Journal of Human Kinetics volume xx/xxxx, x–x DOI: 10.5114/jhk/236110 x
Section II – Exercise Physiology and Sports Medicine

Effects of Mixed Training on Biomechanical Risk Proxies for ACL Injury in Trained Youth Basketball Athletes

by
Loudovikos-Dimitrios Liosis [1,2,] , Jordan Santos-Concejero [2], Raúl Martínez-Santos [2]*

Mixed training may serve as a tool to mitigate injury risk by reducing lower-limb asymmetries, enhancing neuromuscular control, and optimizing landing biomechanics. The purpose of this study was to investigate the effects of mixed training on unilateral lower-limb stiffness (LLS) and the landing error scoring system (LESS) as biomechanical risk proxies associated with anterior cruciate ligament (ACL) injuries. Thirty-two trained youth male basketball athletes were randomly assigned to a French contrast, a contrast, or a complex training protocol in a six-week mesocycle with a training frequency of twice per week. All groups performed pre- and post-training intervention measurements of unilateral drop jump stiffness and the bilateral drop jump LESS. Two-way ANOVAs revealed significant interaction effects between the round and the protocol for non-dominant LLS ($p = 0.03$) and the LESS ($p = 0.003$). Athletes experienced significant and pronounced improvements in non-dominant LLS and the LESS following complex (LLS: $p = 0.0008$, $d = 1.30$; LESS: $p = 0.005$, $d = 1.41$) and contrast (LLS: $p = 0.017$, $d = 1.10$; LESS: $p = 0.007$, $d = 1.35$), but not French contrast training strategies. Linear regression showed significance ($p = 0.009$), with changes in non-dominant LLS accounting for 21% of the variance in LESS changes. Our findings demonstrate the effectiveness of both complex and contrast training as an indirect ACL injury risk minimization tool via improvements in non-dominant LLS and the LESS. Such improvements may be attributed to post-intervention neuromuscular adaptations, including greater higher-threshold motor unit recruitment, rate coding, and synchronization.

***Keywords**: knee; stiffness; connective tissue; sports; landing*

Introduction

One of the most common injuries requiring surgery in youth basketball athletes is an anterior cruciate ligament (ACL) tear (Joseph et al., 2013). Although not as common as in females, an ACL injury rate of 2.3 incidents per 100,000 athletes has been reported in male high school basketball athletes (Joseph et al., 2013). Non-contact ACL injuries account for up to 70–84% of all cases and typically occur during high-risk basketball movements, such as cutting/stopping drills coupled with deceleration/change of direction, and landing from a jump (Kaneko et al., 2017). These patterns underscore the need for ACL injury risk minimization interventions targeted to basketball athletes at the grassroots level (Joseph et al., 2013).

The development of lower-limb stiffness (LLS) has been correlated with more efficient landing biomechanics, which help prevent excessive loading of the ACL and protect athletes from decreases in lower-limb dynamic stability and an increased risk of ACL injury (Blackburn et al., 2013; Zhang et al., 2023b), while simultaneously promoting improvements in various athletic tasks and physical performance variables (Brazier et al., 2019). Exercise modalities targeting unilateral LLS are of paramount importance and should be incorporated into ACL injury risk minimization strategies; in fact, Zhang et al. (2023b)

[1] *Athletics & Recreation-Center of Excellence in Food, Tourism & Leisure, DEREE—The American College of Greece, Athens, Greece.*
[2] *Faculty of Education and Sport, University of the Basque Country, Vitoria-Gasteiz, Spain.*
* Correspondence: loudovikos.liossis@gmail.com, dliossis@acg.edu

CC BY

demonstrated that inadequate levels of LLS during a single-leg drop jump (DJ) test corresponded with lower levels of dynamic stability, knee joint hypermobility, and an increased risk of non-contact ACL injuries. Knee joint stiffness, achieved via greater muscle activation, is considered essential for maintaining joint stability during activities deemed high-risk for ACL injury, such as landing (Ambegaonkar et al., 2011). It must be emphasized that when an athletic task requires increased levels of LLS, a solid strength base must already be established in the corresponding musculature to manage the substantial loading rate demands and limit the inherent injury risk associated with the activity (Brazier et al., 2019).

The constituent elements of mixed training (MT) strategies are compatible with the components of ACL injury risk minimization protocols recommended by Nessler et al. (2017), including plyometrics, integrative neuromuscular training, and strength exercises, and can effectively target the development of LLS. To our knowledge, only one study has explored the effect of MT on neuromuscular strength and landing kinematics from a knee injury perspective in youth athletes. Humphrys et al. (2018) investigated the effects of a 6-week MT program, performed once per week and incorporating bilateral lower-body complex training pairs, on the countermovement jump (CMJ) vertical displacement, CMJ power output, the landing error scoring system (LESS), and single-leg CMJ vertical displacement in youth netball players. Those authors reported significant improvements in CMJ vertical displacement and power output, as well as in the LESS and non-dominant leg CMJ vertical displacement, suggesting that MT can serve as a viable tool to indirectly mitigate injury risk by reducing lower-limb asymmetries, enhancing neuromuscular control, and optimizing landing biomechanics (Humphrys et al., 2018). Future studies should focus on the effect of MT on LLS as a potential mechanism for knee injury risk minimization (Humphrys et al., 2018). Assessment of unilateral LLS may enable practitioners to identify neuromuscular deficits as well as the adaptive neuromuscular reserve for LLS regulation in youth athletes, thereby allowing targeted interventions through specialized injury risk minimization strategies (Tai et al., 2025).

Therefore, the purpose of this study was to investigate the effects of short-term MT on unilateral LLS following a 6-week mesocycle in trained youth basketball players, with the aim of evaluating its indirect potential as an ACL injury risk minimization training strategy, indicated by changes in the LESS. It was hypothesized that MT would increase unilateral LLS in both limbs, with greater adaptations in the non-dominant limb. It was also hypothesized that MT would improve the LESS, reflecting more optimal landing mechanics (Padua et al., 2009).

Methods

Participants

Thirty-two male basketball athletes (age 16.06 ± 0.79 years; body mass 71.34 ± 9.75 kg; body height 183.06 ± 6.53 cm) voluntarily took part in this experiment. All athletes had at least four years of experience as competitive athletes, as well as a minimum of 2 years of supervised resistance training experience, consisting of free weights, plyometrics, and Olympic weightlifting components. The biological maturity of the participants was not assessed in this study. Athletes, parents, and coaches were informed about the purpose and procedures of this study. Informed assent was read and approved by all participants and informed consent forms were signed by the parents of all athletes to confirm the inclusion of their children in the training intervention. All information was delivered in a simplified and easy to comprehend format. Ethical approval was granted by the Institutional Review Board of DEREE—The American College of Greece, Athens, Greece (IRB protocol: #202405432; approval date: 16 May 2024). All procedures of this study were in accordance with the Helsinki declaration of 1975, as revised in 2024. Based on a power analysis conducted before the beginning of this experiment, thirty-two participants were needed to establish a statistical power above 0.80 with an effect size of 0.5 and expected type I error of 0.05.

