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The effect of balance training on changes in values of quantities describing the phenomenon of anticipatory postural adjustments

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Purpose: The aim of this study was to evaluate the effects of a four-week proprioceptive training programme with perturbation stimuli on postural control mechanisms in female basketball players. Changes in postural muscle activity, biomechanical parameters, and compensatory responses were analysed within the framework of early, anticipatory and compensatory postural adjustments. *Methods*: Five female basketball players (22 ± 4 years) participated in the study. Measurements were conducted before and after the training intervention. Postural muscle activity was recorded using surface electromyography, centre of pressure parameters were assessed with a stabilographic platform, and body segment kinematics were measured using inertial measurement units. Tests included static standing and postural perturbations performed with and without prior warning. Muscle activity was analysed in the EPA, APA and CPA phases, together with muscle activation latency, maximum COP velocity, knee joint flexion, and head movement velocity. Non-parametric statistical tests and Spearman's rank correlations were applied. *Results*: After the training programme, a tendency towards increased postural muscle activity was observed, particularly during perturbations with prior warning. Maximum center of pressure velocity during the compensatory phase increased, while head movement velocity decreased, indicating improved dynamic postural control. No significant changes were found in muscle activation latency or static balance parameters. Significant relationships were identified between preparatory muscle activity and compensatory biomechanical responses. *Conclusions*: A four-week proprioceptive training programme may induce neuromuscular adaptations that enhance dynamic postural control in female basketball players, especially under predictable perturbation conditions.

Key words: *electromyography, postural control, anticipatory postural adjustments, proprioceptive training, balance perturbations, female basketball players*

1. Introduction

Maintaining a stable body posture is a dynamic and complex process that requires continuous control and ongoing adjustment of the centre of mass (COM). Proper balance ability not only enables safe and efficient performance of daily activities but also allows for effective responses to sudden and unforeseen changes in the environment. Balance disturbances may result from both internally initiated movements and external mechanical perturbations, such as a sudden displacement of the supporting surface [1], [2]. In this context, postural preparation (PA) and postural compensation mechanisms play a key role, as they are activated in response to destabilising stimuli. Anticipatory postural adjustments (APA) occur just before an expected disturbance of balance and are aimed at limiting or eliminating its potential

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destabilising effects, whereas compensatory postural adjustments (CPA) take place immediately after the perturbation and serve the purpose of restoring balance by activating appropriate muscle groups and correcting the alignment of body segments [1], [3], [4].

Postural control mechanisms are classified into three main types: early postural adjustment (EPA), anticipatory postural adjustment (APA), and compensatory postural adjustment (CPA). EPA typically occurs approximately 600–400 ms before the onset of a perturbation, preparing the body for a potential loss of balance. It is followed by anticipatory postural adjustment APA, which generally occurs around 150 ms before to 50 ms after the perturbation. The final stage involves compensatory postural adjustments CPA, which typically appear within 50–300 ms after the disturbance, allowing the body to counteract destabilisation even before it takes place [4], [5], [7]. The final stage involves compensatory reactions, appearing within 70–300 ms after the disturbance, which are responsible for postural correction and the restoration of stability [6], [7].

These phenomena can be observed, among others, through changes in the activity of postural muscles (electromyography, EMG) [8], [9], displacements of body segments, and analyses of the trajectories of the centre of mass (COM) and the centre of pressure (COP) [2]. Postural reactions may be triggered by internal stimuli (e.g., intentional movements such as reaching for an object) [10] or external ones (e.g., a sudden push). The latter can elicit APA only when the individual is able to anticipate the timing of the perturbation [4], [11], [12]. Importantly, studies have shown that prior knowledge of the type or timing of a perturbation may affect the quality and intensity of the postural response [7].

In recent years, there has been growing interest in studying APA and CPA mechanisms in the sporting context. In athletes, postural mechanisms are often more highly developed than in non-trained individuals, and training effects may influence both the speed of muscle activation and the effectiveness of corrective responses [14], [15]. This is particularly relevant in dynamic disciplines such as basketball, where rapid changes in movement direction and physical contact with opponents impose high demands on the postural control system [13].

Proprioceptive training, aimed at stimulating deep sensory perception, represents an important tool for improving postural control. Exercises performed on unstable surfaces, with eyes closed, under task-specific conditions, or using perturbation platforms, support neuromuscular adaptations by enhancing the precision of responses to balance disturbances [8], [16]–[18]. Such training is widely applied in neurological and orthopaedic rehabilitation (e.g., following stroke or anterior cruciate ligament reconstruction) [9,19,20], as well as in injury prevention in professional sport [13], [15].

However, studies assessing the effects of proprioceptive training with perturbation stimuli in athletes remain scarce – both in terms of clinical effectiveness and the accompanying biomechanical and neuromuscular changes. Previous analyses have focused mainly on clinical populations, such as patients after stroke or with musculoskeletal injuries. The use of advanced diagnostic tools such as EMG, inertial measurement units (IMU) [21], and stabilographic platforms offers the possibility of detailed evaluation of APA and CPA responses also under sport-specific conditions [22].

