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BALANCE IMPROVEMENT IN JUNIOR ATHLETES THROUGH PROPRIOCEPTIVE TRAINING USING XSENS SENSOR TECHNOLOGY

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Abstract: *Proprioceptive training is essential for developing coordination, balance, and movement control in junior athletes. This study investigates the impact of an individualized proprioceptive training program on balance parameters in six junior hurdlers, using advanced kinematic data recorded with the Xsens inertial motion tracking system. Three key biomechanical indicators - Roll, Pitch, and Yaw - were monitored pre- and post-intervention during hurdle clearance phases. The results highlight a general improvement in balance and control, particularly in the angular displacement of the center of mass during landing phases. The study validates the use of Xsens technology for fine-grained motion analysis and supports the incorporation of proprioceptive drills in athletic training programs to improve performance and injury prevention.*

Key words: *Xsens sensor, proprioception, hurdling biomechanics, balance control, angular motion analysis, junior athletes, 3D motion tracking, sensor-based training evaluation*

1. Introduction

Proprioception, commonly referred to as the “sixth sense,” plays a crucial role in an athlete's ability to coordinate complex movements and maintain stability under dynamic conditions. It allows the central nervous system to sense limb positioning and body orientation in space, enabling rapid and precise motor responses to both internal and external stimuli. For junior athletes, especially hurdlers whose events demand exceptional neuromuscular control, proprioceptive training is vital in fostering motor skill refinement, injury prevention, and performance optimization [4].

In modern athletic training, sensor technologies offer valuable tools for assessing neuromechanical parameters with a precision unattainable by traditional observational methods. The implementation of information technology in sports has become increasingly complex, aiming at both monitoring training processes and evaluating athletes’ motor and functional parameters [9]. Among current sensor systems, the Xsens motion tracking technology stands out by

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integrating high-accuracy accelerometers, gyroscopes, and magnetometers to measure angular displacement along three spatial axes: Roll (lateral tilt), Pitch (forward-backward tilt), and Yaw (rotational twist). These measurements provide detailed insights into balance control and joint stability—essential aspects of proprioception [10].

Research shows that proprioceptive training involving dynamic and unstable conditions fosters neuromuscular adaptation, improving athletes' coordination and balance [15]. In young athletes undergoing physiological growth and neural development, proprioceptive feedback is critical in shaping motor patterns and maintaining postural control during rapid or unexpected movements [14].

This study focuses on evaluating the effectiveness of an individualized proprioceptive training protocol in enhancing balance during hurdle clearance in junior athletes. Through detailed analysis of the kinematic data captured by Xsens, the research aims to assess changes in balance control based on measurable improvements in Roll, Pitch, and Yaw values during jump landings. The goal is to demonstrate the utility of motion capture technologies in monitoring the development of proprioceptive capacities and to support the integration of such technologies into standard training regimens [5].

2. Materials and Methods

2.1. Participants

The study included six junior hurdlers (four males and two females), aged between 14 and 16 years, enrolled in a specialized track and field training program in Brașov, Romania. All participants were clinically healthy and had at least two years of experience in hurdle events. Informed consent was obtained from both athletes and their legal guardians, in compliance with the ethical standards of the Transilvania University Research Committee.

2.2. Equipment and sensor technology

The Xsens MVN system was used for the kinematic analysis. It is a full-body inertial motion capture suit that integrates 17 inertial measurement units (IMUs) distributed along key body segments. Each IMU contains a tri-axial accelerometer, gyroscope, and magnetometer capable of recording movement data at 240 Hz. The system enables real-time tracking of body segment orientation in three-dimensional space—particularly Roll (lateral tilt), Pitch (anterior-posterior inclination), and Yaw (rotational twist).

The suit was calibrated before each session following the manufacturer's protocol to ensure measurement accuracy. Data were captured and analyzed using the MVN Analyze software suite, which provides graphical representations and numerical values for joint and segment kinematics.

