Physical Therapy in Sport 39 (2019) 52–63

Contents lists available at ScienceDirect

Physical Therapy in Sport

journal homepage: www.elsevier.com/ptsp

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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ARTICLE INFO

Article history:
Received 17 May 2019
Received in revised form
19 June 2019
Accepted 19 June 2019

Keywords:
Knee
ACL
Injury
Functional evaluation
Inertial sensor

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 re-injury 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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https://doi.org/10.1016/j.ptsp.2019.06.009
1466-853X/

(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 cross-over 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).

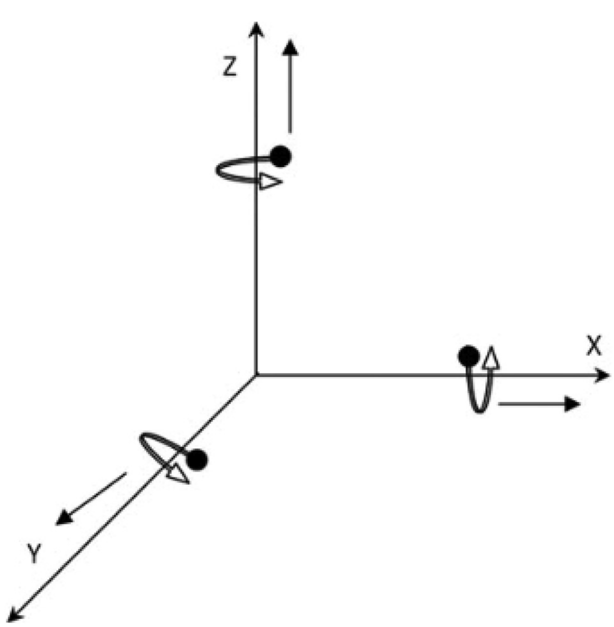

Fig. 1. Earth-fixed global Cartesian reference frame. Z-axis (vertical), X-axis (medial-lateral) and Y-axis (anterior-posterior) orientations.

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.

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

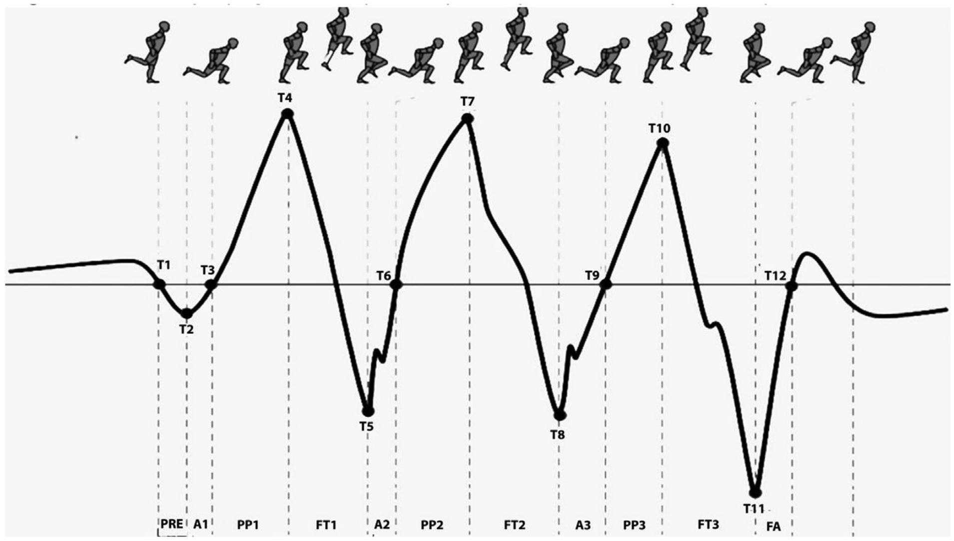

Fig. 2. Horizontal jumping maneuver phases by velocity-time curve analysis description.

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.