The aim of the present study was to assess the effects of a four-week proprioceptive training programme using a perturbation treadmill on postural control mechanisms in female basketball players. The analysis focused on the changes in postural muscle activity (EMG), centre of pressure (COP) displacement, and body segment mobility measured with IMU sensors, before and after the training intervention.

In line with the findings of previous studies, it is assumed that proprioceptive training affects muscle and biomechanical responses associated with postural control. The following research hypotheses were formulated:

- Proprioceptive training increases postural muscle activity during the EPA, APA and CPA phases, reflecting adaptive preparation of the neuromuscular system for upcoming balance disturbances. This effect has previously been observed following proprioceptive training, which resulted in earlier and stronger activation of muscles stabilising the lower limbs [8], [12], [13].
- Proprioceptive training increases the maximum velocity of COP displacement during the CPA phase, which may indicate a more dynamic and effective corrective response following perturbation. The literature suggests that athletes who have undergone deep sensory and proprioceptive training demonstrate faster and more dynamic compensatory reactions [13]–[15].
- A significant relationship will be observed between muscle activity during the EPA/APA phases and the biomechanical parameters of the compensatory response, confirming the functional link between postural preparation and the effectiveness of compensatory reactions. Similar associations between preparatory muscle activity and the dynamics of corrective responses have been reported by Wodarski et al. [10] and García-Aguilar et al. [21].

2. Materials and methods

2.1. Study group

The study involved five female participants at a mean age of 22 ± 4 years, mean height of 172.6 ± 3.6 cm and mean body mass of 66.0 ± 4.9 kg. All participants were active players of women's basketball team at the AZS Silesian University of Technology. Inclusion criteria were: active participation in competitive basketball training and absence of prior participation in structured proprioceptive or perturbation-based training programmes. Exclusion criteria included: neurological disorders affecting balance, current musculoskeletal injuries that could influence postural control, and obesity (body mass index, BMI > 30). The study was approved by the Bioethics Committee for Scientific Research of the Jerzy Kukuczka Academy of Physical Education in Katowice (approval no. 5/2020). Prior to participation, all participants received detailed information about the study procedures and provided written informed consent.

2.2. Measurement station

The testing station consisted of a platform for measuring the distribution of the centre of pressure (COP; WinFDM-S, Zebris; acquisition frequency of 100 Hz, 2560 strain gauges, measurement area of 34 × 54 cm), which was securely fixed at the central point of a treadmill designed for postural perturbation training and assessment (BalanceTutor, MediTouch). Surface electromyography (EMG; Ultium EMG, Noraxon, 2000 Hz) was used to record muscle activity, while inertial measurement units (IMU; Ultium Motion, Noraxon, 200 Hz) were employed to assess body segment mobility. EMG electrodes were placed according to current standards on the skin over the bellies of the following muscles: the tibialis anterior, the medial and lateral heads of the gastrocnemius, and the lumbar portion of the erector spinae – the key muscles involved in balance control in the sagittal plane (Fig. 1). IMU sensors were positioned in accordance with the manufacturer's recommendations – on the head, trunk, and upper and lower limbs. An additional IMU sensor was attached to the treadmill belt, allowing precise detection of the onset of the platform movement (t_0) and synchronisation of all measurement devices.

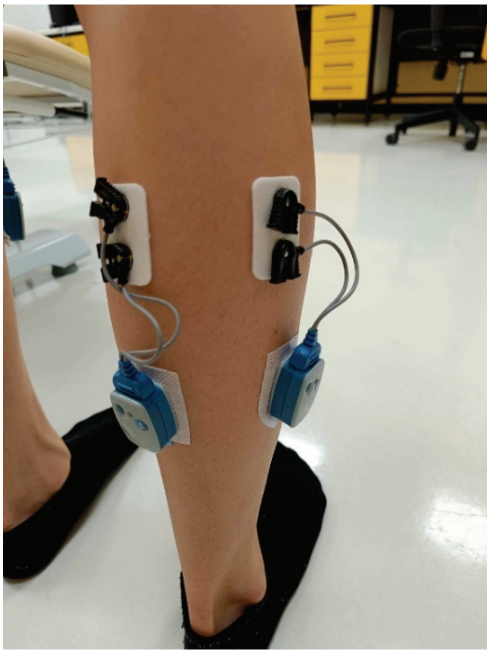

Fig. 1. Arrangement of EMG electrodes on the gastrocnemius muscle

2.3. Measurement procedure

The entire experimental procedure was carried out twice – before and after the four-week series of proprioceptive training sessions (Fig. 2). It consisted of two stages: baseline measurement (resting measurement) and standing measurements with exposure to destabilising stimuli.

