconstruction. Different authors have recommended the utilization of unilateral functional jump tests after anterior cruciate ligament reconstructions to examine the deficits between extremities. In the clinical and performance environment, inertial sensor units (ISUs) have been recently settled up and validated as a new tool for the evaluation of biomechanical impairments in athletes with ACL reconstruction and can to evaluate the athletes who had returned back to elite competition if the exhibit lasting biomechanical jumping pattern alterations in terms of greater support of three-axis peak forces during single-leg horizontal jumping maneuvers, compared with their control counterparts. The present doctoral thesis comprises 2 scientific studies that have been published in scientific JCR journals.

In the first study (Chapter 2), we aimed to examine horizontal jumping biomechanical differences between previously ACL-R elite male handball players who have returned back to competition versus matched sport, competitive level, sex, and age-matched controls.

In the second study (Chapter 3), we aimed to examine the biomechanical differences in horizontal jumping between elite female handball players with previous ACL reconstruction who had returned to their previous sport activity, vs. level-, sex-, and age-matched pairs of control counterparts.

Study 1 (Chapter 2)

In the first study the main purpose was to examine horizontal jumping biomechanical differences between previously ACL-R elite male handball players who returned to sports versus same sport competitive level, sex, and age-matched controls. Twenty-six male participants (6 ACL-R and 20 uninjured controls) were evaluated using an inertial sensor unit (ISU)-based technology to assess jumping biomechanics through a direct mechanics-based approach in two horizontal hopping tasks. Previously ACL-R elite male handball players who have returned to the top level of sports participation demonstrated similar jumping performance and did not displayed any lasting biomechanical and/or performance deficits 6 years after the original surgical ligament repair. The use of ISU-based jumping mechanics analysis in the clinical fields could help to improve the functional and biomechanical evaluations performed in the training court itself.

Study 2 (Chapter 3)

The aim of the second study was to examine the biomechanical differences in horizontal jumping between elite female handball players with previous ACL reconstruction who had returned to their previous sport activity, and level-, sex-, and age-matched pairs of control counterparts. Twenty-one female participants (6 with previous ACL reconstruction and 15 uninjured controls) were evaluated using an inertial sensor unit (ISU)-based technology to assess jumping biomechanics through a direct mechanics-based approach in two horizontal hopping tasks. The athletes with previous ACL reconstruction demonstrated a significant ($P<0.05$) reduction in the unilateral triple hop for distance compared with the healthy controls. Three-dimensional horizontal jumping biomechanics analyses using ISU-based technologies could provide clinicians with more accurate information regarding the horizontal jumping biomechanical patterns among elite handball female athletes.

Resumen

La actual disertación gira en torno a la evaluación Biomecánica de salto después de la reconstrucción de LCA en jugadores de balonmano de élite y su posible afectación en FVS varios años después de RTS. La lesión más común en términos de ausencia a largo plazo o retiro prematuro del deporte por osteoartritis es la lesión del LCA, la lesión del LCA ocurre sin contacto de otro jugador, cuando se da el llamado "valgo dinámico de la rodilla", posición caracterizada por la rotación y aducción de la cadera, la rotación interna tibial y la eversión del pie. No existe un protocolo estandarizado para evaluar la función de la rodilla para el llamado retorno a la competencia, diferentes autores han recomendado la utilización de pruebas funcionales para la evaluación del LCA para examinar los déficits entre extremidades, actualmente, los sensores inerciales se han utilizado para alteraciones duraderas de los patrones de salto en deportistas que han tenido reconstrucción del LCA y han vuelto a la competencia deportiva, estas alteraciones se han mostrado en mayor fuerza de la reacción vertical del suelo en saltos horizontales a una sola pierna en comparación con sus contrapartes de control. Esta tesis doctoral se basa en 2 estudios científicos que han sido publicados en revistas científicas JCR. El primer estudio (Capítulo 2), tenía como objetivo examinar las diferencias biomecánicas de salto horizontal entre los jugadores de balonmano de élite LCA-R que regresaron al deporte al mismo nivel de competencia deportiva versus los controles de la misma edad. En el segundo estudio (Capítulo 3), nuestro objetivo fue examinar las diferencias biomecánicas en el salto horizontal entre jugadoras de balonmano femeninas de élite con reconstrucción previa de LCA que habían regresado a su actividad deportiva, versus los controles de la misma edad.

Estudio 1 (Capítulo 2)

En el primer estudio, el objetivo examinar las diferencias biomecánicas de salto horizontal entre los jugadores de balonmano de élite ACL-R que regresaron al deporte al mismo nivel de competencia deportiva versus los controles de la misma edad. Veintiséis participantes varones (6 LCA-R y 20 controles sin lesiones) fueron evaluados utilizando una tecnología basada en la unidad de sensor inercial (ISU) para evaluar la biomecánica del salto a través de un enfoque directo basado en la mecánica en dos tareas de salto horizontal. Los jugadores de balonmano de élite con reconstrucción previa de LCA que habían regresado al nivel más alto de participación deportiva demostraron un rendimiento de salto similar y no mostraron ningún déficit biomecánico y / o de rendimiento duradero 6 años después de la reparación quirúrgica original del ligamento. El uso del análisis de la mecánica de salto basado en ISU en los campos clínicos podría ayudar a mejorar las evaluaciones funcionales y biomecánicas realizadas en el propio campo de entrenamiento.

Estudio 2 (Capítulo 3)

El objetivo del segundo estudio fue examinar las diferencias biomecánicas en el salto horizontal entre jugadoras de balonmano femeninas de élite con reconstrucción previa de LCA que habían regresado a su actividad deportiva, versus los controles de la misma edad. Veintiuna participantes femeninas (6 con reconstrucción previa de LCA y 15 controles sin lesiones) fueron evaluadas utilizando una tecnología basada en la unidad de sensor inercial (ISU) para evaluar la biomecánica del salto a través de un enfoque directo basado en la mecánica en dos tareas de salto horizontal. Las atletas con reconstrucción previa de LCA demostraron una reducción significativa ($P < 0.05$) en el triple salto unilateral para la distancia en comparación con los controles sanos. Los análisis tridimensionales de biomecánica del salto horizontal utilizando tecnologías basadas en ISU podrían proporcionar a los clínicos información más precisa sobre los patrones biomecánicos del salto horizontal entre las atletas femeninas de balonmano de élite.

Declaration

I, Francisco Antonio Amú Ruiz, do hereby declare that the research presented in this dissertation is based on 2articles (Chapter 2 and 3) that have been published in international peer-reviewed journals. To meet the stylistic requirements of a thesis, the formats of the papers have been
adjusted accordingly throughout. These edits did not substantially change the content of the published articles. The role that I fulfilled within each of the publications is presented below.

This thesis the rationale, design, methodologies used and the results were obtained in two descriptive case- control studies. We hypothesized that the ACL-R players would present lasting biomechanical alterations in terms of greater supported three-axis peak GRF during single-limb horizontal jumping maneuvers compared with their control counterparts, despite having resumed and continued playing at the elite competition for several years after the original ACL injury.

Ph.D. student involvement:

- Data collection.
- Data analysis and results interpretation.
- Writing of the articles included in the present thesis.

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In Memorial to Jaime Humberto Leiva Deantonio, my great Professor, friend and Colleague.

List of Publications

1. Setuain, I, Bikandi, E, Amú-Ruiz F, and Izquierdo M. Horizontal Jumping Biomechanics Among Elite Male Handball Players With and Without Anterior Cruciate Ligament Reconstruction. An Inertial Sensor Unit-Based Study. *Physical Therapy in Sport*. 2019; 39: 52-63.

2. Setuain, I, Bikandi, E, Amú-Ruiz F, Urtasun F, and Izquierdo M. Horizontal Jumping Biomechanics Among Elite Female Handball Players With and Without Anterior Cruciate Ligament Reconstruction. An ISU based study. *BMC sports science. In press*

General Background

In European Union and United Stated of America, injuries associated to sports activities have an incidence rate of 26-34 injuries per 1000 person [1,2]. The probability of a knee injury is big during training seasons significantly greater in competition matches. One of the most harmful knee injury is of the Anterior Cruciate Ligament (ACL) due to its associated long absence from or termination of sport carrier and early osteoarthritis [3,4].Some studies have reported that, female athletes are 6 to 10 times more prone to suffer an ACL injury than their male counterparts during the same jumping and pivoting tasks [5,6].Anatomical, hormonal, neuromuscular and genetical differences between genders have been proposed as explanatory factors in the ACL injury[7-10].

1. Role of the ACL

The ACL is 1 of 4 major ligaments that stabilize the knee. Its primary role is to prevent knee instability by keeping the tibia from sliding forward in relation to the femur. It functions secondarily to restrict excessive knee extension, varus and valgus knee displacement, and tibial rotation [11]. Additionally, the ACL protects the cartilaginous shock absorbers of the knee (the menisci) from damage that could occur during jumping, cutting (rapid deceleration associated with a quick change in direction), and pivoting tasks in sport participation (Fig. 1)

Fig.1. Anterior Cruciate Ligament injury (Copied from: https://cdn.prod-carehubs.net/n1/802899ec472ea3d8/uploads/2019/01/a-medical-illustration-of-an-anterior-cruciate-ligament-ACL-tear-original.jpg)

On the other hand, Quatman et al. [12] demonstrate the relative contribution of both the ACL and MCL to resist knee valgus during landing what explain the triaxiality and knee function.

2. **Mechanisms of ACL injuries**

Near to 80% of ACL tears occur without any contact with another player (non-contact) due to the valgus collpase position of no return of the knee, which is commonly reproduced in or close to full extension; the hip approaching internal rotation and adduction positions, as well as tibial external rotation, and foot eversion [13-15]. (Fig. 2)

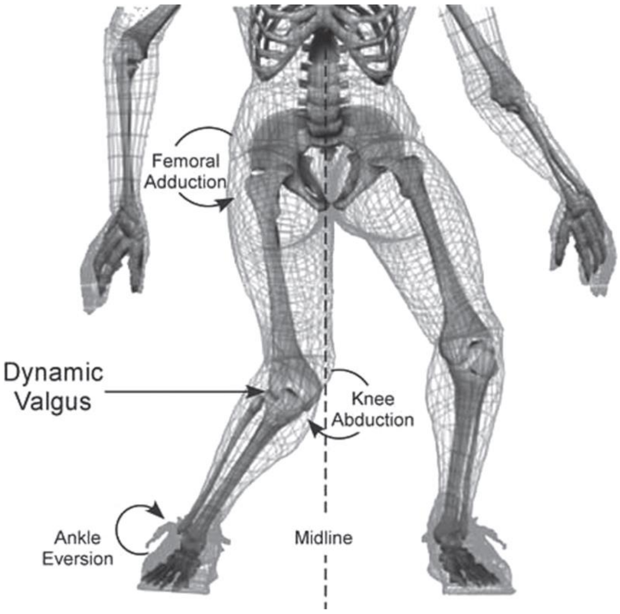

Fig.2. Example of Dynamic Knee Valgus (Hewett et al. 2010) [6]

Differences in decrease of knee flexion, vertical Ground Reaction Forces (vGRF) in vertical jumps and increase of knee dynamic valgus that increase the probability of re-rupture rate[16,17]. Hewett et al. [neuromuscular and hormonal] could show that males produce 3-fold higher external extension moments at landing than females, meanwhile for Kulas et al. [18] found that the trunk-flexor accommodation seemed to be a safe strategy to minimize additional forces on the knee. To clarify the biomechanical consequences of these 2 different kinematic trunk adaptations to the added external trunk load.

According to Kuenze el al. [19] study, where evaluated 168 individuals with previous ACL reconstruction (41 men and 127 women) using a Landing Error Scoring System (LESS) found that the lateral trunk flexion in initial contact was the more likely to commit errors related to dynamic knee valgus in women that in men, this found have allowed to associate the importance of neuromuscular programs to avoid laterality of trunk and its incidence in knee injuries.

3. Return to Sport after ACL reconstruction

Return to sports after ACL reparative surgery is one of the main expectations for athletic patients after suffering this devastating knee injury [20]. Ander et al. [21] reported that the combined return-to-sport rate was 82% at a mean 3.5 years after primary reconstruction and Grassi et al. [22] reported 84% at a mean 5.3 years after revision surgery. On the other hand, Andriolo et al,[23] and Setuain el at. [24] showed that there is no standardized protocol to evaluate return to sport after ligament reconstruction.

Several functional evaluation routines prior to return to sport participation has been proposed during the last years after ACL injury. Barber-Westin and Noyes, reported in their review [16] that only 4% of the analyzed studies included used a hop test, whereas a 9% employed some muscle strength evaluation and 32% of the studies relied on time-based criteria for athlete discharge to full non-restricted sport participation.

Myer et al. [25] recommended the utilisation of unilateral functional jump tests after anterior cruciate ligament reconstructions to examine the deficits between extremities among collegiate recreational athletes and recently, Patterno el al. [26] evaluated whether standard clinical measures to predict the risk of the second ACL injury in 163 athletes (105 female, 58 male) who sustained an ACL injury, underwent ACLR, completed rehabilitation, and were released to prior levels of activity by their surgeon and rehabilitation professional, they were assessed using functional performance on hop testing (UTHD and COHD), this study found that performance on the triple hop for distance test, inclusive of both distance hopped normalized to height and limb symmetry, may be good indicators of the risk of future ACL injuries after ACLR and RTS in young athletes.

On the other hand, there is a wide scientific background of laboratory biomechanical studies that employing some expensive cameras, software and instrumented spaces such as Vicon systems and force plate instrumentations, have detailed the kinetic and kinematic adaptations to ACL injuries in many activities, including walking, running and jumping maneuvers [13,14,27].

4. Biomechanical jumps evaluation using ISU

Inertial Sensor Unit (ISU) systems provide the linear acceleration and angular displacement orientation values in a sensor-fixed Cartesian reference frame (X,Y,Z). 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. [27] The use of a single ISU could provide a real time, fast and inexpensive movement analysis tool [28]. Positioned at the trunk level, ISU devices do not obviously replace higher-precision 3D motion analysis and inverse dynamics technology-based models, but they could potentially be applicable in the clinical setting where the financial investment and highly trained staff are limited [29]. This growing tool have become an innovative non-invasive solution not only for assessing sports-related performance [30] but also a clinical resource in ACL rehabilitation practices [28]. In previous studies in which investigators used ISU-based technologies have highlighted the potential of this measurement technique to identify different persistent movement pattern alterations under conditions of ACL injury [28,29,31]

Setuain et al [32] examined the validity of a force plate recordings and one ISU located at lumbar spine assessing vertical Drop Jumps, they found Robust correlation levels of the IU-based jumping biomechanical evaluation with respect to the force plate across the entire analyzed jumping battery. In this sense, significant and extremely large correlations were found when raw data of both IU and force plate-derived normalized force–time curves were compared. Furthermore, significant and 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.

More recently, the ISU system has allowed biomechanical functional evaluations to be implemented in the clinical scenario after the postoperative ACLR recovery process [33-36] and as part of functional evaluation routines in order to analyze vertical jumping biomechanics among both female [37]and male [38] elite handball players in relation to previous ACL injury.

In the basis of the current scientific literature available, the present investigation hypothesized that there would be differing jumping biomechanics after ACLR that could not be detected by the traditionally performance (distance reached) hopping test batteries applied commonly in relation to return to sport participation. This thesis aimed to describe the design, methodology and results of an assessment in horizontal jumping biomechanics among elite handball players, using an ISU based methodology

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Chapter 1

A Biomechanical Perspective on Rehabilitation of ACL Injuries in Handball. *

*****Setuain et al. 2018 [1]

Team handball is one of the highest demanding sports with regard to requirements of rapid cutting deceleration of cutting, pivoting and jump- landing movements. It is a sport with high knee mechanical constraints, and therefore the most serious injuries reported in handball are knee injuries (7–27%), ACL injury accounting to 50% of all ligamentous knee injuries [2, 3]. The desire of an athlete to return to sport (RTS) after anterior cruciate ligament (ACL) injury is a major indication for ACL reconstruction (ACLR) surgery. At the same time, often, the most important outcome for the athlete, and regardless the level of play, is the capability to return to sport [4, 5]. However, recent systematic reviews and meta- analyses report that 65% of the patients will return to their pre-injury level of sport after ACLR and about half of them after revision [6]. Various types of grafts are used for ACLR and revision surgery. Hamstrings tendons (HT) (usually semitendinosus and gracilis as a four-strand graft) and the patellar tendon (harvested as a bone-patellar tendon-bone (BPTB) are, by far, the most common autografts used. More recently the suitability of the extra-articular graft augmentation for rotational stability restoration in ACL reconstructive surgery has also been discussed. Looking into the best available evidence, it seems that there is no real consensus about the superiority of BPTB or HT grafts for ACLR when treating high-demand athletes. We believe that the graft choice decision in handball, as in other sports, should be multifactorial taking into account the type of player (outside, inside playing position, knee anatomical features), age, associated intra- articular knee injuries, rotational stability, preoperative kinematics and expectancy to return to previous competitive level.

The biomechanical aspect of the ACL rehabilitation procedure has been highlighted during the latest years, due to its intrinsic relationship with proper graft-healing promotion [7–9]. Indeed, the relevance of an adequate motor skills regaining process in order to maximize muscle function and optimize acting net joint moments as well as the neuromuscular coordination in order to manage the ground reaction force resultant vector properly has been put in the spotlight recently [10–12]. These factors aim to enable the athlete to maximize his/her performance after injury, while minimizing the re-injury risk. Regarding ACL injury rehabilitation, many research issues have been addressed during the last years, ranging from the inferior age limit for ACL reconstruction, the importance of pre-habilitation on successful outcomes after repair, the clinical prediction rules for ACLR or conservative management, to the importance of an objective criteria-based rehabilitation progression vs. a rehabilitation protocol [13, 14]. As widely reported, Olsen et al. [15] described the so called position of no return for ACL injuries in handball, being a triplanar motion including increased tibial rotation, femur adduction and internal rotation and a frontal plane knee valgus collapse. Several years later, Quatman et al. [16] corroborated this issue demonstrating significant increases on ACL loading (in vitro) when combining a medial knee joint opening, a rotation and an anterior shear pull. Many investigations have been carried out at the same time trying to elucidate which muscles would prevent knee joint triaxial valgus collapse to a greater extent, in order to design the most effective strategy for both ACL injury prevention and rehabilitation. In this context, ACL injury prevention programmes in handball have targeted several biomechanical (such as knee abduction moment (KAM) and angular excursion reduction) and physiological (semitendinosus to vastus lateralis muscles activation ratio promotion) adaptations that are supposed to contribute to the reduction of the onset of this injury. As it would be explained more in detail through this chapter, it would be important to both sport scientists and athletic trainers and coaches to highlight the importance of landing technique in the management of the ground reaction forces in order to reduce excessive soft tissue stress at the knee level and, hence, this joint injury risk. Thus, it seems that ACL injury prevention programmes in handball targeting this issue need to be implemented in order educate players with better (and safer) landing strategies.

1. Jumping Biomechanics Evaluation in Handball: A Historical Perspective and New Trends.

Vertical jumping performance is considered a key component of many training routines in numerous sport disciplines and conditioning programmes [17–19]. For instance, it has a direct relationship with several explosive activities such as jumping and sprinting [20]. Moreover, in the last 30 years, other athletic tasks such as plyometric exercises have also been studied and implemented by athletic coaches to maximize the performance of explosive activities [21]. 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 [21, 22]. To do so, direct mechanics- based procedures have been utilized to estimate the centre of mass displacement and to detail the biomechanics of jumping [20, 22].

On the other hand, it is well known that an incomplete or deficient rehabilitation programme after an ACL injury may increase the risks of both re-injury and ACL injury in the contralateral unaffected knee [23]. 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].

However, many other methods and instrumentations have recently been developed to evaluate vertical jumps [25]. Briefly, some such as optical cells and contact mats have been developed to assess jumping performance in terms of the jumping time duration [26, 27]. Others, through the description of force and/or vertical velocity by time curves, have estimated the center of mass movement in humans [28, 29]. To describe the direct or inverse mechanics-based biomechanics of vertical jumping maneuvers, force plates have become the gold standard during the last decades [30]. As such, numerous research articles related to vertical jumping related biomechanics focused on both performance enhancement [18, 31, 32] and injury prevention and rehabilitation [8, 33, 34] have been published. Myer et al. (2014) reported an exhaustive biomechanical screening for ACL injury risk identification based on the knee abduction moment (KAM) magnitude. Authors reported that peak knee joint extension moment, peak knee abduction angle, an increased BMI and tibia length accounted for 78% of KAM during bilateral drop landing. The same author [35] recommended, in relation to the functional evaluations after ACL reconstructions, the utilization of unilateral functional jump tests after to examine the deficits between extremities among collegiate recreational athletes. It seems that unilateral actions allow the identification of residual jumping impairments related to a previous injury [36].

However, the equipment needed to perform the abovementioned studies requires a considerable financial investment and implies the necessity for highly trained staff that is familiarized with such laboratory-derived procedures. For many rehabilitation centers, this is not feasible. Recently, the latest advances in microelectromechanical systems have turned inertial sensor units (IUs) into a powerful tool for sports motion analysis related to both performance-related [25, 37] and injury rehabilitation and prevention-related fields [36, 38]. One of the main advantages in comparison to force plate-based procedures could be that IUs enable non-conditioned foot landing, thereby making functional and unplanned movement analyses possible at the laboratory environment or at the training field itself [39] (Fig. 1).

In relation to handball and biomechanical screenings for ACL injury risk determination, Kristianslund and colleagues [40] demonstrated that technique explained more than 60% of the variance encountered on KAM. Several technical aspects were addressed, such as cut width, knee valgus angulations, approaching speed and cutting angle. Also, in a biomechanical investigation of joint loading during side cutting in elite female handball players, Bencke et al. (2013) found external moments of outward rotation, valgus and flexion affecting the knee and external inward rotating moments affecting the hip. The authors highlighted the importance of the medial hamstrings and hip external rotators for counteracting the imposed knee and hip loading during the analysed task. The importance of the medial hamstrings has also been demonstrated in a prospective study by Zebis et al. [41], and weak hip external rotators have also been found to increase knee injury risk in athletes in previous studies [42, 43]. More recently, Zebis et al. [44] found that vastus lateralis to semitendinosus activation ratios can be optimized through 12 weeks of evidence-based ACL prevention neuromuscular training programme on female soccer and handball adolescent players.

These data may imply that using biomechanical methods to obtain information about loading patterns and joint kinematics during jumping, landing and side cutting may direct ACL injury prevention routines as well as enhance ACL rehabilitation programmes.

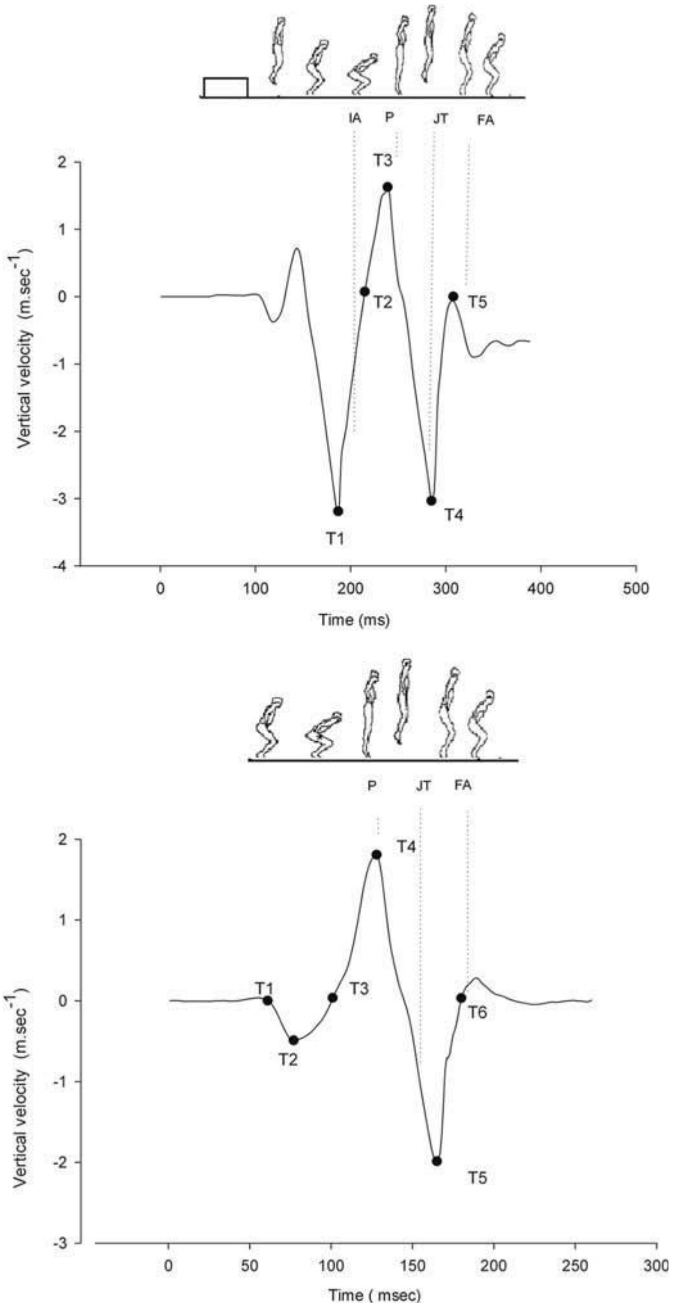

Fig 1. *Z*-vertical axis velocity by time descriptive curves. Vertical bilateral drop jump explicative illustration (**a**). Vertical unilateral countermovement jump explicative illustration (**b**). IA, initial attenuation; P, propulsive phase; JT, jumping time; FA, final attenuation. Modified from vertical jumping biomechanical evaluation through the use of an inertial sensor-based technology. Modified from Setuain I et al. J Sports Sci. 2016;34(9):843-51. doi: 10.1080/02640414.2015.1075057. Epub 2015 Aug 10

2. Jumping Biomechanics in Handball Elite Female Athletes in Relation to ACL Injury.

Due to the intrinsic need for abrupt changes in direction and unplanned action management in handball, as well as the high game intensity, anterior cruciate ligament (ACL) rupture is one of the most devastating injuries that handball players can suffer from [15]. Female athletes have a greater ACL injury risk than do their male counterparts during the same jumping and pivoting tasks [45]. This greater injury risk has been associated with existing neuromuscular, anatomical and hormonal differences between sexes [46]. Moreover, an incomplete or insufficient rehabilitation programme following an ACL injury may increase the risk of both re-injury and injury of the unaffected contralateral knee [23]. 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 (Table 1).

