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Original Research

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

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Abstract

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

Introduction

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

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

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subjects [6]. Reduced hip range of motion, especially internal rotation, also has been found in male soccer players with previous ACL injuries [7].

It is well known that an incomplete or deficient rehabilitation program after an ACL injury may increase the risks of both reinjury and ACL injury in the contralateral unaffected knee [8]. 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 reinjury [9].

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

The development of microelectromechanical systems has produced inertial sensor unit (ISU) systems as a new alternative for sports-related movement performance assessment and as a clinical resource in the ACL rehabilitation field [9]. In brief, ISU systems provide the linear acceleration and angular displacement orientation values in a sensor-fixed Cartesian reference frame (XYZ). Therefore, ISUs offer the possibility of landing outside of a predefined place, as opposed to traditional ground-located force plates. This capability enables a more functional and unplanned movement analysis. Previous studies 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 [15-17]; however, the aforementioned studies used multiple sensors on body segments. These sensors improved the measurement accuracy but rendered the clinician unable to reproduce this type of movement evaluation in a clinical setting [15]. To simplify the measurement methodology, the present study aimed to measure jumping biomechanics by the use of direct mechanics-based procedures. With these procedures, the body's center of mass behavior during the execution of several vertical jumping tasks could be recorded and further analyzed with the obtained vertical velocity by time curves.

Therefore, the purpose of this study was to examine biomechanical jumping profiles in a cohort of elite male handball players with or without previous ACL reconstruction with a single portable ISU. Published studies on subjects with previous ACL reconstruction have reported increased trunk angular excursion [18] as well as greater supported peak vertical ground reaction force (VGRF) [14]. Therefore, the present study hypothesized that different jump phase durations as well as greater supported peak acceleration in the mediolateral and anteroposterior axes and trunk angular displacement excursions would be present in male athletes with previous ACL reconstruction compared with control non-ACL reconstructed athletes and that these differences would primarily occur during unilateral actions. This assumption was formulated despite the fact that several years had passed since the original injury and that the athletes were currently competing at their preinjury performance level.

Material and Methods

Experimental Approach

A descriptive case series study was performed. The experiment was conducted at the athletes' habitual training court. The participants performed a vertical jump test battery that included a 50-cm vertical bilateral drop jump (VBDJ), 20-cm vertical unilateral drop jump (VUDJ), and vertical unilateral countermovement jump (VUCMJ). The jumping test battery chosen for this study has been considered reliable for measuring limb asymmetries after ACL ligament injury in athletes [19-21]. The test-retest intraclass correlation coefficients for jumping variables were greater than 0.95 in a previous study conducted on ACL-reconstructed subjects [22].

Subjects

The study population consisted of 22 elite male handball players (6 ACL-reconstructed cases and 16 non–ACL-injured controls). The average and standard deviation of the time since surgical reconstruction was 6.3 ± 3.4 years. All the athletes were competing in their respective top division national leagues. Athletes were recruited through personal interviews with the team managers of 2 clubs in our region. Previous injury records were obtained via questionnaires before the testing session began and were corroborated subsequently by injury reports from the medical staff at each club. Athletes in the control group with a previous lower limb injury that lasted more than 6 weeks were excluded from the study. This decision was made to avoid jumping pattern bias resulting from potential lasting functional alterations from other severe lower extremity injuries. The participants and coaches were informed in detail about the experimental procedures and the possible risks and benefits of the project. The study was approved by the Ethical Committee of the Public University of Navarra and was performed with accordance with the Declaration of Helsinki, and the study protocol was approved by the Institutional Review Committee of the Public University of Navarra, SP.

Equipment

An inertial orientation tracker (MTx, 3DOF Human Orientation Tracker; Xsens Technologies B.V., Enschede, Netherlands) was attached over the L3 region of the subject's lumbar spine, and this tracker provided kinematic variables at a sampling rate of 100 Hz. A technical explanation describing the inertial sensor-derived variables has been published previously [23].