In the first stage – the resting measurement (*Rx*) – participants were asked to sit on a chair with their hands resting freely on their thighs and their feet placed flat on the floor. After relaxing the lower limb muscles, muscle activity was recorded for 15 seconds. The participants then assumed a standing position – barefoot, on the stabilographic platform mounted on the treadmill belt. The arms remained relaxed alongside the trunk, and the gaze was directed straight ahead (Fig. 3).

In the next stage, measurements were performed in standing conditions – first, under static conditions with eyes open (EO) and eyes closed (EC), and then under postural perturbation conditions. This part of the procedure included four 60-second trials: two with unexpected perturbations (EO-U) and two with prior warning of the direction and timing of the perturbation, provided as a five-second countdown displayed on a screen (EO-W). Each trial consisted of four balance disturbances – two in the forward and two in the backward direction. The first perturbation occurred 10 seconds after the start of the trial, with subsequent disturbances presented at 10-second intervals in a repeated forward–backward sequence (Fig. 4). Before the measurements, participants

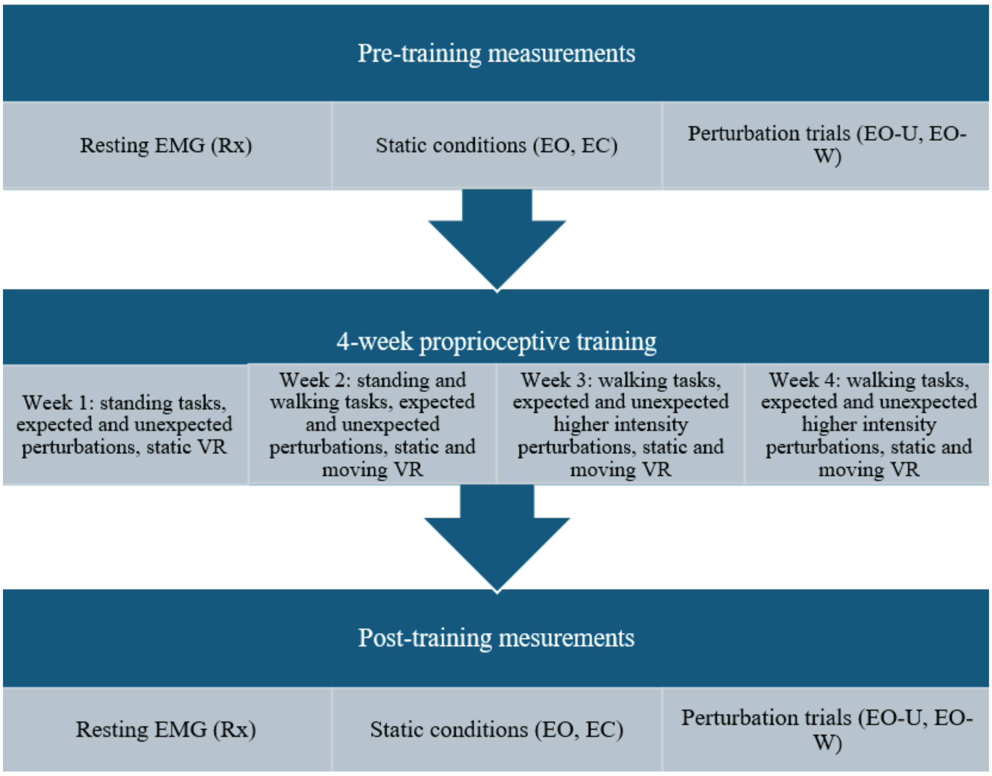

Fig. 2. Overview of the experimental and training protocol

completed a short familiarization phase that included several practice perturbations without data recording. This procedure allowed the participants to become accustomed to the treadmill and the perturbation platform and minimized potential learning effects during the experimental trials.

Fig. 3. Testing station

2.4. Training programme

Each participant completed a four-week proprioceptive training programme using a treadmill designed for the assessment and training of postural perturbation responses (BalanceTutor, MediTouch). Training sessions lasted approximately 20 minutes and were conducted three to four times per week.

The programme included postural reaction exercises in response to destabilising stimuli, performed both in a standing position and during walking. In selected exercises, virtual reality scenarios were used to provide additional visual stimulation during the perturbation tasks. Participants observed a virtual environment displayed on a screen while standing or walking on the perturbation treadmill. Two types of visual conditions were applied: a static VR environment, in which the visual scene remained stationary, and a moving VR environment, in which the visual scene moved at predefined frequencies (0.2–0.7 Hz). The moving visual environment was intended to increase the difficulty of the task by introducing additional visual perturbations and by simulating dynamic environmental conditions that may occur during sports activities.