Table 1. Relationship between mechanism, neuromuscular imbalance, and neuromuscular intervention for ACL injury prevention in female athletes [46]

Injury mechanism component	Underlying neuromuscular imbalance	Targeted neuromuscular intervention component
Knee adduction during landing	Ligament dominance	Improve landing technique
Ligament dominance	Quadriceps dominance	Strengthen posterior chain
Improve landing technique	Leg dominance	Improve side/side symmetry
Low flexion angle in landing	Trunk dominance “core dysfunction”	Core stability and perturbation training

Adapted from Understanding and preventing ACL injuries: current biomechanical and epidemiologic considerations—update 2010. N Am J Sports Phys Ther 2010;5:234-251 [46]

In relation to handball sport, Myklebust et al. [47] 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.

Regarding biomechanical variables that could explain the higher ACL injury incidence observed among female athletes in handball, we should highlight the relevant contribution that knee abduction kinetics and kinematics play on the chance of this devastating injury to occur. In fact, as previously stated KAM displayed during a drop jumping task predicted ACL injury risk with 73% sensitivity and 78% specificity, and previously ACL injured athletes displayed 8° greater valgus angles than their healthy counterparts [8]. These, along with previous research demonstrating the significant correlation between trunk excessive motion and knee abduction load in both side stepping and jumping tasks [46], make this body region a very important mechanical segment to address when assessing ACL injury risk in relation to the sport of handball.

There have been many scientific debates regarding the long-term effects of sustaining an ACL injury. Some researchers have stated that sustaining an ACL injury leads to a 100% greater risk of osteoarthritis development [13]. Whether this increase on joint deterioration rate is due to the surgical procedure received, or due to abnormal lower-limb mechanics adopted from the time of reconstruction or even to native motor skills, is still a cornerstone for both sport clinicians and researchers.

In accordance with this, Setuain et al. [48] examined 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 IU utilization-based simplified analysis was used. Results showed 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 predefined jump phases' duration values) during the execution of the vertical bilateral drop jump (VBDJ) (Fig. 2).

Furthermore, this group of subjects showed altered angular excursion values around the (X-), (Y-) and/or (Y-) 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.

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 [49]. In this context, those reported by Setuain et al. [48] among the previously ACL- reconstructed subjects in the VBDJ may be explained by a previously reported trunk stiffening strategy [50] which could influence proper VGRF attenuation and kinetic energy reutilization through the countermovement phase of the manoeuvre affecting both joint resultant reaction forces and jumping performance. It has been previously reported that an excessively erected trunk position at landing can augment internal knee extension moment, resulting in greater ACL tensile stress when adding extra weight compared to a more flexed trunk position [50].

It could be assumed that force production was compensated by the contralateral non-ACL-reconstructed leg in this bilateral task, leading to not differences in jump performance [10]. Furthermore, this fact may be explained by the elite profile of this study cohort in which exhaustive strength training routines are frequent. With regard to unilateral tasks, the same authors [48] observed significantly ($p < 0.05$) lower trunk angular displacement excursions around the (Y-) and (X-) axes, among previously ACL-reconstructed athletes while executing a VUDJ. In these cases, not the accelerations but the trunk displacements were shown to be decreased among ACL-reconstructed handball players. 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 centre of mass within the balance margins. In this sense, ACL-reconstructed athletes could have adapted their movement pattern through central motor control reprogramming during the unilateral jumping tasks into a more balance-ensuring action, thereby attenuating the imposed accelerations to the centre of mass limiting, in that way, the jumping performance [11, 34]. This fact could partially explain the observed jumping performance attenuation observed during the VUDJ and VUCMJ among both previously ACL-reconstructed players [51, 52]. The sparse existing evidence regarding both short- and long-term biomechanical adaptations to ACL reconstruction among female's handball athletes [47, 48] is a limitation and warrants caution when generalizing these results to younger or more recreational populations. Factors like type of reconstruction (graft type choice, primary vs. revision single vs. double bundle, extra-articular reinforcement), the kind of rehabilitation performed, and the time course from injury to surgical repair and to return to play, could be adequately controlled, in order to avoid bias when designing future investigations regarding this topic.

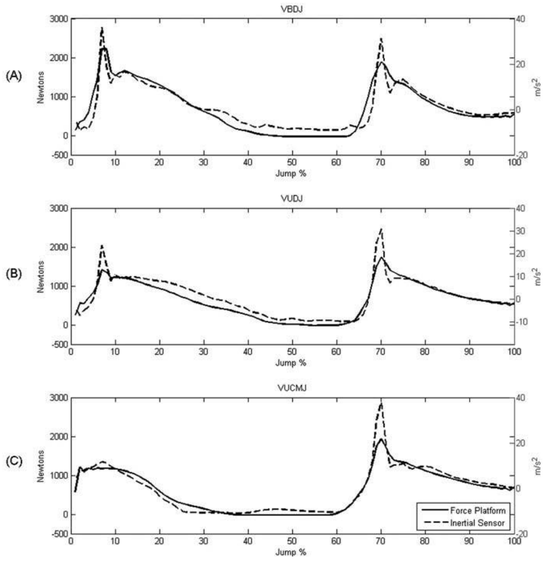

Fig. 2 Vertical force by time IU and force plate curves. Vertical bilateral drop jump (**a**). Vertical unilateral Drop Jump (**b**). Vertical unilateral counter movement jump (**c**). Modified from Setuain I et al. J Sports Sci. 2016;34(9):843-51. doi: 10.1080/02640414.2015.1075057. Epub 2015 Aug 10.

In summary, in view of the existing evidence, it seems that female handball professional players cope with several lasting biomechanical adaptations after ACL reconstruction, despite returning back to competition. This fact could indicate a sex-dependent prevalence of functional consequences to ACL reconstruction, keeping in mind that fully functional restoration is more prevalent among their male counterparts on basketball, soccer and handball [51–53]. Whether this jumping mechanics adaptations predispose them to a higher re-injury rate should be addressed in properly designed prospective follow- up studies.

In line with prevention studies showing a diminished knee flexion, an increased knee valgus torque and excursion along with increased trunk mediolateral accelerations, it seems that female athletes would benefit from prevention training routines targeting these issues. For example, plyometric training in order to minimize GRF at landing [54] and core stability exercises to increase trunk motor control and stability, as well as specific exercises addressing the co-activation of medial hamstrings when performing selected athletic tasks, [44, 55] could be implemented in order to help decrease the ACL injury incidence in this sport population. In addition, technical training in relation to foot positioning during the planting phase for cutting maneuvers should be also supervised during the training routines on the court especially in young handball players, due to its demonstrated relationship with high knee valgus overload [40].

3. Jumping Biomechanics in Handball Elite Male Athletes in Relation to ACL Injury.

As stated in the previous heading, female athletes have a greater ACL injury risk than their male counterparts during the same jumping and pivoting tasks [45], which has been associated with neuromuscular, anatomical and hormonal differences between the sexes [46]. 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 [56]. However, in line with previous relevant research from Quatman et al., it should be kept in mind that many of the neuromuscular imbalances that make females more prone to ACL injury are also present among males albeit to a quite lesser extent [57]. Reduced hip range of motion, especially internal rotation, has also been found in male soccer players with previous ACL injuries [58].

As stated in the previous section, one of the clinical key points surrounding the ACL injury event is the long-term joint health status. In relation to this fact, it seems that a sex-dependent effect exists. In a large retrospective study on ACL-reconstructed athletes, handball activity seems to be associated with a greater risk of osteoarthritis but only for male handball players [59]. Male handball players were more susceptible to have cartilage lesions compared to other sports, while female handball players did not differ from other sports. Overall, males have more cartilage injuries than females.

Studies on long-term biomechanical discrepancies between ACL-reconstructed athletes and healthy, or inter-limb discrepancies, are sparse. Setuain et al. [52] evaluated 22 elite male (6 ACL-reconstructed and 16 uninjured control players) handball players a mean of 6 years after primary ACL reconstruction. The participants performed a vertical jump test battery that included a 50 cm vertical bilateral drop jump (VBDJ), a 20 cm vertical unilateral drop jump (VUDJ) and vertical unilateral countermovement jump (VUCMJ) maneuvers using an IU. 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 correlate with previous research showing fully functional restoration of abilities in top-level male athletes after ACL reconstruction, rehabilitation and subsequent return to sport at the previous level. In agreement with the latest results, Buesfield et al. [51] showed non-significant differences in playing-related abilities among elite professional male basketball players, and Brophy et al. [53] demonstrated similar results in male soccer players. Thus, the restoration of full jumping capacity appears to be common among high- performance male athletes after ACL reconstruction. This fact, keeping in mind the previously observed lasting biomechanical jumping mechanics alterations among female elite handball athletes, could highlight a sex- dependent effect on functional outcome after ACL reconstruction which has been previously described in the literature [60] in a non-professional cohort of athletes.

Finally, in the authors' opinion [1], the existing ACL injury incidence discrepancies between genders should be considered, when targeting injury prevention. However, it still seems adequate to appropriately evaluate male handball athletes, looking for aberrant motor patterns as well as neuromuscular deficiencies in order to specifically intensify ACL prevention training among those males more prone to injury.

4. Summary and Future Perspectives

The present chapter has reviewed the biomechanical aspects of handball jumping, landing and side cutting performance in relation to ACL injury and has highlighted the key elements to address when preparing athletes for handball participation. Besides gender differences with regard to injury risk, biomechanical jumping performances exist, and recent studies also demonstrate that male players seem to recover to a greater extent in the long term, than female athletes. This also emphasizes the perspectives for future research, further understanding of why these gender differences persist and subsequently directing more attention to target these discrepancies during early and late rehabilitation after ACL injury. It also seems evident that utilizing biomechanical experimental methods in optimizing the evaluation of athletes returning to play may have a huge potential, both with existing and well-tested laboratory methods and with newer and more field- based approached like IUs. Future research is needed in this area.

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Aims and layouts of the thesis

Chapter 2

Study 1

Title: Horizontal jumping biomechanics among elite male handball players with and without anterior cruciate ligament reconstruction. An inertial sensor unit-based study.

Research aim: To examine horizontal jumping biomechanical differences between previously ACL-R elite male handball players who returned to sports versus same sport competitive level, sex, and age-matched controls.

Hypothesis: It was hypothesized that ACL-R male professional handball players who had returned back to elite competition would not exhibit lasting biomechanical jumping pattern alterations in terms of greater support of three-axis peak forces during single-leg horizontal jumping maneuvers, compared with their control counterparts.

Chapter 3

Study 2

Title: Horizontal jumping biomechanics among elite female handball players with and without anterior cruciate ligament reconstruction. An ISU based study

Research aim: to examine the biomechanical differences in horizontal jumping between elite female handball players with previous ACL reconstruction who had returned to their previous sport activity, and level-, sex-, and age-matched pairs of control counterparts.

Hypothesis: It was hypothesized that the ACL-R players would present lasting biomechanical alterations in terms of greater supported three-axis peak forces during single-limb horizontal jumping maneuvers compared with their control counterparts, despite have continued with elite competition for several years after the original ACL injury.

Chapter 2

Horizontal jumping biomechanics among elite male handball players with and without anterior cruciate ligament reconstruction. An inertial sensor unit-based study.

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Original Research

Horizontal jumping biomechanics among elite male handball players with and without anterior cruciate ligament reconstruction. An inertial sensor unit-based study

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ABSTRACT

Objectives: Anterior cruciate ligament (ACL) tears are one of the most devastating injuries that any handball player can suffer during landing and pivoting actions. The aim of this study was to analyze the horizontal jumping biomechanics among male elite handball players with or without previous ACLR.
Design: Descriptive study.
Setting: Spanish elite male handball players.
Participants: Twenty-six male participants (6 ACL-R and 20 uninjured controls) were recruited.
Main outcome measures: Two horizontal hopping tasks were evaluated using an inertial sensor unit (ISU)-based technology to assess jumping biomechanics through a direct mechanics-based approach.
Results: Non-significant differences were found in relation to any of the biomechanical or performance related analyzed variables.
Conclusions: Previously ACL-R elite male handball players who have returned to the top level of sports participation do not seem to possess lasting biomechanical and/or performance deficits 6 years after the original surgical ligament repair.

1. Introduction

Handball is a body-contact team sport that elicits high-intensity maneuvers, such as abrupt changes in direction and velocity and sudden landings [1,2]. Due to the intrinsic nature of the sport, the knee joint is exposed to many stressful forces that could result in serious damage to the anterior cruciate ligament (ACL), leading to one of the most devastating injuries among handball players [3-5]. The reported incidences of ACL injury for male handball athletes are 0.11-0.24 injuries per 1000 h of exposure [6]. This is lower than that reported for women, which have a greater ACL injury risk than their male counterparts during the same jumping and pivoting tasks, which has been associated with neuromuscular, anatomical and hormonal differences between the sexes [7]

Some movement biomechanics-based studies have demonstrated that the decreased ground reaction force (GRF) absorption capacity, as well as a disbalanced lower limb symmetry index between the previously ACL-reconstructed (ACL-R) and the contralateral healthy limbs, could be a potential risk factors for ACL reinjury or contralateral injury, due to neuromuscular impairments acquired through the ACL rehabilitation process [8,9]. The clinical relevance of the ACL injury does not rest solely on the ligament disruption itself; but the functional implications of concomitant knee injuries and its ‘implications in the athletes’ function prognosis once the athlete is returning back to top level competition [10]. It seems that the evidence for neuromuscular or biomechanical risk factors for ACL injuries in male athletes could mainly be related to at the trunk and hip joint levels occurring ´dysfunctions´ Additionally, the scientific literature lacks information regarding the best clinical practices for rehabilitation programs or universal functional and clinical evaluation criteria for resuming the sport after injury [10]

This state of no consensus may expose the athlete to both a higher re-injury risk and/or a new injury on the healthy contralateral knee [11]. Thus, the detection and monitorization of subjects with higher injury or re-injury risk through functional, biomechanical and neuromuscular screening evaluations appear to be crucial for injury prevention and rehabilitation in sports medicine [7].

In this context, different jumping performance tasks have been widely employed to determine the readiness for sport participation after ACL reconstruction, aiming to allow for a safe return to competitive sports (RTS) according to the specific sport´s performance demands [10]. RTS is defined as returning to the same level of the same sport played before injury [12]. After ACL reconstruction, the elite athletes desire an RTS in the least amount of time, which could predispose the player to the ACL surgical reconstruction choice [13].

Some studies have reported that male patients returned to sports earlier than female patients [12], with the restoration of full jumping performance capabilities after ACL through their respective rehabilitation process [14-18].

In the clinical and performance environment, inertial sensor units (ISUs) have been recently settled up and validated as a new tool for the evaluation of biomechanical impairments in athletes with ACL reconstruction, due to its low cost and portability [19]. The application of this testing methodology allows clinicians to perform in the field functional and biomechanical evaluations on a quick and friendly manner, in comparison with the gold standard method using force plates [19-23].

The aim of this study was to examine horizontal jumping biomechanical differences between previously ACL-R elite male handball players who returned to sports versus same sport competitive level, sex, and age-matched controls. The hypothesis of the present research is that ACL-R male professional handball players who had returned back to elite competition would not exhibit lasting biomechanical jumping pattern alterations in terms of greater support of three-axis peak forces during single-leg horizontal jumping maneuvers, compared with their control counterparts.

2. Methods

A descriptive case series study design was carried out. The experiment was carried out at the athletes `habitual training court´. The designed jumping task battery included the unilateral triple hop for distance (UTHD) and the unilateral triple crossover hop for distance (COHD). These tests have been previously considered a reliable method for the evaluation of lower limb function in relation to ACL injury [24-26].

2.1 Subjects

Twenty-six male elite handball players competing in their respective highest national division league and European championship were recruited. 26 participants took part in the study; 6were ACL-R (age 27.67 ± 1.26 years; height 188.25 ± 2.31 cm; and weight 92.08 ± 3.48 kg) and 20 uninjured controls (age 24.81 ± 1.27years; height 188.23 ± 1.80 cm; and weight 89.81 ± 2.49 kg). The average and standard deviation of the time since surgical reconstruction was 6.3 ± 3.4 years. Athletes in the control group with a previous lower limb injury lasting more than 6 weeks were excluded from the study to avoid jumping pattern bias due to potential lasting functional alterations associated with 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, which was approved by the Ethics Committee of the University and performed according to the Declaration of Helsinki.

2.2 Equipment

An inertial orientation tracker (MTx, 3DOF Human Orientation Tracker, Xsens Technologies B.V. Enschede, The Netherlands) was attached over the L3-L4 region of the subject's lumbar spine where the human body center of mass is known to be located, and provided data on kinematic and kinetic variables such as accelerations, orientations, and velocity at a sampling rate of 100 Hz. A technical explanation describing the inertial sensor-derived variables has been previously provided [27,28] (Appendix 1).

Briefly, ISU systems provide the linear acceleration and angular displacement orientation values in a sensor-fixed Cartesian reference frame (XYZ). In this way, ISU offers 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. Furthermore, a 10 m-long measuring tape was utilized to measure the distance reached in each horizontal jumping task. The last heel contact was taken as reference for the final jumping length performance.

2.3 Procedures

All participants performed the test at the beginning of a routine training session conducted during the competitive season and at least 48 h after their last competition. The jumping methodology used in this trial has been published and widely extended previously [24,25,29-34]. The athletes were instructed to keep their hands on their hips during the execution of each maneuver. No added technical instructions about the jumping modality were given to the athletes to avoid modifications during the hopping task execution. The participants started in a single limb stance and then performed three consecutive horizontal hops as far as possible (THD test), holding a balanced position for at least 1 s after the last landing. For the COHD, the subjects adopted the same starting position and executed three consecutive crossover hops outside two lanes separated by a 15-cm-wide tape attached on the floor, trying to land as far as possible from the starting line holding a balanced position for at least 1 s after the final landing. The first jumping step from the COHD test was medially directed. A practice trial was performed to ensure the participant's comfort and safety and was followed by two further test trials with 30 s of rest between each repetition. The hopping tasks were performed on a progressive intensity level to avoid possible injury risks associated with the challenging execution of the jumping tasks. Thereby, the participants started with the UTHD and ended with the COHD.

The ISU provides linear acceleration values in a sensor-fixed Cartesian reference frame (XYZ). Before the beginning of the test, while the athlete was standing on the ground with her back in an upright position and the sensor-fixed reference frame was aligned with an Earth-fixed global reference frame (XYZ). The Z-axis represents the vertical direction and points upwards, the X-axis the mediolateral direction and reads right-directed accelerations as positive, and the Y-axis represents the anteroposterior direction interpreting posterior-directed accelerations as positive (Fig.1). The force was calculated from the acceleration values following Newton's 2nd law:

$$F= m*a$$

Where F equals force, m equals body mass, and a equals the acceleration values measured with the ISU. “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 [35]. 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 and hence were the vertical velocity by time descriptive curves depicted.

As this research group reported in previous studies [19,22,23,28], jumping biomechanics assessment through direct mechanics’ procedures by using ISU devices demonstrates high agreement and reliability levels compared with force plates, which are traditionally considered as the gold standard in this area [28].

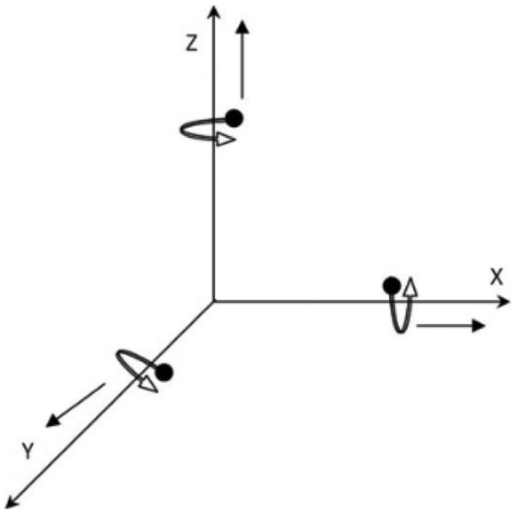

Fig. 1. Earth-fixed global Cartesian reference frame. Z-axis (vertical), X-axis (mediallateral) and Y-axis (anterior-posterior) orientations.

2.4 Data processing and analysis

The data reported by the sensor was analyzed using direct mechanics-based procedures that considered the subject as a mechanical system and estimated the movement and actuation of forces through the center of mass displacement [35,36]. As previously mentioned, the human center of gravity is considered to be located at the L3 lumbar spine level, where the ISU was placed.

To facilitate the biomechanical analysis of the jump, the task was divided into separate phases. The identified phases were based on the results obtained from the vertical velocity curve recordings (Zaxis) through a self-customized computer application implemented in MatLab 7.11 (MathWorks Inc; Natick, MA, USA). The Z velocity signal was used to distinguish the boundaries between the different phases of both tasks and were considered positive when the subject moved upwards (corresponding to the propulsive phases of the three consecutive jumps) and negative when subject moved downwards (corresponding to the pre-loading and landing phases). The different phases of the jumping task have been described succinctly in previous studies [10,19,22,23]. Once the curve determinant points of the jumping task were identified, the different jump phase durations and the acting peak ground reaction force (GRF) values could be calculated for both the UTHD and COHD maneuvers. The outcome of each attempt, measured as the distance in cm, was also recorded. Both required tasks, the UTHD and the COHD, were divided into 12 phases for the 3 hops performed in each task (Fig. 2).

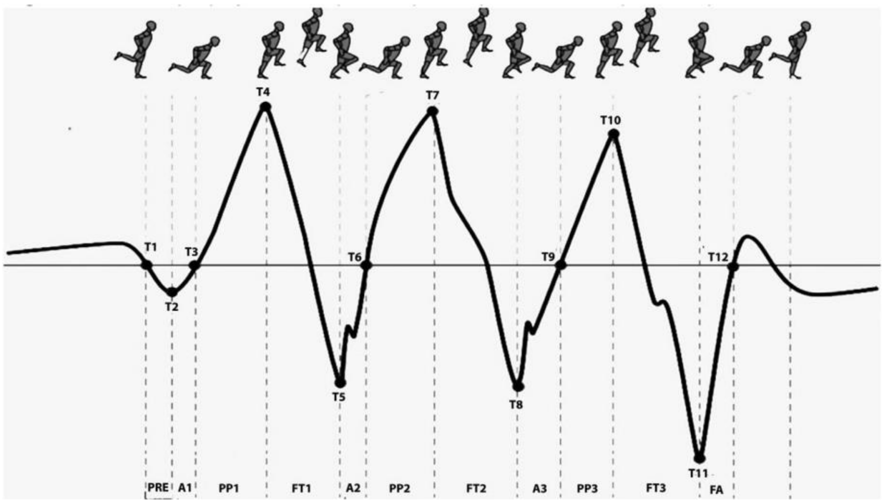

Fig. 2. Horizontal jumping maneuver phases by velocity-time curve analysis description.

For both maneuvers, the initial event (T1) of the first hop started with an active negative (eccentric) acceleration production in the vertical Z-axis (PRE). Then, the T2 event was registered when the center of mass of the athlete reached the maximal vertical negative velocity (first negative peak). The segment T1-T2 represents the negative passive and active work (pre-stretch) corresponding to the propulsive phase (PP). The T3 event corresponded to the instant the Z-velocity first passed zero (when the center of mass of the athlete was in its lowest position) during the transition between the initial absorption (IA1) or pre-load and the propulsive phase (PP1) of the jump. The PP1 concluded in T4, when the maximal vertical velocity (propulsive phase) was achieved. Therefore, the segment T2-T3represents to the IA1, and consequently, the segment T3-T4 correspond to the PP1. T5 was fixed when vertical Z-axis velocity again reached a negative peak due to the active negative (eccentric) action. Therefore, T4-T5 segment corresponded to the flight time of the first hop (FT1) and T5-T6 segment corresponds to the final absorption (FA1) in the transition between the first and the second hop. From T6 to T12 the time points of the remaining two jumps are calculated in the same manner (Fig. 2).

Lastly, the mechanical efficiency ratio calculation was defined as the ratio between the jumping performance (cm) and the sum of the peak tri-axial (X-Y-Z) forces supported at the center of mass level (N). The amount of the sum of three-dimensional forces would penalize or benefit the ratio in the horizontal jumping task. The ME ratio, aims to determine to what extent peak ground reaction forces are supported during the absorptive phases, in relation to the distance reached during the maneuver. Supporting greater peak ground reaction forces during the absorptive phases, could lead to a more harmful mechanical overload which could increase the injury risk.

$$ME = \frac{\text{performance (cm)}}{(Fx + Fy + Fz)}$$

2.5 Statistical analysis

Descriptive statistics (mean, standard error of the mean and IC values at 95%) were calculated for all the collected variables (weight in kg; height in cm; performance in cm; tri-axial GRFs in N). Afterwards, descriptive statistics for the selected variable groups (ACL-R limb and ACL-R healthy limb) were applied. After normal distribution of the data and variances equality were checked through the Shapiro-Wilk and Levene tests respectively, a multivariate analysis of variance (ANOVA) was performed to analyze interaction levels between factors. 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 us with only one fixed factor (ACL-R vs controls). When the variance equality was rejected, the Tamhane's post hoc test was performed. The significance level was set at $p < 0.05$.

Apart from that, intra and inter-group differences were analyzed using magnitude-based inferences (MBI). This statistical method was chosen in order to highlight the practical significance over the statistical (p value) significance, emphasizing that the magnitude of an effect would be more relevant than any statistically significant effect especially in the clinical practice or when treating elite athlete's data [37,38]. The magnitudes of the smallest worthwhile differences were identified by the determination of the effect sizes (Cohen's d) for between-limbs and between group comparisons, using means and standard deviations for each group of variables. Values for Cohen's d statistics were interpreted as follows: <0.15 for trivial, 0.15 to 0.4 for small, 0.4 to 0.75 for medium, 0.75 to 1.10 for large and >1.10 for very large differences [39].

3. Results

No significant differences between ACL-R and non-ACL-R counterparts were found in relation to age, height and weight. Indeed, no significant interaction effects were found between factors for the THD and TCHD tests. Therefore, the results are delimited to the description of the main effects observed. Detailed jumping distance performance and kinetic data is described below for both horizontal jumping tasks.

3.1 Unilateral triple hop for distance (UTHD)

Regarding the UTHD task, non-significant differences were found for distance performance (Table 1) and the analyzed time-force variables (Fig. 3; Appendix A) in ACL-R compared with ACLR healthy and control dominant limbs. However, ACL-R limbs showed a trend towards greater performance during the task compared to control limbs (538,20 ± 112,81 vs 503,64 ± 52,28 cm; Cohen's d = 0,419).

In the same manner, the ACL-R limb of cases showed a trend towards greater mechanical efficiency ratios (0,028 ± 0,007 vs. 0,026 ± 0,004 cm*N_1; Cohen's d = 0,418) when executing this horizontally oriented jumping task compared with that of control limbs (Table 2).