Design and Procedures

This study employed a parallel-group design in which one experimental group followed a French contrast (FCT) MT protocol, a second experimental group performed a traditional complex (CXT) MT protocol, a third experimental group completed a contrast (CT) MT protocol, and

a control group (CG) resumed standard basketball practice and on-court strength and conditioning. Participants were randomly allocated to the FCT group (n = 8), the CXT group (n = 8), the CT group (n = 8), or the CG (n = 8) during a 6-week mesocycle with a training frequency of twice per week. All experimental groups and the CG underwent pre- and post-training measurements, consisting of the evaluation of the kinetic parameter of unilateral LLS and the LESS, used for indirect ACL injury screening.

All experimental protocols incorporated both vertical and horizontal muscle force vector orientation lower-body exercises, the concomitant inclusion of which had been demonstrated to enhance jump performance in youth athletes (Abade et al., 2021). The bilateral and unilateral DJ exercises used to evaluate the LESS and LLS in this study were also characterized by both vertical and horizontal muscle force vectors, with horizontal ground reaction forces stabilizing the body and controlling the center of mass upon landing and vertical ground reaction forces absorbing impact upon landing and propelling the body upward (Fransz et al., 2016). Unilateral strength training has been suggested to be more effective for unilateral jump power patterns, while bilateral strength training appears more effective for bilateral patterns (Zhang et al., 2023a). However, concerns about suboptimal movement mechanics during progressive overloading in unilateral strength exercises (Zhang et al., 2023a), combined with evidence showing minimal differences between unilateral and bilateral plyometric training on unilateral performance and symmetry (Cao et al., 2024), supported the exclusive use of bilateral strength-power training pairs in this study.

The unilateral DJ test was initiated with a box step-off from a height of 25 cm. Participants were then instructed to initiate the take-off by leaning forward, maintain hand placement on their hips, keep their knees at full extension during flight time, and land in an upright position by touching down on the mat with one foot at the same point during each successive trial (Ball et al., 2010). Upon landing, participants were advised to jump as high as possible, while minimizing knee flexion and ground contact time (Ball et al., 2010). A total of three jumps were performed for each leg, with approximately 30 s of rest in between; the best of the three trials was selected for further analysis. The performance variable assessed during unilateral DJs was single-leg LLS. The same procedure used for the unilateral DJ test was applied during the bilateral DJ test; however, for the bilateral assessment, a 40-cm box was positioned at a distance equal to half the participant's body height from the landing zone, which was marked by a line on the ground, and participants executed the drop jump using both legs instead of one (Padua et al., 2015). The testing variable for this task was the LESS.

Upper-body exercises were also included in the training protocols given the potential importance of upper-body strength to contribute to jumping performance (Curovic et al., 2024). Training volume was equalized across the experimental protocols. The constituent elements of the MT protocols and a schematic representation of the experiment are presented in Table 1 and Figure 1C, respectively.

All athletes completed DJ experimental testing five days prior to and five days post-intervention to evaluate performance changes. All testing sessions were conducted in the evening (between 19:00 and 21:00) to minimize diurnal variations in DJ performance and optimize core body temperature, a key factor affected by the circadian rhythm (Trajković et al., 2024). Prior to the pre-experimental measurements, all participants completed a familiarization session during which they were introduced to the testing equipment and evaluated their maximal strength in all resistance training exercises included in the intervention protocols.

At the outset, participants performed a standardized total body warm-up routine consisting of 5 min of light jogging followed by 5 min of dynamic stretching activities and mobility drills. Subsequently, participants undertook a standardized one repetition maximum (1RM) strength testing protocol for the back squat, hip thrust, landmine squat, and bench press exercises as recommended by Li et al. (2019). For the hang power clean (HPC) exercise, participants completed a standardized warm-up routine as suggested by Faigenbaum et al. (2012). Maximal strength testing was conducted over three sessions interspersed with 48-hour rest intervals: session 1 included the HPC exercise; session 2 consisted of the landmine squat and barbell bench press

Articles published in the Journal of Human Kinetics are licensed under an open access Creative Commons CC BY 4.0 license.

exercises; and session 3 included the back squat and hip thrust maximal strength testing.

Pre-experimental measurements were conducted 48 hours after the final maximal strength testing session. Unilateral LLS was measured using an open-source, portable jump mat (Chronojump Boscosystem, Barcelona, Spain) interfaced with a laptop, which has been demonstrated as a valid and reliable testing device for monitoring changes in jump performance (Pueo et al., 2020). For the assessment of the LESS, two tripod-secured Samsung Galaxy A55 smartphones, each equipped with embedded digital video cameras consisting of a 64-megapixel main sensor, an 8-megapixel ultra-wide lens, and a 5-megapixel depth sensor, were used to capture video footage for subsequent analysis. The cameras were positioned 3 m in front of and to the right of the participants to capture frontal and sagittal plane views of all landing efforts; movements were analyzed beginning at the initial ground contact frame, defined as the frame immediately before the foot was flat on the ground, and throughout the period between initial contact and maximum knee flexion (Padua et al., 2015). The LESS has been demonstrated as a valid and reliable clinical screening tool for identifying high-risk movement patterns during DJ landing tasks (Padua et al., 2009).

Statistical Analysis

The statistical analyses for this experiment were conducted using R statistical software (R 4.3.1) within R Studio (R studio, PBC, USA). Descriptive statistics (mean ± SD) were provided for the variables of unilateral LLS and the LESS, followed by normality and sphericity analysis. In cases where the sphericity assumption was violated, the Huynh-Feldt correction factor was applied when epsilon was greater than 0.75, whereas the Greenhouse-Geisser correction factor was applied when epsilon was less than 0.75.

A two-way factorial ANOVA with repeated measures on the first factor (2 rounds: pre-training and post-training x 4 protocols: CXT, CT, FCT, CG) was then conducted to examine pre- to post-intervention differences within and between the experimental protocols. In cases where significant interaction effects were detected, the simple effects method with Bonferroni confidence-interval (CI) adjustment was used to compare pre- and post-intervention data for each dependent variable (LLS, LESS). Significance for all analyses was set at $p < 0.05$. Cohen's d effect sizes and their 95% CIs between pre- and post-experimental measurements were also calculated and interpreted as trivial (0.00–0.19), small (0.20–0.59), medium (0.60–1.19), large (1.20–1.99), or very large (2.00–3.99), using the scale developed by Hopkins et al. (2009).

Finally, a Pearson product-moment correlational analysis was conducted to examine the relationship between changes in LLS and changes in LESS scores, followed by a simple linear regression to determine whether LLS changes could explain changes in landing performance. The regression analysis was exploratory and hypothesis generating, rather than a confirmatory test of pre-specified hypotheses. Correlation magnitudes (r) of 0.1, 0.1–0.3, 0.3–0.5, 0.5–0.7, 0.7–0.9, and >0.9 were interpreted qualitatively as trivial, small, moderate, large, very large, and almost perfect correlations, respectively. Coefficients of determination (R^2) of 0.02, 0.03–0.13, 0.14–0.26, 0.27–0.39, 0.40–0.50, and >0.50 were interpreted qualitatively as small, small-to-medium, medium, medium-to-large, large, and very large effects, respectively.