The difficulty level of the exercises was progressively increased over the following weeks by modify-

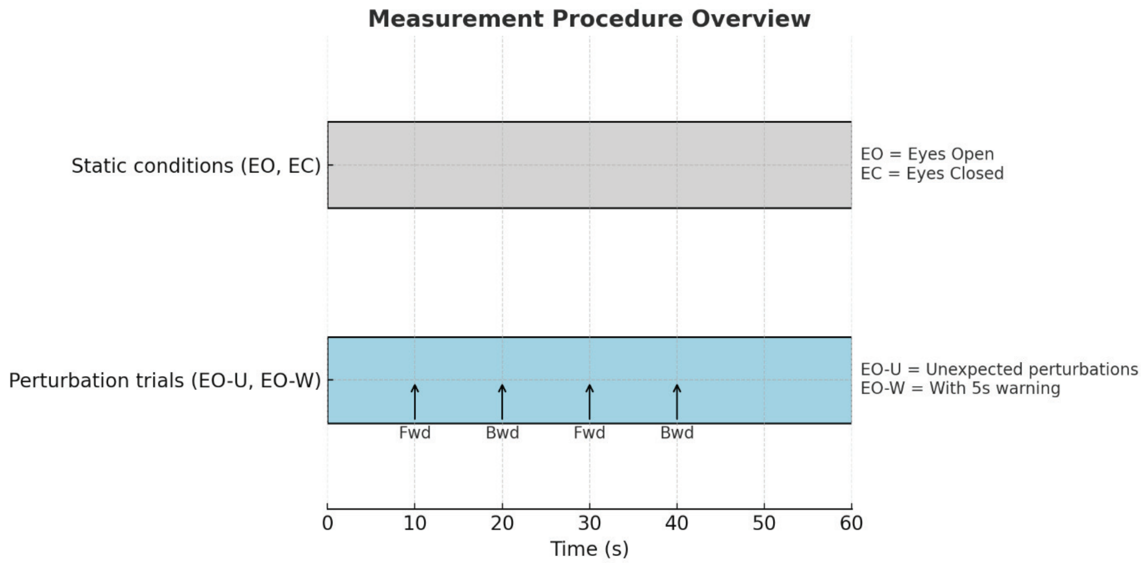

Fig. 4. Measurement procedure for static and perturbation trials. Each 60-second trial consisted of four perturbations: two forward and two backward. EO-U – unexpected perturbations without prior information; EO-W – perturbations with 5-second warning displayed on the screen

ing the direction, intensity and frequency of the perturbations (Fig. 2):

- Week 1 – training focused on maintaining balance in a standing position. Participants performed tasks with unexpected perturbations as well as perturbations preceded by a warning signal. Exercises were conducted both in a real environment and in a static VR environment. Perturbation intensity ranged from levels 1 to 3.
- Week 2 – dynamic tasks were introduced. Participants performed walking tasks on the treadmill under real-environment conditions with both expected and unexpected perturbations. Standing tasks in VR were also continued, including both static VR environments and slowly moving VR environments (0.2 Hz). Perturbation intensity ranged from levels 1 to 5.
- Week 3 – the complexity of the tasks increased further. Participants performed walking tasks with perturbations of higher intensity (levels 1–5). Standing tasks in VR included both static and moving environments with increased visual motion frequencies (0.5–0.7 Hz). Perturbation intensity ranged from levels 1 to 7.
- Week 4 – training focused primarily on dynamic balance during walking. Participants performed gait tasks in both real and virtual environments with perturbations of intensity levels 1–7. Both predictable and unpredictable perturbations were used to stimulate anticipatory and compensatory postural adjustments.

2.5. Analysis of results

The data exported from the Noraxon software were pre-processed in accordance with the algorithm implemented in the MyoResearch 3.18 system. The raw EMG signals were recorded at a sampling frequency of 2000 Hz. In the first step, the EMG signals were full-wave rectified by calculating their absolute values. Subsequently, the signals were smoothed using a moving average filter with a 50 ms window in order to obtain the EMG envelope.

In the first stage of the analysis, the mean resting muscle activity (EMGRx) was calculated based on the results of the *Rx* test. Subsequently, muscle activity recorded during the perturbation trials (EO-U, EO-W) was normalised relative to the EMGRx values obtained during the same measurement session [10]. This normalization procedure was applied to reduce the influence of potential differences in electrode placement and skin–electrode conductivity between the pre- and post-training measurements.

Using data from the IMU sensor mounted on the treadmill belt, the onset of platform movement was identified. This moment (t_0) marked the initiation of the destabilising stimulus for both forward and backward perturbations and served as the temporal reference point for subsequent analysis.

