Optimizing triple jump performance and knee biomechanics in junior figure skaters: a longitudinal evaluation of rotational harness training in Kazakhstan

Optimización del rendimiento del triple salto y de la biomecánica de la rodilla en patinadores artísticos juveniles: una evaluación longitudinal del entrenamiento con arnés rotacional en Kazajistán

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Abstract

Introduction: Triple jumps are essential for competitive progression in junior figure skating but impose high mechanical loads on the knee, increasing the risk of overuse injuries. This study evaluated the long-term effects of rotational harness training on landing biomechanics, technical progression, knee health, and psychological readiness in adolescent skaters.
Methodology: Twenty-eight female athletes aged 11–15 years were randomly assigned to a harness group (n = 14) or a control group (n = 14) and followed for 36 months. Monthly assessments included ground reaction force (GRF), knee flexion angle, rotational velocity (RPM), clinical imaging, and psychological ratings.
Results: The harness group demonstrated significantly lower peak GRF (5.6 ± 0.9 vs. 7.3 ± 1.2 × body weight, p < .001), greater knee flexion (35.2° ± 4.1° vs. 29.8° ± 5.3°, p = .006), and higher RPM (412 ± 22 vs. 338 ± 30, p < .001). Triple-jump mastery occurred earlier in the harness group (13.5 ± 0.4 vs. 14.1 ± 0.5 years, p = .002). Psychological outcomes favored the harness group, with higher perceived stability, greater confidence, and lower fear of injury (all p < .001). Knee pathology incidence was lower in the harness group (2 vs. 6 cases), although this difference was not statistically significant.
Conclusion: These findings suggest that rotational harness training enhances technical performance and psychological readiness while reducing biomechanical risk factors for knee injury. Incorporating harness-based protocols into youth development programs may improve safety and accelerate skill acquisition in figure skating.

Keywords

Adolescent athletes; figure skating; knee biomechanics; rotational harness; triple jump.

Resumen

Introducción: Los saltos triples son esenciales para la progresión competitiva en el patinaje artístico juvenil, pero imponen elevadas cargas mecánicas sobre la rodilla, aumentando el riesgo de lesiones por sobreuso. Este estudio evaluó los efectos a largo plazo del entrenamiento con arnés rotacional sobre la biomecánica del aterrizaje, la progresión técnica, la salud de la rodilla y la preparación psicológica en patinadores adolescentes.
Metodología: Veintiocho atletas femeninas de 11 a 15 años fueron asignadas aleatoriamente a un grupo con arnés (n = 14) o a un grupo control (n = 14) y seguidas durante 36 meses. Las evaluaciones mensuales incluyeron la fuerza de reacción del suelo (FRS), el ángulo de flexión de la rodilla, la velocidad rotacional (RPM), estudios de imagen clínica y valoraciones psicológicas.
Resultados: El grupo con arnés presentó una FRS máxima significativamente menor (5,6 ± 0,9 vs. 7,3 ± 1,2 × peso corporal, p < .001), mayor flexión de rodilla (35,2° ± 4,1° vs. 29,8° ± 5,3°, p = .006) y mayor RPM (412 ± 22 vs. 338 ± 30, p < .001). El dominio del salto triple se alcanzó antes en el grupo con arnés (13,5 ± 0,4 vs. 14,1 ± 0,5 años, p = .002). Los resultados psicológicos favorecieron al grupo con arnés, con mayor estabilidad percibida, mayor confianza y menor temor a la lesión (todos p < .001). La incidencia de patología de rodilla fue menor en el grupo con arnés (2 vs. 6 casos), aunque sin significación estadística.
Conclusión: El entrenamiento con arnés rotacional mejora el rendimiento técnico y la preparación psicológica, al tiempo que reduce factores biomecánicos de riesgo para lesiones de rodilla. Su incorporación en programas juveniles podría mejorar la seguridad y acelerar la adquisición de habilidades en patinaje artístico.

Palabras clave

Arnés rotacional; atletas adolescentes; biomecánica de la rodilla; patinaje artístico; salto triple.