The bilateral and unilateral DJs performed during the familiarization-baseline testing session were used to calculate intraclass correlation coefficients (ICC [3,1]), 95% CIs for the ICC, and coefficients of variation (CV) to determine within- and between-participant variability in DJ performance. Reproducibility was high for all tested variables: LESS: (CV = 6.81%, ICC = 0.91; CI 95%: 0.846–0.951), LLS (dominant limb): (CV = 3.89%, ICC = 0.972; CI 95%: 0.95–0.985), and LLS (non-dominant limb): (CV = 5.35%, ICC = 0.958; CI 95%: 0.926–0.978). The smallest real difference for 95% CIs was 1.44 points for LESS, 1355.7 N/s for dominant LLS, and 1801.51 N/s for non-dominant LLS.

Results

Tables 2 and 3, and Figures 1A and 1B, present peak LLS and LESS performance from baseline to post-intervention.

LLS

A two-way factorial ANOVA revealed a significant interaction effect between the round

and the protocol for non-dominant LLS: $F(3, 28) = 3.46$, $p = 0.03$. Subsequent pairwise comparisons indicated that the CXT protocol (pre-post LLS change = 2960.01 N/m, $p = 0.0008$, $d = 1.30$; CI 95%: 0.31–2.23, large) and the CT protocol (pre-post LLS change: 2661.74 N/m, $p = 0.017$, $d = 1.10$; CI 95%: 0.19–1.97, medium) produced significant improvements in non-dominant LLS. In contrast, the FCT and the CG protocols elicited non-significant ($p > 0.05$) changes in non-dominant LLS. No significant interaction effects ($p > 0.05$) were observed between the round and the protocol for the dominant LLS variable.

LESS

A two-way factorial ANOVA revealed a significant interaction effect between the round and the protocol for the LESS: $F(3, 28) = 5.99$, $p = 0.003$. Subsequent pairwise comparisons indicated that the CXT protocol (pre-post LESS change = 1.25, $p = 0.005$, $d = 1.41$; CI 95%: 0.39–2.39, large) and the CT protocol (pre-post LESS change: 1.12, $p = 0.007$, $d = 1.35$; CI 95%: 0.35–2.30, large) produced significant improvements in the LESS. It should be noted that the improvements were reflected by a lower LESS score.

Correlational Analysis—Linear Regression

The Pearson product-moment correlation analysis revealed a significant negative relationship between changes in non-dominant LLS and changes in LESS scores ($r(30) = −0.45$ (large), $p = 0.009$). Linear regression analysis further indicated that the model was statistically significant ($F(1, 30) = 7.77$, $p = 0.009$), with an $R^2 = 0.21$ (medium), suggesting that approximately 21% of the variance in changes in LESS scores could be explained by changes in non-dominant LLS. The regression coefficient for non-dominant LLS change was negative and statistically significant (b = −0.00015, t (30) = −2.79, $p = 0.009$).

Discussion

This study investigated the effects of three 6-week, volume-equated MT program strategies (CXT, CT, FCT) on bilateral and unilateral DJ performance. The CXT and CT interventions demonstrated significant improvements in non-dominant LLS (CXT, $p = 0.0008$, $d = 1.30$; CT, $p = 0.017$, $d = 1.10$) and the LESS (CXT, $p = 0.005$, $d = 1.41$; CT, $p = 0.007$, $d = 1.35$). No significant interaction effects were detected for the dominant LLS performance variable.

Our findings on non-dominant LLS align with those of Toumi et al. (2004), who reported significant bilateral LLS improvements following 8 weeks of CXT consisting of strength training exercises followed by plyometric drills in male handball players. However, strength and power exercises were performed in series rather than alternated, a configuration suggested to produce lower effects in jump performance compared to traditional CXT setups (Cormier et al., 2022). Additionally, the biomechanical similarity principle was not strictly followed (Galiano et al., 2025), as the leg press exercise was paired with crossover jump plyometrics. In contrast to the protocol used by Toumi et al. (2004), Lu et al. (2026) employed biomechanically similar strength-power complexes by pairing heavy half squats with unloaded hurdle jumps and reported significant improvements in LLS during the first step of a sprint start following 8 weeks of traditional CXT in male sprinters. Our study employed biomechanically similar exercises within a traditional CXT configuration and further enriched the current research pool by showing that the most substantial LLS improvements under both traditional CXT and CT conditions occurred in the non-dominant limb.

To our knowledge, the only study that utilized a unilateral jump test to measure LLS was conducted by Scott et al. (2023), who reported significant unilateral LLS improvements in both the dominant and non-dominant limbs following a 6-week CXT intervention in university rugby league athletes, employing a traditional CXT configuration. In contrast, our study demonstrated significant LLS increments only in the non-dominant limb. Our training intervention appears to have reduced inter-limb stiffness asymmetries commonly observed in basketball athletes, who typically exhibit higher LLS in their dominant limb (Struzik et al., 2020), and in youth athletes around the period of peak height velocity (Madruga-Parera et al., 2019). This reduction may be attributed to neuromuscular adaptations that enhance stiffness regulation, particularly in the non-dominant limb (Tai et al., 2025).

Articles published in the Journal of Human Kinetics are licensed under an open access Creative Commons CC BY 4.0 license.

Table 1. Experimental training protocols for Day 1/Day 2 (Part I).