EMG signals were analysed across three phases of postural reactions: EPA (600–400 ms before the disturbance), APA (150 ms before to 50 ms after the distur-

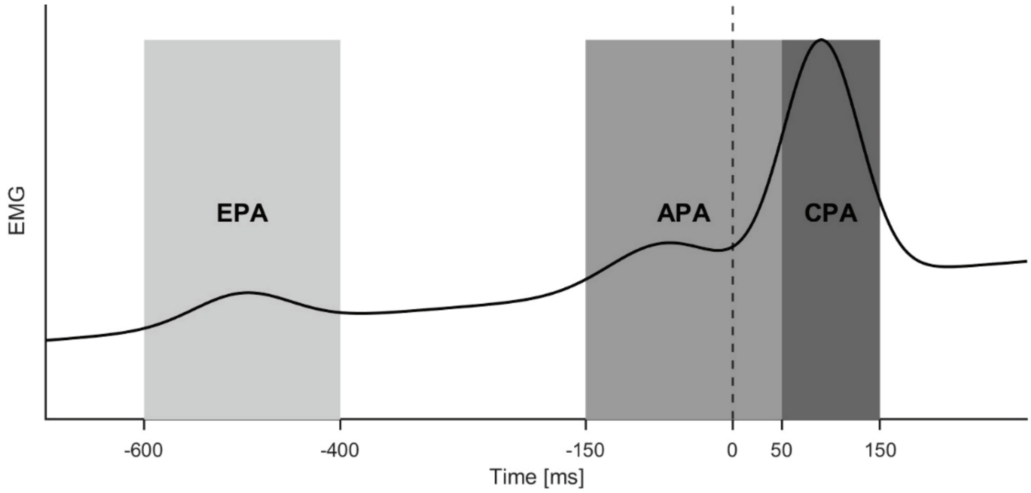

Fig. 5. Schematic representation of the EMG signal envelope and the temporal windows used for analysis relative to the perturbation onset (t_0). The shaded areas indicate the phases analysed in the study: early postural adjustment (EPA: −600 to −400 ms), anticipatory postural adjustment (APA: −150 to +50 ms), and compensatory postural adjustment (CPA: +50 to +150 ms)

bance), and CPA (50–150 ms after the disturbance) [10] (Fig. 5). These temporal windows were used to determine whether the presence of a warning stimulus affected muscle tension during the preparatory and compensatory phases of the postural response.

For each analysed muscle, the activation time was determined as the moment when the EMG signal exceeded a threshold equal to twice the standard deviation relative to the baseline EMG activity recorded during the reference period (1100–900 ms before the disturbance). This approach allowed the identification of the onset of muscle activation relative to the perturbation event and enabled the assessment of muscle response latency.

Subsequently, the analysis examined the effects of the four-week proprioceptive training programme on muscle activity during the EPA, APA, and CPA phases, as well as on muscle activation latency.

A separate analysis was conducted for the maximum COP velocity in response to perturbation within the time window of 50 to 150 ms after its onset. The study examined whether this value changed following the training intervention and whether it correlated with muscle activity during the APA and CPA phases.

To determine whether the participants prepared for the upcoming balance disturbance, knee joint flexion angles were analysed in the EPA and APA phases. In parallel, to provide a more comprehensive assessment of postural stability, head movement velocity was analysed based on data recorded with IMU sensors. The temporal patterns of these variables in response to perturbations and their relationships with muscle activity during the EPA and APA phases were subsequently examined.

All measurement systems (EMG, IMU, and COP platform) were synchronized through the Noraxon acquisition system, allowing precise alignment of biomechanical and electromyographic signals relative to the perturbation onset.

2.6. Statistical analysis

Given the small sample size, the study should be regarded as preliminary. Its aim was to provide an initial indication of potential changes in postural control mechanisms following a short-term proprioceptive intervention and to assess the applicability of the measurement tools employed.

Statistical analysis was performed using JASP software (version 0.19.1.0). Due to the small sample size and the lack of normal distribution (Shapiro–Wilk test), non-parametric statistical tests were applied. The Wilcoxon signed-rank test for dependent samples was used to compare results obtained before and after training, as well as between the warning and no-warning conditions.

Relationships between variables (muscle activity, COP parameters, knee flexion angle, head movement velocity) were assessed using Spearman's rank correlation coefficient. Results were considered statistically significant at $p < 0.05$. Given the exploratory nature of this pilot study and the small sample size, p-values between 0.05 and 0.1 were interpreted as trends that may indicate potential effects requiring confirmation in larger samples.

3. Results

In this chapter, the results of the analysis of muscle activity, biomechanical parameters, and the dynamics of postural responses to destabilising stimuli is presented, taking into account the effects of the four-week proprioceptive training and the presence of a warning stimulus.

3.1. Effect of the warning stimulus and proprioceptive training on muscle activity in response to perturbation

The study analysed lower-limb and erector spinae muscle activity in response to forward and backward perturbations across three phases of postural reactions: early (EPA), anticipatory (APA), and compensatory (CPA). The obtained values were compared both between the warning and no-warning conditions and between measurements taken before and after the four-week proprioceptive training.

Effect of the warning stimulus

Comparison between the warning and no-warning conditions revealed several differences that approached the threshold of statistical significance in the EPA, APA and CPA phases (Table 1).

In the EPA phase, during backward perturbations (before training), higher activity levels of the gastrocnemius lateralis (p = 0.063) and erector spinae (p = 0.063) muscles were observed under the warning condition.