Introduction

Figure skating is a sport characterized by high technical complexity and early specialization, particularly among junior athletes in Kazakhstan. To progress through the Candidate for Master of Sport (CMS) pathway and qualify for international competitions, skaters must master multi-rotational jumps such as the triple toe loop (3T), Salchow (3S), and loop (3Lo) at a young age (ISU, 2022). These jumps are not only performance benchmarks but also biomechanical stressors that place significant demands on the developing musculoskeletal system.

The execution of triple jumps involves extreme ground reaction forces (GRFs), often reaching six to eight times the athlete's body weight during takeoff and landing (Hewett et al., 2016). These forces concentrate stress on the patella-femoral joint, menisci, and surrounding soft tissues, increasing the risk of overuse injuries such as tendinopathy, cartilage degeneration, and chondromalacia patellae (Slattery & Kweon, 2018; Cabell & Bateman, 2018). Adolescents are particularly vulnerable due to incomplete neuromuscular development and skeletal immaturity, especially during growth spurts (Schmidt et al., 2025).

Injury surveillance among junior skaters reveals that over 60% report knee pain during peak training seasons, with many progressing to meniscal or cartilage lesions without adequate biomechanical monitoring (Drazdova, 2026). Psychological barriers, including fear of injury and avoidance behaviors, further impede technical progression and confidence (Haraldsdottir & Watson, 2021). These challenges underscore the need for integrated training approaches that address both physical and psychological dimensions of athlete development.

Rotational harness systems have gained traction as off-ice training tools designed to simulate jump mechanics while reducing GRF impact. These systems offer controlled lift and landing support, potentially improving proprioception, vestibular adaptation, and landing biomechanics (Song & Kim, 2021; ISU, 2022). While anecdotal evidence supports their use in Central Asia, empirical studies evaluating their long-term effects on performance and injury prevention in adolescent skaters remain limited.

This study aims to evaluate the biomechanical, clinical, and psychological outcomes of rotational harness training in junior figure skaters in Kazakhstan. Using a mixed-methods longitudinal design over 36 months, the research investigates whether harness-based training improves triple jump performance, reduces knee injury incidence, and enhances psychological resilience. By integrating objective biomechanical data with clinical assessments and athlete perceptions, this study aims to inform evidence-based practices for safer, more effective youth training protocols.

Method

Design

This study employed a longitudinal mixed-methods design spanning 36 months to evaluate the biomechanical, clinical, and psychological effects of rotational harness training in junior figure skaters. The research was carried out at the National Sports Science and Medicine Center in Almaty, Kazakhstan, with monthly assessments to monitor performance progression, injury incidence, and psychological outcomes.

Participants

Participants were twenty-eight female figure skaters aged 11 to 15 years, recruited from regional training centers in Almaty and Ust-Kamenogorsk. All athletes were registered as Candidates for the Master of Sport (CMS) and had at least 3 years of competitive experience. Eligibility criteria included the ability to perform at least two distinct triple jumps (e.g., 3T, 3S, or 3Lo), absence of acute musculoskeletal injury, and parental consent. The sample was representative of the national junior skating population and provided a suitable cohort for evaluating developmental training interventions.

Before giving their informed consent to participate, every participant was given a thorough explanation of the training and test protocols, goals, risks, and research methods. This study was approved by the Ethics Committee of the Kazakh Academy of Sport and Tourism (Protocol No. KAST-2021-014). Written informed consent was obtained from all participants and their legal guardians prior to enrollment. All procedures were conducted in accordance with the Declaration of Helsinki.

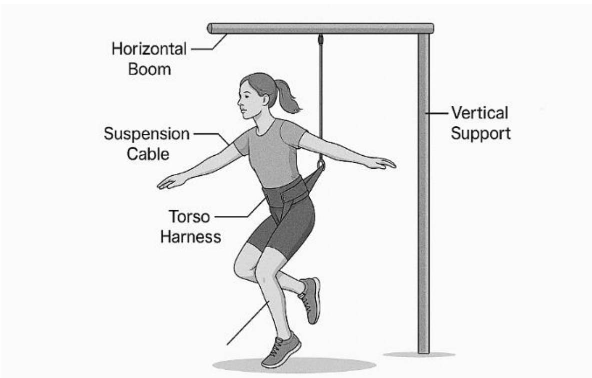
Participants were randomly assigned to either the rotational harness training group (n = 14) or the control group (n = 14) using a computerized randomization protocol. Randomization was stratified to ensure balance in baseline characteristics, including age, jump proficiency, and musculoskeletal health. Allocation concealment was maintained by assigning group codes prior to baseline assessments. No crossover occurred during the study period, and both groups were monitored under identical clinical and biomechanical evaluation schedules.