Week	Week 1–2	Weeks 3–4	Week 5–6
		French Contrast Training*	
Exercise 1A	Squat/Hang Power Clean & Jerk[1]	Squats/Hang Power Clean &	Squats/Hang Power Clean & Jerk
Sets x Reps	1 x 3 @ 80/70% 1RM	Jerk	1 x 3 @ 90/80% 1RM
		1 x 3 @ 85/75% 1RM	
Exercise 1B	CMJS/DJs[4]	CMJs/DJs	CMJs/DJs
Sets x Reps	1 x 3	1 x 4	1 x 5
Exercise 1C	Barbell Squat Jumps[5]	Barbell Squat Jumps	Barbell Squat Jumps
Sets x Reps	1 x 3 @ 35% 1RM	1 x 3 @ 40% 1RM	1 x 3 @ 45% 1RM
Exercise 1D	Assisted CMJs[6]	Assisted CMJs	Assisted CMJs
Sets x Reps	1 x 3	1 x 4	1 x 5
Exercise 2A	Landmine Squat/Brb Hip	Landmine Squat/Brb Hip	Landmine Squat/Brb Hip Thrusts
Sets x Reps	Thrusts[2]	Thrusts	1 x 3 @ 90/90% 1RM
	1 x 3 @ 80/80% 1RM	1 x 3 @ 85/85% 1RM	
Exercise 2B	BJs[7]	BJs	BJs
Sets x Reps	1 x 3	1 x 4	1 x 5
Exercise 2C	Landmine Jumps/S. Plyo.	Landmine Jumps/S. Plyo.	Landmine Jumps/S. Plyo. Thrusts
Sets x Reps	Thrusts[3]	Thrusts	1 x 3 @ 45% 1RM
	1 x 3 @ 35% 1RM	1 x 3 @ 40% 1RM	
Exercise 2D	Downhill BJs[8]	Downhill BJs	Downhill BJs
Sets x Reps	1 x 3	1 x 4	1 x 5
Exercise 3A	Barbell Bench Press[9]	Barbell Bench Press	Barbell Bench Press
Sets x Reps	1 x 3 @ 80% 1RM	1 x 3 @ 85% 1RM	1 x 3 @ 90% 1RM
Exercise 3B	Plyo. Push-Ups[10]	Plyo. Push-Ups	Plyo. Push-Ups
Sets x Reps	1 x 3	1 x 4	1 x 5
Exercise 3C	Smith Throws[11]	Smith Throws	Smith Throws
Sets x Reps	1 x 3 @ 35% 1RM	1 x 3 @ 40% 1RM	1 x 3 @ 45% 1RM
Exercise 3D	Incline Plyo. Push-Ups[12]	Incline Plyo. Push-Ups	Incline Plyo. Push-Ups
Sets x Reps	1 x 3	1 x 4	1 x 5
		Complex Training**	
Exercise 1A	Hang Power Clean & Jerk/Squat[1]	Hang Power Clean & Jerk/Squat	Hang Power Clean & Jerk/Squat
Sets x Reps	2 x 3 @ 80/70% 1RM	2 x 3 @ 85/75% 1RM	2 x 3 @ 90/80% 1RM
Exercise 1B	DJ/CMJs[4]	DJs/CMJs	DJs/CMJs
Sets x Reps	2 x 3	2 x 4	2 x 5
Exercise 2A	Landmine Squat/Brb Hip	Landmine Squat/Brb Hip	Landmine Squat/Brb Hip Thrusts
Sets x Reps	Thrusts[2]	Thrusts	2 x 3 @ 90/90% 1RM
	2 x 3 @ 80/80% 1RM	2 x 3 @ 85/85% 1RM	
Exercise 2B	BJs[7]	BJs	BJs
Sets x Reps	2 x 3	2 x 4	2 x 5
Exercise 3A	Barbell Bench Press[9]	Barbell Bench Press	Barbell Bench Press
Sets x Reps	2 x 3 @ 80% 1RM	2 x 3 @ 85% 1RM	2 x 3 @ 90 % 1RM
Exercise 3B	Plyometric Push-Ups[10]	Plyometric Push-Ups	Plyometric Push-Ups
Sets x Reps	2 x 3	2 x 4	2 x 5

CMJs = countermovement jumps, DJs = drop jumps, Brb = barbell, BJs = broad jumps, S. Plyo. Thrusts = Smith-machine plyometric thrust, Plyo = plyometric

[1] Squats were performed on day 1 and hang power clean and jerks were performed on day 2 of each microcycle

[2] Landmine squats were performed on day 1 and barbell hip thrusts were performed on day 2 of each microcycle

[3] Landmine jumps were performed on day 1 and Smith-machine plyometric thrusts were performed on day 2 of each microcycle

[4,5,6,7,8,9,10,11,12] Same exercise for both training days of each microcycle

** Exercises 1A–1D, 2A–2D, and 3A–3D were performed in sequence, with 20 s of rest between exercises.*

*** Exercises 1A & 1B, 2A & 2B, and 3A & 3B were performed in sequence with 3 minutes of rest.*

**** Exercises 1A & 1B, 2A & 2B, and 3A & 3B were performed in sequence with minimal rest*

Table 1. Experimental training protocols for Day 1/Day 2 (Part II).

Week	Week 1–2	Weeks 3–4	Week 5–6
		Contrast Training***	
Exercise 1A	Hang Power Clean & Jerk/Squat[1]	Hang Power Clean & Jerk/Squat	Hang Power Clean & Jerk/Squat
Sets x Reps	2 x 3 @ 80/70% 1RM	2 x 3 @ 85/75% 1RM	2 x 3 @ 90/80% 1RM
Exercise 1B	Hang Power Clean & Jerk/Squat[1]	Hang Power Clean & Jerk/Squat	Hang Power Clean & Jerk/Squat
Sets x Reps	2 x 3 @ 30/40% 1RM	2 x 3 @ 35/45% 1RM	2 x 3 @ 40/50% 1RM
Exercise 2A	Landmine Squat/Brb Hip	Landmine Squat/Brb Hip	Landmine Squat/Brb Hip Thrusts
Sets x Reps	Thrusts[2]	Thrusts	2 x 3 @ 90/90% 1RM
	2 x 3 @ 80/80% 1RM	2 x 3 @ 85/85% 1RM	
Exercise 2B	Landmine Squat/Brb Hip	Landmine Squat/Brb Hip	Landmine Squat/Brb Hip Thrusts
Sets x Reps	Thrusts[2]	Thrusts	2 x 3 @ 50/50% 1RM
	2 x 3 @ 40/40% 1RM	2 x 3 @ 45/45% 1RM	
Exercise 3A	Barbell Bench Press	Barbell Bench Press	Barbell Bench Press
Sets x Reps	2 x 3 @ 80% 1RM	2 x 3 @ 85% 1RM	2 x 3 @ 90 % 1RM
Exercise 3B	Barbell Bench Press	Barbell Bench Press	Barbell Bench Press
Sets x Reps	2 x 3 @ 40% 1RM	2 x 3 @ 45% 1RM	2 x 3 @ 50 % 1RM

CMJs = countermovement jumps, DJs = drop jumps, Brb = barbell, BJs = broad jumps, S. Plyo. Thrusts = Smith-machine plyometric thrust, Plyo = plyometric

[1] Squats were performed on day 1 and hang power clean and jerks were performed on day 2 of each microcycle

[2] Landmine squats were performed on day 1 and barbell hip thrusts were performed on day 2 of each microcycle

[3] Landmine jumps were performed on day 1 and Smith-machine plyometric thrusts were performed on day 2 of each microcycle

[4,5,6,7,8,9,10,11,12] Same exercise for both training days of each microcycle

** Exercises 1A–1D, 2A–2D, and 3A–3D were performed in sequence, with 20 s of rest between exercises.*

*** Exercises 1A & 1B, 2A & 2B, and 3A & 3B were performed in sequence with 3 minutes of rest.*

**** Exercises 1A & 1B, 2A & 2B, and 3A & 3B were performed in sequence with minimal rest*

Table 2. Post-hoc unilateral lower-limb stiffness comparisons of experimental protocols following a significant round*protocol interaction.

Variable	Limb	Round	Protocol	LLS Δ	CI 95%	p_{adj}
DJ Stiffness	ND	1–2	CXT	2960.01	1050.9, 4869.2	0.0008*
DJ Stiffness	ND	1–2	CT	2661.7	643.4, 4680.1	0.017*
DJ Stiffness	ND	1–2	FCT	2996.6	−432.25, 5025.4	0.087
DJ Stiffness	ND	1–2	CG	−576.3	−1996.1, 843.4	0.369

*DJ = drop jump, ND = non-dominant, LLS = lower-limb stiffness, p_{adj} = p-value adjustment, CI = confidence intervals, CXT = complex training, CT = contrast training, FCT = French contrast training, CG = control condition, * = statistically significant values*

Table 3. Post-hoc landing error scoring system comparisons of experimental protocols following a significant round*protocol interaction.