Procedures

The ages and anthropometric characteristics of the athletes were recorded before the testing session (Table 1). Leg dominance was defined as the leg the athletes would use if they were required to push off the ground and then throw a ball, as previously described in handball [24]. The distribution of the predefined jumping leg among the studied population included 17 left-limb- and 5 right-limb-dominant male participants. Among the ACL-reconstructed participants, 2 of 6 athletes had a previous ACL injury in their dominant leg.

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

All the participants performed the test at the beginning of a routine training session during the competitive season that was at least 48 hours after their last competition. Jumping methodology descriptions have been published elsewhere [25]. In brief, each participant was allowed to carry out 2 practice trials to ensure comfort with the task before data collection. Two further test trials were performed, with approximately 10 seconds of rest between jumps [25]. The number of repetitions of each jumping task was constant, and the jump battery protocol was fixed. The jump task execution order was from easy to complex execution requirements to avoid possible injury risks associated with the intensity of the jumping tasks.

Table 1
Anthropometric data

	All Participants	Controls	ACL Reconstructed
Age, y	25.59 (1.01)	24.81 (1.27)	27.67 (1.26)
Weight, kg	90.43 (2.01)	89.81 (2.49)	92.08 (3.48)
Height, cm	188.24 (1.42)	188.23 (1.80)	188.25 (2.31)

Values expressed as mean and (SEM).

Direct mechanics-based procedures were used to estimate the center of mass displacement and to detail the jumping biomechanics. The direct mechanics procedure is based on the description of the subject as a mechanical system and the estimation of movement and actuation of forces through displacement of the center of mass [26]. The positioning of the ISU at the lumbar spine level, the presumptive location of the human center of gravity [27], and the vertical velocity by time descriptive curves were both based on this approach.

Data Processing and Analysis

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

For the VBDJ and VUDJ, the T1 event was signaled by an abrupt positive change in vertical (Z-axis) velocity, which determined the start of the active negative (eccentric) action of the initial absorption phase, when the center of mass of the athlete was in its lowest position. The T2 event corresponded to the instant that the vertical velocity first passed zero in the transition between the initial absorption and the propulsive phases of the jump. The T3 event corresponded to the instant in which the maximum positive vertical velocity was achieved. Subsequently, the T4 event was documented when the vertical velocity again reached a maximum value, and the final T5 event was noted when the vertical velocity returned to zero after the jump (Figure 1A).

For the VUCMJ, the action (the T1 event) began when the first negative Z-acceleration was produced. Next, negative passive and active work (pre-stretch) was performed during the "propulsive phase." The subsequent T2 event was determined when the maximum vertical negative velocity was reached (lowest position of the center of mass). T3 was denoted by the instant the vertical velocity first passed through zero in the transition between the initial absorption (countermovement in the case of VUCMJ) and the propulsive phases of the jump. The T4 event corresponded to the instant at which the maximum positive vertical velocity was achieved. Subsequently, the T5 event occurred when the vertical (Z-axis) velocity again reached a maximum value, and the final T6 event was denoted by the point when the vertical velocity reached zero after the jump (Figure 1B).

For every cycle, the Z-velocity signal was used to distinguish the peak from the transition phases of each jump (for example, subject moving upwards = positive Z-velocity at the propulsive phase; subject moving downwards = negative Z-velocity at the landing phase). All of the information was combined to define the boundaries between the different relevant phases: initial absorption, propulsive, and final absorption for the drop jumps (bilateral and unilateral) and propulsive and final absorption for the countermovement jumps (Figure 1A and 1B).

The absorption phase of the jump was defined as the portion of the jump in which the subject endured negative acceleration relative to the instant previous to the initial contact (or active impulse exertion) and the management of the impact against the ground (negative followed by positive vertical axis acceleration corresponding to the vertical axis decomposition of the ground reaction force recorded by the ISU). There were 2 absorption phases described for the Drop Jumps: initial absorption (IA; T1–T2 events) and final absorption (FA; T4–T5 events). For VUCMJ, an alternative final absorption phase (FA; T5–T6 events) was described (Figure 1A and 1B).