Procedure

The rotational harness training group participated in three supervised off-ice sessions per week. Each session utilized a rotational harness system designed to replicate the mechanics of triple jumps while minimizing ground reaction forces during landings. Training focused on rotational technique, core activation, and safe landing strategies, with real-time biomechanical feedback provided by coaches and physiologists. On-ice training continued in accordance with national federation guidelines.

The control group trained on ice six times per week, performing approximately 25 jump repetitions per session without external support or biomechanical feedback. Both groups followed a standardized strength and plyometric conditioning program, which included exercises targeting the quadriceps, gluteal muscles, and hip stabilizers. Certified sports physiologists supervised all sessions to ensure consistency and safety.

Figure 1. Rotational harness training setup and protocol used in the intervention group



Instrument

The study employed the following three instruments chosen for their relevance to the study's variables.

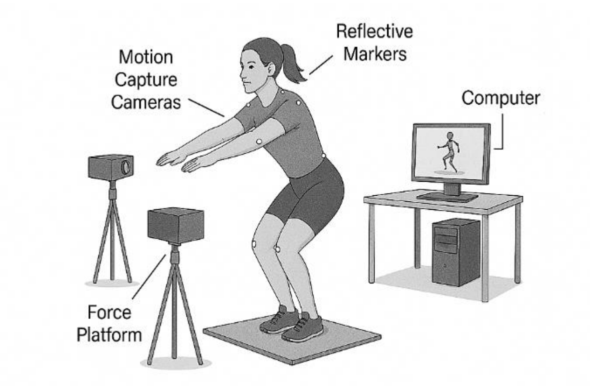
- Clinical evaluation of knee health

Knee joint assessments were conducted monthly by a pediatric orthopedic sports medicine physician with over a decade of experience in adolescent musculoskeletal care. Evaluations included musculoskeletal ultrasound, magnetic resonance imaging (MRI), and functional goniometry to assess tendon integrity, meniscal status, and cartilage condition. Pathological findings were classified using the Outerbridge grading system, which identifies cartilage softening, fibrillation, fissuring, and subchondral bone exposure.

- Biomechanical outcome measures

Biomechanical data were collected monthly. Ground reaction force (GRF) was measured using AMTI force platforms at a sampling rate of 1000 Hz and normalized to body weight. Knee flexion angles during landings were recorded using a three-dimensional motion capture system with eight cameras and reflective markers placed on anatomical landmarks. Rotational velocity (RPM) was assessed using an AV200 optical system during off-ice simulations. Performance progression was tracked using standardized coach-reported forms that documented successful execution of triple jumps and the age at first mastery.

Figure 2. Biomechanical assessment setup used to evaluate ground reaction force, knee flexion angles, and rotational velocity during simulated jump landings



- Psychological and perceptual measures

Psychological outcomes were assessed through monthly Likert-scale ratings and post-intervention semi-structured interviews. Athletes rated their perceived knee stability, fear of injury, and confidence during landings on a 5-point scale. Interviews were transcribed and analyzed using Braun and Clarke's thematic analysis framework to identify patterns in confidence, fear, and self-efficacy. Coaches also rated technical readiness and psychological resilience. These qualitative findings were triangulated with biomechanical and clinical data to enhance contextual validity.

Data analysis

All statistical analyses were performed using SPSS version 27. Normality of continuous variables was assessed using the Shapiro-Wilk test. Between-group comparisons were conducted using independent-samples t-tests for continuous variables and chi-square tests for categorical variables. Effect sizes were calculated using Cohen's d. Spearman's rank correlation was used to examine relationships between biomechanical and psychological variables. Missing data below 5% were addressed using multiple imputations. Statistical significance was set at $p < .05$.

Results

Baseline demographic characteristics of the participants are presented in Table 1. Both groups were comparable in terms of age, height, weight, and body mass index (BMI), with no statistically significant differences observed (p>0/05). This confirms the equivalence of the harness and control groups prior to intervention and supports the validity of subsequent outcome comparisons.