Variable	Round	Protocol	LESS Δ	CI 95%	p_{adj}
DJ LESS	1–2	CXT	−1.25	−1.99, −0.51	0.005*
DJ LESS	1–2	CT	−1.13	−1.82, −0.43	0.007*
DJ LESS	1–2	FCT	−0.25	−0.63, 0.14	0.17
DJ LESS	1–2	CG	0.13	−0.57, 0.82	0.69

*DJ = drop jump, LESS = landing error scoring system, p_{adj} = p-value adjustment, CI = confidence intervals, CXT = complex training, CT = contrast training, FCT = French contrast training, CG = control condition, * = statistically significant values*

Articles published in the Journal of Human Kinetics are licensed under an open access Creative Commons CC BY 4.0 license.

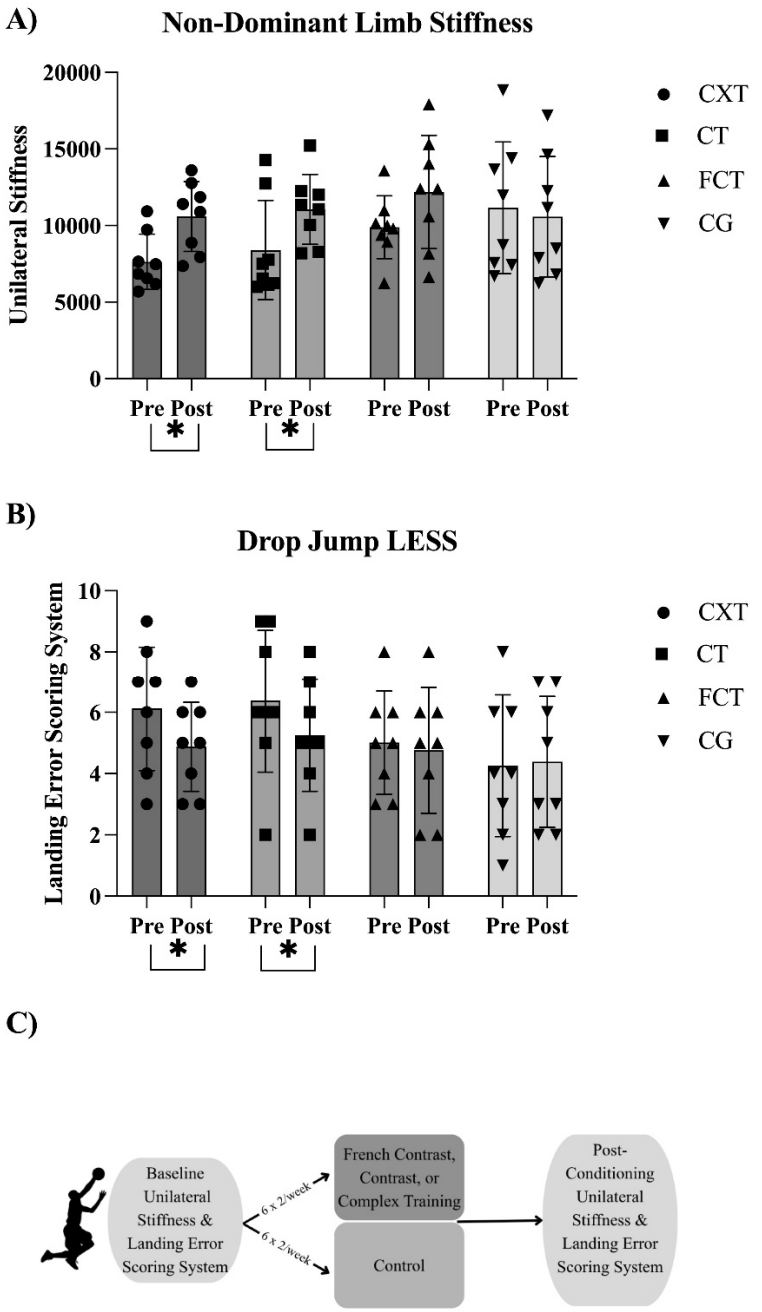


Figure 1. Changes in neuromuscular and landing performance measures following the intervention and overview of the experimental protocol. A) Peak lower-limb stiffness responses from baseline to post-intervention; B) Landing error scoring system responses from baseline to post-intervention; C) Schematic representation of experimental protocols.

CXT = complex training, CT = contrast training, FCT = French contrast, CG = control condition; LESS = landing error scoring system

Athletes with lower stiffness have been shown to exhibit an increased risk of ligamentous injuries (Blackburn et al., 2013; Lipps et al., 2014). Conversely, LLS improvements can protect the knee joint from perturbation and extreme loads that increase the risk of ACL injuries (Nagai et al., 2018). It has been shown that increased quadriceps tensile stiffness reduces peak ACL loading during simulated pivot landings (Lipps et al., 2014), while higher hamstring stiffness has been associated with optimized landing biomechanics and reduced ACL loading (Blackburn et al., 2013). Given the evidence-based recommendations to target LLS in ACL injury risk minimization strategies, it seems surprising that MT has not yet been applied for injury risk mitigation, despite its potential to elicit favourable LLS changes.

Brazier et al. (2019) were the first to propose the use of MT in injury risk minimization intervention strategies. To our knowledge, no previous study has evaluated the indirect effects of short-term MT on ACL injury risk through LESS improvements in youth basketball athletes. The LESS is a reliable indirect screening tool for ACL injury in basketball, a sport characterized by repetitive jumping (Limroongreungrat et al., 2022). However, a poor LESS score does not necessarily indicate higher injury rates but rather reflects high-risk landing mechanics associated with increased lower-limb injury risk (Beese et al., 2015). Our study demonstrated that both CXT and CT strategies induced favourable improvements in the LESS, suggesting that the experimental intervention reduced high-risk movement patterns. It seems plausible that improvements in non-dominant LLS contributed to the enhanced landing strategy. It should be noted, however, that both LLS and the LESS are indirect indicators of ACL injury risk; therefore, any observed improvements reflect changes in biomechanical risk proxies rather than direct assessments of ACL injury occurrence. Additionally, it should be acknowledged that both variables were assessed during sagittal-plane landing tasks, potentially overlooking important biomechanical insights that could be obtained from multiplanar rotational landing assessments, which may be more suitable for identifying athletes at increased ACL injury risk (Jamkrajang et al., 2025).

Our study established a negative correlation between changes in non-dominant LLS and LESS scores from baseline to post-intervention, validating the connection between stiffness and the optimization of landing mechanics. We further demonstrated that changes in non-dominant LLS accounted for 21% of the variance in LESS changes. Although the regression model in this study is not a perfect fit and was primarily exploratory, the findings suggest that improvements in non-dominant LLS are an important factor in optimizing landing biomechanics and could play a key role in ACL injury risk minimization programs for youth basketball athletes. Poorer LESS scores have been observed in younger individuals (14–18 years) compared to older athletes (18–23 years), with increases in LLS reducing the likelihood of excessive loading on passive structures (ACL) of the knee joint and supporting power output production and movement efficiency (Hanzlíková et al., 2025).

