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Research article

The effects of six weeks of combined balance and plyometric training on postural control performance in elite badminton players: A pilot randomized, controlled study

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ABSTRACT

Background/Objectives: The athletic performance in badminton players largely depends on the capability of dynamic postural control to quickly restore balance when performing high-paced movements (e.g., frequent single-leg jumps). Our aim was to examine the effects of a novel intervention that combines balance training on an unstable surface and plyometric training on the performance of restoring balance after jumping, as well as related postural control in elite badminton players.

Methods: Sixteen elite male badminton players were randomly allocated to either a combined balance and plyometric training group (CT, n = 8) or a plyometric training group (PT, n = 8). The CT group participated in a six-week training program, which included three training sessions per week. Each session comprised 40 min of plyometric exercises and 20 min of balance training. The PT group underwent plyometric training using the identical protocol as that of the CT group. All participants underwent identical technical training in badminton throughout the duration of the study. At baseline and immediately after the intervention, participants completed a single-leg jumping test. The capacity to restore balance was evaluated using the time to stabilization (TTS) after landing; and the related center of pressure (COP) fluctuations were also recorded. The effect of intervention was examined by two-way repeated-measures of ANOVA.

Results: The primary two-way repeated-measures ANOVA models showed no significant interactions between group and time on either the time to stability in the dominant leg (D-TTS) or the time to stability in the non-dominant leg (N-TTS) ($p > 0.70$). Significant main effects of time, group, and their interactions on dominant legs of the anterior-posterior displacement difference (D-COP_{AP}) (time: $p = 0.001$; group: $p = 0.001$; interaction: $p = 0.014$), non-dominant legs of the anterior-posterior displacement difference (N-COP_{AP}) (time: $p < 0.001$; group: $p = 0.003$; interaction: $p = 0.021$) and non-dominant legs of the medial-lateral displacement difference (N-

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COP_{ML}) (time: $p < 0.001$; group: $p < 0.001$; interaction: $p = 0.026$), that is, compared to baseline of both groups and post PT, the COP metrics were significantly reduced after CT. Secondarily, within the CT and PT group, after the intervention, the N-TTS (CT: $p = 0.001$, post: 0.58 ± 0.87; PT: $p = 0.03$, post: 0.71 ± 0.11) was significantly decreased compared to baseline (CT pre: 0.76 ± 0.16; PT pre: 0.88 ± 0.13).

Conclusion: This pilot study demonstrated that, compared to PT-only, the 6-week CT which combines balance training induced comparable improvements in the capacity to restoring balance after landing from a single-leg jump, and significantly improved the postural control performance as measured by COP metrics.

1. Introduction

Competitive badminton requires athletes to perform high-paced movements with high intensity, examples include frequent rapid accelerations, lunges, abrupt halts, and changes of direction (COD) [1–3]. The ability to accurately execute these prompt movements in response to the moving shuttlecock in badminton athletes depends on intact dynamic balance, which enables appropriate changes in body direction continuity during the game [4]. Hence, strategies such as plyometric training, aimed at improving the capacity to restore balance after jumping and related postural control are highly sought-after to enhance the on-court performance of badminton players.

An effective strategy is plyometric training (PT). PT primarily aims to enhance various physical capabilities (e.g., such as jumping, linear running sprinting speed, agility, COD, and coordination, among others) [5]. Studies have indicated that PT can efficiently improve the performance of dynamic postural stability [6] and COD speed [7,8] by separately shortening the muscle eccentric-concentric contraction cycle [9] and augmenting neural adaptations via the increased number of motor unit recruitment [10]. Still, in addition to the functionalities of each of these components separately, the synchronization and coordination across them are critical to the athletic performance of badminton. Strategies targeting the facilitation of such interactions may thus provide additional benefits for the performance of badminton.

Recent efforts have been devoted to developing novel types of the combined training (CT), consisting of at least two types of training programs (e.g., balance training and PT) [11,12]. This strategy can concurrently enhance multiple underlying components pertaining to dynamic balance capacity [13]. Recent studies have emerged to explore the benefits of CT on the functional performance of badminton athletes [14]. For example, it was reported that compared to PT alone, the CT program incorporating balance training and PT can significantly enhance the dynamic balance (i.e., decreased sway length) and the quickness performance (i.e., faster time to complete dynamic balance tasks) of male elite badminton players [15,16]. However, the impact of CT on the ability to restore balance during single-leg jump landings, a crucial aspect of badminton on-court performance, remains insufficiently characterized [17].