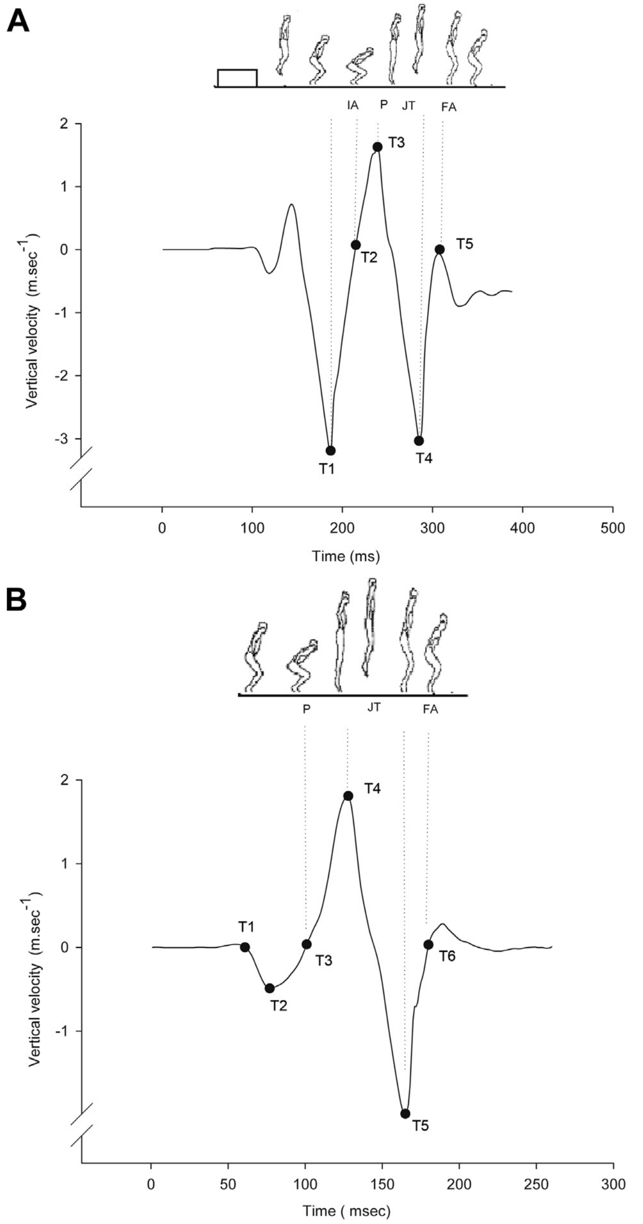

Figure 1. Vertical Z-axis linear velocity descriptive curves. (A) Vertical bilateral drop jump. (B) Vertical unilateral countermovement jump. IA, initial absorption; P, propulsive phase; JT, jumping time; FA, final absorption.

The propulsive phase of the jump was defined as the portion of the jump in which the subject exerted a positive force, representing an active concentric action against the ground (positive vertical axis acceleration recorded by the ISU) (Figure 1A and 1B). This phase corresponds to T2-T3 events for drop jumps and T3-T4 events for the VUCMJ.

The flight time of the jump was determined as the portion of the jump in which the subject was not exerting any force against the ground (no positive vertical axis accelerations recorded by the ISU) (Figure 1A and 1B). This phase corresponds to T3–T4 events for drop jumps and T4-T5 events for the VUCMJ.

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

Descriptive statistical methods were used to calculate the mean and standard error of the mean. The different outcomes were verified to have normal distributions using the Levene test. In the case of the VBDJ, only a 2-tailed unpaired *t*-test was performed to compare the means between groups (controls versus previously ACL-reconstructed subjects). For the 2 unilateral jumping modalities, a one-way analysis of variance was performed to compare differences between limbs with subsequent Bonferroni post hoc comparisons. When the variance equality was rejected, the Tamhane post hoc test was performed. The significance level was set at $P \leq .05$.

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

Results

There were no significant ($P \leq .05$) differences between the groups with regard to any of the anthropometric-related registered variables (Table 1).