In the APA phase, during forward perturbations, higher muscle activity values under the warning condition were observed in the tibialis anterior (p = 0.063), gastrocnemius lateralis (p = 0.063), gastrocnemius medialis (p = 0.063) and erector spinae (p = 0.063) muscles.

In the CPA phase, a trend toward differences (p = 0.063) were found for the erector spinae, gastrocnemius lateralis, and gastrocnemius medialis muscles.

Although these values did not reach statistical significance, they may indicate potential differences that warrant further analysis in studies with a larger sample size.

Effect of proprioceptive training

A comparison of muscle activity before and after proprioceptive training revealed the most pronounced changes under the forward perturbation condition with a warning (Table 2).

Table 1. Differences in muscle activity between the warning and no-warning conditions in the EPA, APA and CPA phases

Muscle	Direction of perturbation	Phase	Result
Gastrocnemius lateralis (GL)	backward	EPA	increase in activity upon warning
Erector spinae (ES)	backward	EPA	increase in activity upon warning
Tibialis anterior (TA)	forward	APA	increase in activity upon warning
Gastrocnemius lateralis (GL)	forward/ backward	APA	increase in activity upon warning
Gastrocnemius medialis (GM)	forward	APA	increase in activity upon warning
Erector spinae (ES)	forward	APA	increase in activity upon warning
Erector spinae (ES)	backward	CPA	increase in activity upon warning
Gastrocnemius lateralis (GL)	backward	CPA	increase in activity upon warning
Gastrocnemius medialis (GM)	forward/ backward	CPA	increase in activity upon warning

Table 2. Differences in muscle activity before and after proprioceptive training in the EPA and APA phases

Muscle	Direction of perturbation	Phase	Result
Tibialis anterior (TA)	forward	EPA	increase in activity after training
Gastrocnemius medialis (GM)	forward	EPA	increase in activity after training
Tibialis anterior (TA)	forward	APA	increase in activity after training
Gastrocnemius medialis (GM)	forward	APA	increase in activity after training

In the EPA phase, values approaching statistical significance were observed for the tibialis anterior (p = 0.063) and gastrocnemius medialis (p = 0.063) muscles under the warning condition.

In the APA phase, results of a similar nature (p = 0.063) were also obtained for the same muscles under the warning condition.

In the remaining cases, no significant changes were observed ($p > 0.1$); however, a general tendency for increased muscle activity following training was noted, particularly under conditions in which participants were informed about the timing and direction of the upcoming perturbation.

3.2. Muscle activation timing

The study also analysed muscle activation timing (latency relative to t_0) in the four examined muscles in response to forward and backward perturbations, both with and without a warning, before and after the training sessions. Neither the presence of a warning nor the training intervention had a significant effect on reducing muscle activation latency (all $p > 0.1$).

3.3. Knee joint flexion

Knee joint flexion angle was analysed during the preparatory phase, prior to the onset of the perturbation.

For forward perturbations with a warning, there was a tendency towards increased knee flexion following proprioceptive training (p = 0.063). Under no-warning conditions, the differences were not significant (p = 0.438).

For backward perturbations under the no-warning condition, a trend towards greater knee flexion was also observed following training (p = 0.063), whereas no significant differences were found under the warning condition (p = 0.313).

3.4. COP parameters under static conditions

Postural control parameters under static conditions – both with eyes open and eyes closed – were compared before and after training. The assessed variables included mean COP velocity, velocity in the anteroposterior (AP) and mediolateral (ML) directions, COP displacement range in both directions, the asymmetry index, and limb loading.

No significant changes were observed in any of the analysed parameters (all $p > 0.4$). Mean COP velocity remained unchanged (EO: p = 0.416; EC: p = 1.000), as did the velocity and displacement range in the AP and ML directions. The asymmetry index and limb loading also remained unaltered.

3.5. Analysis of maximum COP velocity during the CPA phase

The maximum COP displacement velocity during the compensatory phase (50–150 ms after perturbation) was analysed in response to forward and backward perturbations, both with and without a warning, before and after the proprioceptive training (Table 3).

Table 3. Comparison of maximum centre of pressure (COP) velocity during the compensatory phase (CPA; 50–150 ms after perturbation) under warning and no-warning conditions, before and after proprioceptive training

Direction of perturbation	Warning	Comparison	*p*-value
Forward	no-warning	before vs. after	0.063
Forward	warning	before vs. after	0.063
Backward	no-warning	before vs. after	0.125
Backward	warning	before vs. after	0.125

For forward perturbations, a increase in maximum COP velocity was observed following training (p = 0.063). For backward perturbations, similar changes were noted, but they did not reach statistical significance (p = 0.125).

3.6. Head movement velocity

Head movement velocity was analysed across three time phases: EPA, APA, and CPA. Comparisons were made separately for forward and backward directions, under warning and no-warning conditions, before and after training.