Given the inter-limb asymmetry in leg stiffness observed in basketball athletes (Struzik et al., 2020), which has been attributed, at least in part, to the more frequent use of the dominant limb during sport-specific activities (Arboix-Alió et al., 2025), it is possible that in our study the dominant limb had already reached a ceiling effect due to long-term sport-specific loading histories, while the non-dominant limb retained greater neural adaptive potential; this potential may be attributed to enhanced motor neuron excitability, increased motor unit recruitment, increased higher-threshold motor unit activation, improved rate coding, better intermuscular coordination, and reduced inhibition from the Golgi tendon organ and Renshaw cells, possibly resulting from the manifestation of post-activation performance enhancement (Shen et al., 2025). Asymmetrical limb loading, the magnitude of which may depend on whether landing tasks are performed unilaterally or bilaterally (Chen et al., 2026), has been identified as a modifiable potential risk factor for ACL injury (Hewett et al., 2016). Reductions in inter-limb stiffness asymmetry have been shown to act as a protective factor against injury and facilitate performance optimization (Struzik et al., 2020).

This study should be interpreted in light of its limitations. The MT strategies of this study employed bilateral strength-power potentiation complexes. It has been previously suggested that unilateral training may have more profound effects on unilateral jump performance measures, power

Articles published in the Journal of Human Kinetics are licensed under an open access Creative Commons CC BY 4.0 license.

production patterns, and lower-limb asymmetries in basketball, whereas bilateral training is more advantageous for bilateral outcomes (Zhang et al., 2023a, 2024). Specifically, unilateral plyometric training performed from moderate drop heights (approximately 60 cm) has been suggested as a potential strategy to enhance neuromuscular adaptability, improve single-leg force control, and increase injury resilience during simulated high-speed landings (Zhao et al., 2026). Additionally, this study did not conduct a comprehensive kinetic analysis, the absence of which may have obscured disproportionate force dissipation during jump performance resulting from altered kinetics (Pontillo et al., 2021). Future studies should investigate whether incorporating unilateral strength-power pairings within short-term MT strategies can elicit greater improvements in unilateral LLS and subsequent LESS outcomes, and whether kinetic data analysis can better inform ACL injury risk assessment and occurrence by identifying abnormal biomechanical patterns.

In addition, our study did not assess strength capacities for hip external rotation, hip abduction, knee flexion, or knee extension. Insufficient hip abductor strength has been shown to be a contributing factor to dynamic valgus biomechanics, stronger lateral quadriceps and weaker medial hamstring strength create neuromuscular imbalances, and hip external rotator weakness negatively affects dynamic control of the lower limbs during landing tasks; all of these are modifiable risk factors for ACL injuries (Kuntz et al., 2022). Additionally, electromyographic data analysis could have further substantiated strength capacity assessments by identifying which muscles should be prioritized for targeted training interventions (Cui et al., 2023). Future research should examine whether MT strategies affect hip and knee isometric strength and electromyographic measures alongside LLS and the LESS, and investigate the residual LESS variance explained by hip and knee strength variables. These limitations should be addressed in longer, season-long training interventions that more closely align with long-term ACL injury risk minimization strategies, which were not evaluated in the present study (Watson et al., 2026).

Finally, the absence of significant findings following the FCT protocol may be attributed to the advanced nature of this MT strategy, the effectiveness of which may have been confounded by participants' baseline strength levels. Indeed, previous work has suggested that strength levels may act as a moderating variable in athletes' physiological responses to the FCT method (Cormier et al., 2022). Additionally, a biomechanical similarity mismatch between bilateral training and unilateral LLS performance measures may have prevented the realization of greater performance gains (Zhang et al., 2023a). However, individualized training responses to FCT were observed in our study, with 60% of participants demonstrating non-dominant LLS improvements exceeding the smallest real difference. Notably, the non-dominant limb has been shown to exhibit greater dynamic knee valgus, hip abductor moments, and knee valgus moments at peak vertical ground reaction force during single-leg lateral jump landings (Warathanagasame et al., 2026). Therefore, the individual improvements observed in the non-dominant limb following the FCT protocol should not be overlooked, as they may be clinically relevant despite the absence of significant group-level effects. Future research should consider splitting participants into groups based on relative strength and enhancing movement specificity to explore potential differences in outcome measures.

Conclusions

This study showed that both CXT and CT MT strategies improved non-dominant LLS and enhanced landing mechanics, as evidenced by lower LESS scores. Improvements in non-dominant LLS not only correlated with lower LESS scores, but also accounted for 21% of the variance in LESS changes from pre- to post-intervention. Accordingly, CXT and CT should be incorporated in ACL injury risk minimization training strategies to optimize landing mechanics via improvements in non-dominant LLS and reductions in inter-limb stiffness asymmetry. Future research should delineate the extent to which other performance variables explain the residual variance in the LESS to support the development of targeted ACL injury risk minimization programs.

It is recommended that practitioners implement CXT/CT strategies as part of a 6-week pre-season mesocycle, with a training frequency of two sessions per week, to optimize non-dominant LLS and landing mechanics in youth basketball athletes. Training guidelines should include high

volumes and loads of approximately 80% of 1RM for strength exercises and 30–40% 1RM for ballistic and loaded plyometric activities, with particular emphasis on maintaining movement pattern similarity within each strength-power pair. Recovery intervals of three minutes should be used between strength-power pairs, with minimal rest recommended within CT pairs and 3 min of rest within CXT pairs.

Author Contributions: Conceptualization: L.-D.L., R.M.-S. and J.S.-C.; methodology: L.-D.L., R.M.-S. and J.S.-C.; software: L.-D.L.; validation: L.-D.L., R.M.-S. and J.S.-C.; formal analysis: L.-D.L., J.S.-C. and R.M.-S.; investigation: L.-D.L., J.S.-C. and R.M.-S.; resources: L.-D.L.; data curation: L.-D.L., J.S.-C. and R.M.-S.; writing—original draft preparation: L.-D.L.; writing—review & editing: L.-D.L., R.M.-S. and J.S.-C.; visualization: L.-D.L.; supervision: J.S.-C. and R.M.-S.; project administration: L.-D.L., R.M.-S. and J.S.-C.; funding acquisition: J.S.-C., R.M.-S. and L.-D.L. All authors have read and agreed to the published version of the manuscript.

ORCID iD:

Loudovikos Dimitrios Liosis: https://orcid.org/0009-0000-8061-2661

Jordan Santos-Concejero: https://orcid.org/0000-0001-9467-525X

Raúl Martínez-Santos: https://orcid.org/0000-0001-8504-7489

Funding Information: This research was funded by the Basque Government, grant number IT1836-26, and financially supported by the Center of Excellence for Food, Leisure, and Tourism of DEREE-The American College of Greece for the purchase of the equipment needed to conduct this experiment.

Institutional Review Board Statement: This study was conducted following the principles of the Declaration of Helsinki, and approved by the Institutional Review Board of DEREE—The American College of Greece, Athens, Greece (IRB protocol: #202405432; approval date: 16 May 2024).

Informed Consent: Informed consent was obtained from the parents of all participants included in the study.

Conflicts of Interest: The authors declare no conflict of interest.