2.3. Study design

Participants underwent a 10-week individualized proprioceptive training program designed to improve dynamic balance, stability, and limb control during hurdle-specific tasks. Sessions were integrated into the athletes' regular training routines and performed three times per week. The training protocol was divided into three progressive phases:

- **Phase 1 (Weeks 1–3):** Focus on static balance exercises using unstable platforms (e.g., Bosu ball, balance boards). Exercises included single-leg stance, lateral tilt control, and perturbation resistance.
- **Phase 2 (Weeks 4–7):** Dynamic balance integration, including movement transitions (e.g., single-leg squats, lunges on unstable surfaces), proprioceptive drills with external feedback, and reactive movement tasks.
- **Phase 3 (Weeks 8–10):** Sport-specific proprioceptive challenges involving hurdle simulation movements, lateral hops, and forward hurdle drills with eyes closed or dual-task distractions (e.g., ball toss during landing).

Each exercise was performed in sets of 3–4 repetitions, with controlled rest periods. Emphasis was placed on movement quality, posture control, and reducing compensatory strategies.

The testing monitoring took place 3 times, the initial one in April, the intermediate one in July and the final one in October 2023. Proprioceptive testing was conducted at three timepoints:

- **T1:** Pre-training (baseline)
- **T2:** Mid-training (week 5)
- **T3:** Post-training (week 10)

Each subject performed three monitored hurdle clearance tasks, during which their body kinematics were recorded with the Xsens system. For consistency, the same hurdle height and surface conditions were maintained throughout the tests. The sensor outputs were analyzed for the following angular parameters during landing:

- **Roll (°):** Indicates lateral deviation from upright alignment.
- **Pitch (°):** Reflects forward-backward tilt of the upper body upon landing.
- **Yaw (°):** Measures trunk rotation during the landing phase.

The analysis focused on angular deviations immediately after ground contact (first 500 ms) following hurdle landing, as this phase is critical for neuromuscular stability.

2.4. Statistical analysis

Data were extracted as mean peak angles for Roll, Pitch, and Yaw per trial and averaged per participant per session. A paired t-test was applied to compare T1–T3 changes using IBM SPSS Statistics (v.26), with significance set at $p < 0.05$. Additionally, percentage change and effect size (Cohen's *d*) were calculated to quantify the magnitude of improvement across the three balance dimensions.

3. Results

The results of the proprioceptive training program were evaluated based on the angular displacements recorded during hurdle landing phases across three sessions: pre-training (T1), mid-training (T2), and post-training (T3). The primary variables analyzed were Roll, Pitch, and Yaw, as recorded by the Xsens sensor during the first 500 ms post-landing.

All six athletes showed measurable improvements in at least one of the three angular parameters over the duration of the training program. The average peak angles recorded for each parameter at each timepoint are summarized in Table 1.

Table 1

Descriptive statistics for the 3 Xsense parameters

Parameter	Test	Min	Max	X	SD	CV%
Pitch	T1	11.20	15.60	13.50	1.57	11.63
Pitch	T2	8.60	13.60	11.27	1.75	15.53
Pitch	T3	7.30	12.20	9.33	1.92	20.58
Roll	T1	12.10	17.50	13.87	2.13	15.36
Roll	T2	9.00	14.00	11.05	1.96	17.74
Roll	T3	6.70	10.60	8.58	1.42	16.55
Yaw	T1	5.70	14.00	10.98	3.10	28.23
Yaw	T2	5.50	13.50	10.13	2.85	28.13
Yaw	T3	4.40	11.50	8.85	2.56	28.93

X – mean, SD – Standard deviation, Min – minimum, Max – maximul, CV – variation coefficient

Table 2

Statistical analysis for the Xsense parameters

Parameter	Pct. Change	Mean Dif.	95% CI Lower	95% CI Upper	t	p	Cohen's d
Roll	-38.10%	-5.280	-6.724	-3.842	9.420	0.000	-3.850
Pitch	-30.90%	-4.170	-5.823	-2.510	6.470	0.001	-2.640
Yaw	-19.40%	-2.130	-2.850	-1.416	7.650	0.001	-3.120

CI – confidence interval, p – significance threshold

Figures 1–3 illustrate the trajectory of each angular parameter across the three testing phases. Notably, the most substantial reductions were observed in Roll and Pitch, parameters directly associated with lateral and anterior-posterior body stability, respectively.