VBDJ

Duration of Jumping Phases

There were no significant ($P \geq .05$) differences between the groups with regard to any of the recorded variables for the VBDJ jump phase durations (Figure 2).

Peak Acceleration Values

The control athletes showed significantly greater X-axis peak acceleration in the FA phase of the VBDJ compared with the athletes with a previously reconstructed ACL ($P = .008$; 95% confidence interval [95% CI] 4.91-30.63; Figure 3A). No other significant differences were found for any of the other axes for any of the described jump phases (Table 2).

Mean Orientation Values

There were no significant ($P \geq .05$) differences for the absolute angular excursion within the jump phases between the extremities in the X-, Y- or Z-axis (Table 2).

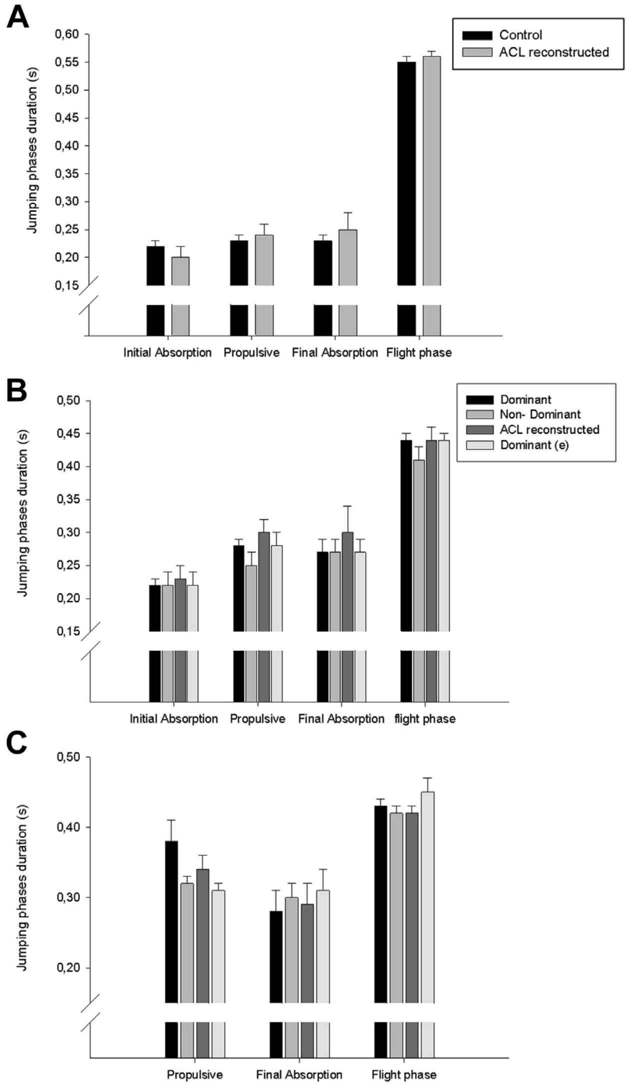

Figure 2. Time phase durations. (A) vertical bilateral drop jump; (B) vertical unilateral drop jump; (C) vertical unilateral countermovement jump. ACL, anterior cruciate ligament.

VUDJ

Peak Acceleration Values

In the control subjects, the dominant leg displayed significantly ($P < .05$) greater peak acceleration in the X-axis compared with the contralateral leg ($P = .005$; 95% CI 3.83-31.50) during the IA phase of the VUDJ (Figure 4A). This pattern of laterality dependence between the different limbs was not observed in the limbs of athletes with a previously reconstructed ACL (Figure 4).