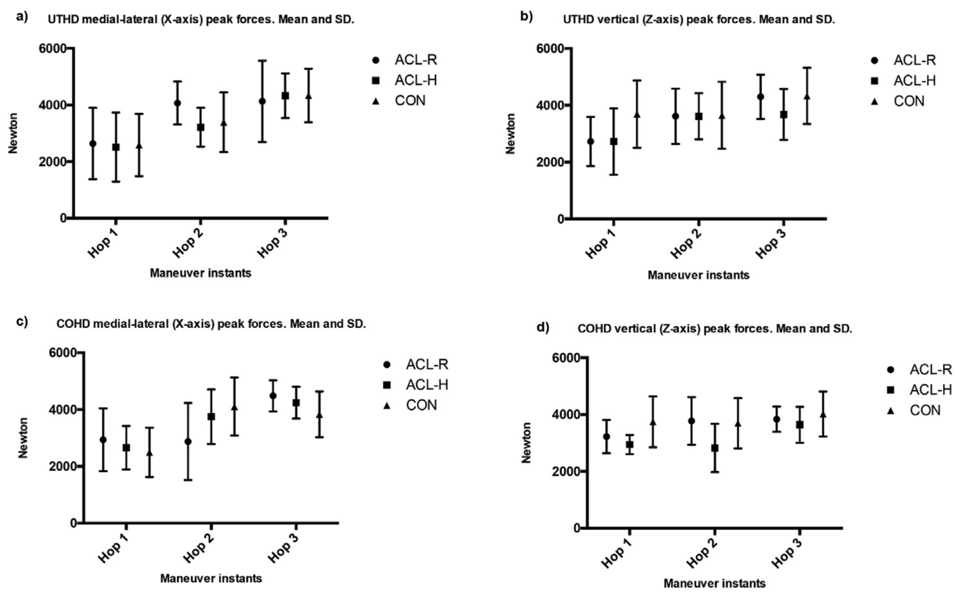

Fig. 3. Between groups peak vertical and medial-lateral forces comparison during the unilateral triple hop for distance (UTHD) and the unilateral cross over hop for distance maneuvers. Mean and SD. Abbreviations: (UTHD), unilateral triple hop for distance; (COHD), unilateral cross over hop for distance; 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).

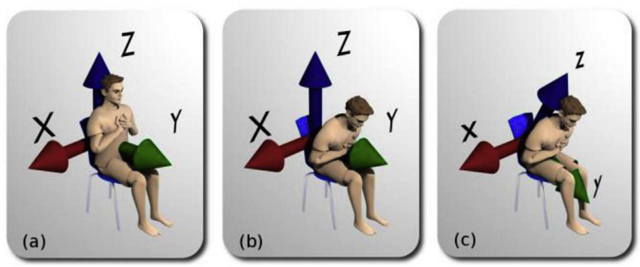

Fig. A1. Changes in global and IU's local Cartesian reference axes when the subject is trying to stand up at the beginning of the 30-s CST. The first figure, (a), depicts the initial position; global and local reference axes coincide. When the subject changes position, the global axis remains unchanged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