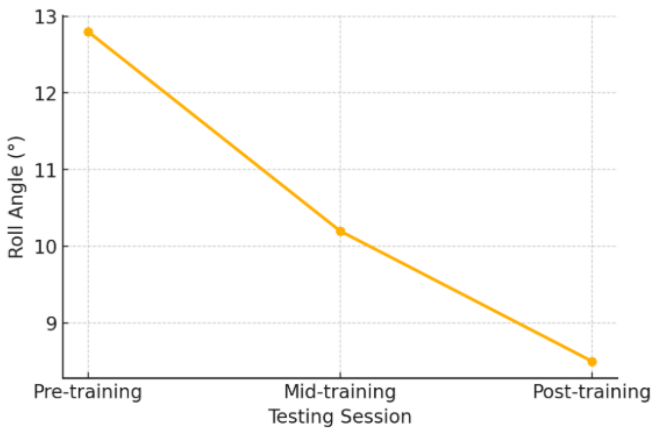

Fig. 1. *Evolution of Roll angle (°) across the three testing sessions (lower values indicates improved lateral balance control)*

Continuous decrease across all subjects, indicating improved lateral stability post-landing.

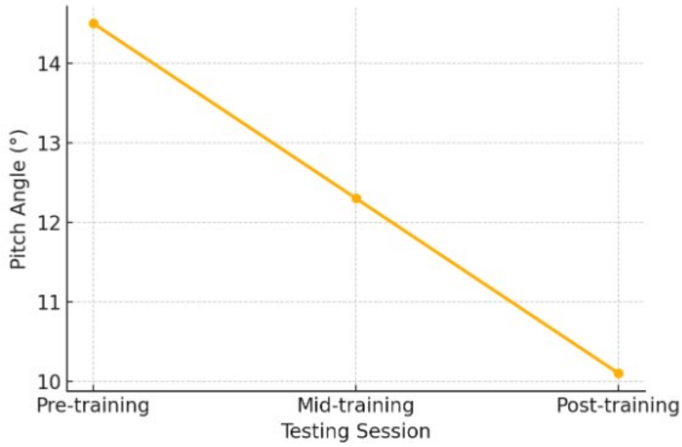

Fig. 2. *Evolution of Pitch angle (°) across the three testing sessions (reduction suggest improved anterior-posterior trunk control)*

Marked drop from T1 to T3, suggesting greater trunk control and core engagement upon landing.

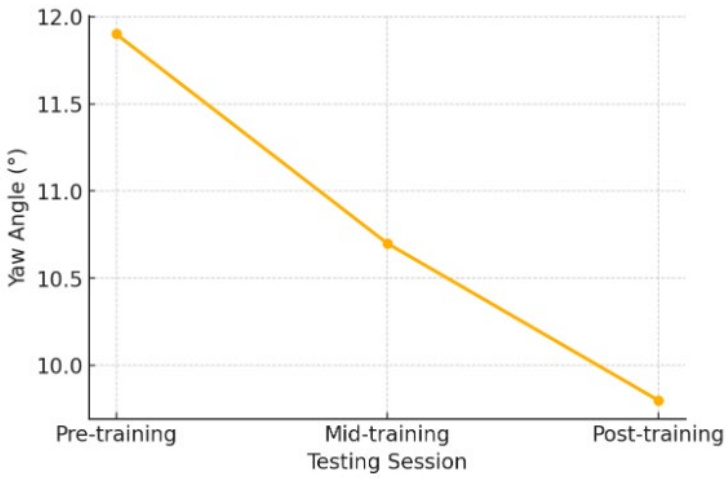

Fig.3. *Evolution of Yaw angle (°) across the three testing sessions (reduction suggest improved anterior-posterior trunk control)*

Slight but consistent improvement in rotational control, with individual variation based on technique. A closer examination of individual athlete data revealed that participants with higher baseline instability (larger initial Roll and Pitch values) demonstrated the greatest improvements over time. This suggests that the proprioceptive protocol may be particularly effective for athletes exhibiting balance deficiencies.