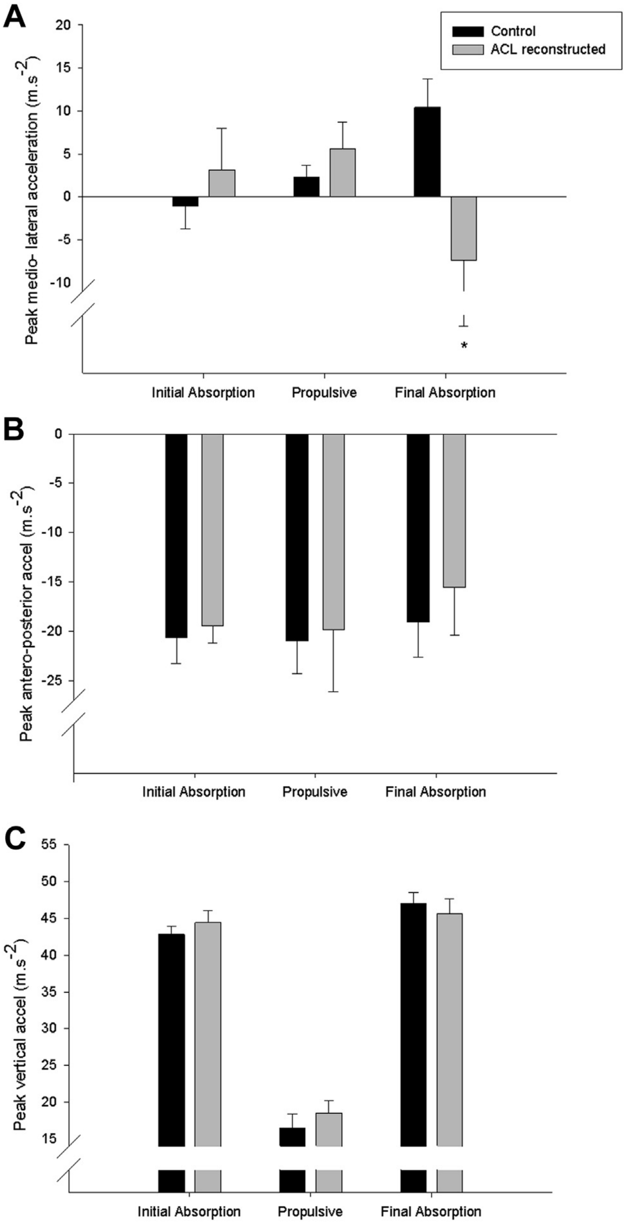

Figure 3. Vertical bilateral drop jump peak acceleration. (A) X, mediolateral axis; (B) Y, antero-posterior axis; (C) Z, vertical axis. *$P < .05$ compared to the control group.

Table 2
VBDJ inertial orientation tracker—derived descriptive values

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

Values expressed as mean and (standard error of the mean).

VBDJ = vertical bilateral drop jump; ACL = anterior cruciate ligament; IA = initial absorption; med-lat = mediolateral; ant-post = anteroposterior; P = propulsive; FA = final absorption.

* *t*-test $P < .05$ with respect to control group.

Duration of Jumping Phases

No significant ($P \geq .05$) differences were found between the extremities for any of the recorded variables for the VUDJ jump phase durations (Figure 2B).

Mean Orientation Values

The nondominant legs of the control athletes showed significantly greater angular excursions around the Z-axis (rotational transversal plane movement at the L3-L4 lumbar vertebrae level) compared with their contralateral limbs in the IA phase ($P = .006$; 95% CI 1.30-11.55), the P phase ($P = .001$; 95% CI 4.00-19.84) and the FA phase ($P = .006$; 95% CI −10.83 to 1.56) compared with the contralateral dominant limbs. This pattern of laterality dependence between different limbs was not observed in previously ACL-reconstructed limbs (Table 2).

VUCMJ

Peak Acceleration Values

No significant differences ($P \geq .05$) were found between limbs for any of the analyzed axes (Figure 5A).

Duration of Jumping Phases

There were no significant ($P \geq .05$) differences between groups with respect to any of the recorded variables for the VUCMJ jump phase durations (Figure 2C).