3.2 Triple cross-over hop for distance (COHD)

With respect to the COHD, non-significant differences were found between groups in terms of distance performance (Table 1). However, a trend towards greater performance in the ACL-R limb of cases was observed compared to that in control limbs (434,6 ± 87,2 vs 407,8 ± 81, 1 cm; Cohen's d = 0,319). Indeed, the ACL-R limbs of the cases also displayed a better behavior in mechanical efficiency ratios (0,024 ± 0,005 vs. 0,021 ± 0004 cm*N_1; Cohen's d = 0,628) when executing this crossover jumping task compared with the control limbs (Table 2). More detailed COHD kinetic data and statistical results are added as supplementary material (Fig. 3, Appendix B).

Table 1. Horizontal jumping performance for unilateral triple hop and unilateral cross-over hop for distance. Descriptive statistics, significance and effect size calculations for each group.

		ACLR Injured Limb	**ACLR Healthy Limb**	**Control Limb**	**Sig. (*p*)**	***ES (d)***
	N	6	6	38		
UTHD	Performance	538,20 ± 112,81	563,00 ± 53,08	503,64 ± 52,28	0,342	*0.419*
	95% CI	398,13 - 678,27	507,29 - 618,71	485,10 - 522,18		***(small)***
	n	6	6	36		
UCOHD	Performance	434,60 ± 87,15	473,67 ± 67,04	407,79 ± 81,11	0,684	*0.319*
	95% CI	326,39 - 542,81	403,32 - 544,02	379,03 - 436,55		***(small)***

*Values are mean ± standard deviation, 95% confidence interval (inferior -superior value). P value from ANOVA calculations between ACLR injured limb and Control Limb. Standardised effect size interpreted as Cohen's d values between ACLR injured limb and Control Limb. Abbreviations: UTHD, unilateral triple hop for distance; UCOHD, unilateral cross-over hop for distance; n, sample size; SD, standard deviation; 95% CI, 95% confidence interval; ES, effect size; d, Cohen's d. * = p <.05.*

Table 2. UTHD manoeuvre phases breakdown in terms of centre of mass force orientation values. Descriptive statistics and effect size calculations.

	Force Orientation in N (mean ± SD)	**ACLR Injured Limb**	**ACLR Healthy Limb**	**Control Limb**	**Sig.(*p*)**	***ES (d)***
1st Hop	**X-axis**	2638,43 ± 1260,13	2512,01 ± 1221,94	2586,54 ± 1098,30	*0,999*	*0,044*
	95% CI	1073,78 - 4203,10	1229,67 - 3794,36	2197,10 - 2975,97		***(small)***
	Y-axis	3040,64 ± 960,64	3096,02 ± 834,67	3324,11 ± 845,50	*0,721*	*0,314*
	95% CI	1847,84 - 4233,43	2220,08 - 3971,95	3024,30 - 3623,91		***(small)***
	Z-axis	2728,15 ± 868,65	2726,03 ± 1166,875	3693,49 ± 1186,50	*0,442*	*0,939^*
	95% CI	1649,58 - 3806,72	1501,46 - 3950,58	3272,78 - 4114,208		***(large)***
2nd Hop	**X-axis**	4067,86 ± 757,27	3214,71 ± 688,59	3391,20 ± 1054,99	*0,300*	*0,747*
	95% CI	3127,59 - 5008,14	2492,07 -3937,34	3017,12 - 3765,29		***(medium)***
	Y-axis	4042,21 ± 1069,26	3643,58 ± 1138,24	3980,37 ± 1075,11	*0,968*	*0,058*
	95% CI	2714,54 - 5369,87	2449,07 - 4838,09	3599,15 - 4361,59		***(small)***
	Z-axis	3615,45 ± 972,73	3613,46 ± 813,39	3647,88 ± 1182,87	*0,971*	*0,030*
	95% CI	2407,65 - 4823,25	2759,86 - 4467,07	3228,45 - 4067,30		***(small)***
3rd Hop	**X-axis**	4131,08 ± 1436,95	4328,33 ± 788,49	4339,24 ± 946,92	*0,827*	*0,175*
	95% CI	2346,86 - 5915,29	3500,86 - 5155,80	4003,48 - 4675,00		***(small)***
	Y-axis	4311,44 ± 938,38	4400,30 ± 934,28	4167,64 ± 943,54	*0,960*	*0,153*

95% CI	3146,29 - 5476,59	3419,83 - 5380,76	3833,08 - 4502,21		***(small)***
Z-axis	4303,50 ± 779,58	3678,57 ± 893,47	4332,58 ± 991,72	*0,997*	*0,033*
95% CI	3335,52 - 5271,48	2740,93 - 4616,20	3980,93 - 4684,23		***(small)***

*Values are mean ± standard deviation, 95% confidence interval (inferior – superior value). P value from ANOVA calculations between ACLR injured limb and Control Dominant Limb. Standardised effect size interpreted as Cohen's d values between ACLR injured limb and Control Dominant Limb. Abbreviations: UTHD, unilateral triple hop for distance;n, sample size; SD, standard deviation; 95% CI, 95% confidence interval; ES, effect size; d, Cohen's d. * = p <.05. ^ = d > 0.8.*

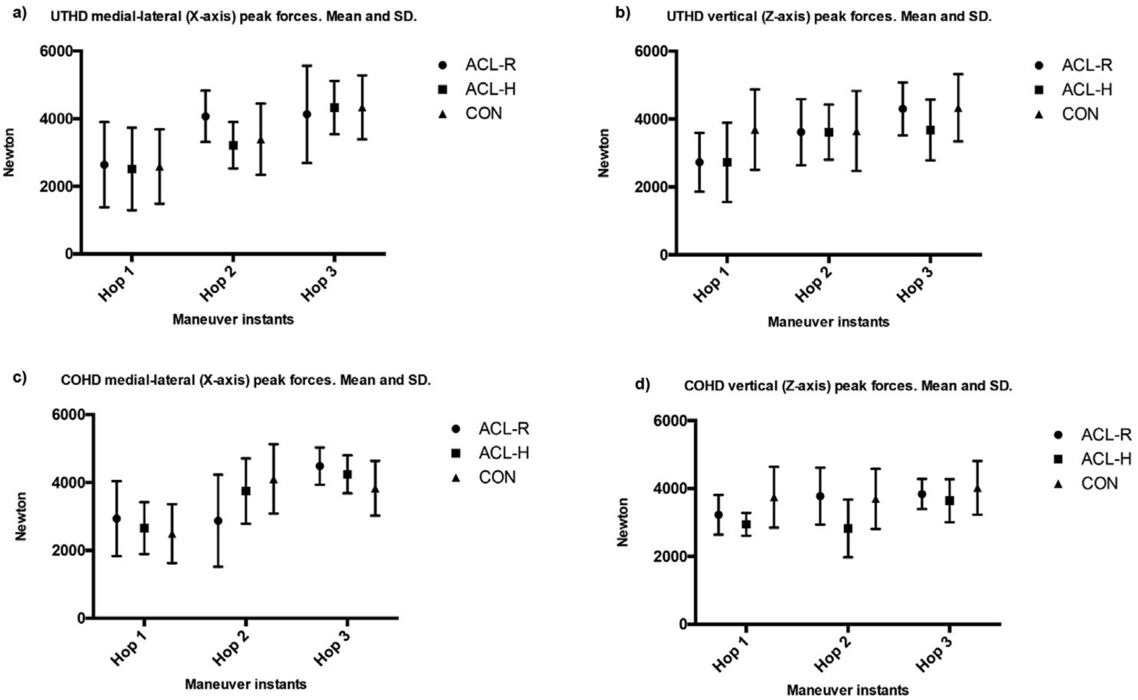

Fig. 3. Between groups peak vertical and medial-lateral forces comparison during the unilateral triple hop for distance (UTHD) and the unilateral cross over hop for distance maneuvers. Mean and SD. Abbreviations: (UTHD), unilateral triple hop for distance; (COHD), unilateral cross over hop for distance; ACL-R, anterior cruciate ligament group reconstructed limb; ACL-H, anterior cruciate ligament group-healthy limb; control group-dominant limb.

4. *Discussion*

The aim of this study was to examine the biomechanics of two horizontal jumping tasks among professional top-level male handball athletes using an ISU-based methodology. The main focus was placed on the identification of lasting jumping biomechanical adaptations among previously ACL-R athletes. The results did not show any sign of lasting biomechanical alteration in ACL-R participants who returned to full competition at high intensity and exigency levels, with a mean of seven years since the original ACLR. In fact, the trend showed greater jumping performance and mechanical efficiency ratios among the previously ACL-R limbs of cases. Several years after the original surgical repair, players who had previously undergone ACLR were able to restore their full jumping performance.

According to that result, previously ACL-R limbs of cases, reported a non-significant trend towards higher UTHD performance compared to control limbs (538,20 ± 112,81 cm vs 503,64 ± 52,28 cm) but lower performance compared to their own contralateral healthy limb (538,20 ± 112,81 cm vs 563,00 ± 53,08 cm) (Table 1). During the execution of both horizontal jumping tasks, ACL-R athletes were more prone (although not significantly) to better absorbing the bearing Z- (vertical) and Y- (horizontal) axis ground reaction forces during the absorption phases of the tasks analyzed (Tables 2 and 3).

Table 3. UCOHD manoeuvre phases breakdown in terms of centre of mass force orientation values. Descriptive statistics and effect size calculations.

	Force Orientation in N (mean ± SD)	**ACLR Injured Limb**	**ACLR Healthy Limb**	**Control Limb**	**Sig.(*p*)**	***ES (d)***
1st Hop	**X-axis**	2935,13 ± 1101,22	2652,61 ± 762,60	2493,03 ± 866,71	*0,793*	*0,449*
	95% CI	1567,78 - 4302,48	1852,31 - 3452,90	2185,71 - 2800,35		***(small)***
	Y-axis	2884,26 ± 471,22	3196,00 ± 976,72	2992,94 ± 1089,19	*0,988*	*0,139*
	95% CI	2299,16 - 3469,35	2170,99 - 4221,01	2606,73 - 3379,15		***(small)***
	Z-axis	3225,43 ± 582,42	2944,86 ± 336,88	3745,46 ± 896,97	*0,214*	*0,703*
	95% CI	2502,25 - 3948,60	2591,33 - 3298,39	3427,41 - 4063,51		***(medium)***
2nd Hop	**X-axis**	2874,38 ± 1354,53	3747,85 ± 961,96	4104,19 ± 1024,07	*0,138*	*1,034^*

	95% CI	1192,51 - 4556,25	2738,33 - 4757,37	3741,07 - 4467,31		***(Very large)***
	Y-axis	3028,58 ± 943,33	3470,56 ± 952,46	3659,14 ± 983,87	*0,973*	*0,654*
	95% CI	1857,28 - 4199,87	2471,02 - 4470,11	3310,28 - 4008,00		***(medium)***
	Z-axis	3775,66 ± 837,82	2821,94 ± 850,61	3695,08 ± 887,36	*0,825*	*0,093*
	95% CI	2735,37 - 4815,95	1929,28 - 3714,61	3380,44 - 4009,73		***(small)***
3rd Hop	**X-axis**	4486,11 ± 547,42	4243,21 ± 561,70	3830,18 ± 808,13	*0,169*	*0,719*
	95% CI	3911,63 - 5060,59	3653,74 - 4832,68	3556,63 - 4103,73		***(medium)***
	Y-axis	3505,42 ± 1159,60	4052,91 ± 784,53	4134,88 ± 916,51	*0,477*	*0,606*
	95% CI	2065,59 - 4945,25	3229,60 - 4876,22	3809,90 - 4459,86		***(medium)***
	Z-axis	3839,15 ± 445,12	3640,11 ± 631,98	4021,99 ± 791,08	*0,847*	*0,296*
	95% CI	3286,45 - 4391,84	2976,89 - 4303,33	3741,49 - 4302,50		***(small)***

*Values are mean ± standard deviation, 95% confidence interval (inferior – superior value). P value from ANOVA calculations between ACLR injured limb and Control Dominant Limb. Standardised effect size interpreted as Cohen's d values between ACLR injured limb and Control Dominant Limb. Abbreviations: UTHD, unilateral triple hop for distance;n, sample size; SD, standard deviation; 95% CI, 95% confidence interval; ES, effect size; d, Cohen's d. * = p <.05. ^ = d > 0.8.*

In the authors' opinion, the greater GRF management variability reported by controls and ACL-R healthy limbs in comparison to the ACL-R limbs of cases (Tables 2 and 3) could be explained by the concept of stress dissipation through movement variability augmentation, as explained by Hamill, Palmer and Van Emmerick [40], who proposed that absolute coordination with low variability could be linked to forces being concentrated in small surface areas, possibly resulting in greater tissue stress and a greater chance for overuse injury. Future studies should be carried out with an appropriate experimental design to answer this question.

Analyzing the UTHD and COHD jump task between the ACL-R limb and the controls, we found that the ACL-R limb of the cases displayed greater jumping performance compared to that of their control counterparts. As both dominant and non-dominant limbs were included in the control group and case group (where dominant and non-dominant limbs were equally affected), we cannot associate these results with a dominance effect. Regarding player demarcation, there were 3 lateral extremes, 2 pivots and one goalkeeper among the cases and all kinds of demarcations in the control group. Thus, in this context, linking the better performance observed among cases to a playing position could be somewhat speculative. In the author's opinion, the actual difference observed could be related to both a greater jumping ability at baseline, prior to injury in these players as well as to a full jumping capacity restoration after ACL reconstruction.

The mechanical efficiency ratios were slightly higher on ACL-R limbs of cases than in control limbs when executing both horizontal jumping maneuvers (Table 4); the lower peak external force reduced the performance achieved during the test. These results are consistent with the study hypothesis, which posited that ACL-R elite handball male players would not possess lasting biomechanical movement pattern alterations in terms of greater support of three-axis peak forces during single-leg horizontal jumping maneuvers despite being back to elite competition several years after the original ACL injury compared with their control counterparts.

Table 4. Horizontal jumping performance and three-dimensional force-based mechanical efficiency ratios. Descriptive statistics and effect size (Cohen's *d*) calculations.

Horizontal Jumping Tasks		**ACLR Injured**	**ACLR Healthy**	**Control Limb**	***ACLR Injured vs ACLR Healthy***		***ACLR Injured vs Control Limb***	
					ES (d)	*Dif.*	*ES (d)*	*Dif.*
UTHD	Mean (±SD)	0,028 ± 0,007	0,031 ± 0,005	0,026 ± 0,004	0,517	***medium***	*0,418*	***medium***
	95% CI	0,020 - 0,036	0,026 - 0,036	0,024 - 0,027				
UCOHD	Mean (±SD)	0,024 ± 0,005	0,027 ± 0,007	0,021 ± 0,004	0,446	***medium***	0,628	***medium***
	95% CI	0,018 - 0,031	0,020 - 0,034	0,020 - 0,023				

Values are mean ± standard deviation, 95% confidence interval and standardised effect size. Abbreviations: UTHD, unilateral triple hop for distance; UCOHD, unilateral cross over hop for distance; n, sample size; SD, standard deviation; 95% CI, 95% confidence interval; ES, effect size; d, Cohen's d.

Setuain et al. [18] previously found in a study with the same cohort of athletes that previously ACL-R elite male handballers demonstrated a vertical jumping biomechanical profile similar to control players, including similar jumping performance values in both bilateral and unilateral jumping maneuvers, several years after ACLR.

According to several studies, the fully functional restoration of jumping capacity could be a common achievement in high-level male athletes after ACL reconstruction [14,15,16] and showed no significant differences in any combined performance test among players with ACL reconstruction compared with an age-, size-, and position-matched control group of professional male basketball players. Similar outcomes were reported by Brophy et al. [15] in a cohort of male soccer players.

The UTHD and COHD tests have been included in many functional lower limb testing routines [30,41-43], that have been traditionally used to determine the return-to-sport readiness after ACL reconstruction and rehabilitation. In this scenario, the emerging ISU-based jumping mechanics analysis enables more comprehensive performance and biomechanical tests, helping both sport scientists and clinicians to generate more accurate motor skills evaluations to apply an individual deficit-based clinical rehabilitation program that would lead the patient through the rehabilitation process in a safe and customized manner [19,22,23].

In a meta-analysis, Ardern et al. [44] showed that up to 55% of players returned to competitive sports after ACL reconstruction; a younger age favored returning to the pre-injury level of the sport, and men had greater odds of returning to their pre-injury level of sports than women. In addition, ACL-R patients classified as having restored normal knee function (determined by a minimum score of 9,6 ± 1,5 in the IKDC questionnaire) after surgical repair and rehabilitation had approximately twice the odds of returning to their pre-injury level of sport participation. The restoration of a symmetrical jumping performance could indicate that these previously ACL-R handball male players had successfully relearned their prior motor patterns, with no lasting biomechanical adaptations observed 6 years after their surgical ligament repair.

The utilization of ISUs can provide a real-time assessment tool for determining how athletes are mechanically managing several vertical or horizontal ordinary training exercises to prevent undesirable aberrant motor patterns. These assessments can be made in the clinical setting or in the training court itself [19,21-23]. In this sense, single inertial unit systems appear to provide a real-time, fast and inexpensive movement analysis tool in both the clinical setting and in the training habitual location itself. Although positioned at the trunk level, ISU devices obviously do not replace higher-precision 3D motion analysis and inverse dynamics technology-based models, but they could potentially be applicable in the clinical setting in order to measure gross whole body-supported 3-dimensional axes accelerations, orientations, and jump phase durations.

Some limitations in the present study may limit the extrapolation of these results to other populations, such as the small sample size (6 ACL-R and 20 healthy controls), the unknown postoperative rehabilitation protocols applied on each injured player, or the heterogeneity of grafts employed for primary ACL reconstruction. There was a lack of standardization of the postoperative rehabilitation protocol and the graft type used for the ligament repair among ACL-R athletes. The heterogeneity of the rehabilitation process may have introduced biased in the long-term outcomes of physical activity level and sport-specific performance. However, previous studies have reported that there are no differences in the long-term function of the knee between reconstructions using different graft types [45]. Furthermore, the use of a single ISU placed at the trunk level limited the information collected to the knee joint biomechanics. Consequently, the behavior of the center of mass during the different hopping tasks was determined through direct mechanics-based human body analysis, and thus, the whole body was considered as a single system of mass and inertia. The net force calculations for specific joints were outside the scope of the present study. Although positioned at the trunk level, ISU devices obviously do not replace higher-precision 3D motion analysis and inverse dynamics technology-based models, for body segments´ movement description. ISUs could alternatively be applicable in the clinical setting in order to measure gross whole body-supported 3-dimensional axes accelerations, orientations, and jump phase durations by center of gravity behavior recording during the jumping tasks performed. The authors also admit that the power of the study could be an important limitation. However, as we mentioned in the original manuscript, our intention was to recruit all elite professional handball players available in our region. We included the professional profile of athletes because we wanted to know whether jumping performance deficits could also persist among fully trained, highly supervised handball athletes. For example, it could be interesting to note that previous work that examined similar variables of jumping performance was performed with previously ACL-R non-professional athletes and an analogous sample size [46,47].

In summary, previously ACL-R elite male handball players who have returned to the top level of sports participation demonstrated similar jumping performance and did not displayed any lasting biomechanical and/or performance deficits 6 years after the original surgical ligament repair. These findings are in agreement with previous researches showing full functional restoration capacity of male top level athletes after ACL reconstruction, rehabilitation and posterior return to previous activity level sports.

On the other hand, the use of ISU-based jumping mechanics analysis in the clinical fields could help to improve the functional and biomechanical evaluations performed in the training court itself, thereby improving the decision-making process for appropriate rehabilitation program design and return-to-sport readiness following ACL injuries.

Conflicts of interest

The authors declare NO conflict of interest.

Ethics approval and consent to participate

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 Ethics Committee.

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Appendix A. UTHD manoeuvre phases breakdown in terms of centre of mass force orientation values. Descriptive statistics and effect size calculations.

*Values are mean ± standard deviation, 95% confidence interval (inferior – superior value). P value from ANOVA calculations between ACLR injured limb and Control Dominant Limb. Standardised effect size interpreted as Cohen's d values between ACLR injured limb and Control Dominant Limb. Abbreviations: UTHD, unilateral triple hop for distance;n, sample size; SD, standard deviation; 95% CI, 95% confidence interval; ES, effect size; d, Cohen's d. * = p <.05. ^ = d > 0.8.*

	Force Orientation in N (mean ± SD)	ACLR Injured Limb	ACLR Healthy Limb	Control Limb	Sig.(*p*)	*ES (d)*
1st Hop	**X-axis**	2638,43 ± 1260,13	2512,01 ± 1221,94	2586,54 ± 1098,30	*0,999*	*0,044*
	95% CI	1073,78 - 4203,10	1229,67 - 3794,36	2197,10 - 2975,97		***(small)***
	Y-axis	3040,64 ± 960,64	3096,02 ± 834,67	3324,11 ± 845,50	*0,721*	*0,314*
	95% CI	1847,84 - 4233,43	2220,08 - 3971,95	3024,30 - 3623,91		***(small)***
	Z-axis	2728,15 ± 868,65	2726,03 ± 1166,875	3693,49 ± 1186,50	*0,442*	*0,939^*
	95% CI	1649,58 - 3806,72	1501,46 - 3950,58	3272,78 - 4114,208		***(large)***
2nd Hop	**X-axis**	4067,86 ± 757,27	3214,71 ± 688,59	3391,20 ± 1054,99	*0,300*	*0,747*
	95% CI	3127,59 - 5008,14	2492,07 -3937,34	3017,12 - 3765,29		***(medium)***
	Y-axis	4042,21 ± 1069,26	3643,58 ± 1138,24	3980,37 ± 1075,11	*0,968*	*0,058*
	95% CI	2714,54 - 5369,87	2449,07 - 4838,09	3599,15 - 4361,59		***(small)***
	Z-axis	3615,45 ± 972,73	3613,46 ± 813,39	3647,88 ± 1182,87	*0,971*	*0,030*
	95% CI	2407,65 - 4823,25	2759,86 - 4467,07	3228,45 - 4067,30		***(small)***
3rd Hop	**X-axis**	4131,08 ± 1436,95	4328,33 ± 788,49	4339,24 ± 946,92	*0,827*	*0,175*
	95% CI	2346,86 - 5915,29	3500,86 - 5155,80	4003,48 - 4675,00		***(small)***
	Y-axis	4311,44 ± 938,38	4400,30 ± 934,28	4167,64 ± 943,54	*0,960*	*0,153*
	95% CI	3146,29 - 5476,59	3419,83 - 5380,76	3833,08 - 4502,21		***(small)***
	Z-axis	4303,50 ± 779,58	3678,57 ± 893,47	4332,58 ± 991,72	*0,997*	*0,033*
	95% CI	3335,52 - 5271,48	2740,93 - 4616,20	3980,93 - 4684,23		***(small)***

Appendix B. UCOHD manoeuvre phases breakdown in terms of centre of mass force orientation values. Descriptive statistics and effect size calculations.

	Force Orientation in N (mean ± SD)	ACLR Injured Limb	ACLR Healthy Limb	Control Limb	Sig.(*p*)	*ES (d)*
1st Hop	**X-axis**	2935,13 ± 1101,22	2652,61 ± 762,60	2493,03 ± 866,71	*0,793*	*0,449*
	95% CI	1567,78 - 4302,48	1852,31 - 3452,90	2185,71 - 2800,35		***(small)***
	Y-axis	2884,26 ± 471,22	3196,00 ± 976,72	2992,94 ± 1089,19	*0,988*	*0,139*
	95% CI	2299,16 - 3469,35	2170,99 - 4221,01	2606,73 - 3379,15		***(small)***
	Z-axis	3225,43 ± 582,42	2944,86 ± 336,88	3745,46 ± 896,97	*0,214*	*0,703*
	95% CI	2502,25 - 3948,60	2591,33 - 3298,39	3427,41 - 4063,51		***(medium)***
2nd Hop	**X-axis**	2874,38 ± 1354,53	3747,85 ± 961,96	4104,19 ± 1024,07	*0,138*	*1,034^*
	95% CI	1192,51 - 4556,25	2738,33 - 4757,37	3741,07 - 4467,31		***(Very large)***
	Y-axis	3028,58 ± 943,33	3470,56 ± 952,46	3659,14 ± 983,87	*0,973*	*0,654*
	95% CI	1857,28 - 4199,87	2471,02 - 4470,11	3310,28 - 4008,00		***(medium)***
	Z-axis	3775,66 ± 837,82	2821,94 ± 850,61	3695,08 ± 887,36	*0,825*	*0,093*
	95% CI	2735,37 - 4815,95	1929,28 - 3714,61	3380,44 - 4009,73		***(small)***
3rd Hop	**X-axis**	4486,11 ± 547,42	4243,21 ± 561,70	3830,18 ± 808,13	*0,169*	*0,719*
	95% CI	3911,63 - 5060,59	3653,74 - 4832,68	3556,63 - 4103,73		***(medium)***
	Y-axis	3505,42 ± 1159,60	4052,91 ± 784,53	4134,88 ± 916,51	*0,477*	*0,606*
	95% CI	2065,59 - 4945,25	3229,60 - 4876,22	3809,90 - 4459,86		***(medium)***
	Z-axis	3839,15 ± 445,12	3640,11 ± 631,98	4021,99 ± 791,08	*0,847*	*0,296*
	95% CI	3286,45 - 4391,84	2976,89 - 4303,33	3741,49 - 4302,50		***(small)***

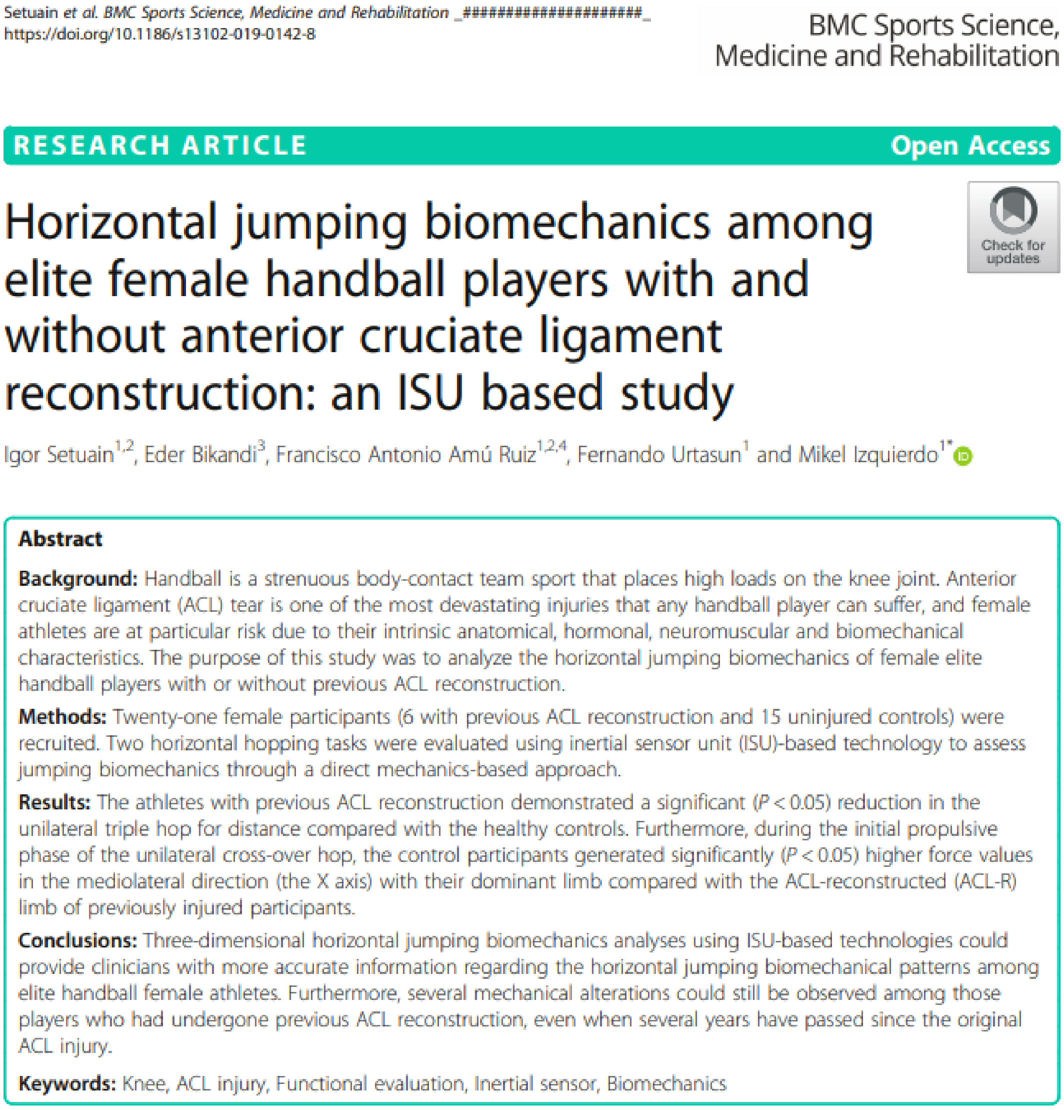
*Values are mean ± standard deviation, 95% confidence interval (inferior – superior value). P value from ANOVA calculations between ACLR injured limb and Control Dominant Limb. Standardised effect size interpreted as Cohen's d values between ACLR injured limb and Control Dominant Limb. Abbreviations: UTHD, unilateral triple hop for distance; n, sample size; SD, standard deviation; 95% CI, 95% confidence interval; ES, effect size; d, Cohen's d. * = p <.05. ^ = d > 0.8.*

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ptsp.2019.06.009.