In the EPA phase, a reduction in head velocity was observed under the warning condition during forward perturbations (p = 0.063). A similar pattern was noted in the APA phase (p = 0.063). In the CPA phase, a decrease in head velocity occurred during backward perturbations with a warning (p = 0.063). Overall, these findings may indicate a tendency toward improved head control following training, particularly in the presence of a warning stimulus.

3.7. Correlations between muscle activity, knee flexion, COP parameters and head movements

To further explore postural responses, Spearman's rank correlation analysis was conducted between selected biomechanical parameters and muscle activity. The relationships assessed included muscle activity during the preparatory phases (EPA and APA), knee flexion angle immediately prior to perturbation, maximum COP displacement velocity during the compensatory phase (CPA), and head movement velocity (Table 4).

In the first stage, the relationships between postural muscle activity and COP parameters were analysed. A correlation was observed between tibialis anterior activity during the EPA phase and maximum COP velocity in the CPA phase ($\rho = 0.95$, $p = 0.017$). Additionally, gastrocnemius lateralis activity in the EPA phase showed a high correlation coefficient with maximum COP velocity in the CPA phase ($\rho = 0.82$, $p = 0.083$), suggesting a potential association that warrants further investigation.

Next, the relationship between knee flexion angle and COP velocity was analysed. A correlation was found between knee flexion during backward perturbations and COP velocity in the APA phase for forward perturbations ($p = 0.017$). Additionally, several configurations showed relatively strong correlations, although the corresponding p-values were higher ($p = 0.083$).

In the next analysis, it was examined whether higher muscle tension during the EPA and APA phases was correlated with greater knee flexion. No significant relationships were found between these variables in any of the analysed configurations of perturbation direction or warning condition ($p > 0.1$).

Table 4. Summary of Spearman correlations between muscle activity, knee flexion angle, and COP parameters in response to postural perturbations, taking into account perturbation direction, presence of a warning stimulus, and measurement time.

		Correlation coefficient ρ	p-value
Muscle activity TA (EPA)	COP velocity (CPA)	0.95	0.017
Muscle activity GL (EPA)	COP velocity (CPA)	0.82	0.083
Knee flexion angle	COP APA)	0.88	0.017
COP velocity (APA)	COP velocity (EPA)	0.93	0.017

In the final stage, the relationships between head movement velocity and other parameters – postural muscle activity, COP and knee flexion – were assessed. No significant associations were found between head velocity in any temporal phase (EPA, APA, CPA) and muscle activity, COP parameters, or knee flexion angle, regardless of perturbation direction, warning condition, or measurement time (pre- or post-training).

Detailed results of the correlation analysis are presented in Table 4.

4. Discussion

The aim of the present study was to assess the effects of a four-week proprioceptive training programme involving postural perturbations on postural control mechanisms in female basketball players. Changes in postural muscle activity, COP trajectories, and kinematic parameters of body segments were analysed across the EPA, APA, and CPA phases. The results largely support the research hypotheses, although it should be emphasised that some effects were directional in nature and did not reach statistical significance.

Regarding the first hypothesis, which posited that proprioceptive training would increase postural muscle activity during the EPA, APA, and CPA phases, the results provide partial support. An increase in postural muscle activity was observed following training, particularly in forward perturbations under the warning condition. Although these changes did not reach statistical significance ($p \approx 0.063$), they may indicate an adaptive enhancement of postural preparation. Increased activation was noted, among others, in the following muscles: tibialis anterior, gastrocnemius, and erector spinae. Similar effects have been reported by Moura et al. [12] and Aman et al. [8], indicating that the ability to anticipate a perturbation leads to earlier activation of muscle groups during the anticipatory phase. The post-training increase in muscle activity under the warning condition may also reflect improved effectiveness of postural preparation. Comparable relationships have been observed in studies of athletes returning to activity after injury, where proprioceptive exercises enhanced activation of muscles stabilising the lower limbs [13].

The presence of a warning stimulus contributed to greater muscle activation in the EPA and APA phases, confirming the assumption that preparatory mechanisms are triggered by the anticipation of an upcoming destabilisation. These findings are consistent with previous studies emphasising that information about an impending perturbation increases muscle activity during the EPA and APA phases [4], [7], [12]. This effect is particularly relevant in high-performance sports, where the ability to anticipate environmental changes is crucial for maintaining stability and preventing injuries.

The second hypothesis assumed that proprioceptive training would lead to an increase in the maximum COP displacement velocity during the CPA phase. In line with this assumption, an increase in the maximum COP velocity during the compensatory phase was observed following the proprioceptive training, particularly in the warning condition. This increase suggests a modification in the dynamics of post-perturbation responses. However, it should be noted that a higher COP velocity does not unambiguously indicate the direction of this change – it may reflect either a more decisive and rapid corrective response or a greater displacement of the centre of pressure in reaction to the perturbation. Determining the nature of this change requires an additional analysis of the COP displacement direction relative to the treadmill movement. Due to the lack of a clear directional trend, the hypothesis should be considered only partially confirmed – the increase in COP velocity may indicate either a more energetic corrective response or a greater centre of pressure excursion. Similar observations were reported by Lyu et al. [14] and Winter et al. [15], who described alterations in APA and CPA strategies among athletes and untrained individuals, emphasizing that differences in the velocity and direction of COP displacement may reflect distinct postural stabilization strategies.