Mean Orientation Values

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

Discussion

The purpose of this study was to examine the biomechanical jumping pattern in a cohort of elite male handball players with or without previous ACL reconstruction by the use of an ISU placed on the lumbar spine. The main finding of the present study was that control participants demonstrated the ability to support greater X-axis peak acceleration at the FA phase of the VBDJ compared with athletes with a previously reconstructed ACL (Figure 2). Furthermore, the nondominant leg of non—ACL-reconstructed participants displayed greater angular excursions around the Z-axis while they performed a VUDJ during all 3 predefined jumping phases (Table 3). Surprisingly, this dominance effect was not observed in participants with a previously reconstructed ACL. Finally, athletes with a previously reconstructed ACL experienced greater mediolateral trunk displacement in the FA phase of the VUCMJ compared with non-ACL-reconstructed controls (Table 4). These results partially rejected the study hypothesis; although the movement pattern appeared to be slightly different between groups, jumping performance was not affected by previous ACL reconstruction.

These results could be especially relevant because previous investigations by our group demonstrated

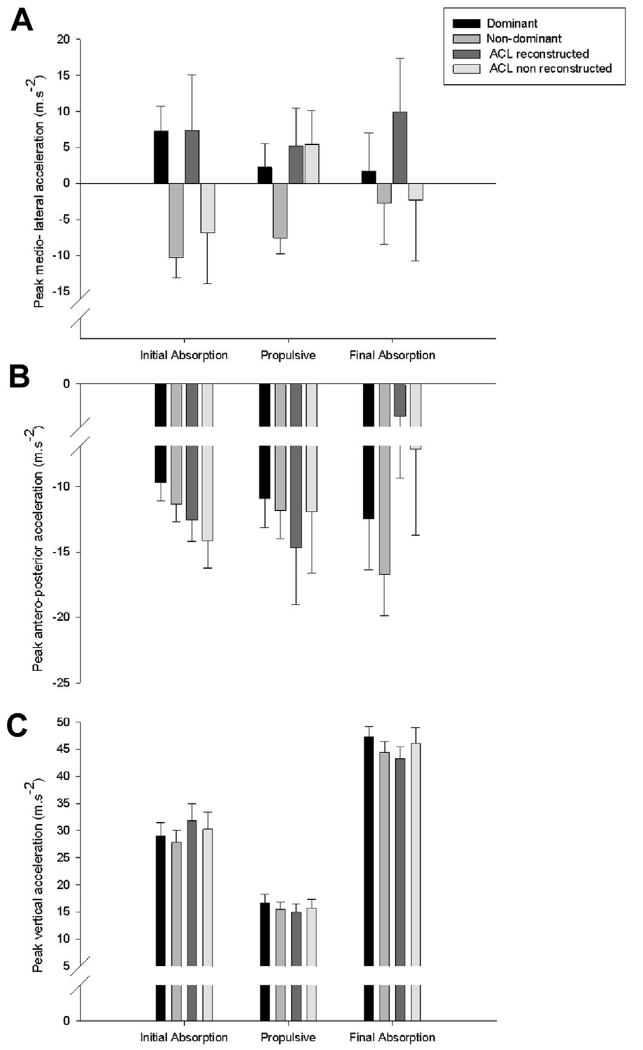

Figure 4. Vertical unilateral drop jump peak acceleration. (A) X, mediolateral axis; (B) Y, anteroposterior axis; (C) Z, vertical axis.