Received: 08 December 2025

Accepted: 07 September 2026

References

Abade, E., Silva, N., Ferreira, R., Baptista, J., Gonçalves, B., Osório, S., & Viana, J. (2021). Effects of adding vertical or horizontal force-vector exercises to in-season general strength training on jumping and sprinting performance of youth football players. *Journal of Strength and Conditioning Research*, *35*(10), 2769–2774. https://doi.org/10.1519/JSC.0000000000003221

Ambegaonkar, J. P., Shultz, S. J., Perrin, D. H., Schmitz, R. J., Ackerman, T. A., & Schulz, M. R. (2011). Lower body stiffness and muscle activity differences between female dancers and basketball players during drop jumps. *Sports Health*, *3*(1), 89–96. https://doi.org/10.1177/1941738110385998

Arboix-Alió, J., Buscà, B., Peralta-Geis, M., Montalvo, A., & Fort-Vanmeerhaeghe, A. (2025). The relationship between change-of-direction performance indicators and inter-limb asymmetries in elite youth female basketball players. *Journal of Human Kinetics*, *96*, 235–246. https://doi.org/10.5114/jhk/202104

Articles published in the Journal of Human Kinetics are licensed under an open access Creative Commons CC BY 4.0 license.

Ball, N. B., Stock, C. G., & Scurr, J. C. (2010). Bilateral contact ground reaction forces and contact times during plyometric drop jumping. *Journal of Strength and Conditioning Research*, *24*(10), 2762–2769. https://doi.org/10.1519/JSC.0b013e3181cc2408

Beese, M. E., Joy, E., Switzler, C. L., & Hicks-Little, C. A. (2015). Landing Error Scoring System differences between single-sport and multi-sport female high school-aged athletes. *Journal of Athletic Training*, *50*(8), 806–811. https://doi.org/10.4085/1062-6050-50.7.01

Blackburn, J. T., Norcross, M. F., Cannon, L. N., & Zinder, S. M. (2013). Hamstrings stiffness and landing biomechanics linked to anterior cruciate ligament loading. *Journal of Athletic Training*, *48*(6), 764–772. https://doi.org/10.4085/1062-6050-48.4.01

Brazier, J., Maloney, S., Bishop, C., Read, P. J., & Turner, A. N. (2019). Lower extremity stiffness: Considerations for testing, performance enhancement, and injury risk. *Journal of Strength and Conditioning Research*, *33*(4), 1156–1166. https://doi.org/10.1519/JSC.0000000000002283

Cao, J., Xun, S., Zhang, R., & Zhang, Z. (2024). Effects of unilateral, bilateral and combined plyometric jump training on asymmetry of muscular strength and power, and change-of-direction in youth male basketball players. *Journal of Sports Science & Medicine*, *23*(4), 754–766. https://doi.org/10.52082/jssm.2024.754

Chen, Y., Chou, T., Chang, E., & Huang, Y. (2026). Sagittal plane landing mechanics differences between limbs during single- and double-leg jump landings: Implications for ACL injury risk in females. *Journal of Human Kinetics*, Advance online publication. https://doi.org/10.5114/jhk/207104

Cormier, P., Freitas, T. T., Loturco, I., Turner, A., Virgile, A., Haff, G. G., Blazevich, A. J., Agar-Newman, D., Henneberry, M., Baker, D. G., McGuigan, M., Alcaraz, P. E., & Bishop, C. (2022). Within-session exercise sequencing during programming for complex training: Historical perspectives, terminology, and training considerations. *Sports Medicine*, *52*(10), 2371–2389. https://doi.org/10.1007/s40279-022-01715-x

Curovic, I., Grecic, D., Rhodes, D., Alexander, J., & Harper, D. J. (2024). Potential importance of maximal upper body strength-generating qualities and upper body strength training for performance of high-intensity running and jumping actions: A scoping review. *Sports*, *12*(12), 357. https://doi.org/10.3390/sports12120357

Cui, H., Cao, Z., Wang, S., Zhang, H., Chen, Z., Wu, X., Zhao, Y., Qie, S., & Li, W. (2023). Surface electromyography characteristics of patients with anterior cruciate ligament injury in different rehabilitation phases. *Frontiers in Physiology*, *14*, 1116452. https://doi.org/10.3389/fphys.2023.1116452

Faigenbaum, A. D., McFarland, J. E., Herman, R. E., Naclerio, F., Ratamess, N. A., Kang, J., & Myer, G. D. (2012). Reliability of the one-repetition-maximum power clean test in adolescent athletes. *Journal of Strength and Conditioning Research*, *26*(2), 432–437. https://doi.org/10.1519/JSC.0b013e318220db2c

Fransz, D. P., Huurnink, A., de Boode, V. A., Kingma, I., & van Dieën, J. H. (2016). Time series of ground reaction forces following a single-leg drop jump landing in elite youth soccer players consist of four distinct phases. *Gait & Posture*, *50*, 137–144. https://doi.org/10.1016/j.gaitpost.2016.09.002

Galiano, C., Nuñez, F., Floría, P., & Coll, J. (2025). Power up: Comparing PAPE responses in free-weight vs. flywheel resistance training systems. *Applied Sciences*, *15*, 8426. https://doi.org/10.3390/app15158426

Hanzlíková, I., Válová, K., Lehnert, M., Dvořáček, M., Doleželová, E., & Grinberg, A. (2025). The relationship between attentional control and injury-related biomechanics in young female volleyball players. *Frontiers in Physiology*, *16*, 1622026. https://doi.org/10.3389/fphys.2025.1622026

Hewett, T. E., Myer, G. D., Ford, K. R., Paterno, M. V., & Quatman, C. E. (2016). Mechanisms, prediction, and prevention of ACL injuries: Cut risk with three sharpened and validated tools. *Journal of Orthopaedic Research*, *34*(11), 1843–1855. https://doi.org/10.1002/jor.23414

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine & Science in Sports & Exercise*, *41*(1), 3–13. https://doi.org/10.1249/MSS.0b013e31818cb278

Humphrys, B., Aspe, R., Clarke, R., & Hughes, J. (2018). The effects of complex training on neuromuscular development of the lower limbs in youth netball players. *Journal of Athletic Enhancement*, *7*, 309. https://doi.org/10.4172/2324-9080.1000309

Jamkrajang, P., Suwanmana, S., Boonkerd, C. & Verheul, J. (2026). Rotational vs. straight landings: Exploring task-specific responses to inform ACL-injury risk screening. *Journal of Human Kinetics*, *100*, 63–73. https://doi.org/10.5114/jhk/200765

Joseph, A. M., Collins, C. L., Henke, N. M., Yard, E. E., Fields, S. K., & Comstock, R. D. (2013). A multisport epidemiologic comparison of anterior cruciate ligament injuries in high school athletics. *Journal of Athletic Training*, *48*(6), 810–817. https://doi.org/10.4085/1062-6050-48.6.03

Kaneko, S., Sasaki, S., Hirose, N., Nagano, Y., Fukano, M., & Fukubayashi, T. (2017). Mechanism of anterior cruciate ligament injury in female soccer players. *Asian Journal of Sports Medicine*, *8*(1), e38205. https://doi.org/10.5812/asjsm.38205

Kuntz, A., Peters, O., Bello, A., Perkins, R., Monti, R., & Murray, L. (2022). An anterior cruciate ligament (ACL) injury risk screening and reduction program for high school female athletes: A pilot study. *International Journal of Sports Physical Therapy*, *17*(7), 1318–1329. https://doi.org/10.26603/001c.40370