Table 1. Demographic Characteristics of Participants (N = 28)

Variable	Harness Group (n = 14)	Control Group (n = 14)	p-values
Age (years)	13.5 ± 0.4	14.1 ± 0.5	0.418
Height (cm)	161.6 ± 5.70	160.7 ± 5.19	0.908
Weight (kg)	51.5 ± 6.88	50.5 ± 5.84	0.722
BMI (kg/m^2)	19.7 ± 1.65	19.6 ± 1.60	0.609

At 36 months, the harness group demonstrated substantially safer and more efficient landing mechanics than controls. As shown in table 2, peak vertical ground reaction force was lower in the harness group (M = 5.6, SD = 0.9 ×BW) than in controls (M = 7.3, SD = 1.2 ×BW), with a large between-group difference (d = −1.60) and a statistically significant mean difference of −1.70 ×BW, 95% CI [−2.53, −0.87], t(≈24.11) = −4.24, p < .001. Knee flexion at landing was greater in the harness group (M =

35.2°, SD = 4.1°) than in controls (M = 29.8°, SD = 5.3°), d = 1.14, mean difference 5.40°, 95% CI [1.71, 9.09], t(≈24.46) = 3.02, p = .006. Rotational velocity was also higher with harness training (M = 412, SD = 22 RPM vs. M = 338, SD = 30 RPM), d = 2.81, mean difference 74 RPM, 95% CI [53.47, 94.53], t(≈23.85) = 7.44, p < .001).

Table 2. The Biomechanical and knee kinematic outcomes at 36 months (between-group)

Variables	Harness (n = 14) M ± SD	Control (n = 14) M ± SD	Mean Difference (95% CI)	t	p	Cohen's d
Peak GRF (×BW)	5.6 ± 0.9	7.3 ± 1.2	−1.70 [−2.53, −0.87]	-4.24	< .001	1.60
Knee flexion at landing (°)	35.2 ± 4.1	29.8 ± 5.3	5.40 [1.71, 9.09]	3.02	.006	1.14
Rotational velocity (RPM)	412 ± 22	338 ± 30	74.0 [53.47, 94.53]	7.44	< .001	2.81

Performance parameters favored harness training. According to Table 3, the proportion of skaters consistently landing clean triple jumps was 78.6% (11/14) in the harness group and 42.9% (6/14) in controls (relative risk = 1.83, 95% CI [0.94, 3.56]; Fisher's exact *p* = .120). Age at first triple mastery was earlier in the harness group (*M* = 13.5, *SD* = 0.4 years) than controls (*M* = 14.1, *SD* = 0.5 years), *d* = −1.33, mean difference −0.60 years, 95% CI [−0.95, −0.25], *t*(≈24.80) = −3.51, *p* = .002).

Table 3. Performance parameters and Clinical Events

Variables	Harness	Control	Estimate (95% CI)	Test	*p*
Clean triple landings (n, %)	11/14 (78.6%)	6/14 (42.9%)	RR = 1.83 [0.94, 3.56]	Fisher's exact	.120
Age at first triple mastery (y)	13.5 ± 0.4	14.1 ± 0.5	Δ = −0.60 [−0.95, −0.25]	*t* ≈ −3.51 (df≈24.80)	.002
Knee pathology during the study	2/14	6/14	RR = 0.33 [0.08, 1.38]	Fisher's exact	.209

Psychological outcomes were favorable in the harness group: perceived knee stability was higher (*M* = 4.3, *SD* = 0.5 vs. *M* = 3.2, *SD* = 0.7; *d* = 1.81; mean difference 1.10, 95% CI [0.62, 1.58], *t* ≈ 4.78, *p* < .001), fear of injury was lower (*M* = 2.1, *SD* = 0.4 vs. *M* = 3.6, *SD* = 0.6; *d* = −2.94; mean difference −1.50, 95% CI [−1.90, −1.10], *t* ≈ −7.78, *p* < .001), and confidence during landing was higher (*M* = 4.5, *SD* = 0.4 vs. *M* = 3.0, *SD* = 0.8; *d* = 2.37; mean difference 1.50, 95% CI [1.00, 2.00], *t* ≈ 6.27, *p* < .001) as explained in table 4.