The third hypothesis, which assumed a relationship between muscle activity in the EPA/APA phases and the biomechanical parameters of the compensatory response, was confirmed. Correlation analysis revealed that tibialis anterior activity during the EPA phase was associated with maximum COP velocity in the CPA phase ($\rho = 0.95$, $p = 0.017$). This finding indicates a link between early muscle activation and the characteristics of the compensatory response. It may be assumed that increased pre-perturbation muscle tension facilitates more effective postural preparation; however, in some cases, it may also result in excessive stiffness of body segments, potentially delaying the subsequent compensatory reaction. Relationships of a similar nature were also observed in other configurations, although these reflected directional trends that did not reach statistical significance. Comparable conclusions were reported by García-Aguilar et al. [21], who indicated that postural preparation is functionally linked to compensatory responses. Nevertheless, the influence of increased preparatory muscle activation on the effectiveness of compensatory reactions requires further, more detailed investigation.

An increase in knee flexion angle was also observed during the EPA phase. Greater flexion of the lower limbs in the initial phase of the postural response may represent a strategy aimed at improving control of the centre of mass by lowering it. Similar relationships were described by Lyu et al. [14], who demonstrated that trained individuals exhibit greater knee and hip flexion during the preparatory phases (EPA and APA), which is associated with enhanced postural stability and a more effective response to balance perturbations.

An important observation is that despite changes in muscle activity, the timing of muscle activation relative to the onset of perturbation (latency) did not change significantly after the training programme. This may suggest that temporal parameters of the response are less susceptible to short-term training interventions. Previous studies have also indicated that changes in latency tend to occur only after longer training periods or when performing more complex tasks [8], [15]. The kinematic analysis of the head segment revealed a decrease in its movement velocity after training, which may indicate improved control of the cervical and trunk regions. These findings are consistent with the observations of Röijezon et al. [19], who emphasised the importance of head–trunk coordination in adaptation to perturbations, particularly in the context of contact sports. However, it should be noted that in the present study, this effect did not always reach statistical significance and therefore requires further verification.

Under static conditions (EO and EC), no significant changes in COP parameters were observed after training, suggesting that the effects of proprioceptive training primarily concern dynamic responses. Similar results were reported in a study by Sekir et al. [17], in which improvements in balance were not reflected in static stance measures, but became evident only during tasks requiring postural reactions.

The obtained results are consistent with findings reported in the literature, indicating that proprioceptive training supports improved postural control and reduces the risk of lower limb injuries [13], [18]. The observed increases in postural muscle activity, together with changes in COP parameters and knee flexion angle observed after the four-week intervention period, may reflect adaptations in postural control strategies. However, due to the lack of a control group, it cannot be ruled out that part of these changes may also be related to task familiarization or adaptation to the perturbation protocol.

In the context of sports such as basketball, which require rapid reactions and the ability to maintain balance following physical contact with opponents or sudden changes in movement direction, such adaptations may be relevant both for enhancing movement efficiency and for preventing overloads and injuries. From this perspective, proprioceptive training, particularly when incorporating perturbation stimuli, represents a valuable complement to the motor preparation process [22].

In summary, the findings of this study suggest that even a short, four-week proprioceptive training program may enhance postural control mechanisms, particularly under dynamic and unpredictable conditions typical of competitive sports.

Limitations of the study

A limitation of the present study is the relatively small number of participants and the lack of a control group. Therefore, it cannot be unequivocally determined whether the observed changes resulted solely from the proprioceptive training programme or were partially influenced by task familiarization or adaptation to the perturbation protocol during repeated measurements. Future studies including a control group would allow a clearer distinction between training-induced adaptations and learning effects associated with repeated exposure to the experimental task.

Furthermore, all measurements were conducted under controlled laboratory conditions which, although ensuring high repeatability of the perturbation protocol, may not fully reflect the dynamics of real on-court situations. It should also be noted that the training period was relatively short and the long-term retention of the observed effects was not assessed.

5. Conclusions

The observed changes in muscle activity, knee flexion angle and COP parameters suggest potential neuromuscular adaptations to balance disturbances. The lack of significant differences in muscle response latency and under static conditions indicates that the short-term training program primarily affected dynamic parameters related to postural control. The results support the inclusion of proprioceptive training in athletic preparation programs, both for injury prevention and for optimizing motor performance. However, full confirmation of these findings requires further studies involving a larger sample size, a control group, and a longer observation period. The present study indicates that a four-week proprioceptive training program incorporating dynamic perturbations may be associated with changes in postural control mechanisms in female basketball players, particularly with respect to muscle activity during the preparatory and compensatory phases.

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