Li, F., Wang, R., Newton, R. U., Sutton, D., Shi, Y., & Ding, H. (2019). Effects of complex training versus heavy resistance training on neuromuscular adaptation, running economy and 5-km performance in well-trained distance runners. *PeerJ*, *7*, e6787. https://doi.org/10.7717/peerj.6787

Limroongreungrat, W., Mawhinney, C., Kongthongsung, S., & Pitaksathienkul, C. (2022). Landing error scoring system: Data from youth volleyball players. *Data in Brief*, *41*, 107916. https://doi.org/10.1016/j.dib.2022.107916

Lipps, D. B., Oh, Y. K., Ashton-Miller, J. A., & Wojtys, E. M. (2014). Effect of increased quadriceps tensile stiffness on peak anterior cruciate ligament strain during a simulated pivot landing. *Journal of Orthopaedic Research: Official Publication of the Orthopaedic Research Society*, *32*(3), 423–430. https://doi.org/10.1002/jor.22531

Lu, X., Liu, W., Zhao, G. & Fan, Y. (2026). Effects of three resistance strength training methods on the biomechanics and kinematics of the lower limbs during the first step of sprinters' start. *Journal of Human Kinetics*, Advance online publication. https://doi.org/10.5114/jhk/217150

Madruga-Parera, M., Romero-Rodríguez, D., Bishop, C., Beltran-Valls, M. R., Latinjak, A. T., Beato, M., & Fort-Vanmeerhaeghe, A. (2019). Effects of maturation on lower limb neuromuscular asymmetries in elite youth tennis players. *Sports*, *7*(5), 106. https://doi.org/10.3390/sports7050106

Nagai, T., Schilaty, N. D., Strauss, J. D., Crowley, E. M., & Hewett, T. E. (2018). Analysis of lower extremity proprioception for anterior cruciate ligament injury prevention: Current opinion. *Sports Medicine*, *48*(6), 1303–1309. https://doi.org/10.1007/s40279-018-0889-1

Nessler, T., Denney, L., & Sampley, J. (2017). ACL injury prevention: What does research tell us? *Current Reviews in Musculoskeletal Medicine*, *10*(3), 281–288. https://doi.org/10.1007/s12178-017-9416-5

Padua, D. A., Marshall, S. W., Boling, M. C., Thigpen, C. A., Garrett Jr, W. E., & Beutler, A. I. (2009). The landing error scoring system (LESS) is a valid and reliable clinical assessment tool of jump-landing biomechanics: The JUMP-ACL study. *The American Journal of Sports Medicine*, *37*(10), 1996–2002. https://doi.org/10.1177/0363546509343200

Padua, D. A., DiStefano, L. J., Beutler, A. I., de la Motte, S. J., DiStefano, M. J., & Marshall, S. W. (2015). The landing error scoring system as a screening tool for an anterior cruciate ligament injury-prevention program in elite-youth soccer athletes. *Journal of Athletic Training*, *50*(6), 589–595. https://doi.org/10.4085/1062-6050-50.1.10

Pontillo, M., Hines, S. M., & Sennett, B. J. (2021). Prediction of ACL injuries from vertical jump kinetics in Division I collegiate athletes. *International Journal of Sports Physical Therapy*, *16*(1), 156–161. https://doi.org/10.26603/001c.18819

Pueo, B., Penichet-Tomás, A., & Jiménez-Olmedo, J. M. (2020). Reliability and validity of the Chronojump open-source jump mat system. *Biology of Sport*, *37*(3), 255–259. https://doi.org/10.5114/biolsport.2020.95636

Scott, D. J., Ditroilo, M., Orange, S. T., & Marshall, P. (2023). The Effect of complex training on physical performance in Rugby League players. *International Journal of Sports Physiology and Performance*, *18*(3), 240–247. https://doi.org/10.1123/ijspp.2021-0565

Articles published in the Journal of Human Kinetics are licensed under an open access Creative Commons CC BY 4.0 license.

Shen, X., Li, H., Yan, K., Zhang, S., & Li, L. (2025). Effects of 8-week complex and resistance training on strength and power in adolescent long jumpers. *Scientific Reports*, *15*(1), 21329. https://doi.org/10.1038/s41598-025-05800-9

Struzik, A., Zawadzki, J., Rokita, A., & Pietraszewski, B. (2020). Application of an accelerometric system for determination of stiffness during a hopping task. *Applied Bionics and Biomechanics*, 3826503. https://doi.org/10.1155/2020/3826503

Tai, W. H., Peng, H. T., Lin, J. Z., & Li, P. A. (2025). Adaptive neuromuscular co-contraction strategies under varying approach speeds and distances during single-leg jumping: An exploratory study. *Life*, *15*(12), 1859. https://doi.org/10.3390/life15121859

Toumi, H., Best, T. M., Martin, A., & Poumarat, G. (2004). Muscle plasticity after weight and combined (weight + jump) training. *Medicine & Science in Sports & Exercise*, *36*(9), 1580–1588. https://doi.org/10.1249/01.mss.0000139896.73157.21

Trajković, N., Milić, V., Đurković, T., Rešetar, T., & Korobeynikov, G. (2024). Diurnal variations in upper and lower body power in adolescent volleyball players: Exploring time-of-day effects on performance. *Sports*, *12*(12), 320. https://doi.org/10.3390/sports12120320

Warathanagasame, P., Subedi, M., Sinsurin, K., & Suttiwong, J. (2026). Higher risk of non-contact anterior cruciate ligament injury in the non-dominant limb during single-leg lateral jump landing in active individuals. *Journal of Human Kinetics*, *103*, 97–106. https://doi.org/10.5114/jhk/205897

Watson, S. L., Gohal, C., Owen, M. M., Bajaj, P. M., Plantz, M. A., & Tjong, V. K. (2026). A systematic review and meta-analysis of anterior cruciate ligament injury prevention programs: Training to stay in the game. *The American Journal of Sports Medicine*, *54*(3), 733–740. https://doi.org/10.1177/03635465251376670

Zhang, W., Chen, X., Xu, K., Xie, H., Li, D., Ding, S., & Sun, J. (2023a). Effect of unilateral training and bilateral training on physical performance: A meta-analysis. *Frontiers in Physiology*, *14*, 1128250. https://doi.org/10.3389/fphys.2023.1128250

Zhang, Y., Hu, Z., Li, B., Qiu, X., Li, M., Meng, X., Kim, S., & Kim, Y. (2023b). Gender differences in lower extremity stiffness during a single-leg landing motion in badminton. *Bioengineering*, *10*(6), 631. https://doi.org/10.3390/bioengineering10060631

Zhang, W., Chen, X., Xu, K., Xie, H., Chen, J., Zhu, Z., Ji, H., Li, D., & Sun, J. (2024). The potential of a targeted unilateral compound training program to reduce lower limb strength asymmetry and increase performance: a proof-of-concept in basketball. *Frontiers in Physiology*, *15*, 1361719. https://doi.org/10.3389/fphys.2024.1361719

Zhao, J., Łosińska, K., Chen, L., & Aschenbrenner, P. (2026). Neuromuscular adaptation to varying drop jump heights: A muscle synergy approach in elite handball players. *Journal of Human Kinetics*, *101*, 147–164. https://doi.org/10.5114/jhk/217230