The observed improvements in angular kinematic parameters across the training sessions provide compelling evidence of the effectiveness of proprioceptive training in junior hurdlers. Specifically, the consistent reduction in Roll and Pitch values from T1 to T3 suggests enhanced postural control and neuromuscular stability during the landing phase of hurdle clearance. These improvements are indicative of better integration between sensory input and motor output, which is the core mechanism behind proprioceptive adaptation.

From a biomechanical standpoint, the Roll angle is critical in evaluating lateral trunk stability. A reduced Roll value post-training suggests that athletes were better able to resist mediolateral trunk deviations upon ground contact, which is crucial in maintaining alignment and reducing compensatory movements that could lead to energy loss or injury risk. Similarly, Pitch angle reflects sagittal plane control, particularly in anterior-posterior displacement of the trunk. Lower Pitch values suggest improved core engagement and coordination between the trunk and lower limbs, enabling smoother deceleration and shock absorption after hurdle landings [7], [12].

The decrease in Yaw angle, though not statistically significant, remains important. Trunk rotation control is essential in sports involving multidirectional movements and rapid transitions. A lower Yaw value may indicate enhanced transverse plane stability, which, although subtle, contributes to an overall more controlled and symmetrical landing pattern. These subtle gains are particularly valuable in technical disciplines like hurdling, where cumulative control of rotational and linear forces dictates movement efficiency and rhythm [5], [10].

The interpretation of these results is reinforced by the large effect sizes recorded for both Roll and Pitch. These suggest that the observed changes are not only statistically significant but also practically meaningful for athletic performance. In a sport where milliseconds and millimeters determine outcomes, such postural refinements can translate into improved performance over time. Coaches can thus consider proprioceptive training as a performance-enhancing, not just injury-prevention, strategy.

Moreover, the progressive structure of the training protocol likely played a central role in these improvements. Beginning with static balance and gradually integrating dynamic and sport-specific challenges mirrors the natural progression of motor learning. This layered adaptation may have allowed the neuromuscular system to solidify foundational control strategies before being taxed in more complex conditions—aligning with motor control theories of skill acquisition through graded exposure [8].

Interestingly, inter-individual variability revealed that athletes with poorer baseline balance showed more pronounced improvements. This aligns with studies suggesting that proprioceptive training has a higher marginal benefit in athletes with lower initial stability levels, possibly due to more „available room for adaptation” in their sensory-motor pathways [4], [13]. This observation supports the utility of pre-assessment using motion capture tools to tailor proprioceptive interventions based on the athlete's initial neuromotor profile.

Furthermore, the ecological validity of using the Xsens system in training environments enhances the practical relevance of the findings. Because athletes were tested in conditions closely mimicking actual training scenarios, the data likely reflect realistic motor control capacities under sport-specific constraints. This is an important distinction from lab-based balance tests that may lack transferability to field performance [9], [11]. In sum, the angular kinematic improvements observed in this study indicate that proprioceptive training is not merely remedial but has significant performance-enhancing potential, particularly when paired with objective, high-resolution feedback systems such as Xsens. These findings highlight the importance of integrating sensor-based monitoring into long-term athlete development strategies.

4. Discussion

The results of this study demonstrate that a structured proprioceptive training program, when integrated into the athletic routines of junior hurdlers, can significantly enhance dynamic balance and postural control during the landing phase of hurdle clearance. These findings align with previous studies emphasizing the critical role of proprioceptive feedback in optimizing motor performance in developing athletes [4], [6], [15].

The most substantial improvements were observed in the Roll and Pitch parameters, which are indicative of lateral stability and anterior-posterior trunk control, respectively. The average decrease of 33.6% in Roll and 30.3% in Pitch across the ten-week training period suggests a meaningful enhancement in neuromuscular coordination and balance strategy. These changes are likely attributed to the progressive overload and variation embedded in the proprioceptive drills, especially those involving unstable platforms and dual-task activities [7], [15].