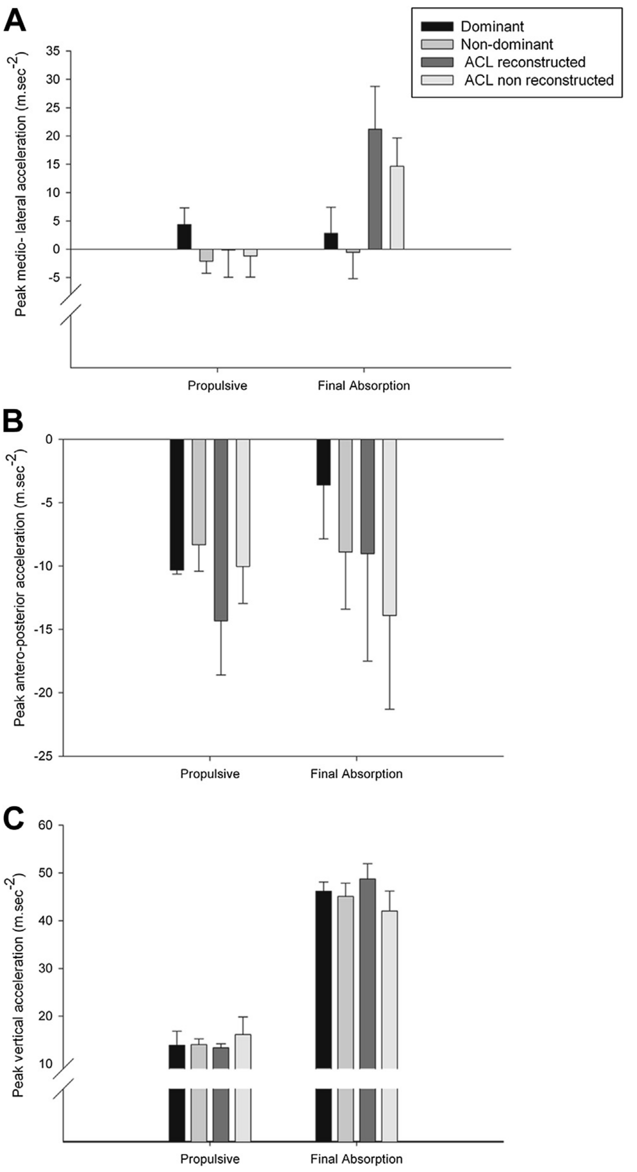

Figure 5. Vertical unilateral countermovement jump peak acceleration. (A) X, mediolateral axis; (B) Y, anteroposterior axis; (C) Z, vertical axis.

long-term residual jumping functional and biomechanical alterations in a cohort of competitive elite female handball athletes who were evaluated at a similar time after ACL reconstruction with the same methodology [25]. This results could indicate a possible gender-dependent outcome after ACL reconstruction, which has been described previously in the literature [28] in a nonprofessional cohort of athletes.

Several authors have studied sagittal and frontal plane lower limb kinematics during Drop Jumps and compared the results by gender, ACL injury, and age [16,29-31]; however, multiplane kinetic and kinematic examinations of these jumps in previously ACL-reconstructed subjects based on direct mechanics procedures have not been conducted. Non—ACL-reconstructed athletes in the present study demonstrated greater X-axis peak acceleration compared with ACL-reconstructed participants during the FA phase of the VBDJ (Table 2). These results could indicate a better capacity of non—ACL-reconstructed athletes to dissipate the VGRF into the other spatial axes, although this assumption could not be verified because the vertical accelerations were not different between groups.

Interestingly, non—ACL-reconstructed athletes demonstrated an exacerbated laterality-dependent Z-axis orientation asymmetry when jumping with either the dominant or non-dominant limb; this was not observed in ACL-reconstructed cases during the execution of a VUDJ (Table 3). Thus, the nondominant legs of the control athletes showed significantly greater angular excursions around the Z-axis (rotational transversal plane movement described at the trunk level) compared with the contralateral limbs in the IA, P

Table 3
VUDJ inertial orientation tracker–derived descriptive values

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

Values expressed as mean and (standard error of the mean).

VUDJ = vertical unilateral drop jump; ACL = anterior cruciate ligament; IA = initial absorption; med-lat = mediolateral; ant-post = anteroposterior; P = propulsive; FA = final absorption.

* Analysis of variance test $P < .05$ with respect to control dominant limb.

and FA phases of the VUDJ. Some controversy exists in the literature regarding the biomechanical evidence for a dominance effect during single unilateral vertical jumping tasks in healthy and/or previously ACL-reconstructed individuals. Some authors have argued that rehabilitation [32] or training effects [33] could attenuate asymmetry in extremities in healthy individuals, whereas others have reported no dominance effects [34].