Therefore, in this pilot randomized-controlled study, we examined the effects of a 6-week CT consisting of balance training and PT on the time to stability (TTS) after landing from the single-leg jump, and the related postural sway as assessed by the center of pressure (COP), in a group of elite male badminton players. Specifically, we hypothesized that compared to PT, the CT protocol would induce greater enhancements in TTS and less postural sway (e.g., diminished sway distance of COP) when landing after single-leg jump in elite male badminton players.

2. Methods

2.1. Participants

The sample size of this study was calculated using G-Power 3.1.9.6 (Heinrich Heine University, Germany), setting the Effect Size f to 0.4 and the power to 0.95, and the sample size should be more than 16 people. Study subject inclusion criteria are as follows. After the screening, sixteen healthy elite male badminton players were recruited for this study and were randomly assigned to either the combined training group (CT, n = 8) or the plyometric training group (PT, n = 8) (Table 1). Specifically, one research staff who was not involved in any other study procedure used a random-digit generator code in Matlab (Matlab 2023b, The MathWorks Inc., United States) to obtain a list of the randomization number for two groups (i.e., “1” for control and “2” for intervention group). Then following the recruitment order of each participant, he/she was randomized into the group according to the corresponding digit (i.e., 1 or 2) on the list. The study employed a single-blind design, where the participants were unaware of their group allocation to minimize potential bias. The researchers responsible for data collection and analysis were also blinded to the group assignments to ensure objectivity in

Table 1

The demographics and training experience of the participants in PT and CT group.

	PT (n = 8)	CT (n = 8)
Age (Years)	19.13 ± 2.23	20.50 ± 1.07
Height (cm)	179.13 ± 6.06	177.75 ± 5.06
Weight (kg)	69.88 ± 8.94	68.13 ± 7.22
Training Experience (Years)	10.63 ± 1.06	11.38 ± 1.41

the assessment process.

2.2. Study design

The study employed a pilot randomized controlled trial (RCT) design. The participants were recruited from one badminton club. The inclusion criteria were : (1) Right-side dominance and engaged in three weekly training sessions, each lasting 2–3 h, encompassing both technical and physical training components; (2) Elite athletes who have advanced to the quarterfinals of national youth games, achieved finalist status at provincial competitions, or participated in even higher-level tournaments; (3) Demonstrated proficiency in conducting the dynamic Balance Test and participating in plyometric training. The exclusion criteria were: (1) Participants had a history of anterior cruciate ligament (ACL), meniscus, ankle, hamstring, or other lower-extremity injuries resulting in compromised dynamic postural stability within the past three years; and (2) Players had visual impairments that affected their postural stability, vestibular deficits, or neurologic dysfunctions based on their self-reported information. The Research Ethics Committee of Beijing Sport University approved the study protocol (Approval number: 2020008H), and all procedures were conducted according to the Declaration of Helsinki [18]. Prior to the commencement of the experiment, participants were thoroughly informed about the potential benefits and inherent risks associated with the study. Subsequently, they provided their informed consent by signing the necessary documentation.

2.3. Exercise intervention

During the study, the participants adhered strictly to their usual dietary habits and were instructed to refrain from consuming any beverages containing caffeine or alcohol. All the participants completed three sessions of the training per week with 24–48 h of rest between each session for 6 weeks. This training protocol and intervention period were established and valid in multiple previous work of our group and others [13,19,20]. Participants in the CT group completed a balance training program (Supplementary Table 2) under unstable conditions, utilizing equipment such as the Swiss ball, BOSU ball, and Balance pad. The PT group received identical training but on the solid floor. Both the CT and PT groups followed the same plyometric training protocol (refer to Supplementary Table 3). Before the training, all participants completed a two-week familiarization period, including three weekly sessions of balance and plyometric exercises. During this familiarization period, participants received instructions from a certified strength and conditioning coach. All the training and testing procedures were administered by the study personnel to ensure the safety of participants.

2.4. Measurements

2.4.1. The single-leg jump task

Before and after the final session of training, participants were required to complete the single-leg jump task to assess their dynamic balance control within two days. At the beginning of the test, participants completed the warm-up, including 5-min dynamic stretch, 8-min movement integration, and 8-min neural activation.

During the assessment, participants were asked to stand on an in-ground force plate (Kistler 9281CA, KISTLER, Winterthur, Switzerland, 1000 Hz) and then perform the six trials of single-leg jump (three for each leg) forward to a targeting line over a fence at the midpoint with height of 30 cm. The distance between the targeting line and the initial position of the participant is set at 40 % of the participant's height. Participants were asked to maintain single-leg standing for 10 s after landing [21]. The order of the six trials was randomized and a 30-s rest was provided between each trial. The TTS and COP time series of each trial were recorded.