Chapter 3

Horizontal jumping biomechanics among elite female handball players with and without anterior cruciate ligament reconstruction. An ISU based study



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RESEARCH ARTICLE Open Access

Horizontal jumping biomechanics among elite female handball players with and without anterior cruciate ligament reconstruction: an ISU based study

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Abstract

Background: Handball is a strenuous body-contact team sport that places high loads on the knee joint. Anterior cruciate ligament (ACL) tear is one of the most devastating injuries that any handball player can suffer, and female athletes are at particular risk due to their intrinsic anatomical, hormonal, neuromuscular and biomechanical characteristics. The purpose of this study was to analyze the horizontal jumping biomechanics of female elite handball players with or without previous ACL reconstruction.

Methods: Twenty-one female participants (6 with previous ACL reconstruction and 15 uninjured controls) were recruited. Two horizontal hopping tasks were evaluated using inertial sensor unit (ISU)-based technology to assess jumping biomechanics through a direct mechanics-based approach.

Results: The athletes with previous ACL reconstruction demonstrated a significant ($P < 0.05$) reduction in the unilateral triple hop for distance compared with the healthy controls. Furthermore, during the initial propulsive phase of the unilateral cross-over hop, the control participants generated significantly ($P < 0.05$) higher force values in the mediolateral direction (the X axis) with their dominant limb compared with the ACL-reconstructed (ACL-R) limb of previously injured participants.

Conclusions: Three-dimensional horizontal jumping biomechanics analyses using ISU-based technologies could provide clinicians with more accurate information regarding the horizontal jumping biomechanical patterns among elite handball female athletes. Furthermore, several mechanical alterations could still be observed among those players who had undergone previous ACL reconstruction, even when several years have passed since the original ACL injury.

Keywords: Knee, ACL injury, Functional evaluation, Inertial sensor, Biomechanics

1. Introduction

Handball is a body-contact team sport that elicits high-intensity maneuvers such as abrupt changes in direction, velocity and sudden single leg landings [1, 2]. The nature of the sport and the high intensity of games, makes the knee joint to be exposed to many stressful forces that could result the anterior cruciate ligament (ACL), rupture, which constitutes one of the most devastating injuries among handball players [3, 4].

The reported incidences of ACL injury for male and female handball athletes are approximately 0.24 and 0.86 injuries per 1000 hours of exposure, respectively [5]. Therefore, female athletes are 6 to 10 times more likely to suffer an ACL injury than their male counterparts during the same jumping and pivoting tasks [5, 6]. Anatomical, hormonal and neuromuscular differences between sexes have been proposed as explanatory factors for this discrepancy in the ACL injury rates between sexes [7-10].

The clinical relevance of ACL injury does not rest solely on the ligament disruption itself; the functional implications of concomitant associated knee injuries for the athletes' function can play an important role in the clinical prognosis of the athlete after injury [11]. Additionally, the scientific literature lacks information regarding the best clinical practices for rehabilitation programs or universal functional and clinical evaluation criteria for resuming the sport after injury [11].

This ambiguity may expose the athlete to both higher risk of graft rupture and a new injury of the healthy contralateral knee [12]. Thus, the detection and monitoring of subjects with a higher risk of injury or re-injury using functional, biomechanical or neuromuscular screening evaluations appears to be crucial either for prevention and rehabilitation in sports medicine [13].

Functional performance evaluations have traditionally been highlighted as a key point in relation to decisions regarding resuming play after ACL injury [2, 13-16]. In this context, unilateral hopping tests have demonstrated a good ability to identify lower limb impairments during both vertical and horizontal jumping maneuvers [15-17].

Several biomechanical and neuromuscular impairments at the trunk, hip and knee joint levels have been widely reported in the literature as a result of motion analysis and inverse mechanics procedures during the abovementioned and other sport-specific tasks [18-21]. Unfortunately, these testing procedures require from expensive and complex laboratory resources (such as camera-motion analysis systems and/or force plates) and are associated with a high financial investment and trained staffs that are familiar with such laboratory-derived procedures. The recent development of ISU-based biomechanical evaluations presents clinicians with the opportunity to perform several functional and biomechanical jumping evaluations on the training court itself [22-28].

In relation to handball, Myklebust et al. [29] observed long-term differences in strength, jumping test scores and anterior-posterior knee joint laxity between ACL-injured and uninjured professional and recreational players after an injury. In addition, Setuain et al. [28] presented a validation study that reported promising results validating the utilization of the ISU versus force plate recordings during vertical jumping tasks. Later, the same research group probed the potential of ISU-based evaluations to assess vertical jumping biomechanical among both female [25]and male [26] elite handball players in relation to previous ACL injury. The authors found long-term, sex-specific functional adaptations after ACL reconstruction, being the female athletes more likely than males to experience lasting biomechanical jumping alterations after an ACL reconstruction [25]. The application of the ISU-based biomechanical jumping to identify movement pattern alterations after ACL injury has also been proven in previous studies [22, 23].

The aim of this study was to examine the biomechanical differences in horizontal jumping between elite female handball players with previous ACL reconstruction who had returned to their previous sport activity, and level-, sex-, and age-matched pairs of control counterparts. The hypothesis of the present research was that the ACL-R players would present lasting biomechanical alterations in terms of greater supported three-axis peak forces during single-limb horizontal jumping maneuvers compared with their control counterparts, despite have continued with elite competition for several years after the original ACL injury.

2. Methods

A descriptive case series study design was selected. The examinations were conducted at the athlete's habitual training court. The jumping task battery included the unilateral triple hop for distance (UTHD) and the unilateral triple cross-over hop for distance (COHD). These tests have been established as reliable methods for evaluating lower limb function in relation to ACL injury in previous investigations [16, 30, 31].

2.1 Subjects

Twenty-one female elite handball players competing in their highest national division league and European championships were recruited. The sample comprised 6 athletes who had undergone ACL reconstruction, two of them bilaterally (age 26.4 ± 1.4 years; height 169.0 ± 1.6 cm; and weight 61.8 ± 1.4 kg), and 15 uninjured controls (age 25.1 ± 1.4 years; height 175.0 ± 1.4 cm; and weight 69.5 ± 1.8 kg). Among the athletes with bilateral reconstructions, both limbs were recorded as ACL-R limbs. The average and standard deviation of the data collection time since surgical reconstruction was 6.0 ± 3.5 years. For the control group, athletes who had sustained a previous lower limb injury lasting more than 6 weeks were excluded to avoid jumping pattern bias due to potential functional alterations resulting from severe lower extremity injury. 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.

2.2 Equipment

An inertial orientation tracker (MTx, 3DOF Human Orientation Tracker, Xsens Technologies B.V. Enschede, The Netherlands) was attached over the L3-L4 region of the subject's lumbar spine and provided data on kinematic and kinetic variables such as accelerations, orientations and velocity at a sampling rate of 100 Hz. A technical explanation describing the inertial sensor-derived variables has been previously provided (Appendix A) [32]. Furthermore, a 10-m-long measuring tape was utilized to measure the distance in each horizontal jumping task. The last heel contact was recorded for the final measure.

2.3 Procedures

Lower limb dominance was determined as previously described by Bencke et al. [2] in their work with handball players. The limb that pushed off the ground for a jump when a regular handball throw was performed was considered dominant [2]. All the participants performed the test at the beginning of a routine training session conducted during the competitive season and at least 48 hours after their last competition. The jumping methodology used in this trial has been published previously [17, 24, 30, 31, 33-36]. The subjects were instructed that during the execution of each maneuver, they should keep their hands on their hips. No added technical instructions about the jumping modality were given to the athletes to avoid modifications during the task performance. The participants started in a single-limb stance position. They then performed three consecutive horizontal hops as far as possible, holding the position for at least one second after the last landing. For the COHD, the subjects adopted the same starting position and executed three consecutive cross-over hops outside two lanes separated by a 15-cm-wide tape attached on the floor, trying to land as far as possible while maintaining their balance for one second at the final landing. The first jumping step was interiorly directed. A practice trial was performed to ensure the participant’s comfort and safety and was followed by two further test trials interspersed with 30 seconds of rest. The jumping tasks were performed in order from easiest to most complex to avoid possible injury risks associated with the intensity of the maneuver. The participants thus started with the UTHD and ended with the COHD.

ISU provides linear acceleration values in a sensor-fixed Cartesian reference frame (XYZ). Before starting the measurement, the inertial sensor unit is calibrated and the sensor axes are aligned with anatomical directions. The acceleration signal consists of gravitational and inertial components. The inertial sensor unit registers gravity as a static vertical component, in addition to the dynamic acceleration caused by changes in velocity during locomotion. The gravity component must be subtracted to estimate the dynamic acceleration. The 3D orientation data provide the position of the inertial unit with respect to the gravitational vector, allowing the calculation of the inertial component for each axis. The gravitational constant was estimated by leaving the inertial sensor unit still on a flat surface for two seconds. In previous studies [25-28], body-worn inertial sensor and accompanying custom algorithms has demonstrated high agreement and reliability levels compared with force plates, [28] (Figure 1).

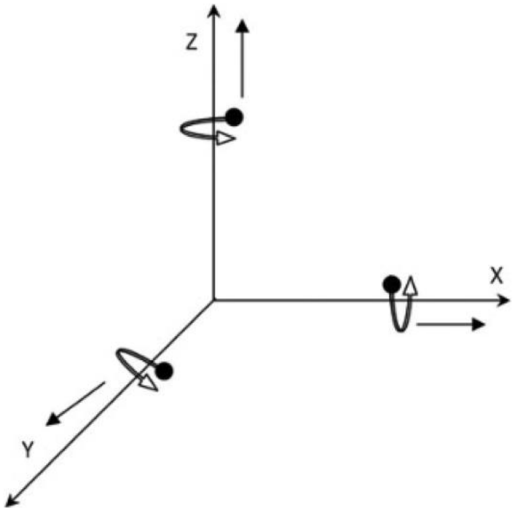

Fig. 1. Z-axis (vertical), X-axis (medial-lateral) and Y-axis (anterior-posterior) orientations.

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2.4 Data processing and analysis

The data reported by the sensor was analyzed using direct mechanics-based procedures that considered the subject as a mechanical system and estimated the movement and actuation of forces through the center of mass displacement [37, 38]. As previously mentioned, the human center of gravity is considered to be located at the L3 lumbar spine level, where the ISU was placed. The data processing description was previously published by this research group [29]

Briefly, in order to facilitate the biomechanical analysis of the jump, the task was divided into separate phases. The identified phases were based on the results obtained from the vertical velocity curve recordings (Z-axis) through a self-customized computer application implemented with MatLab 7.11 (Math WorksInc; Natick, MA, USA). The *Z*- velocity signal was used to distinguish the boundaries between the different phases of both tasks and were considered positive when the subject moved upwards (corresponding to the propulsive phases of the three consecutive jumps) and negative when subject moved downwards (corresponding to the pre-loading and landing phases).

The different phases of the jumping task have been described succinctly in previous studies [25-29] (Figure 2).

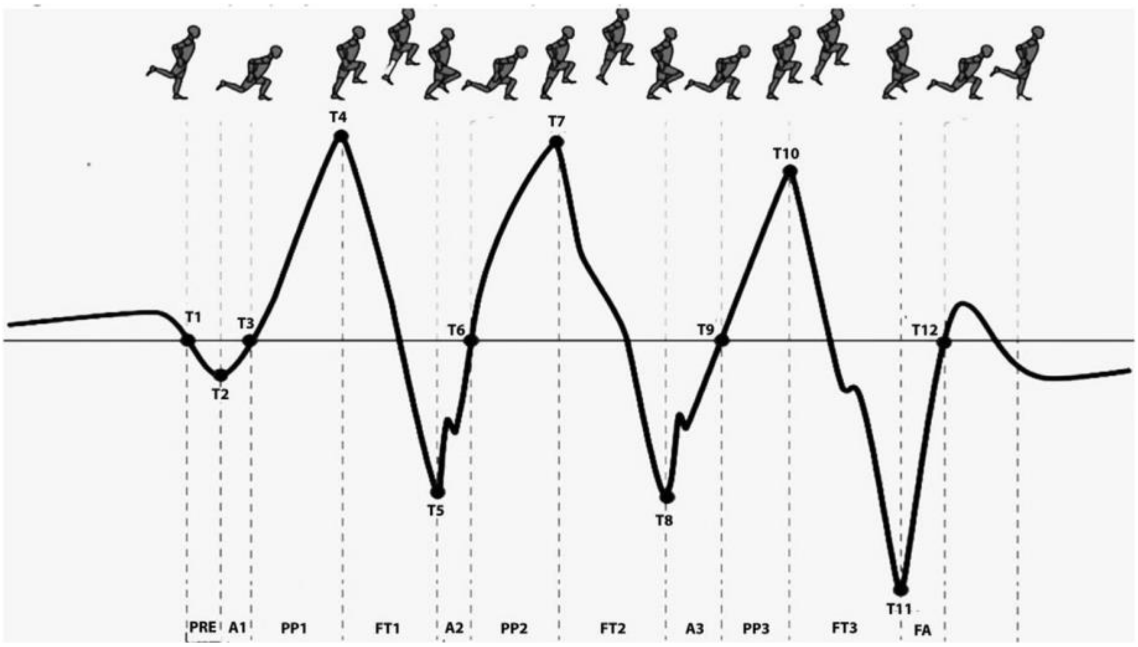

Fig. 2. Horizontal jumping task jumping phases by velocity by time curve analysis description The segment T1-T3 represents the negative passive and active work (pre-stretch) corresponding to the propulsive phase (PP). The T3 event corresponded to the instant the *Z*-velocity first passed zero (when the centre of mass of the athlete was in its lowest position) during the transition between the initial absorption (A1) or pre-load and the propulsive phase (PP1) of the jump. The PP1 concluded in T4, when the maximal vertical velocity (propulsive phase) was achieved. Therefore, the segment T2-T3 represents the countermovement of the jump, and consequently, the segment T3-T4 corresponds to the PP1. Segment T4-t5 represents the flight time of the first jump (FT1). The same curve cut-off points were described thorough the whole triple hop analysed. Thus, absorptive (eccentric, T5-T6; T8-T9 and T11-T12) and propulsive (concentric; T6-T7, T9-T10) phases were similarly described.

Lastly, the mechanical efficiency ratio (ME) calculation was defined as the ratio between the jumping performance (cm) and the sum of the peak ground reaction forces supported at the centre of mass level (N). The amount of the sum of three-dimensional forces would penalize or benefit the ratio in the horizontal jumping task. The ME, aims to determine to what extent the supported peak ground reaction forces are during the absorptive phases, in relation to the distance reached during the maneuver. Supporting greater peak ground reaction forces during the absorptive phases, could lead to a more harmful mechanical overload which could increase the injury risk.

$$\boldsymbol{ME = \frac{performance(cm)}{(Fx + Fy + Fz)}}$$

2.5 Statistical analysis

Descriptive statistics (mean, standard error of the mean and IC values at 95%) were calculated for all the collected variables (weight in kg; height in cm; performance in cm; 3 axis GRFs in N). Afterwards, descriptive statistics for the selected variable groups (ACL-R injured limb, ACL-R healthy limb, Control dominant limb) were applied. After normal distribution of the data and variances equality were checked through the Shapiro-Wilk and Levene tests respectively, 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 ACL-R group and the non-dominant limb was matched to the non-involved limb of the ACLR group [19]. 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 limb us with only one fixed factor (group; ACL-R vs controls). When the variance equality was rejected, the Tamhane's post hoc test was performed. The significance level was set at $p < 0.05$. "SPSS® statistical software (V. 20.0, Chicago, IL, USA) was used for the abovementioned statistical calculations**.**

Apart from that, intra and inter-group differences were analysed using magnitude-based inferences (MBI). This statistical method was chosen in order to highlight the practical significance over the statistical (p value) significance, emphasizing that the magnitude of an effect would be more relevant than any statistically significant effect especially in the clinical practice or when treating elite athlete's data [40, 41]. The magnitudes of the smallest worthwhile differences were identified by the determination of the effect sizes (Cohen´s d) for between-limbs and between group comparisons, using means and standard deviations for each group of variables. Values for Cohen's d statistics were interpreted as follows: <0.15 for trivial, 0.15 to 0.4 for small, 0.4 to 0.75 for medium, 0.75 to 1.10 for large and >1.10 for very large differences [41].

3. Results

After the data processing, the number of analysed limbs in both control and ACL-R group was the following: 8 ACL-R reconstructed limbs and 4 ACL-R in both

UTHD and COHD maneuvers; 13 dominant and non-dominant limbs in the UTHD and 14 dominant and non-dominant limbs in the COHD of the control group.The ACL-R players were significantly ($p < 0.05$) lighter and smaller than their non-ACL-R counterparts. No significant interaction effects were found between factors for UTHD and COHD tests. Therefore, the results are delimitated to the description of the main effects observed.

3.1 Unilateral Triple Hop for Distance (UTHD)

Regarding the UTHD, the dominant limb of the controls reached a significantly better distance performance on the UTHD task compared with the injured limb of the ACL-R participants ($p < 0.05$). Indeed a non statistical trend although a large effect size was find in realtion to a gretater X mediolateral force production during the first hop in controls in comparison to ACL- reconstructed players. (Table 1). No further significant differences were found for any time or force variables (Figure 3).

The ACL-R limbs of cases demonstrated a trend towards greater mechanical efficiency ratios (0.079 ± 0.02 vs. 0.070 ± 0.05; Cohen´s d = 0.4) when executing this horizontally oriented jumping task (Table 2).

3.2 Triple Cross-Over Hop for Distance (COHD)

Regarding the COHD, no significant differences were found between the groups in terms of performance (reached distance)(Table 1). However, a significant group-by-limb interaction was observed for the PP X-axis forces ($F = 4.353$; $p = 0.010$). The Bonferroni post-hoc analysis revealed that the dominant limbs of the controls displayed significantly greater X-medial-lateral axis forces than the injured limbs of the ACL-R group ($p < 0.05$). No significant differences were found for the remaining analyzed variables (Figure 3).

The ACL-R limbs of the cases demonstrated a trend towards lower mechanical efficiency ratios (0.058 ± 0.02 vs. 0.085 ± 0.02; Cohen´s d = 1.4) when executing this side-to-side and horizontally oriented jumping task.

For more information, available complementary material is included about the 3-axial forces results for the UTHD (Appendix A) and the COHD (Appendix B)

Table 1. Horizontal jumping performance for unilateral triple hop and unilateral cross-over hop for distance. Descriptive statistics, significance and effect size calculations for each group.

Horizontal Jumping Tasks	**ACLR Injured limb**			**ACLR Healthy Limb**			**Control Dominant Limb**			***ACLR Injured vs ACLR Healthy***		***ACLR Injured vs Control Dom***	
	n	Mean (±SD)	95% CI	*n*	Mean (±SD)	95% CI	*n*	Mean (±SD)	95% CI	*ES (d)*	*Difference*	*ES (d)*	*Difference*
UTHD	8	0,079 (±0,022)	0,061 - 0,097	4	0,072 (±0,014)	0,049 - 0,094	13	0,070 (±0,021)	0,057 - 0,083	*0,379*	***small***	*0,418*	***medium***
UCOHD	8	0,058 (±0,015)	0,046 - 0,071	4	0,064 (±0,022)	0,0287 - 0,1001	14	0,085 (±0,023)	0,072 - 0,098	*0,318*	***small***	*1,39*	***very large****

Values are mean ± standard deviation, 95% confidence interval (inferior – superior value). P value from ANOVA calculations between ACLR injured limb and Control Dominant Limb. Standardized effect size interpreted as Cohen's d values between ACLR injured limb and Control Dominant Limb. Abbreviations: UTHD, unilateral triple hop for distance; UCOHD, unilateral cross-over hop for distance; n, sample size; SD, standard deviation; 95% CI, 95% confidence interval; ES, effect size; *d*, Cohen's *d*. * = *p* <.05. ^ = *d*> 0.8.

Table 2. Horizontal jumping performance and three-dimensional force-based mechanical efficiency ratios. Descriptive statistics and effect size (Cohen's *d*) calculations.

		ACLR Injured Limb	**ACLR Healthy Limb**	**Control Dominant Limb**	**Control Non-Dominant Limb**	**Significance (*p*)**	***ES (d)***
UTHD	N	8	4	15	15		
	Performance	389 ± 61.05	398.25 ± 87.76	436 ± 37.84	430.29 ± 47.91	0.047*	*d = 0.925^*
	95% CI	337.97 – 440.03	258.61 – 537.89	411.95 – 460.05	402.62 – 457.95		
UCOHD	n	8	4	15	15		
	Performance	289.63 ± 58.24	310.5 ± 70.90	326.14 ± 44.84	329.31 ± 60.61	0.115	*d = 0.7025*
	95% CI	240.94 – 338.31	197.68 – 423.32	300.25 – 352.03	292.68 – 365.94		

Values are mean ± standard deviation, 95% confidence interval and standardized effect size. Abbreviations: UTHD, unilateral triple hop for distance; UCOHD, unilateral cross over hop for distance; n, sample size; SD, standard deviation; 95% CI, 95% confidence interval; ES, effect size; *d*, Cohen's *d*. * *d*>1.10.

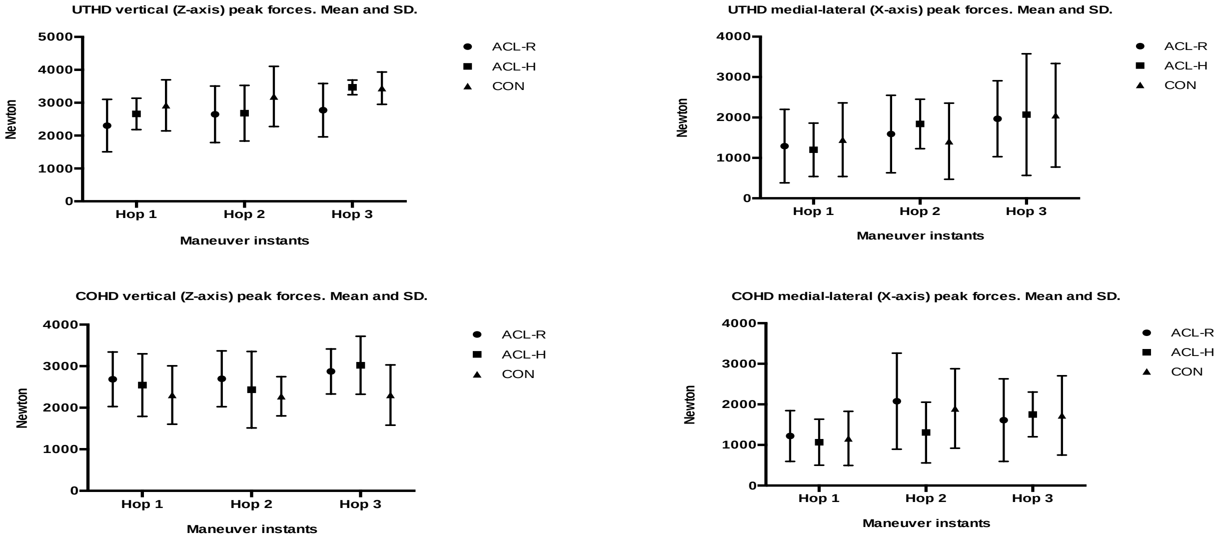

Figure 3. Between groups peak vertical and medial-lateral forces comparison during the unilateral triple hop for distance (UTHD) and the unilateral cross over hop for distance maneuvers. Mean and SD.

Abbreviations: (UTHD), unilateral triple hop for distance; (COHD), unilateral cross over hop for distance; ACL-R, anterior cruciate ligament group-reconstructed limb; ACL-H, anterior cruciate ligament group-healthy limb; control group-dominant limb.

4. Discussion

The purpose of this study was to examine the biomechanics of two horizontal hopping tasks among top-level professional female handball athletes using an ISU-based methodology. The analysis focused on the identification of persistent jumping biomechanics adaptations in the ACL-R limbs of previously injured athletes. The results of the present work showed that although the ACL-R participants had returned to full competition at high intensity and exigency levels, slight jumping biomechanics alterations seemed to persist.