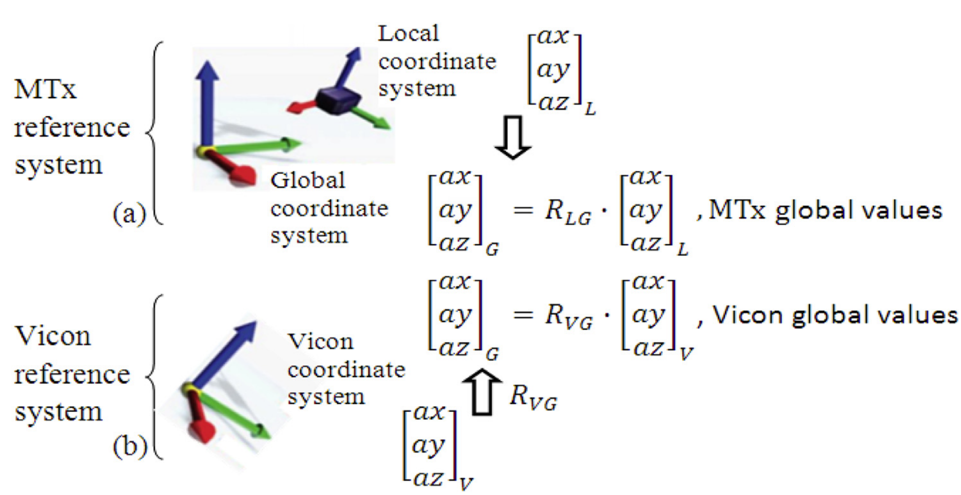

Fig. A2. Reference systems changes to obtain the global values from MTx and Vicon. Sub-indexes "L", "G" and "V" refer to the MTx local, global and Vicon local coordinate systems respectively and RLG and RVG to the rotation matrices to change coordinates from the first indicated reference system to the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

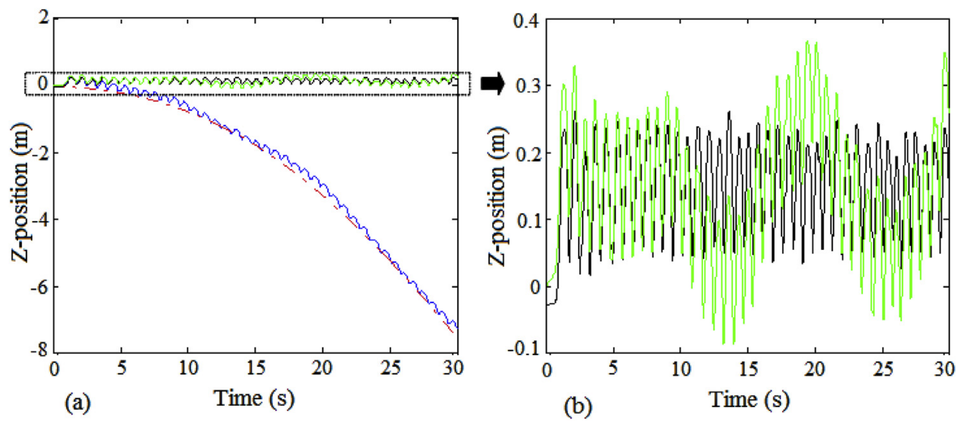

Fig. A3. (a) shows the Z-position signal (blue line) gravity error correction (green line), and the Vicon reference signal (black line). Red line is the tendency line based on fourth level polynomial estimation that tracks the gravity error, Part (b) shows the corrected and reference signal enlargement.

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).

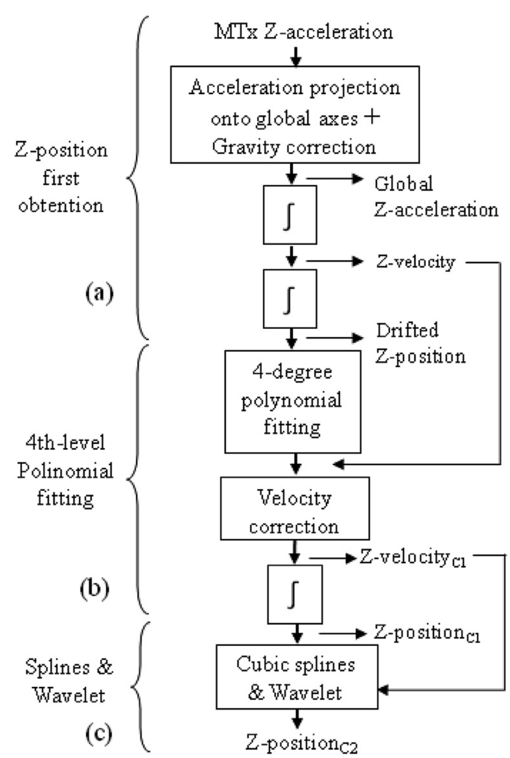

Fig. A4. Z-position free-drift obtaining algorithm: double integration process, part (a), first correction (C1), part (b). and second correction (C2), part (c).

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:

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

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

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	*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	*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*. * = $p < .05$. ^ = $d > 0.8$.

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