Table 4. Psychological Outcomes at 36 Months

Variables	Harness M ± SD	Control M ± SD	Mean Difference (95% CI)	t	p	Cohen's d
Perceived knee stability	4.3 ± 0.5	3.2 ± 0.7	1.10 [0.62, 1.58]	4.78	< .001	1.81
Fear of injury	2.1 ± 0.4	3.6 ± 0.6	−1.50 [−1.90, −1.10]	−7.78	< .001	−2.94
Confidence during landing	4.5 ± 0.4	3.0 ± 0.8	1.50 [1.00, 2.00]	6.27	< .001	2.37

Clinical knee findings favored the harness group descriptively: 2 cases of Grade I patellar tendinopathy occurred in the harness group, compared with 6 Grade II+ cartilage/meniscal pathologies in controls. The between-group comparison did not reach statistical significance at α = .05 (relative risk = 0.33, 95% CI [0.08, 1.38]; Fisher's exact *p* = .209), but the direction and magnitude are consistent with a clinically meaningful risk reduction.

Discussion

This 36-month evaluation examined whether rotational harness training could enhance triple-jump performance while improving knee biomechanics and psychological readiness in junior figure skaters. The harness group demonstrated significantly lower peak ground reaction forces (GRF), greater knee flexion at landing, and higher rotational velocity compared to controls. These biomechanical improvements were accompanied by earlier mastery of the triple jump and more favorable psychological outcomes, including higher perceived stability, greater confidence, and reduced fear of injury. Although the incidence of knee pathology was lower in the harness group, this difference did not reach statistical significance, likely due to the small sample size and low event frequency.

The reduction in landing forces aligns with prior research showing that figure skating jumps typically generate GRFs of six to eight times body weight (Hewett et al., 2016; Saunders et al., 2014; Cabell & Bateman, 2018). By reducing these forces to approximately 5.6 × body weight, the harness system mitigates a key mechanical risk factor for patellofemoral and meniscal injuries. Greater knee flexion observed in the harness group supports evidence that increased sagittal-plane flexion improves energy absorption and reduces joint stress (Blackburn & Padua, 2008; Pollard et al., 2010; Tamura et al., 2020). These findings suggest that the harness acts as a motor-learning scaffold, enabling repeated, high-quality practice under reduced load, which fosters safer neuromuscular strategies (Mazurkiewicz et al., 2018; King, 2005).

Earlier mastery of the triple jump in the harness group is consistent with the literature emphasizing the technical complexity of multi-rotational jumps and the need for repeated, precise practice to consolidate rotational mechanics (Lockwood & Gervais, 1997; Lockwood et al., 2006; King, 2005). Psychological improvements observed here, lower fear and higher confidence, are in line with studies showing that fear of injury can lead to stiff-landing strategies and increased knee loading, whereas confidence supports optimal mechanics (Powers, 2010; Haraldsdottir & Watson, 2021). These psychosocial benefits are critical, as adolescent athletes often experience heightened injury anxiety during skill progression (Brewer, 2017; Codner et al., 2023).

Although clinical knee outcomes were not statistically significant, the trend toward fewer and milder lesions in the harness group aligns with epidemiological data on overuse injuries in figure skating (Han et al., 2018). This finding is consistent with pathomechanical models linking abnormal patellofemoral loading and proximal control deficits to anterior knee pain (Powers et al., 2017; Greuel et al., 2019). The Outerbridge classification remains a practical framework for monitoring cartilage health in such cohorts (Slattery & Kweon, 2018).

Adolescence introduces additional risk factors, as growth spurts temporarily reduce coordination and tissue tolerance (Parry et al., 2024; Johnson et al., 2023; Kentiba & Drazdova, 2026). Neuromuscular training (NMT) programs have been shown to improve landing mechanics and reduce the risk of knee injury in young female athletes (Gu et al., 2025; Ramezani et al., 2024; Hopper et al., 2017; Sugimoto et al., 2021). The present findings complement this evidence by demonstrating that task-specific, load-controlled practice, rather than generalized conditioning, can simultaneously enhance performance and reduce biomechanical risk factors.

Conclusions

The convergence of biomechanical, psychological, and developmental evidence supports rotational harness training as a practical, mechanistically sound adjunct to traditional figure skating training. Integrating harness sessions during periods of technical progression and growth may improve safety, accelerate skill acquisition, and reduce the cumulative stress associated with high-impact landings.

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