Consequently, the previously ACL-injured limbs of the cases showed lower UTHD performance in terms of distance (Table 1), and reduced mediolateral force generation on the propulsive phases of these horizontally oriented jumps, especially in the COHD maneuver (Figure 3). These findings may suggest that at the initial propulsion (the pre-loading phase preceding the first hop), the ACL-R limbs of the previously injured athletes generated lower frontal plane forces compared with the dominant limbs of the control athletes. Furthermore, during the execution of both horizontal jumping tasks, the ACL-R athletes were more prone (although not significantly) to generate lower Z-axis (vertical) and Y-axis (horizontal) forces. Interestingly, the newly proposed mechanical efficiency ratios demonstrated a trend towards lower values for the ACL-R limbs of the cases compared with the dominant limbs of the controls when executing these horizontally oriented jumping maneuvers, specially the CTHD. This could highlight that female handball players exhibit greater peak external force penalization (supporting ground reaction forces) when jumping with their previously ACL-R limb for the distance reached in comparison to that supported by controls. These results partially agree the study hypothesis, which posited that the ACL-R players would experience lasting biomechanical movement pattern alterations in terms of greater supporting three-axis peak forces during single-limb horizontal jumping maneuvers compared with their control counterparts despite having performed in elite competition for several years since the original ACL injury.

This results, contrast with those obtained by the same research group employing the same jumping test battery and biomechanical analysis methodology among male elite handball players. In that study, the authors did not find any meaningful biomechanical adaptations among previously ACL reconstructed in comparison to control (non ACL injured) players. In this sense, it seems that male handball professional players are able to recover their lower limb full performance capacities without lasting biomechanical alterations that can be in contrast observed among their female counterparts. Although evidence exists referring no sex influence in relation to increased risk for ACL graft failure among sportspeople, [42] may be, this statistical trend would change when controlling for sex, handball sport, and level of competence of the participants. This question should be addressed in properly designed investigations.

Traditionally, lower limb functional evaluations have been carried out in order to determine the athlete capacities with regard to return to sport participation. Indeed, jumping biomechanical have also been performed in relation to injury risk factor identification showing huge correlation between poor unilateral limb performance values and knee dynamic instability [31]. In this context, ground reaction forces acting at the trunk level have been considered to have significant effects on lower limb segment behavior due to the inertia moment of force generation [43]. Consequently, frontal plane kinematic or kinetic parameters measured at the trunk level have been shown to be significantly associated with knee valgus production [43]. In this context, ISU systems have become a reliable instrumentation for trunk displacement-derived 3D force calculations in different functional tasks [25-28]. It has been shown, an upward trunk position when landing from a jump could lead to greater anterior shear forces at the knee joint and higher vertical peak ground reaction forces, exposing the ACL to a higher injury risk [35, 43].

Thus, despite knee joint moment description is not possible when analysing a jumping task through a direct mechanic's approach, by placing an ISU on the L3-L4 level, clinicians by using this jumping biomechanical analysis method, could look for jumping aberrant patterns identification that have been previously linked to a greater knee joint injury risk due to excessive mechanical overload during high demand athletic tasks.

In this way, it is possible that ACL-R female athletes could have developed lasting movement pattern adaptations during single-limb actions in the attempt to improve lower limb stiffness through movement pattern reprogramming at the central nervous system level [44]. This fact would help to explain the smaller medial-lateral force produced at the center of mass level during both UTHD and COHD task, as a positive effect of the rehabilitation. These results are in contrast with previous investigations from the same research group and cohort of athletes that analyzed vertical jumping maneuvers [26]. In that research, ACL-reconstructed athletes generated higher medial-laterally oriented peak forces than their control counterparts. In the authors' opinion, this controversy could arise from a specific jumping direction-based motor retraining strategy adopted among cases to preserve knee joint integrity. In fact, the reduced mechanical efficiency ratios observed for the ACLR limbs of cases on the COHD task, which is known to place higher valgus stress on the knee joint than the UTHD, could support this hypothesis. However, this assumption should be adequately tested with studies designed to answer the specific question.

The identification of lasting functional and biomechanical jumping alterations several years after the injury in both the present and previous research [25-27], could be linked to an inadequate rehabilitation process or the approval of excessively early return to play by sports medicine staff when managing ACL injuries. This fact becomes clinically relevant in this context, as the time lapse between the time of reconstruction and return to sport participation, is known to affect ACL graft failure [42.], The application of the ISU bed biomechanical jumping evaluations, could become useful for a more accurate motion analysis at the clinical setting level that would allow the clinician to plan an objective, clinically reasonable rehabilitation program based on the observed biomechanical alterations.

Some potential limitations could be observed in the present study. Given the uniqueness of the analyzed population, which was limited to an exclusive cohort of female professional handball athletes, the results should be interpreted with caution and in relation to this sport level, discipline and sex. Additionally, there was a lack of standardization of the postoperative rehabilitation protocols and the graft type used for the ligament repair among the ACL-R athletes. The heterogeneity of the rehabilitation process may have biased the long-term outcome in terms of physical activity level and sport-specific performance. However, previous studies have reported that no differences exist between reconstructions using different graft types in relation to long-term function of the knee [29]. Furthermore, the use of a single ISU placed at the trunk level limited the information collected regarding the knee joint biomechanics. The, net moments of force calculations for specific joints were outside the scope of the present study which in turn tries to describe the centre of mass behavior thorough a direct mechanic’s approach. This is not as exhaustive as inverse mechanics procedures, but instead could be more friendly (in the field testing) and easy to handle for sport clinicians.

5. Conclusions

In conclusion, elite female handball players with previous ACL reconstruction demonstrated an attenuated jumping capacity in the THD test. Indeed, they also displayed lower X-medial-lateral axis peak force generation, especially during the first propulsive phase of the CTHD. This fact could be interpreted as a protective effect against the lower limb collapse. As main clinical implication, ISU systems can aid the implementation of real-time simple biomechanical jumping examinations by sports medicine professionals in clinical settings to reduce the residual uncertainty that often arises during the ACL rehabilitation process regarding the return to sports. However, due to the uniqueness of the analyzed cohort the present results must be considered with caution and restricted to the intrinsic characteristics of these top level female handball players.

Declarations

Ethics approval and consent to participate

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.

Athletes involved in this study gave their written consent to use anonymized data for statistical and scientific use.

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Conflict of interests

The authors declare that they have no conflict of interests.

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Authors' contribution

IS, MI were conceiving this study, for acquiring data, and drafting the manuscript. IS, EB, FA, FU, MI were responsible for final version of the manuscript. IS, EB, MI, were responsible for statistical analysis, and advised regarding interpretation of the results. EB, FA, FU were responsible for literature search. IS, EB, MI were responsible for acquiring data and interpretation of the results. All authors read and approved the manuscript and figures.

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Appendix A. UTHD manoeuvre phases breakdown in terms of centre of mass force orientation values. Descriptive statistics and effect size calculations.

Jumping Phase	Force Orientation in N (mean ± SD)	ACLR Injured Limb (n = 8)	ACLR Healthy Limb (n = 4)	Control Dominant Limb (n = 13)	Non-Dominant Limb (n = 14)	Significance (*p*)	*ES (difference)*
Propulsive Phase	**X-axis**	599.42 ± 155.98	607.15 ± 265.62	830.11 ± 365.95	507.22 ± 325.11	*p* = 0.661	*d = 0.82^*
	95% CI	469.02 – 729.82	184.48 – 1029.81	597.59 – 1062.62	319.51 – 694.93		*(large)*
	Y-axis	765.74 ± 222.55	891.21 ± 101.28	802.73 ± 203.81	797.74 ± 206.14	*p* = 1.000	*d = 0.173*
	95% CI	579.68 - 951.79	730.05 – 1052.37	673.24 – 932.22	678.72 – 916.76		*(small)*
	Z-axis	811.96 ± 137.67	790.16 ± 134.91	870.41 ± 182.6	915.11 ± 241.66	*p* = 1.000	*d = 0.361*
	95% CI	696.87 – 927.06	575.49 – 1004.84	754.40 – 986.43	775.58 – 1054.65		*(medium)*
1st Hop	**X-axis**	1293.57 ± 909.32	1202.87 ± 660.51	1451.71 ± 909.88	1498.56 ± 713.08	*p* = 1.000	*d = 0.174*
	95% CI	533.36 – 2053.90	151.86 – 2253.9	873.60 – 2029.82	1086.84 – 1910.28		*(small)*
	Y-axis	1037.29 ± 333.54	814.87 ± 257.09	802.2 ± 824.36	787.28 ± 704.69	*p* = 1.000	*d = 0.373*
	95% CI	758.44 – 1316.13	405.78 – 1223.96	278.42 – 1325.97	380.4 – 1194.16		*(medium)*
	Z-axis	2303.09 ± 797.26	2659.54 ± 477.15	2922.86 ± 778.01	2544.5 ± 666.32	*p* = 0.404	*d = 0.787*
	95% CI	1636.57 – 2969.62	1900.29 – 3418.79	2428.54 – 3417.18	2159.78 – 2929.22		*(large)*
2nd Hop	**X-axis**	1590.05 ± 957.49	1840.39 ± 611.25	1413.52 ± 942.99	1333.46 ± 942.99	*p* = 1.000	*d = 0.185*
	95% CI	789.57 – 2390.53	867.75 – 2813.03	814.37 – 2012.66	1053.1 – 1613.83		*(small)*
	Y-axis	868.44 ± 591.61	858.06 ± 193.06	493.76 ± 447.62	793.88 ± 563.89	*p* = 0.707	*d = 0.714*
	95% CI	373.85 – 1363.04	550.86 – 1165.27	209.36 – 778.16	468.30 – 1119.46		*(large)*
	Z-axis	2648.47 ± 857.21	2681.81 ± 847.16	3190.98 ± 915.12	2699.45 ± 674.86	*p* = 0.915	*d = 0.612*
	95% CI	1931.82 – 3365.13	1333.79 – 4029.82	2609.54 – 3772.42	2309.80 – 3089.10		*(medium)*
3rd Hop	**X-axis**	1969.65 ± 938.47	2071.64 ± 1504.19	2055.81 ± 1281.66	1838.99 ± 1017.65	*p* = 1.000	*d = 0.077*
	95% CI	1185.07 –	321.86 –	1241.48 –	1251.41 –		*(small)*

	2754.24	4465.14	2870.14	2426.57		
Y-axis	1031.70 ± 875.99	1101.86 ± 592.34	336.1 ± 244.68	1091.64 ± 1324.03	*p* = 0.315	*d = 1.081*
95% CI	299.36 – 1764.05	159.31 – 2044.40	180.64 – 491.56	327.17 – 1856.11		*(very large)*
Z-axis	2773.44 ± 813.69	3468.91 ± 223.22	3444.95 ± 490.07	3277.19 ± 781.74	*p* = 0.317	*d = 0.999^*
95% CI	2093.18 – 3453.70	3113.71 – 3824.11	3133.58 – 3756.33	2825.82 – 3728.55		*(very large)*

Values are mean ± standard deviation, 95% confidence interval (inferior – superior value). P value from ANOVA calculations between ACLR injured limb and Control Dominant Limb. Standardised effect size interpreted as Cohen's d values between ACLR injured limb and Control Dominant Limb. Abbreviations: UTHD, unilateral triple hop for distance; n, sample size; SD, standard deviation; 95% CI, 95% confidence interval; ES, effect size; *d*, Cohen's *d*. * = *p* <.05. ^ = *d*> 0.8

Appendix B. UCOHD manoeuvre phases breakdown in terms of centre of mass force orientation values. Descriptive statistics and effect size calculations.

Jumping Phase	Force Orientation in N (mean ± SD)	ACLR Injured Limb (n = 8)	ACLR Healthy Limb (n = 4)	Control Dominant Limb (n = 13)	Non-Dominant Limb (n = 14)	Significance (p)	*ES (difference)*
Propulsive Phase	**X-axis**	469.97 ± 226.22	349.14 ± 238.81	297.88 ± 174.81	236.70 ± 196.74	p = 0.049*	*d = 1.35^*
	95% CI	439.37 – 700.60	204.82 – 493.45	151.74 – 444.03	76.35 – 549.76		*(very large)*
	Y-axis	731.12 ± 180.48	714.86 ± 102.75	647.14 ± 120.06	609.58 ± 64.196	p = 1.000	*d = 0.548*
	95% CI	626.91 – 835.32	652.77 – 776.95	546.79 – 747.51	507.43 – 711.73		*(medium)*
	Z-axis	782.56 ± 233.48	745.28 ± 171.38	840.48 ± 419.5	629.25 ± 132.87	p = 1.000	*d = 0.170*
	95% CI	647.65 – 917.26	641.71 – 848.84	489.77 – 1191.19	417.83 – 840.68		*(small)*
1st Hop	**X-axis**	1220.44 ± 625.86	1067.51 ± 567.42	1161.92 ± 667.21	935.87 ± 324.24	p = 1.000	*d = 0.090*
	95% CI	859.08 – 1581.80	724.62 – 1410.39	604.11 – 1719.72	419.93 – 1451.81		*(very small)*
	Y-axis	1183.73 ± 1205.41	982.58 ± 559.52	1149.43 ± 947.99	1820.19 ± 961.91	p = 1.000	*d = 0.032*
	95% CI	487.74 – 1879.71	644.47 – 1320.69	356.89 – 1941.98	289.57 – 3350.81		*(trivial)*
	Z-axis	2684.76 ± 655.69	2545.92 ± 753.18	2307.59 ± 701.92	2627.54 ± 410.39	p = 1.000	*d = 0.555*
	95% CI	2306.24 – 3063.35	2090.78 – 3001.06	1720.77 – 2894.41	1974.51 – 3280.57		*(medium)*
2nd Hop	**X-axis**	2078.80 ± 1184.57	1307.29 ± 749.36	1899.84 ± 979.54	1263.94 ± 787.38	p = 1.000	*d = 0.165*
	95% CI	1394.85 – 2762.76	854.46 – 1760.12	1080.92 – 2718.75	11.04 – 2516.83		*(small)*
	Y-axis	1287.44 ± 990.76	887.71 ± 558.86	1315.97 ± 559.21	1744.57 ± 435.83	p = 1.000	*d = 0.035*
	95% CI	715.39 – 1859.49	549.99 – 1225.42	848.46 – 1783.48	1051.07 – 2438.08		*(trivial)*
	Z-axis	2697.85 ± 671.88	2434.93 ± 919.48	2276.73 ± 470.11	2239.18 ± 1128.61	p = 1.000	*d = 0.726*
	95% CI	2309.92 – 3085.78	1879.32 – 2990.55	1883.71 – 2669.74	443.32 – 4035.05		*(large)*
3rd Hop	**X-axis**	1611.41 ± 1017.16	1753.74 ± 551.85	1729.41 ± 977.62	1245.67 ± 294.01	p = 1.000	*d = 0.118*
	95% CI	1024.12 – 2198.70	1420.26 – 2087.22	912.10 – 2546.71	777.83 – 1713.50		*(small)*
	Y-axis	921.57 ± 890.30	759.77 ± 591.66	1321.52 ± 709.56	543.63 ± 178.89	p = 1.000	*d = 0.496*
	95% CI	407.53 – 1435.62	402.23 – 1117.30	728.31 - 1973	258.98 – 828.28		*(medium)*
	Z-axis	2873.45 ± 540.75	3022.63 ± 698.38	2306.72 ± 724.34	2628.47 ± 745.60	p = 0.353	*d = 0.887^*
	95% CI	2561.23 – 3185.68	2600.61 – 3444.66	1701.16 – 2912.28	1442.05 – 3814.88		*(large)*

Chapter 4

Conclusions, practical applications and future perspectives

Study 1 (Chapter 2)

Conclusion 1: elite male handball players who have returned to the top level of sports participation demonstrated similar jumping performance and did not displayed any lasting biomechanical and/or performance deficits 6 years after the original surgical ligament repair.

Practical application 1: the use of ISU-based jumping mechanics analysis in the clinical fields could help to improve the functional and biomechanical evaluations performed in the training court itself.

Future perspective 1: the use of ISU can improve the decision-making process for appropriate rehabilitation program design and return-to-sport readiness following ACL injuries.

Study 2 (Chapter 3)

Conclusion 2: elite female handball players with previous ACL reconstruction demonstrated an attenuated jumping capacity in the THD test.

Practical application 2: the use of ISU systems can aid the implementation of real-time simple biomechanical jumping examinations by sports medicine professionals in clinical settings to reduce the residual uncertainty that often arises during the ACL rehabilitation process regarding the return to sports.

Future perspective 2: the use of ISU can improve the decision-making process for appropriate rehabilitation program design and return-to-sport readiness following ACL injuries.

As part of future perspectives, our investigation group is carrying out a research focusing in ACL injury risk factor in a longitudinal cohort 5 years' study (2 years already completed) among elite female football players (2nd national division in Spain). Fitness level as well several biomechanical and anthropometric related variables are being recording since 2018 aiming conclude at 2022 with up to 300 players being evaluated. One of the preliminary results found a potential relationship between Dynamic Knee valgus in DJ with some anthropometric variables and its contribution for explaining the vGRF. We hope to continue this research and explain better the Knee function and performance evaluation using ISU and its implications in ACL injury risk.

4. Conclusiones, aplicaciones prácticas y perspectivas futuras

Estudio 1 (Capítulo 2)

Conclusión 1: los jugadores elite de balonmano quienes retornaron a la maxima competición, demostraron similar desempeño en el salto y no mostraron ningún deficit biomecánico y/o de rendimiento 6 años después de la operación original de reparación de ligamento.

Aplicación práctica 1: el uso del análisis de la mecánica de salto basado en ISU en el campo clinico, podría ayudar a mejorar las evaluaciones funcionales y biomecánicas realizadas en el propio campo de entrenamiento.

Perspectiva futura 1: el uso de ISU puede mejorar el proceso de toma de decisiones para el diseño apropiado del programa de rehabilitación y la preparación para el retorno al deporte después de las lesiones de LCA.

Estudio 2 (Capítulo 3)

Conclusión 2: las jugadoras elite de balonmano con reconstrucción previa de LCA demostraron una capacidad de salto atenuada en la prueba THD.

Aplicación práctica 2: el uso de sistemas ISU puede ayudar a la implementación de exámenes biomecánicos de salto en tiempo real por parte de profesionales de la medicina deportiva en entornos clínicos para reducir la incertidumbre residual que a menudo surge durante el proceso de rehabilitación del LCA con respecto al retorno al deporte.

Perspectiva futura 2: el uso de ISU puede mejorar el proceso de toma de decisiones para el diseño apropiado del programa de rehabilitación y la preparación para el retorno al deporte después de las lesiones de LCA.

Como parte de las perspectivas futuras, estamos llevando a cabo una investigación enfocada en los factores de riesgo lesión del LCA en una cohorte longitudinal de 5 años de estudio (2 años ya completados) entre mujeres futbolistas de élite (2^{da} división nacional de España). Nivel de condición física y también varias variables biomecánicas y antropométricas relacionadas, han sido recolectadas desde 2018 apuntando a concluir en el 2022con cerca de 300 jugadoras evaluadas. Uno de los resultados preliminares encontrados es una potencial relación entre el valgo dinámico de la rodilla en saltos Dj con algunas variables antropométricas y su contribución para explicar la FRV del suelo. Esperamos continuar esta investigación y explicar mejor la función de la rodilla y la evaluación física usando sensores inerciales y sus implicaciones en el riesgo de lesión del LCA.

Chapter 5

Relevant Papers.

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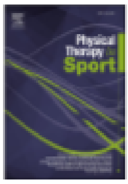

Original Research

Horizontal jumping biomechanics among elite male handball players with and without anterior cruciate ligament reconstruction. An inertial sensor unit-based study

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ABSTRACT

Objectives: Anterior cruciate ligament (ACL) tears are one of the most devastating injuries that any handball player can suffer during landing and pivoting actions. The aim of this study was to analyze the horizontal jumping biomechanics among male elite handball players with or without previous ACLR.
Design: Descriptive study.
Setting: Spanish elite male handball players.
Participants: Twenty-six male participants (6 ACL-R and 20 uninjured controls) were recruited.
Main outcome measures: Two horizontal hopping tasks were evaluated using an inertial sensor unit (ISU)-based technology to assess jumping biomechanics through a direct mechanics-based approach.
Results: Non-significant differences were found in relation to any of the biomechanical or performance related analyzed variables.
Conclusions: Previously ACL-R elite male handball players who have returned to the top level of sports participation do not seem to possess lasting biomechanical and/or performance deficits 6 years after the original surgical ligament repair.

1. Introduction

Handball is a body-contact team sport that elicits high-intensity maneuvers, such as abrupt changes in direction and velocity and sudden landings (Bencke et al., 2013; Gorostiaga, Izquierdo, Iturralde, Ruesta, & Ibáñez, 1999). Due to the intrinsic nature of the sport, the knee joint is exposed to many stressful forces that could result in serious damage to the anterior cruciate ligament (ACL), leading to one of the most devastating injuries among handball players (Boden, Dean, Feagin, & Garrett, 2000; Hewett, Ford, Hoogenboom, & Myer, 2010; Olsen, Myklebust, Engebretsen, Holme, & Bahr, 2003). The reported incidences of ACL injury for male handball athletes are 0.11–0.24 injuries per 1000 h of exposure. (Prodromos, Han, Rogowski, Joyce, & Shi, 2007). This is lower than that reported for women, which have a greater ACL injury risk than their male counterparts during the same jumping and pivoting tasks, which has been associated with neuromuscular, anatomical and hormonal differences between the sexes (Hewett et al., 2010)]

Some movement biomechanics-based studies have demonstrated that the decreased ground reaction force (GRF) absorption capacity, as well as a disbalanced lower limb symmetry index between the previously ACL-reconstructed (ACL-R) and the contralateral healthy limbs, could be a potential risk factors for ACL reinjury or contralateral injury, due to neuromuscular impairments acquired through the ACL rehabilitation process (Dai, Butler, Garrett, & Queen, 2012; Paterno et al., 2011). The clinical relevance of the ACL injury does not rest solely on the ligament disruption itself; but the functional implications of concomitant knee injuries and its 'implications in the athletes' function prognosis once the athlete is returning back to top level competition

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(Setuain et al., 2017). it seems that the evidence for neuromuscular or biomechanical risk factors for ACL injuries in male athletes could mainly be related to at the trunk and hip joint levels occurring dysfunctions" Additionally, the scientific literature lacks information regarding the best clinical practices for rehabilitation programs or universal functional and clinical evaluation criteria for resuming the sport after injury (Setuain et al., 2017).

This state of no consensus may expose the athlete to both a higher re-injury risk and/or a new injury on the healthy contralateral knee (Grindem, Snyder-Mackler, Moksnes, Engebretsen, & Risberg, 2016). Thus, the detection and monitorization of subjects with higher injury or reinjury risk through functional, biomechanical and neuromuscular screening evaluations appear to be crucial for injury prevention and rehabilitation in sports medicine (Hewett, 2000).

In this context, different jumping performance tasks have been widely employed to determine the readiness for sport participation after ACL reconstruction, aiming to allow for a safe return to competitive sports (RTS) according to the specific sport 's performance demands (Setuain et al., 2017). RTS is defined as returning to the same level of the same sport played before injury (Ardern, Webster, Taylor, & Feller, 2011). After ACL reconstruction, the elite athletes desire an RTS in the least amount of time, which could predispose the player to the ACL surgical reconstruction choice. (Ardern, Taylor, Feller, & Webster, 2012).

Some studies have reported that male patients returned to sports earlier than female patients (Ardern et al., 2011), with the restoration of full jumping performance capabilities after ACL through their respective rehabilitation process (Busfield, Kharrazi, Starkey, Lombardo, & Seegmiller, 2009; Brophy et al., 2012; Mehran et al., 2016; Moya-Angeler, Vaquero, & Forriol, 2017; Setuain, Bencke, Alfaro-Adrián, & Izquierdo, 2018).

In the clinical and performance environment, inertial sensor units (ISUs) have been recently settled up and validated as a new tool for the evaluation of biomechanical impairments in athletes with ACL reconstruction, due to its low cost and portability (Setuain et al., 2015b). The application of this testing methodology allows clinicians to perform in the field functional and biomechanical evaluations on a quick and friendly manner, in comparison with the gold standard method using force plates (Dowling, Favre, & Andriacchi, 2011; Dowling, Favre, & Andriacchi, 2012; Setuain, Millor, Alfaro, Gorostiaga, & Izquierdo, 2015a; b; c).

The aim of this study was to examine horizontal jumping biomechanical differences between previously ACL-R elite male handball players who returned to sports versus same sport-competitive-level, sex, and age-matched controls. The hypothesis of the present research is that ACL-R male professional handball players who had returned back to elite competition would not exhibit lasting biomechanical jumping pattern alterations in terms of greater support of three-axis peak forces during single-leg horizontal jumping maneuvers, compared with their control counterparts.

2. Methods

A descriptive case series study design was carried out. The experiment was carried out at the athletes' habitual training court" . The designed jumping task battery included the unilateral triple hop for distance (UTHD) and the unilateral triple crossover hop for distance (COHD). These tests have been previously considered a reliable method for the evaluation of lower limb function in relation to ACL injury (Myer et al., 2012; Noyes, Barber, & Mangine, 1991; Risberg et al., 1994).

2.1. Subjects

Twenty-six male elite handball players competing in their respective highest national division league and European championship were recruited. 26 participants took part in the study; 6 were ACL-R (age 27.67 ± 1.26 years; height 188.25 ± 2.31 cm; and weight 92.08 ± 3.48 kg) and 20 uninjured controls (age 24.81 ± 1.27 years; height 188.23 ± 1.80 cm; and weight 89.81 ± 2.49 kg). The average and standard deviation of the time since surgical reconstruction was 6.3 ± 3.4 years. Athletes in the control group with a previous lower limb injury lasting more than 6 weeks were excluded from the study to avoid jumping pattern bias due to potential lasting functional alterations associated with 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, which was approved by the Ethics Committee of the University and performed according to the Declaration of Helsinki.

2.2. Equipment

An inertial orientation tracker (MTx, 3DOF Human Orientation Tracker, Xsens Technologies B.V. Enschede, The Netherlands) was attached over the L3-L4 region of the subject's lumbar spine where the human body center of mass is known to be located, and provided data on kinematic and kinetic variables such as accelerations, orientations, and velocity at a sampling rate of 100 Hz. A technical explanation describing the inertial sensor-derived variables has been previously provided (Millor, Lecumberri, Gómez, Martínez-Ramírez, & Izquierdo, 2013; Setuain et al., 2016) (Appendix 1). "Briefly, ISU systems provide the linear acceleration and angular displacement orientation values in a sensor-fixed Cartesian reference frame (XYZ). In this way, ISU offers 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.

Furthermore, a 10 m-long measuring tape was utilized to measure the distance reached in each horizontal jumping task. The last heel contact was taken as reference for the final jumping length performance.