Finally, the VUCMJ did not reveal any meaningful discriminative capacity between groups (Figure 3C, Table 3). It has been widely reported [35] that in drop jumps, the height from which the drop is performed directly affects the magnitude of the resultant ground reaction force. Because this force is often the triggering event in an ACL injury, perhaps more physically demanding activities (such as drop rather than countermovement jumps) should be used to challenge the lower limb absorption capacity and thereby make potential deficits among different cohorts more evident.

Trunk-supported accelerations have been shown to positively correlate with the VGRF produced at initial contact during walking [36]. The results of the present

Table 4
VUCMJ inertial orientation tracker–derived descriptive values

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

Values expressed as mean and (standard error of the mean).

VUCMJ = vertical unilateral counter movement jump; ACL = anterior cruciate ligament; IA = initial absorption; med-lat = mediolateral; ant-post = anteroposterior; P = propulsive; FA = final absorption.

† Analysis of variance test $P < .05$ with respect to control nondominant.

study are in contrast with previous research based on inverse mechanics, which stated that several VGRF asymmetries exist among previously ACL-reconstructed subjects once having returned back to sports in both the short and long term [19,37]. Moreover, some evidence argues that increased trunk flexion and contralateral leg swing exist in previously ACL-reconstructed subjects for a maximum of 12 months after surgery [18,38]. This strategy reflects an attempt to attenuate the knee extension internal moment by transferring the acting moments to the adjacent joints (hip and ankle) to protect the integrity of the ACL graft [18,38]. This exacerbated forward trunk displacement while landing was not observed in our cohort of previously ACL-reconstructed elite male handball players.

With respect to biomechanical jumping alterations once resuming a non restricted activity level resumed after ACL surgical reconstruction, the discrepancies with the available scientific literature could be explained by the lack of available studies focusing on cohorts stratified by gender, activity level, and time since the original injury and reconstruction [28,39]. All the athletes with previous ACL reconstruction in the present investigation were top-level professional handball players that had resumed their previous activity level after ACL reconstruction. This point, together with the fact that several years had passed since the original injury event, could have favored the lack of differences between the groups. In agreement with the results of the present investigation, Busfield et al [40] showed nonsignificant differences in playing-related abilities among elite professional male basketball players, and Brophy et al [41] 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.

A unique potential clinical implication of the present study is that clinicians can use a single ISU to perform a biomechanical examination of several vertical jumping tests to measure supported acceleration in 3 dimensions and jumping performance (jump phase duration) in previously ACL-reconstructed male athletes, even if several years have passed since the original injury. Traditional inverse mechanics-based research that uses both force plates and infrared motion capture cameras for kinetic and kinematic movement description, respectively, requires both a considerable financial investment and a highly trained staff familiar with such laboratory-derived procedures. The development of microelectromechanical systems has produced ISU as a new alternative for movement performance assessments in medical and clinical practice [9]. Inertial sensors with accelerometers, gyroscopes and, in some cases, magnetometers are innovative, noninvasive solutions for assessing sports-related performance [42] that can be used as a clinical resource during ACL rehabilitation [15]. Furthermore, ISU offers the possibility of landing outside a predefined place, in contrast to traditional ground-located force plates. This fact enables more functional and unplanned movement analyses.

Previous studies have highlighted the potential of these measurement techniques to identify different persistent movement pattern alterations in relation to ACL injuries [15-17]. Basing the analysis on body center of mass behavior makes the technique easier to handle for clinicians to perform. Therefore, clinicians could directly assess a patient's functional and biomechanical status in terms of jumping phase duration and magnitude of supported accelerations based on the athlete's center of mass either during or years after an ACL rehabilitation program.

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

Conclusions

Previously ACL-reconstructed elite male handball athletes demonstrated similar jumping performance but slightly different (X-), (Y-), and (Z-) spatial peak acceleration and angular excursion distribution strategies compared with non–ACL-reconstructed controls. These findings are in agreement with previous studies that showed full functional restoration of abilities in top-level male athletes after ACL reconstruction, rehabilitation and consequent return to previous activity level.

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