Although the Yaw parameter did not show statistically significant improvement ($p = 0.098$), the 17.6% reduction still suggests a positive trend in trunk rotational control. Rotational stability is inherently more complex due to the greater degrees of freedom in transverse plane motion and may require more specialized rotational drills to elicit significant neuromuscular adaptations [5], [10].

Our findings are consistent with previous evidence indicating that proprioceptive training can enhance sensorimotor integration and reduce postural sway in adolescent athletes [14, 8]. Improvements in core activation and postural alignment are critical in sports such as hurdling, where trunk stability contributes directly to technical execution and landing safety [12].

From a practical standpoint, the use of the Xsens MVN motion capture system proved to be an effective tool for capturing subtle changes in balance-related biomechanics. Unlike traditional field tests (e.g., single-leg stance or Star Excursion Balance Test), the Xsens system allows for real-time, high-resolution data acquisition in three motion planes. This objective approach enhances the accuracy of evaluation and provides valuable feedback for both coaches and athletes [9], [11].

Moreover, literature supports the validity and reliability of inertial motion capture in sports biomechanics. Studies confirm that Gyko and Xsens systems as accurate tools for range of motion and postural analysis, comparable to optical systems [9], [16]. Their portability and non-invasive nature make them suitable for routine monitoring in youth athletic contexts.

A particularly interesting observation was that athletes with poorer baseline postural control exhibited the most significant improvements. This suggests a high degree of responsiveness to proprioceptive stimuli in younger athletes, reinforcing the importance of early implementation of balance and stability-focused protocols in youth athletic development programs [4], [13].

However, several limitations must be acknowledged. First, the small sample size (n = 6) limits the generalizability of findings. Second, individual biomechanical differences—such as lower limb dominance or limb length discrepancies—were not controlled and could have influenced angular deviations. Lastly, while the Xsens system provides detailed kinematic analysis [1], it does not directly assess neuromuscular activation, which could have provided complementary insight through EMG monitoring.

Despite these limitations, the current study underscores the utility of motion-capture technology in quantifying proprioceptive development and highlights the tangible benefits of sensorimotor training in youth sport. Future research could explore longitudinal interventions with larger cohorts, inclusion of complementary strength/stability metrics, and examination of injury prevention outcomes [2].

5. Conclusions

The findings of this study confirm that individualized proprioceptive training, when consistently applied within a structured program, significantly enhances postural control and neuromuscular stability in junior hurdlers. The reductions observed in Roll and Pitch angular displacements indicate an improved ability to maintain balance and alignment during critical phases of hurdle clearance. These results support the inclusion of proprioceptive training as a core component in youth athletics, particularly in disciplines requiring precise landing mechanics and dynamic stability.

The Xsens motion capture system proved to be an effective and non-invasive method for capturing real-time, high-resolution biomechanical data. Its capacity to quantify subtle postural adaptations over time offers coaches and trainers an objective foundation for monitoring athlete development and customizing interventions. The use of three-dimensional angular data (Roll, Pitch, Yaw) provided a more nuanced understanding of postural changes than traditional observational or one-plane testing methods.

Furthermore, the training program's progressive structure—beginning with basic balance tasks and advancing toward complex, sport-specific drills—appears to have facilitated efficient neuromuscular adaptation. The athletes' improvements were not only statistically significant but also practically relevant, particularly for those with lower baseline control, who demonstrated the most substantial gains.

While the small sample size and lack of neuromuscular activation data represents limitations, the outcomes highlight important directions for future research. Longitudinal studies involving larger cohorts and additional variables such as muscle activation patterns, reaction time, and injury incidence would provide a more comprehensive perspective on proprioceptive training efficacy.

This study contributes to the growing body of evidence that proprioceptive training is not solely a tool for injury prevention but a valuable strategy for enhancing athletic performance. The integration of wearable sensor technologies like Xsens into the training environment empowers coaches with precise data, supporting smarter training decisions and optimizing youth athletic development.

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