2.3. Procedures

All participants performed the test at the beginning of a routine training session conducted during the competitive season and at least 48 h after their last competition. The jumping methodology used in this trial has been published and widely extended previously (Hamilton, Shultz, Schmitz, & Perrin, 2008; Myer, Ford, Khoury, & Hewett, 2011; Noyes et al., 1991; Patterson, Delahunt, Sweeney, & Caulfield, 2014; Petsching et al., 1998; Reid, Birmingham, Stratford, Alcock, & Giffin, 2007; Risberg & Ekeland, 1994; Van der Harst and Gokeler, 2007). The athletes were instructed to keep their hands on their hips during the execution of each maneuver. No added technical instructions about the jumping modality were given to the athletes to avoid modifications during the hopping task execution. The participants started in a single-limb stance and then performed three consecutive horizontal hops as far as possible (THD test), holding a balanced position for at least 1 s after the last landing. For the COHD, the subjects adopted the same starting position and executed three consecutive crossover hops outside two lanes separated by a 15-cm-wide tape attached on the floor, trying to land as far as possible from the starting line holding a balanced position for at least 1 s after the final landing. The first jumping step from the COHD test was medially directed. A practice trial was performed to ensure the participant's comfort and safety and was followed by two further test trials with 30 s of rest between each repetition. The hopping tasks were performed on a progressive intensity level to avoid possible injury risks associated with the challenging execution of the jumping tasks. Thereby, the participants started with the UTHD and ended with the COHD.

The ISU provides linear acceleration values in a sensor-fixed Cartesian reference frame (*XYZ*). Before the beginning of the test, while the athlete was standing on the ground with her back in an upright position and the sensor-fixed reference frame was aligned with an Earth-fixed global reference frame (*XYZ*). The *Z*-axis represents the vertical direction and points upwards, the *X*-axis the mediolateral direction and reads right-directed accelerations as positive, and the *Y*-axis represents the anteroposterior direction interpreting posterior-directed accelerations as positive (Fig. 1). The force was calculated from the acceleration values following Newton's 2nd law:

F = m*a

Where *F* equals force, *m* equals body mass, and *a* equals the acceleration values measured with the ISU. "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 (Hatze et al., 1998). 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[3]and hence were the vertical velocity by time descriptive curves depicted" As this research group reported in previous studies (Setuain et al., 2015a; b; c; Setuain et al., 2016), jumping biomechanics assessment through direct mechanics procedures by using ISU devices demonstrates high agreement and reliability levels compared with force plates, which are traditionally considered as the gold standard in this area (Setuain et al., 2016).

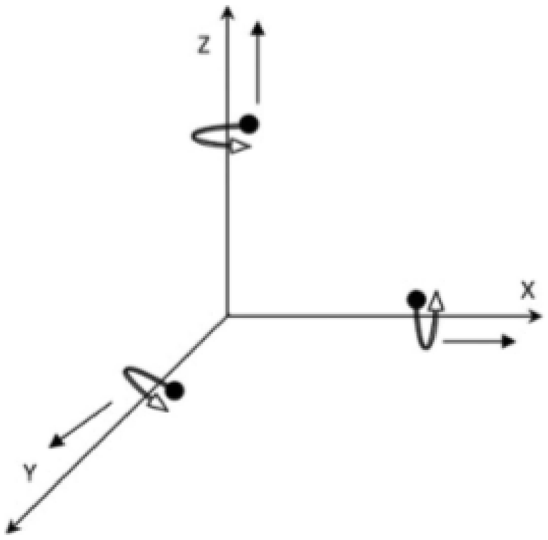


Fig. 1. Earth-fixed global Cartesian reference frame. Z-axis (vertical), X-axis (medial-lateral) and Y-axis (anterior-posterior) orientations.

2.4. *Data processing and analysis*

The data reported by the sensor was analyzed using direct mechanics-based procedures that considered the subject as a mechanical system and estimated the movement and actuation of forces through the center of mass displacement (Hatze, 1998; Linthorne, 2011). As previously mentioned, the human center of gravity is considered to be located at the L3 lumbar spine level, where the ISU was placed.

To facilitate the biomechanical analysis of the jump, the task was divided into separate phases. The identified phases were based on the results obtained from the vertical velocity curve recordings (Z-axis) through a self-customized computer application implemented in MatLab 7.11 (MathWorks Inc; Natick, MA, USA). The Z-velocity signal was used to distinguish the boundaries between the different phases of both tasks and were considered positive when the subject moved upwards (corresponding to the propulsive phases of the three consecutive jumps) and negative when subject moved downwards (corresponding to the pre-loading and landing phases). The different phases of the jumping task have been described succinctly in previous studies (Setuain et al., 2015a; b; c; Setuain et al., 2017). Once the curve determinant points of the jumping task were identified, the different jump phase durations and the acting peak ground reaction force (GRF) values could be calculated for both the UTHD and COHD maneuvers. The outcome of each attempt, measured as the distance in cm, was also recorded. Both required tasks, the UTHD and the COHD, were divided into 12 phases for the 3 hops performed in each task (Fig. 2).

For both maneuvers, the initial event (T1) of the first hop started with an active negative (eccentric) acceleration production in the vertical *Z*-axis (PRE). Then, the T2 event was registered when the center of mass of the athlete reached the maximal vertical negative velocity (first negative peak). The segment T1-T2 represents the negative passive and active work (pre-stretch) corresponding to the propulsive phase (PP). The T3 event corresponded to the instant the Z-velocity first passed zero (when the center of mass of the athlete was in its lowest position) during the transition between the initial absorption (IA1) or pre-load and the propulsive phase (PP1) of the jump. The PP1 concluded in T4, when the maximal vertical velocity (propulsive phase) was achieved. Therefore, the segment T2-T3 represents to the IA1, and consequently, the segment T3-T4 corresponds to the PP1. T5 was fixed when vertical *Z*-axis velocity again reached a negative peak due to the active negative (eccentric) action. Therefore, T4-T5 segment corresponded to the flight time of the first hop (FT1) and T5-T6 segment corresponds to the final absorption (FA1) in the transition between the first and the second hop. From T6 to t12 the time points of the remaining two jumps are calculated in the same manner (Fig. 2).

Lastly, the mechanical efficiency ratio calculation was defined as the ratio between the jumping performance (cm) and the sum of the peak tri-axial (*x*-*y*-*z*) forces supported at the center of mass level (N). The amount of the sum of three-dimensional forces would penalize or benefit the ratio in the horizontal jumping task. The ME ratio, aims to determine to what extent peak ground reaction forces are supported during the absorptive phases, in relation to the distance reached during the maneuver. Supporting greater peak ground reaction forces during the absorptive phases, could lead to a more harmful mechanical overload which could increase the injury risk.

$$ME = \frac{\text{performance (cm)}}{(Fx + Fy + Fz)}$$

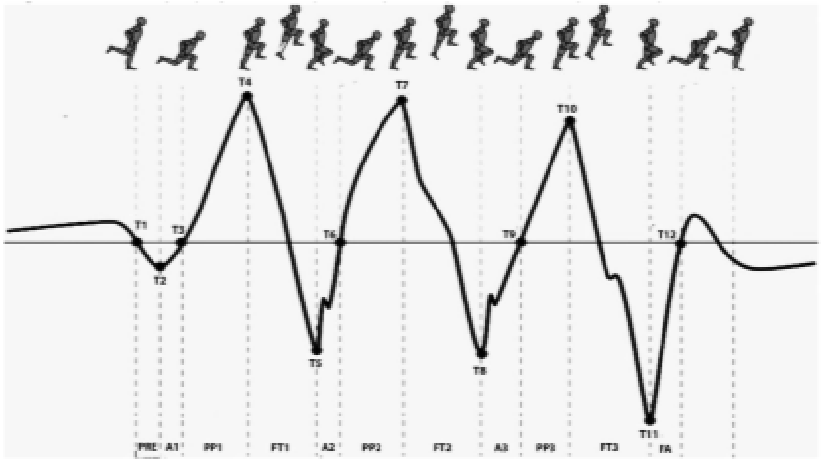


Fig. 2. Horizontal jumping maneuver phases by velocity-time curve analysis description.

2.5. Statistical analysis

Descriptive statistics (mean, standard error of the mean and IC values at 95%) were calculated for all the collected variables (weight in kg; height in cm; performance in cm; tri-axial GRFs in N).

Afterwards, descriptive statistics for the selected variable groups (ACL-R limb and ACL-R healthy limb) were applied. After normal distribution of the data and variances equality were checked through the Shapiro-Wilk and Levene tests respectively, a multivariate analysis of variance (ANOVA) was performed to analyze interaction levels between factors. 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 us with only one fixed factor (ACL-R vs controls). When the variance equality was rejected, the Tamhane's post hoc test was performed. The significance level was set at $p < 0.05$.

Apart from that, intra and inter-group differences were analyzed using magnitude-based inferences (MBI). This statistical method was chosen in order to highlight the practical significance over the statistical (p value) significance, emphasizing that the magnitude of an effect would be more relevant than any statistically significant effect especially in the clinical practice or when treating elite athlete's data (Buchheit, 2016; Hopkins, Marshall, Batterham, & Hanin, 2009). The magnitudes of the smallest worthwhile differences were identified by the determination of the effect sizes (Cohen's d) for between-limbs and between group comparisons, using means and standard deviations for each group of variables. Values for Cohen's d statistics were interpreted as follows: <0.15 for trivial, 0.15 to 0.4 for small, 0.4 to 0.75 for medium, 0.75 to 1.10 for large and >1.10 for very large differences (Cohen, 1988).

3. Results

No significant differences between ACL-R and non-ACL-R counterparts were found in relation to age, height and weight. Indeed, no significant interaction effects were found between factors for the THD and TCHD tests. Therefore, the results are delimited to the description of the main effects observed. Detailed jumping distance performance and kinetic data is described below for both horizontal jumping tasks.

3.1. Unilateral triple hop for distance (UTHD)

Regarding the UTHD task, non-significant differences were found for distance performance (Table 1) and the analyzed time-force variables (Fig. 3; Appendix B) in ACL-R compared with ACL-R healthy and control dominant limbs. However, ACL-R limbs showed a trend towards greater performance during the task compared to control limbs (538,20 ± 112,81 vs 503,64 ± 52,28 cm; Cohen's $d = 0{,}419$).

In the same manner, the ACL-R limb of cases showed a trend towards greater mechanical efficiency ratios (0,028 ± 0,007 vs. 0,026 ± 0,004 cm*N^{-1}; Cohen's $d = 0{,}418$) when executing this horizontally oriented jumping task compared with that of control limbs (Table 2).

3.2. Triple cross-over hop for distance (COHD)

With respect to the COHD, non-significant differences were found between groups in terms of distance performance (Table 1). However, a trend towards greater performance in the ACL-R limb of cases was observed compared to that in control limbs (434,6 ± 87,2 vs 407,8 ± 81, 1 cm; Cohen's $d = 0{,}319$). Indeed, the ACL-R limbs of the cases also displayed a better behavior in mechanical efficiency ratios (0,024 ± 0,005 vs. 0,021 ± 0004 cm*N^{-1}; Cohen's $d = 0{,}628$) when executing this crossover jumping task compared with the control limbs (Table 2). More detailed COHD kinetic data and statistical results are added as supplementary material (Fig. 3, Appendix C).

4. Discussion

The aim of this study was to examine the biomechanics of two horizontal jumping tasks among professional top-level male handball athletes using an ISU-based methodology. The main focus was placed on the identification of lasting jumping biomechanical adaptations among previously ACL-R athletes. The results did not show any sign of lasting biomechanical alteration in ACL-R participants who returned to full competition at high intensity and exigency levels, with a mean of seven years since the original ACLR. In fact, the trend showed greater jumping performance and mechanical efficiency ratios among the previously ACL-R limbs of

Table 1
Horizontal jumping performance for unilateral triple hop and unilateral cross-over hop for distance. Descriptive statistics, significance and effect size calculations for each group.

		ACLR Injured Limb	ACLR Healthy Limb	Control Limb	Significance (*p*)	*ES (d)*
UTHD	n	6	6	38		
	Performance	538,20 ± 112,81	563,00 ± 53,08	503,64 ± 52,28	0,342	*d = 0.419*
	95% CI	398,13–678,27	507,29–618,71	485,10–522,18		***(small)***
UCOHD	n	6	6	36		
	Performance	434,60 ± 87,15	473,67 ± 67,04	407,79 ± 81,11	0,684	*d = 0.319*
	95% CI	326,39–542,81	403,32–544,02	379,03–436,55		***(small)***

Values are mean ± standard deviation, 95% confidence interval (inferior -superior value). P value from ANOVA calculations between ACLR injured limb and Control Limb. Standardised effect size interpreted as Cohen's d values between ACLR injured limb and Control Limb. Abbreviations: UTHD, unilateral triple hop for distance; UCOHD, unilateral cross-over hop for distance; n, sample size; SD, standard deviation; 95% CI, 95% confidence interval; ES, effect size; d, Cohen's d. * = p < .05.

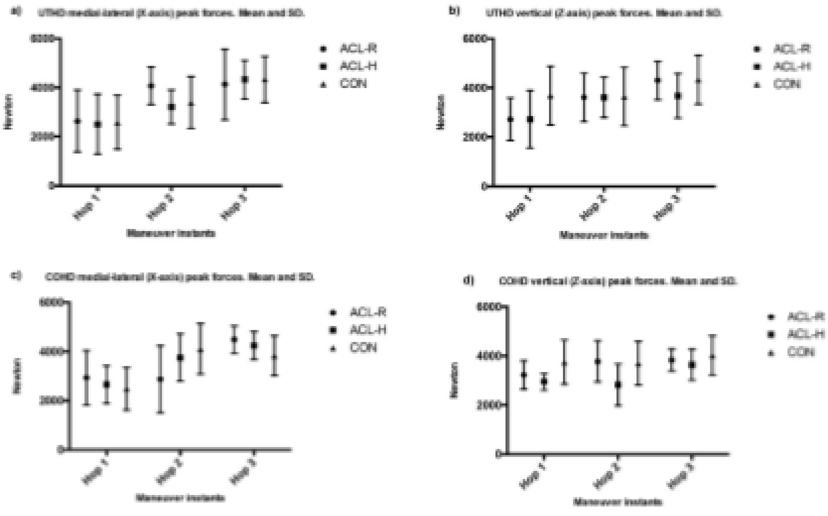


Fig. 3. Between groups peak vertical and medial-lateral forces comparison during the unilateral triple hop for distance (UTHD) and the unilateral cross over hop for distance maneuvers. Mean and SD. Abbreviations: (UTHD), unilateral triple hop for distance; (COHD), unilateral cross over hop for distance; ACL-R, anterior cruciate ligament group-reconstructed limb; ACL-H, anterior cruciate ligament group-healthy limb; control group-dominant limb.

Table 2
UTHD manoeuvre phases breakdown in terms of centre of mass force orientation values. Descriptive statistics and effect size calculations.

	Force Orientation in N (mean ± SD)	ACLR Injured Limb (n = 6)	ACLR Healthy Limb (n = 6)	Control Limb (n = 38)	Significance (*p*)	*ES (difference)*
1st Hop	**X-axis**	2638,43 ± 1260,13	2512,01 ± 1221,94	2586,54 ± 1098,30	*p = 0,999*	*0044*
	95% CI	1073,78–4203,10	1229,67–3794,36	2197,10–2975,97		***(small)***
	Y-axis	3040,64 ± 960,64	3096,02 ± 834,67	3324,11 ± 845,50	*p =0,721*	*0314*
	95% CI	1847,84–4233,43	2220,08–3971,95	3024,30 ± 3623,91		***(small)***
	Z-axis	2728,15 ± 868,65	2726,03 ± 1166,875	3693,49 ± 1186,50	*p =0,442*	*0939^*
	95% CI	1649,58–3806,72	1501,46–3950,58	3272,78 ± 4114,208		***(large)***
2nd Hop	**X-axis**	4067,86 ± 757,27	688,59 3214,71 ±	3391,20 ± 1054,99	*p =0,300*	*0747*
	95% CI	3127,59–5008,14	2492,07–3937,34	3017,12–3765,29		***(medium)***
	Y-axis	4042,21 ± 1069,26	3643,58 ± 1138,24	3980,37 ± 1075,11	*p =0,968*	*0058*
	95% CI	2714,54–5369,87	2449,07–4838,09	3599,15 ± 4361,59		***(small)***
	Z-axis	3615,45 ± 972,73	3613,46 ± 813,39	3647,88 ± 1182,87	*p =0,971*	*0030*
	95% CI	2407,65–4823,25	2759,86–4467,07	3228,45 ± 4067,30		***(small)***
3rd Hop	**X-axis**	4131,08 ± 1436,95	4328,33 ± 788,49	4339,24 ± 946,92	*p =0,827*	*0175*
	95% CI	2346,86 ± 5915,29	3500,86–5155,80	4003,48–4675,00		***(small)***
	Y-axis	4311,44 ± 938,38	4400,30 ± 934,28	4167,64 ± 943,54	*p =0,960*	*0153*
	95% CI	3146,29 ± 5476,59	3419,83 ± 5380,76	3833,08–4502,21		***(small)***
	Z-axis	4303,50 ±				
779,58	3678,57 ± 893,47	4332,58 ± 991,72	*p =0,997*	*0033*		
	95% CI	3335,52 ± 5271,48	2740,93 ± 4616,20	3980,93 ± 4684,23		***(small)***

Values are mean ± standard deviation, 95% confidence interval (inferior – superior value). P value from ANOVA calculations between ACLR injured limb and Control Dominant Limb. Standardised effect size interpreted as Cohen's d values between ACLR injured limb and Control Dominant Limb. Abbreviations: UTHD, unilateral triple hop for distance; n, sample size; SD, standard deviation; 95% CI, 95% confidence interval; ES, effect size; d, Cohen's d. * = p < .05. ^ = d > 0.8.

cases. Several years after the original surgical repair, players who had previously undergone ACLR were able to restore their full jumping performance.

According to that result, previously ACL-R limbs of cases, reported a non-significant trend towards higher UTHD performance compared to control limbs (538,20 ± 112,81 cm vs 503,64 ± 52,28 cm) but lower performance compared to their own contralateral healthy limb (538,20 ± 112,81 cm vs 563,00 ± 53,08 cm) (Table 1). During the execution of both horizontal jumping tasks, ACL-R athletes were more prone (although not significantly) to better absorbing the bearing Z- (vertical) and Y- (horizontal) axis ground reaction forces during the absorption phases of the tasks analyzed. (Tables 2 and 3).

In the authors' opinion, the greater GRF management variability reported by controls and ACL-R healthy limbs in comparison to the ACL-R limbs of cases (Tables 2 and 3) could be explained by the concept of stress dissipation through movement variability augmentation, as explained by Hamill, Palmer, and Van Emmerik (2012), who proposed that absolute coordination with low variability could be linked to forces being concentrated in small surface areas, possibly resulting in greater tissue stress and a greater chance for overuse injury (Hamill et al., 2012). Future studies should be carried out with an appropriate experimental design to answer this question.

Analyzing the UTHD and COHD jump task between the ACL-R limb and the controls, we found that the ACL-R limb of the cases displayed greater jumping performance compared to that of their control counterparts. As both dominant and non-dominant limbs were included in the control group and case group (where dominant and nondominant limbs were equally affected), we cannot associate these results with a dominance effect. Regarding player demarcation, there were 3 lateral extremes, 2 pivots and one goalkeeper among the cases and all kinds of demarcations in the control group. Thus, in this context, linking the better performance observed among cases to a playing position could be somewhat speculative. In the author's opinion, the actual difference observed could be related to both a greater jumping ability at baseline, prior to injury in these players as well as to a full jumping capacity restoration after ACL reconstruction.

The mechanical efficiency ratios were slightly higher on ACL-R limbs of cases than in control limbs when executing both horizontal jumping maneuvers (Table 4); the lower peak external force reduced the performance achieved during the test.

These results are consistent with the study hypothesis, which posited that ACL-R elite handball male players would not possess lasting biomechanical movement pattern alterations in terms of greater support of three-axis peak forces during single-leg horizontal jumping maneuvers despite being back to elite competition several years after the original ACL injury compared with their control counterparts.

Setuain et al. (2018) previously found in a study with the same cohort of athletes that previously ACL-R elite male handballers demonstrated a vertical jumping biomechanical profile similar to control players, including similar jumping performance values in both bilateral and unilateral jumping maneuvers, several years after ACLR (Setuain et al., 2018).

According to several studies, the fully functional restoration of jumping capacity could be a common achievement in high-level male athletes after ACL reconstruction (Buesfield et al., 2009; Brophy et al., 2012; Mehran et al., 2016) and showed no significant differences in any combined performance test among players with ACL reconstruction compared with an age-, size-, and position-matched control group of professional male basketball players. Similar outcomes were reported by Brophy et al. (2012) in a cohort of male soccer players (Brophy et al., 2012).

The UTHD and COHD tests have been included in many functional lower limb testing routines (Hamilton et al., 2008; Logerstedt et al., 2012; Abrams et al., 2014; Williams et al., 2015), that have been traditionally used to determine the return-to-sport readiness after ACL reconstruction and rehabilitation. In this scenario, the emerging ISU-based jumping mechanics analysis enables more comprehensive performance and biomechanical tests, helping both sport scientists and clinicians to generate more accurate motor skills evaluations to apply an individual deficit-based clinical rehabilitation program that would lead the patient through the rehabilitation process in a safe and customized manner (Setuain et al., 2015a; b; c).

In a meta-analysis, Ardern, Taylor, Feller, and Webster (2014) showed that up to 55% of players returned to competitive sports after ACL reconstruction; a younger age favored returning to the pre-injury level of the sport, and men had greater odds of returning to their pre-injury level of sports than women (Ardern et al., 2014).

Table 3
UCOHD manoeuvre phases breakdown in terms of centre of mass force orientation values. Descriptive statistics and effect size calculations.

	Force Orientation in N (mean ± SD)	ACLR Injured Limb (n = 6)	ACLR Healthy Limb (n = 6)	Control Limb (n = 36)	Significance (*p*)	*ES (difference)*
1st Hop	**X-axis**	2935,13 ± 1101,22	2652,61 ± 762,60	2493,03 ± 866,71	*p* =0,793	*0449*
	95% CI	1567,78 ± 4302,48	1852,31 ± 3452,90	2185,71–2800,35		***(small)***
	Y-axis	2884,26 ± 471,22	3196,00 ± 976,72	2992,94 ± 1089,19	*p* =0,988	*0139*
	95% CI	2299,16 ± 3469,35	2170,99 ± 4221,01	2606,73 ± 3379,15		***(small)***
	Z-axis	3225,43 ± 582,42	2944,86 ± 336,88	3745,46 ± 896,97	*p* =0,214	*0703*
	95% CI	2502,25 ± 3948,60	2591,33 ± 3298,39	3427,41–4063,51		***(medium)***
2nd Hop	**X-axis**	2874,38 ± 1354,53	3747,85 ± 961,96	4104,19 ± 1024,07	*p* =0,138	*1034**
	95% CI	1192,51 ± 4556,25	2738,33–4757,37	3741,07–4467,31		***(Very large)***
	Y-axis	3028,58 ± 943,33	3470,56 ± 952,46	3659,14 ± 983,87	*p* =0,973	*0654*
	95% CI	1857,28 ± 4199,87	2471,02 ± 4470,11	3310,28–4008,00		***(medium)***
	Z-axis	3775,66 ± 837,82	2821,94 ± 850,61	3695,08 ± 887,36	*p* =0,825	*0093*
	95% CI	2735,37 ± 4815,95	1929,28 ± 3714,61	3380,44–4009,73		***(small)***
3rd Hop	**X-axis**	4486,11 ± 547,42	4243,21 ± 561,70	3830,18 ± 808,13	*p* =0,169	*0719*
	95% CI	3911,63 ± 5060,59	3653,74 ± 4832,68	3556,63 ± 4103,73		***(large)***
	Y-axis	3505,42 ± 1159,60	4052,91 ± 784,53	4134,88 ± 916,51	*p* =0,477	*0606*
	95% CI	2065,59 ± 4945,25	3229,60 ± 4876,22	3809,90 ± 4459,86		***(medium)***
	Z-axis	3839,15 ± 445,12	3640,11 ± 631,98	4021,99 ± 791,08	*p* =0,847	*0296*
	95% CI	3286,45 ± 4391,84	2976,89 ± 4303,33	3741,49 ± 4302,50		***(small)***

Values are mean ± standard deviation, 95% confidence interval (inferior – superior value). P value from ANOVA calculations between ACLR injured limb and Control Dominant Limb. Standardised effect size interpreted as Cohen's d values between ACLR injured limb and Control Dominant Limb. Abbreviations: UTHD, unilateral triple hop for distance; n, sample size; SD, standard deviation; 95% CI, 95% confidence interval; ES, effect size; d, Cohen's d. * = d > 0.8.

Table 4
Horizontal jumping performance and three-dimensional force-based mechanical efficiency ratios. Descriptive statistics and effect size (Cohen's *d*) calculations.

Horizontal Jumping Tasks	ACLR Injured limb			ACLR Healthy Limb			Control Limb			ACLR Injured vs ACLR Healthy		ACLR Injured vs Control Dom	
	n	Mean (±SD)	95% CI	*n*	Mean (±SD)	95% CI	*n*	Mean (±SD)	95% CI	*ES (d)*	*Dif.*	*ES (d)*	*Dif.*
UTHD	6	0,028 ± 0,007	0020–0,036	6	0,031 ± 0,005	0026–0,036	38	0,026 ± 0004	0,024–0027	0,517	**medium**	*0,418*	**medium**
UCOHD	6	0,024 ± 0,005	0018–0,031	6	0,027 ± 0,007	0020–0,034	36	0,021 ± 0004	0,020–0023	0,446	**medium**	0,628	**medium**

Values are mean ± standard deviation, 95% confidence interval and standardised effect size. Abbreviations: UTHD, unilateral triple hop for distance; UCOHD, unilateral cross over hop for distance; n, sample size; SD, standard deviation; 95% CI, 95% confidence interval; ES, effect size; d, Cohen's d.

In addition, ACL-R patients classified as having restored normal knee function (determined by a minimum score of 9,6 ± 1,5 in the IKDC questionnaire) after surgical repair and rehabilitation had approximately twice the odds of returning to their pre-injury level of sport participation. The restoration of a symmetrical jumping performance could indicate that these previously ACL-R handball male players had successfully relearned their prior motor patterns, with no lasting biomechanical adaptations observed 6 years after their surgical ligament repair.

The utilization of ISUs can provide a real-time assessment tool for determining how athletes are mechanically managing several vertical or horizontal ordinary training exercises to prevent undesirable aberrant motor patterns. These assessments can be made in the clinical setting or in the training court itself (Dowling et al., 2012; Setuain et al., 2015a; b; c). In this sense, single inertial unit systems appear to provide a real-time, fast and inexpensive movement analysis tool in both the clinical setting and in the training habitual location itself[4]. Although positioned at the trunk level, ISU devices obviously do not replace higher-precision 3D motion analysis and inverse dynamics technology-based models, but they could potentially be applicable in the clinical setting in order to measure gross whole body-supported 3-dimensional axes accelerations, orientations, and jump phase durations. "

Some limitations in the present study may limit the extrapolation of these results to other populations, such as the small sample size (6 ACL-R and 20 healthy controls), the unknown postoperative rehabilitation protocols applied on each injured player, or the heterogeneity of grafts employed for primary ACL reconstruction. There was a lack of standardization of the postoperative rehabilitation protocol and the graft type used for the ligament repair among ACL-R athletes. The heterogeneity of the rehabilitation process may have introduced biased in the long-term outcomes of physical activity level and sport-specific performance. However, previous studies have reported that there are no differences in the long-term function of the knee between reconstructions using different graft types (Myklebust, Holm, Mæhlum, Engebretsen, & Bahr, 2003). Furthermore, the use of a single ISU placed at the trunk level limited the information collected to the knee joint biomechanics. Consequently, the behavior of the center of mass during the different hopping tasks was determined through direct mechanics-based human body analysis, and thus, the whole body was considered as a single system of mass and inertia. The net force calculations for specific joints were outside the scope of the present study. Although positioned at the trunk level, ISU devices obviously do not replace higher-precision 3D motion analysis and inverse dynamics technology-based models, for body segments' movement description. ISUs could alternatively be applicable in the clinical setting in order to measure gross whole body-supported 3-dimensional axes accelerations, orientations, and jump phase durations by centre of gravity behavior recording during the jumping tasks performed.The authors also admit that the power of the study could be an important limitation. However, as we mentioned in the original manuscript, our intention was to recruit all elite professional handball players available in our region. We included the professional profile of athletes because we wanted to know whether jumping performance deficits could also persist among fully trained, highly supervised handball athletes. For example, it could be interesting to note that previous work that examined similar variables of jumping performance was performed with previously ACL-R non-professional athletes and an analogous sample size (Decker, Torry, Noonan, Riviere, & Sterett, 2002; Paterno, Ford, Myer, Heyl, & Hewett, 2007).

In summary, previously ACL-R elite male handball players who have returned to the top level of sports participation demonstrated similar jumping performance and did not displyed any lasting biomechanical and/or performance deficits 6 years after the original surgical ligament repair. These findings are in agreement with previous researches showing full functional restoration capacity of male top level athletes after ACL reconstruction, rehabilitation and posterior return to previous activity level sports"

On the other hand, the use of ISU-based jumping mechanics analysis in the clinical fields could help to improve the functional and biomechanical evaluations performed in the training court itself, thereby improving the decision-making process for appropriate rehabilitation program design and return-to-sport readiness following ACL injuries.

Conflicts of interest

The authors declare NO conflict of interest.

Ethics approval and consent to participate

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 Ethics Committee.

Appendix D. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ptsp.2019.06.009.

Appendix A. Technical explanation of ISU technology-derived analysis [32].

Instrumentation

An ISU integrating 3 accelerometers, 3 gyroscopes and 3 magnetometers (MTx, Xsens Technologies B.V. Enschede, Netherlands) attached over the L3 region of the subject's lumbar spine provided the kinematic data recorded in each trial at a sampling rate of 100 Hz.MTx combines itself nine individual MEMS sensors to furnish accurate3D orientation as well as other kinematic data such as: 3D acceleration, 3D rate of turn (rate gyro) and 3D earth-magnetic field.

Optical motion analysis system (Vicon Nexus 1.0) was used as truth-reference and it was time synchronized with the MTx to compare both signal results.

The ISU provided linear acceleration and rate of turn in a sensor-fixed Cartesian reference frame (x-y-z). Before the beginning of the test, with the subject sitting on the chair and his back in upright position, the sensor-fixed reference frame was aligned with the Earth-fixed global reference frame (XYZ), whose Z axis lies on the vertical pointing upwards, its X axis lies on the lateral direction and its Y axis on the anterior-posterior direction (Figure A1).

Fig. A1. Changes in global and IU's local Cartesian reference axes when the subject is trying to stand up at the beginning of the 30-s CST. The first figure, (a), depicts the initial position; global and local reference axes coincide. When the subject changes position, the global axis remains unchanged (b) whereas the IU's local reference axis rotates with the physical device (c).

Orientation data consisting in the Euler angles (in XYZ or roll-pitch-yaw order) defined the rotation that aligned the global axis to the sensor-fixed reference frame at each time instant. Then, linear acceleration in the global reference frame was obtained from the acceleration and orientation data provided by the IU (Figure A2A). Furthermore, optical data were also collected using a 100 Hz six-camera Vicon system (Vicon Motion System, Oxford, UK), in order to check the new method's accuracy. Specifically, in our study, a Vicon Nexus 1.0 was employed, using only three from the six available cameras. They were previously calibrated and the data from the two systems were time-synchronized through sync pulses in order to compare both of them in an off-line analysis with Matlab (Math Works, Massachusetts, USA). One 4 mm Vicon reflective marker was placed on the MTx to acquire its three-dimensional position for subsequent comparisons.

Signal Processing

Drift effect correction.

Z-position signal, obtained through double integration of the Z-acceleration, was used to detect the subject's up and down positions and hence automatically obtain the number of complete sit-stand-sit repetitions during the 30-s CST. However, the raw Z-acceleration signal provided by the ISU has to be treated as previously mentioned. Firstly, the coordinate reference system needed to be changed from local to global. Secondly, the gravity acceleration component, roughly estimated as 9.8 m/s2, had to be removed (Figure A3).

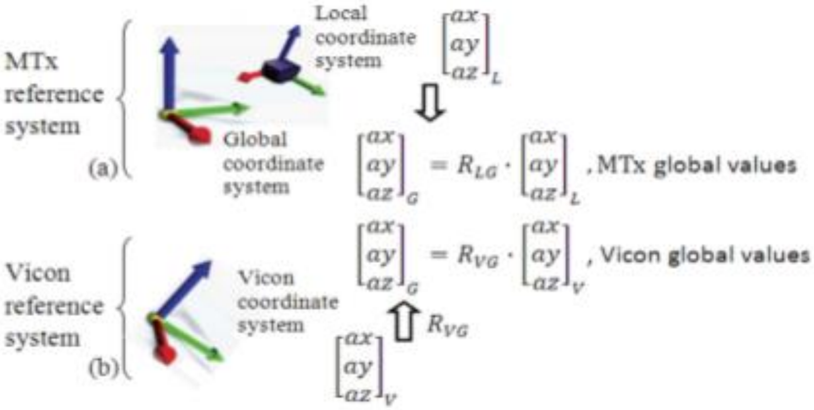


Fig. A2. Reference systems changes to obtain the global values from MTx and Vicon. Sub-indexes "L", "G" and "V" refer to the MTx local, global and Vicon local coordinate systems respectively and RLG and RVG to the rotation matrices to change coordinates from the first indicated reference system to the second one.

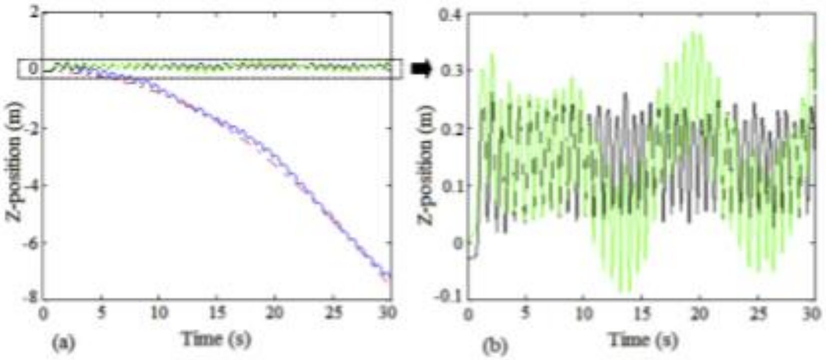


Fig. A3. (a) shows the Z-position signal (blue line) gravity error correction (green line), and the Vicon reference signal (black line). Red line is the tendency line based on fourth level polynomial estimation that tracks the gravity error, Part (b) shows the corrected and reference signal enlargement.

Finally, relative position was obtained through double integration of the acceleration data (Figure A4), assuming resting initial conditions. However, this straightforward process was hindered by noise in the acceleration signal as well as by approximation errors due to numerical integration. This drift effect that occurs for various reasons (e.g., vibration or environmental temperature fluctuations) can, in practice, make the position or velocity signals became unusable within several seconds. Therefore, an added step to solve this problem is needed. Here, a new method based on polynomial curve adjustment and splines approximation is proposed. In doing so, we will be able to achieve a correct Z-position overcoming the drift error problem.

Our correction method first tries to estimate the drift caused by a small DC bias in the Z-acceleration signal principally due to assuming a gravity component of 9.8 m/s2.This gross approximation leaves a small continuous component which gives rise to a quadratic component in the double-integrated signal. Here, a fourth order polynomial was used to obtain the estimation parameters from the position signal, without incurring in over-fitting. Then, the derivative of the estimated polynomial was employed to adjust the velocity signal and get the position signal through integration (Figure A4B).

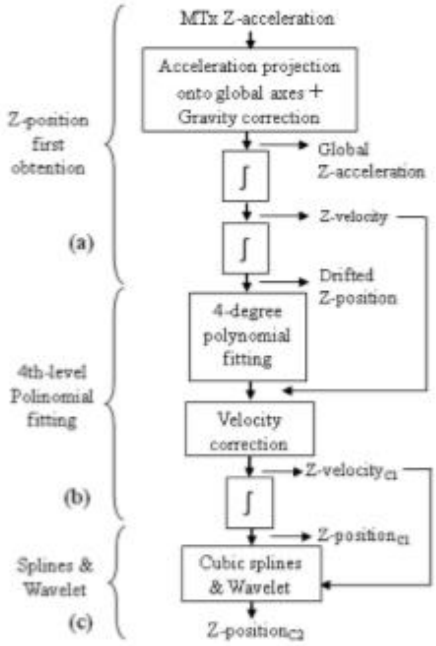


Fig. A4. Z-position free-drift obtaining algorithm: double integration process, part (a), first correction (C1), part (b), and second correction (C2), part (c).

Reference systems unification.

Vicon reference system had to be changed to the global axes used by the MTx. To this purpose, some calibration measures from the Vicon system collected after each measurement were used to obtain the rotation matrix needed to make the coordinates change (Fig. 2B)). This arrangement makes it possible to compare the trajectory reconstructed from ISU's data and the one provided by the Vicon system.

Statistical parameters for comparisons.

Comparisons were done based on parameters such as the Euclidean error (EE), (1.1), and accuracy, defined as the percentage of the whole signal without error. Furthermore, statistical parameters such as the root mean squared error (RMSE), (1.2), and the correlation coefficient (r) were also obtained to check our method's accuracy:

$$EE = \left\| \sum_{n=1}^{N} Zposition_{Vicon}(n) - Zposition_{MTx}(n) \right\| \qquad (1.1)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{n=1}^{N} Zposition_{Vicon}(n) - Zposition_{MTx}(n)} \qquad (1.2)$$

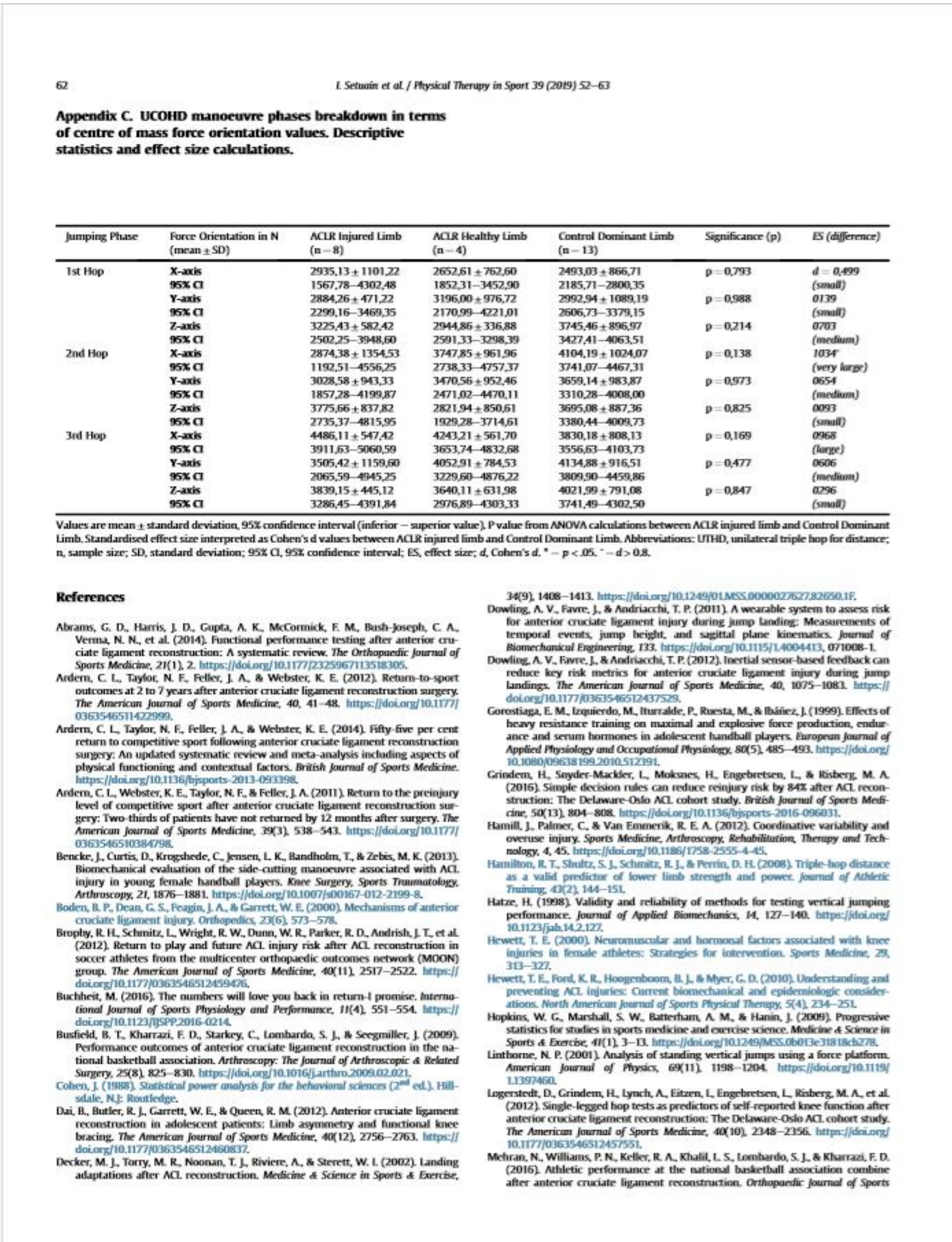
Modified-BMFLC vs PB-algorithm

The method reported in the present study was compared to a recent Modified-BMFLC drift-correction algorithm. The 30-s CST meets the quasi-periodic motion requirement for this drift-correction algorithm to be applied. In the literature there are other methods to correct the drift effect, but this was probably the first one which tried to cancel it when obtaining the position from the acceleration signal. Firstly, the cutoff frequency and the order of the high-pass filter were selected according to the 30-s CST conditions. A fourth level filter was chosen and the cutoff frequency was set at the movement's fundamental frequency. Finally, in order to achieve a good BMFLC algorithm performance, 200 intermediate sub-frequencies were selected between the movement's fundamental and tenth harmonic frequencies.

Appendix B. UTHD manoeuvre phases breakdown in terms of centre of mass force orientation values. Descriptive statistics and effect size calculations.

Jumping Phase	Force Orientation in N (mean ± SD)	ACLR Injured Limb (n = 8)	ACLR Healthy Limb (n = 4)	Control Dominant Limb (n = 13)	Significance (*p*)	*ES (difference)*
1st Hop	**X-axis**	2638,43 ± 1260,13	2512,01 ± 1221,94	2586,54 ± 1098,30	*p* = 1.000	*d* = *0,044*
	95% CI	533.36–2053.90	151.86–2253.9	873.60–2029.82		*(small)*
	Y-axis	3040,64 ± 960,64	3096,02 ± 834,67	3324,11 ± 845,50	*p* = 0,999	*d* = *0,314*
	95% CI	1847,84–4233,43	2220,08–3971,95	3024,30–3623,91		*(small)*
	Z-axis	2728,15 ± 868,65	2726,03 ± 1166,87	3693,49 ± 1186,50	*p* = 0.442	*d* = *0.939*^
	95% CI	1649,58–3806,72	1501,46–3950,58	3272,78–4114,20		*(large)*
2nd Hop	**X-axis**	4067,86 ± 757,27	3214,71 ± 688,59	3391,20 ± 1054,99	*p* = 0,300	*d* = *0,747*
	95% CI	3127,59–5008,14	2492,07–3937,34	3017,12–3765,29		*(medium)*
	Y-axis	4042,21 ± 1069,26	3643,58 ± 1138,24	3980,37 ± 1075,11	*p* = 0,968	*d* = *0,058*
	95% CI	2714,54–5369,87	2449,07–4838,09	3599,15–4361,59		*(small)*
	Z-axis	3615,45 ± 972,73	3613,46 ± 813,39	3647,88 ± 1182,87	*p* = 0.971	*d* = *0.030*
	95% CI	2407,65–4823,25	2759,86–4467,07	3228,45–4067,30		*(small)*
3rd Hop	**X-axis**	4131,08 ± 1436,95	4328,33 ± 788,49	4339,24 ± 946,92	*p* = 0,827	*d* = *0,175*
	95% CI	2346,86–5915,29	3500,86–5155,80	4003,48–4675,00		*(small)*
	Y-axis	4311,44 ± 938,38	4400,30 ± 934,28	4167,64 ± 943,54	*p* = 0,960	*d* = *0,153*
	95% CI	3146,29–5476,59	3419,83–5380,76	3833,08–4502,21		*(small)*
	Z-axis	4303,50 ± 779,58	3678,57 ± 893,47	4332,58 ± 991,72	*p* = 0,997	*d* = *0,033*
	95% CI	3335,52–5271,48	2740,93 ± 4616,20	3980,93 ± 4684,23		*(small)*

Values are mean ± standard deviation, 95% confidence interval (inferior – superior value). P value from ANOVA calculations between ACLR injured limb and Control Dominant Limb. Standardised effect size interpreted as Cohen's d values between ACLR injured limb and Control Dominant Limb. Abbreviations: UTHD, unilateral triple hop for distance; n, sample size; SD, standard deviation; 95% CI, 95% confidence interval; ES, effect size; *d*, Cohen's *d*. * = $p < .05$. ^ = $d > 0.8$.



Appendix C. UCOHD manoeuvre phases breakdown in terms of centre of mass force orientation values. Descriptive statistics and effect size calculations.

Jumping Phase	Force Orientation in N (mean ± SD)	ACLR Injured Limb (n = 8)	ACLR Healthy Limb (n = 4)	Control Dominant Limb (n = 13)	Significance (p)	*ES (difference)*
1st Hop	**X-axis**	2935,13 ± 1101,22	2652,61 ± 762,60	2493,03 ± 866,71	p = 0,793	*d = 0,499*
	95% CI	1567,78–4302,48	1852,31–3452,90	2185,71–2800,35		*(small)*
	Y-axis	2884,26 ± 471,22	3196,00 ± 976,72	2992,94 ± 1089,19	p = 0,988	*0139*
	95% CI	2299,16–3469,35	2170,99–4221,01	2606,73–3379,15		*(small)*
	Z-axis	3225,43 ± 582,42	2944,86 ± 336,88	3745,46 ± 896,97	p = 0,214	*0703*
	95% CI	2502,25–3948,60	2591,33–3298,39	3427,41–4063,51		*(medium)*
2nd Hop	**X-axis**	2874,38 ± 1354,53	3747,85 ± 961,96	4104,19 ± 1024,07	p = 0,138	*1034ˆ*
	95% CI	1192,51–4556,25	2738,33–4757,37	3741,07–4467,31		*(very large)*
	Y-axis	3028,58 ± 943,33	3470,56 ± 952,46	3659,14 ± 983,87	p = 0,973	*0654*
	95% CI	1857,28–4199,87	2471,02–4470,11	3310,28–4008,00		*(medium)*
	Z-axis	3775,66 ± 837,82	2821,94 ± 850,61	3695,08 ± 887,36	p = 0,825	*0093*
	95% CI	2735,37–4815,95	1929,28–3714,61	3380,44–4009,73		*(small)*
3rd Hop	**X-axis**	4486,11 ± 547,42	4243,21 ± 561,70	3830,18 ± 808,13	p = 0,169	*0968*
	95% CI	3911,63–5060,59	3653,74–4832,68	3556,63–4103,73		*(large)*
	Y-axis	3505,42 ± 1159,60	4052,91 ± 784,53	4134,88 ± 916,51	p = 0,477	*0606*
	95% CI	2065,59–4945,25	3229,60–4876,22	3809,90–4459,86		*(medium)*
	Z-axis	3839,15 ± 445,12	3640,11 ± 631,98	4021,99 ± 791,08	p = 0,847	*0296*
	95% CI	3286,45–4391,84	2976,89–4303,33	3741,49–4302,50		*(small)*

Values are mean ± standard deviation, 95% confidence interval (inferior – superior value). P value from ANOVA calculations between ACLR injured limb and Control Dominant Limb. Standardised effect size interpreted as Cohen's d values between ACLR injured limb and Control Dominant Limb. Abbreviations: UTHD, unilateral triple hop for distance; n, sample size; SD, standard deviation; 95% CI, 95% confidence interval; ES, effect size; *d*, Cohen's *d*. * = $p < .05$. ˆ = $d > 0.8$.

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RESEARCH ARTICLE **Open Access**

Horizontal jumping biomechanics among elite female handball players with and without anterior cruciate ligament reconstruction: an ISU based study

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Abstract

Background: Handball is a strenuous body-contact team sport that places high loads on the knee joint. Anterior cruciate ligament (ACL) tear is one of the most devastating injuries that any handball player can suffer, and female athletes are at particular risk due to their intrinsic anatomical, hormonal, neuromuscular and biomechanical characteristics. The purpose of this study was to analyze the horizontal jumping biomechanics of female elite handball players with or without previous ACL reconstruction.

Methods: Twenty-one female participants (6 with previous ACL reconstruction and 15 uninjured controls) were recruited. Two horizontal hopping tasks were evaluated using inertial sensor unit (ISU)-based technology to assess jumping biomechanics through a direct mechanics-based approach.

Results: The athletes with previous ACL reconstruction demonstrated a significant ($P < 0.05$) reduction in the unilateral triple hop for distance compared with the healthy controls. Furthermore, during the initial propulsive phase of the unilateral cross-over hop, the control participants generated significantly ($P < 0.05$) higher force values in the mediolateral direction (the X axis) with their dominant limb compared with the ACL-reconstructed (ACL-R) limb of previously injured participants.

Conclusions: Three-dimensional horizontal jumping biomechanics analyses using ISU-based technologies could provide clinicians with more accurate information regarding the horizontal jumping biomechanical patterns among elite handball female athletes. Furthermore, several mechanical alterations could still be observed among those players who had undergone previous ACL reconstruction, even when several years have passed since the original ACL injury.

Keywords: Knee, ACL injury, Functional evaluation, Inertial sensor, Biomechanics

Background

Handball is a body-contact team sport that elicits high-intensity maneuvers such as abrupt changes in direction, velocity and sudden single leg landings [1, 2]. The nature of the sport and the high intensity of games, makes the knee joint to be exposed to many stressful forces that could result the anterior cruciate ligament (ACL), rupture, which constitutes one of the most devastating injuries among handball players [3, 4].

The reported incidences of ACL injury for male and female handball athletes are approximately 0.24 and 0.86 injuries per 1000 h of exposure, respectively [5]. Therefore, female athletes are 6 to 10 times more likely to suffer an ACL injury than their male counterparts during the same jumping and pivoting tasks [5, 6]. Anatomical, hormonal and neuromuscular differences between sexes have been proposed as explanatory factors for this discrepancy in the ACL injury rates between sexes [7–10].

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The clinical relevance of ACL injury does not rest solely on the ligament disruption itself; the functional implications of concomitant associated knee injuries for the athletes' function can play an important role in the clinical prognosis of the athlete after injury [11]. Additionally, the scientific literature lacks information regarding the best clinical practices for rehabilitation programs or universal functional and clinical evaluation criteria for resuming the sport after injury [11].

This ambiguity may expose the athlete to both higher risk of graft rupture and a new injury of the healthy contralateral knee [12]. Thus, the detection and monitoring of subjects with a higher risk of injury or re-injury using functional, biomechanical or neuromuscular screening evaluations appears to be crucial either for prevention and rehabilitation in sports medicine [13].

Functional performance evaluations have traditionally been highlighted as a key point in relation to decisions regarding resuming play after ACL injury [2, 13–16]. In this context, unilateral hopping tests have demonstrated a good ability to identify lower limb impairments during both vertical and horizontal jumping maneuvers [15–17].

Several biomechanical and neuromuscular impairments at the trunk, hip and knee joint levels have been widely reported in the literature as a result of motion analysis and inverse mechanics procedures during the abovementioned and other sport-specific tasks [18–21]. Unfortunately, these testing procedures require from expensive and complex laboratory resources (such as camera-motion analysis systems and/or force plates) and are associated with a high financial investment and trained staffs that are familiar with such laboratory-derived procedures. The recent development of ISU-based biomechanical evaluations presents clinicians with the opportunity to perform several functional and biomechanical jumping evaluations on the training court itself [22–28].

In relation to handball, Myklebust et al. [29] observed long-term differences in strength, jumping test scores and anterior-posterior knee joint laxity between ACL-injured and uninjured professional and recreational players after an injury. In addition, Setuain et al. [28] presented a validation study that reported promising results validating the utilization of the ISU versus force plate recordings during vertical jumping tasks. Later, the same research group probed the potential of ISU-based evaluations to assess vertical jumping biomechanical among both female [25] and male [26] elite handball players in relation to previous ACL injury. The authors found long-term, sex-specific functional adaptations after ACL reconstruction, being thefemale athletes more likely than males to experience lasting biomechanical jumping alterations after an ACL reconstruction [25]. The application of the ISU-based biomechanical jumping to identify movement pattern alterations after ACL injury has also been proven in previous studies [22, 23].

The aim of this study was to examine the biomechanical differences in horizontal jumping between elite female handball players with previous ACL reconstruction who had returned to their previous sport activity, and level-, sex-, and age-matched pairs of control counterparts. The hypothesis of the present research was that the ACL-R players would present lasting biomechanical alterations in terms of greater supported three-axis peak forces during single-limb horizontal jumping maneuvers compared with their control counterparts, despite have continued with elite competition for several years after the original ACL injury.

Methods

A descriptive case series study design was selected. The examinations were conducted at the athlete's habitual training court. The jumping task battery included the unilateral triple hop for distance (UTHD) and the unilateral triple cross-over hop for distance (COHD). These tests have been established as reliable methods for evaluating lower limb function in relation to ACL injury in previous investigations [16, 30, 31].

Subjects

Twenty-one female elite handball players competing in their highest national division league and European championships were recruited. The sample comprised 6 athletes who had undergone ACL reconstruction, two of them bilaterally (age 26.4 ± 1.4 years; height 169.0 ± 1.6 cm; and weight 61.8 ± 1.4 kg), and 15 uninjured controls (age 25.1 ± 1.4 years; height 175.0 ± 1.4 cm; and weight 69.5 ± 1.8 kg). Among the athletes with bilateral reconstructions, both limbs were recorded as ACL-R limbs. The average and standard deviation of the data collection time since surgical reconstruction was 6.0 ± 3.5 years. For the control group, athletes who had sustained a previous lower limb injury lasting more than 6 weeks were excluded to avoid jumping pattern bias due to potential functional alterations resulting from severe lower extremity injury. 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.

Equipment

An inertial orientation tracker (MTx, 3DOF Human Orientation Tracker, Xsens Technologies B.V. Enschede, The Netherlands) was attached over the L3-L4 region of the subject's lumbar spine and provided data on kinematic and kinetic variables such as accelerations, orientations and velocity at a sampling rate of 100 Hz. A technical explanation describing the inertial sensor-derived variables has been previously provided (Additional file 1: Appendix A) [32]. Furthermore, a 10-m-long measuring tape was utilized to measure the distance in each horizontal jumping task. The last heel contact was recorded for the final measure.

Procedures

Lower limb dominance was determined as previously described by Bencke et al. [2] in their work with handball players. The limb that pushed off the ground for a jump when a regular handball throw was performed was considered dominant [2]. All the participants performed the test at the beginning of a routine training session conducted during the competitive season and at least 48 h after their last competition. The jumping methodology used in this trial has been published previously [17, 24, 30, 31, 33–36]. The subjects were instructed that during the execution of each maneuver, they should keep their hands on their hips. No added technical instructions about the jumping modality were given to the athletes to avoid modifications during the task performance. The participants started in a single-limb stance position. They then performed three consecutive horizontal hops as far as possible, holding the position for at least 1 second after the last landing. For the COHD, the subjects adopted the same starting position and executed three consecutive cross-over hops outside two lanes separated by a 15-cm-wide tape attached on the floor, trying to land as far as possible while maintaining their balance for 1 second at the final landing. The first jumping step was interiorly directed. A practice trial was performed to ensure the participant's comfort and safety and was followed by two further test trials interspersed with 30 s of rest. The jumping tasks were performed in order from easiest to most complex to avoid possible injury risks associated with the intensity of the maneuver. The participants thus started with the UTHD and ended with the COHD.

ISU provides linear acceleration values in a sensor-fixed Cartesian reference frame (XYZ). Before starting the measurement, the inertial sensor unit is calibrated and the sensor axes are aligned with anatomical directions. The acceleration signal consists of gravitational and inertial components. The inertial sensor unit registers gravity as a static vertical component, in addition to the dynamic acceleration caused by changes in velocity during locomotion. The gravity component must be subtracted to estimate the dynamic acceleration. The 3D orientation data provide the position of the inertial unit with respect to the gravitational vector, allowing the calculation of the inertial component for each axis. The gravitational constant was estimated by leaving the inertial sensor unit still on a flat surface for 2 seconds. In previous studies [25–28], body-worn inertial sensor and accompanying custom algorithms has demonstrated high agreement and reliability levels compared with force plates, [28] (Fig. 1).

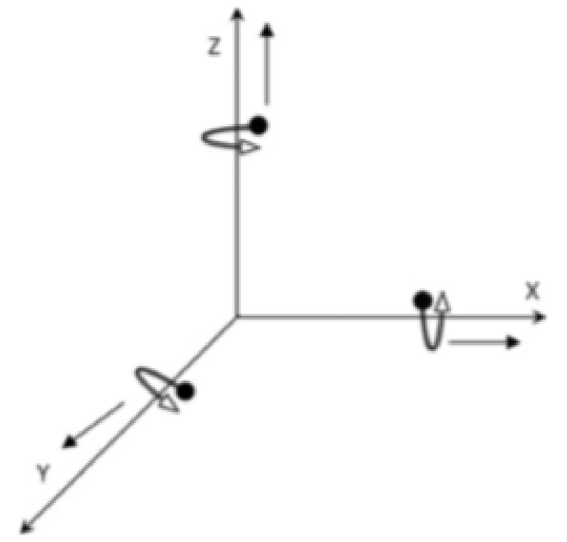

Fig. 1 Z-axis (vertical), X-axis (medial-lateral) and Y-axis (anterior-posterior) orientations

Data processing and analysis

The data reported by the sensor was analyzed using direct mechanics-based procedures that considered the subject as a mechanical system and estimated the movement and actuation of forces through the center of mass displacement [37–39]. As previously mentioned, the human center of gravity is considered to be located at the L3 lumbar spine level, where the ISU was placed. The data processing description was previously published by this research group [29].

Briefly, in order to facilitate the biomechanical analysis of the jump, the task was divided into separate phases. The identified phases were based on the results obtained from the vertical velocity curve recordings (Z-axis) through a self-customized computer application implemented with MatLab 7.11 (MathWorksInc; Natick, MA, USA). The Z- velocity signal was used to distinguish the boundaries between the different phases of both tasks and were considered positive when the subject moved upwards (corresponding to the propulsive phases of the three consecutive jumps) and negative when subject moved downwards (corresponding to the pre-loading and landing phases). The different phases of the jumping task have been described succinctly in previous studies [25–29] (Fig. 2).

Lastly, the mechanical efficiency ratio (ME) calculation was defined as the ratio between the jumping performance (cm) and the sum of the peak ground reaction forces supported at the centre of mass level (N). The amount of the sum of three-dimensional forces would penalize or benefit the ratio in the horizontal jumping task. The ME, aims to determine to what extent the

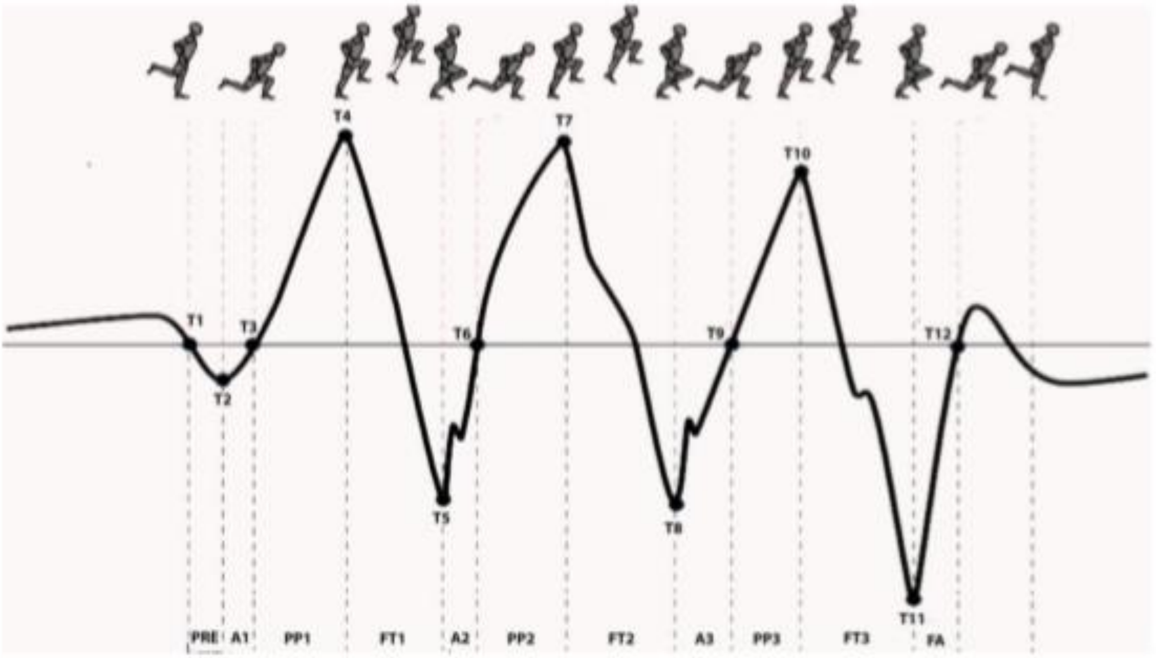

Fig. 2 Horizontal jumping task jumping phases by velocity by time curve analysis description The segment T1-T3 represents the negative passive and active work (pre-stretch) corresponding to the propulsive phase (PP). The T3 event corresponded to the instant the Z-velocity first passed zero (when the centre of mass of the athlete was in its lowest position) during the transition between the initial absorption (A1) or pre-load and the propulsive phase (PP1) of the jump. The PP1 concluded in T4, when the maximal vertical velocity (propulsive phase) was achieved. Therefore, the segment T2-T3 represents the countermovement of the jump, and consequently, the segment T3-T4 corresponds to the PP1. Segment T4-T5 represents the flight time of the first jump (FT1). The same curve cut-off points were described thorough the whole triple hop analysed. Thus, absorptive (eccentric, T5-T6; T8-T9 and T11-T12) and propulsive (concentric; T6-T7, T9-T10) phases were similarly described

supported peak ground reaction forces are during the absorptive phases, in relation to the distance reached during the maneuver. Supporting greater peak ground reaction forces during the absorptive phases, could lead to a more harmful mechanical overload which could increase the injury risk.

$$ME = \frac{performance\ (cm)}{(Fx + Fy + Fz)}$$

Statistical analysis

Descriptive statistics (mean, standard error of the mean and IC values at 95%) were calculated for all the collected variables (weight in kg; height in cm; performance in cm; 3 axis GRFs in N).

Afterwards, descriptive statistics for the selected variable groups (ACL-R injured limb, ACL-R healthy limb, Control dominant limb) were applied. After normal distribution of the data and variances equality were checked through the Shapiro-Wilk and Levene tests respectively, 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 ACL-R group and the non-dominant limb was matched to the non-involved limb of the ACLR group [19]. 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 limb us with only one fixed factor (group; ACL-R vs controls). When the variance equality was rejected, the Tamhane's post hoc test was performed. The significance level was set at $p < 0.05$. "SPSS" statistical software (V. 20.0, Chicago, IL, USA) was used for the abovementioned statistical calculations.

Apart from that, intra and inter-group differences were analysed using magnitude-based inferences (MBI). This statistical method was chosen in order to highlight the practical significance over the statistical (p value) significance, emphasizing that the magnitude of an effect would be more relevant than any statistically significant effect especially in the clinical practice or when treating elite athlete's data [40, 41]. The magnitudes of the smallest worthwhile differences were identified by the determination of the effect sizes (Cohen's d) for between-limbs and between group comparisons, using means and standard deviations for each group of variables. Values for Cohen's d statistics were interpreted as follows: < 0.15 for trivial, 0.15 to 0.4 for small, 0.4 to 0.75 for medium, 0.75 to 1.10 for large and > 1.10 for very large differences [41].

Results

After the data processing, the number of analysed limbs in both control and ACL-R group was the following: 8 ACL-R reconstructed limbs and 4 ACL-R in both UTHD and COHD maneuvers; 13 dominant and non-dominant limbs in the UTHD and 14 dominant and non-dominant limbs in the COHD of the control group. The ACL-R players were significantly ($p < 0.05$) lighter and smaller than their non-ACL-R counterparts. No significant interaction effects were found between factors for UTHD and COHD tests. Therefore, the results are delimitated to the description of the main effects observed.

Unilateral triple hop for distance (UTHD)

Regarding the UTHD, the dominant limb of the controls reached a significantly better distance performance on the UTHD task compared with the injured limb of the ACL-R participants ($p < 0.05$). Indeed a non statistical trend although a large effect size was find in realtion to a gretater X mediolateral force production during the first hop in controls in comparison to ACL- reconstructed players. (Table 1). No further significant differences were found for any time or force variables (Fig. 3).

The ACL-R limbs of cases demonstrated a trend towards greater mechanical efficiency ratios (0.079 ± 0.02 vs. 0.070 ± 0.05; Cohen's d = 0.4) when executing this horizontally oriented jumping task (Table 2).

Triple cross-over hop for distance (COHD)

Regarding the COHD, no significant differences were found between the groups in terms of performance (reached distance) (Table 1). However, a significant group-by-limb interaction was observed for the PP X-axis forces ($F = 4.353$; $p = 0.010$). The Bonferroni post-hoc analysis revealed that the dominant limbs of the controls displayed significantly greater X-medial-lateral axis forces than the injured limbs of the ACL-R group ($p < 0.05$). No significant differences were found for the remaining analyzed variables (Fig. 3).

The ACL-R limbs of the cases demonstrated a trend towards lower mechanical efficiency ratios (0.058 ± 0.02 vs. 0.085 ± 0.02; Cohen's d = 1.4) when executing this side-to-side and horizontally oriented jumping task.

For more information, available complementary material is included about the 3-axial forces results for the UTHD (Additional file 1: Appendix B) and the COHD (Additional file 1: Appendix C).

Discussion

The purpose of this study was to examine the biomechanics of two horizontal hopping tasks among top-level professional female handball athletes using an ISU-based methodology. The analysis focused on the identification of persistent jumping biomechanics adaptations in the ACL-R limbs of previously injured athletes. The results of the present work showed that although the ACL-R participants had returned to full competition at high intensity and exigency levels, slight jumping biomechanics alterations seemed to persist.

Consequently, the previously ACL-injured limbs of the cases showed lower UTHD performance in terms of distance (Table 1), and reduced mediolateral force generation on the propulsive phases of this horizontally oriented jumps, specially in the COHD maneuver (Fig. 3). These findings may suggest that at the initial propulsion (the pre-loading phase preceding the first hop), the ACL-R limbs of the previously injured athletes generated lower frontal plane forces compared with the dominant limbs of the control athletes. Furthermore, during the execution of both horizontal jumping tasks, the ACL-R athletes were more prone (although not significantly) to generate lower Z-axis (vertical) and Y-axis (horizontal) forces. Interestingly, the newly proposed mechanical efficiency ratios demonstrated a trend towards lower values for the ACL-R limbs of the cases compared with the

Table 1 Horizontal jumping performance for unilateral triple hop and unilateral cross-over hop for distance. Descriptive statistics, significance and effect size calculations for each group

		ACLR Injured Limb	ACLR Healthy Limb	Control Dominant Limb	Control Non-Dominant Limb	Significance (*p*)	*ES (d)*
UTHD	n	8	4	15	15		
	Performance	389 ± 61.05	398.25 ± 87.76	436 ± 37.84	430.29 ± 47.91	0.047*	*d* = 0.925^
	95% CI	337.97–440.03	258.61–537.89	411.95–460.05	402.62–457.95		
UCOHD	n	8	4	15	15		
	Performance	289.63 ± 58.24	310.5 ± 70.90	326.14 ± 44.84	329.31 ± 60.61	0.115	*d* = 0.7025
	95% CI	240.94–338.31	197.68–423.32	300.25–352.03	292.68–365.94		

Values are mean ± standard deviation, 95% confidence interval (inferior – superior value). *P* value from ANOVA calculations between ACLR injured limb and Control Dominant Limb. Standardised effect size interpreted as Cohen's d values between ACLR injured limb and Control Dominant Limb. Abbreviations: *UTHD* Unilateral triple hop for distance, *UCOHD* Unilateral cross-over hop for distance, *n* Sample size, *SD* Standard deviation, *95% CI* 95% confidence interval, *ES* Effect size, *d* Cohen's *d*. * = $p < .05$. ^ = $d > 0.8$

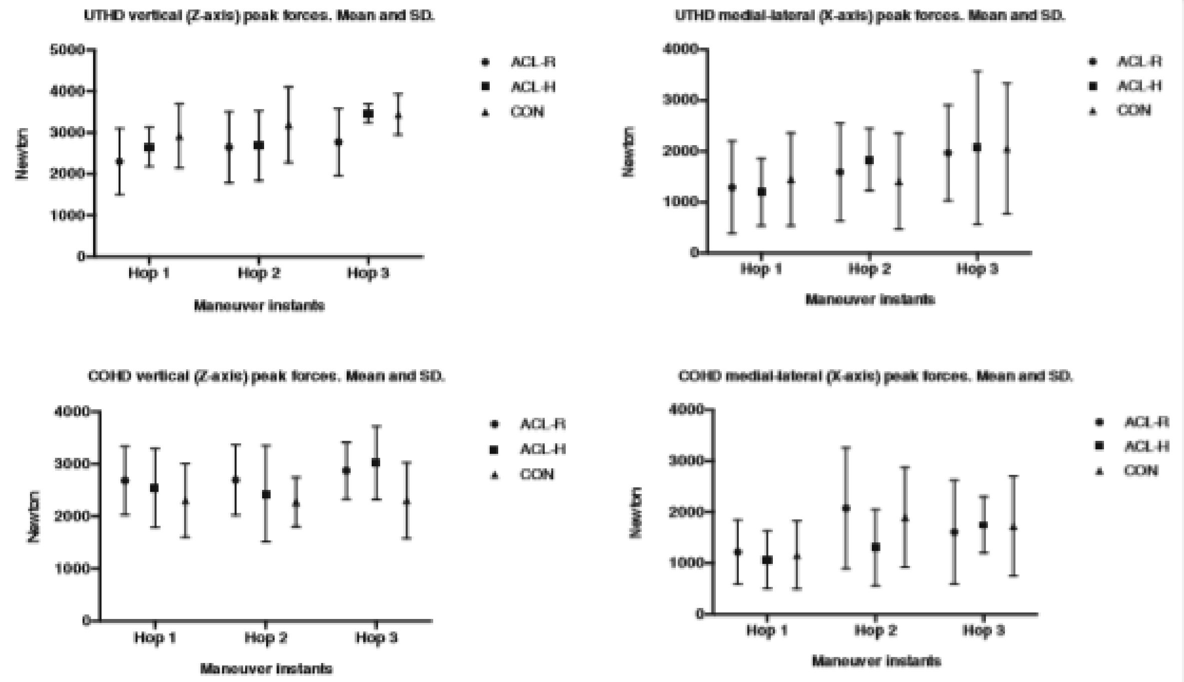

Fig. 3 Between groups peak vertical and medial-lateral forces comparison during the unilateral triple hop for distance (UTHD) and the unilateral cross over hop for distance maneuvers. Mean and SD. Abbreviations: (UTHD), unilateral triple hop for distance; (COHD), unilateral cross over hop for distance; ACL-R, anterior cruciate ligament group-reconstructed limb; ACL-H, anterior cruciate ligament group-healthy limb; control group-dominant limb

dominant limbs of the controls when executing this horizontally oriented jumping maneuvers, specially the CTHD. This could highlight that female handball players exhibit greater peak external force penalization (supporting ground reaction forces) when jumping with their previously ACL-R limb for the distance reached in comparison to that supported by controls. These results partially agree the study hypothesis, which posited that the ACL-R players would experience lasting biomechanical movement pattern alterations in terms of greater supporting three-axis peak forces during single-limb horizontal jumping maneuvers compared with their control counterparts despite having performed in elite competition for several years since the original ACL injury.

This results, contrast with those obtained by the same research group employing the same jumping test battery and biomechanical analysis methodology among male elite handball players. In that study, the authors did not find any meaningful biomechanical adaptations among previoulsy ACL reconstructed in comparison to control (non ACL injured) players. In this sense, it seems that male handball professional players are able to recover their lower limb full performance capacities without lasting biomechanical alterations that can be in contrast

Table 2 Horizontal jumping performance and three-dimensional force-based mechanical efficiency ratios. Descriptive statistics and effect size (Cohen's *d*) calculations

Horizontal Jumping Tasks	ACLR Injured limb			ACLR Healthy Limb			Control Dominant Limb			*ACLR Injured vs ACLR Healthy*		*ACLR Injured vs Control Dom*	
	n	Mean (±SD)	95% CI	*n*	Mean (±SD)	95% CI	*n*	Mean (±SD)	95% CI	*ES (d)*	*Difference*	*ES (d)*	*Difference*
d > 1.10	8	0,079 (±0, 022)	0,061 - 0, 097	4	0,072 (±0, 014)	0,049 - 0,094	13	0,070 (±0, 021)	0,057 - 0, 083	*0,379*	*small*	*0,418*	*medium*
d > 1.10	8	0,058 (±0, 015)	0,046 - 0, 071	4	0,064 (±0, 022)	0,0287 - 0, 1001	14	0,085 (±0, 023)	0,072 - 0, 098	*0,318*	*small*	*1,39*	*very large*[a]

Values are mean ± standard deviation, 95% confidence interval and standardised effect size. Abbreviations: UTHD, unilateral triple hop for distance; UCOHD, unilateral cross over hop for distance; n, sample size; SD, standard deviation; 95% CI, 95% confidence interval; ES, effect size; *d*, Cohen's *d*. [a] *d* > 1.10

observed among their female counterparts. Although evidence exists referring no sex influence in relation to increased risk for ACL graft failure among sportspeople, [42] may be, this statistical trend would change when controlling for sex, handball sport, and level of competence of the participants. This question should be addressed in properly designed investigations.

Traditionally, lower limb functional evaluations have been carried out in order to determine the athlete capacities with regard to return to sport participation. tIndeed, jumping biomechanical have also been performed in relation to injury risk factor identification showing huge correlation between poor unilateral limb performance values and knee dynamic instability [31]. In this context, ground reaction forces acting at the trunk level have been considered to have significant effects on lower limb segment behavior due to the inertia moment of force generation [43, 44]. Consequently, frontal plane kinematic or kinetic parameters measured at the trunk level have been shown to be significantly associated with knee valgus production [43]. In this context, ISU systems have become a reliable instrumentation for trunk displacement-derived 3D force calculations in different functional tasks [25–28]. It has been shown, an upward trunk position when landing from a jump could lead to greater anterior shear forces at the knee joint and higher vertical peak ground reaction forces, exposing the ACL to a higher injury risk [35, 43].

Thus, despite knee joint moment description is not possible when analysing a jumping task through a direct mechanics approach, by placing an ISU on the L3-L4 level, clinicians by using this jumping biomechanical analysis method, could look for jumping aberrant patterns identification that have been previously linked to a greater knee joint injury risk due to excessive mechanical overload during high demand athletic tasks.

In this way, it is possible that ACL-R female athletes, could have developed lasting movement pattern adaptations during single-limb actions in the attempt to improve lower limb stiffness through movement pattern reprogramming at the central nervous system level [45, 46]. This fact would help to explain the smaller medial-lateral force produced at the center of mass level during both UTHD and COHD task, as a positive effect of the rehabilitation.. These results are in contrast with previous investigations from the same research group and cohort of athletes that analyzed vertical jumping maneuvers [26]. In that research, ACL-reconstructed athletes generated higher medial-laterally oriented peak forces than their control counterparts. In the authors' opinion, this controversy could arise from a specific jumping direction-based motor retraining strategy adopted among cases to preserve knee joint integrity. In fact, the reduced mechanical efficiency ratios observed for the ACLR limbs of cases on the COHD task, which is known to place higher valgus stress on the knee joint than the UTHD, could support this hypothesis. However, this assumption should be adequately tested with studies designed to answer the specific question.

The identification of lasting functional and biomechanical jumping alterations several years after the injury in both the present and previous research [25–27], could be linked to an inadequate rehabilitation process or the approval of excessively early return to play by sports medicine staff when managing ACL injuries. This fact becomes clinically relevant in this context, as the time lapse between the time of reconstruction and retourn to sport participation, is know to affet ACL graft failure [42], The application of the ISU bed biomechanical jumping evaluations, could become useful for a more accurate motion analysis at the clinical setting level that would allow the clinician to plan an objective, clinically reasonable rehabilitation program based on the observed biomechanical alterations.

Some potential limitations could be observed in the present study. Given the uniqueness of the analyzed population, which was limited to an exclusive cohort of female professional handball athletes, the results should be interpreted with caution and in relation to this sport level, discipline and sex. Additionally, there was a lack of standardization of the postoperative rehabilitation protocols and the graft type used for the ligament repair among the ACL-R athletes. The heterogeneity of the rehabilitation process may have biased the long-term outcome in terms of physical activity level and sport-specific performance. However, previous studies have reported that no differences exist between reconstructions using different graft types in relation to long-term function of the knee [29]. Furthermore, the use of a single ISU placed at the trunk level limited the information collected regarding the knee joint biomechanics.. The, net moments of force calculations for specific joints were outside the scope of the present study which in turn tries to describe the centre of mass behavior thorough a direct mechanics approach. This is not as exhaustive as inverse mechanics procedures, but instead could be more friendly (in the field testing) and easy to handle for sport clinicians.

Conclusions

In conclusion, elite female handball players with previous ACL reconstruction demonstrated a attenuated jumping capacity in the THD test. Indeed, they also displayed lower X-medial-lateral axis peak force generation, especially during the first propulsive phase of the CTHD. This fact could be interpreted as a protective effect against the lower limb collapse. As main clinical implication, ISU systems can aid the implementation of real-time simple biomechanical jumping examinations by sports medicine professionals in clinical settings to reduce the residual uncertainty that often arises during the ACL rehabilitation process regarding the return to sports. However, due to the uniqueness of the analyzed cohort the present results must be considered with caution and restricted to the intrinsic characteristics of these top level female handball players.

Supplementary information

Supplementary information accompanies this paper at https://doi.org/10.1186/s13102-019-0142-8.

Additional file 1: Appendix A. Technical explanation of ISU technology-derived analysis [32]. **Appendix B.** UTHD manoeuvre phases breakdown in terms of centre of mass force orientation values. Descriptive statistics and effect size calculations. **Appendix C.** UCOHD manoeuvre phases breakdown in terms of centre of mass force orientation values. Descriptive statistics and effect size calculations.

Abbreviations

ACL: Anterior Cruciate Ligament; ACL-R: ACL-Reconstructed; COHD: Cross-Over Hop for Distance; GRF: Ground Reaction Force; ISU: Inertial Sensor Unit; ME: Mechanical Efficiency ratio; UTHD: Unilateral Triple Hop for Distance

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Authors' contribution

IS, MI were conceiving this study, for acquiring data, and drafting the manuscript. IS, EB, FA, FU, MI were responsible for final version of the manuscript. IS, EB, MI, were responsible for statistical analysis, and advised regarding interpretation of the results. EB, FA, FU were responsible for literature search. IS, EB, MI were responsible for acquiring data and interpretation of the results. All authors read and approved the manuscript and figures.

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Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Ethics approval and consent to participate

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.
Athletes involved in this study gave their written consent to use anonymized data for statistical and scientific use.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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