The baseline and post-intervention tests were completed at the same time of the day, and participants were asked to wear the same clothing and shoes.

2.5. Data processing

To measure the capacity to restoring balance, the primary outcome was TTS (as shown in Equation [1]), a robust indicator of lower limb stability and motor coordination capacity that contributes to the rapid ability for stabilization [22,23], including the dominant leg (D-TTS) and the non-dominant leg (N-TTS). The secondary outcomes were the COP metrics, including the anterior-posterior (AP) displacement difference ($\mathrm{COP_{AP}}$) (as shown in Equation [2]), medial-lateral (ML) displacement difference ($\mathrm{COP_{ML}}$) (as shown in Equation [3]), and total displacement distance ($\mathrm{COP_{PL}}$) (as shown in Equation [4]), of forwarding jump with both dominant (D-$\mathrm{COP_{AP}}$, D-$\mathrm{COP_{ML}}$ and D-$\mathrm{COP_{PL}}$) or non-dominant legs (N-$\mathrm{COP_{AP}}$, N-$\mathrm{COP_{ML}}$, N-$\mathrm{COP_{PL}}$) [24].

All the COP and TTS data were filtered using a low-pass filter with a cut-off frequency of 13.33 Hz. TTS in the anterior-posterior (APTTS) and medial-lateral (MLTTS) directions was determined when the data corresponding to the unbounded polynomial reached or fell within the range of variation.

$$\mathrm{TTS} = \sqrt{\mathrm{APTTS}^2 + \mathrm{MLTTS}^2} \qquad [1]$$

$$\mathrm{COP_{AP}} = \sum_{1}^{10} (\mathrm{x_t} - \overline{\mathrm{x}})^2 \qquad [2]$$

$$\mathrm{COP}_{\mathrm{ML}} = \sum_{1}^{10} (y_t - \bar{y})^2 \qquad [3]$$

$$\mathrm{COP}_{\mathrm{PL}} = \sum_{0}^{9} \sqrt{(x_{t+1} - x_t)^2 + (y_{t+1} - y_t)^2} \qquad [4]$$

where, X_T and Y_T are the back and forth, left and right displacement at T seconds and the value of T is 1–10 s.

2.6. Statistical analyses

The statistical analysis was performed using IBM SPSS statistical software package (Version 25.0, IBM, Chicago, IL, USA). All data were presented as means and SD. Shapiro-Wilk test was used to identify the data of normal distribution.

If the data was normally distributed, the differences in the demographics (i.e., age, weight, height and, training experience) and outcomes (i.e., D-TTS, N-TTS, D-COP$_{AP}$, N-COP$_{AP}$, D-COP$_{ML}$, N-COP$_{ML}$, D-COP$_{PL,}$ and, N-COP$_{PL}$) between groups at baseline were examined using one-way ANOVA. Non-parametric test (i.e., Wilcoxon signed-rank test) was used if the data was not normally distributed. When a significant difference in any of these variables was observed, we included them in the model of the following analyses examining the effects of intervention as covariate, since it may potentially influence the effects of intervention.

Then to examine the effects of the intervention on primary outcomes (i.e., D-TTS, N-TTS) and secondary outcomes (i.e., D-COP$_{AP}$, N-COP$_{AP}$, D-COP$_{ML}$, N-COP$_{ML}$, D-COP$_{PL,}$ and, N-COP$_{PL}$), we used two-way repeated-measure ANOVA models when the data was normally distributed. The dependent variable for each model was each of the primary and secondary outcomes. The model effects were group (CT and PT), time (pre- and post-intervention) and their interaction. If a significant interaction was found, an LSD post-hoc comparison was performed to identify where the significance was. We also performed an exploratory analysis to examine the effects of time (i.e., pre- and post-intervention) on the performance within the PT and CT group using one-way ANOVA. When the data was not normally distributed, we used the Wilcoxon signed-rank test.

The level of significance was set at $p < 0.05$ for the comparisons of primary outcomes and at $p < 0.006$ for secondary outcomes via Bonferroni correction to account for multiple comparisons. Partial η^2 was used to assess the effect size where the significance was observed.

3. Results

All participants completed the study, and their data were all included in the analysis. The Shapiro-Wilk test demonstrated that all the data were normally distributed ($p = 0.06$–0.997) (see Supplementary Table 1). No significant differences in age, body weight, height and training experience were observed between CT and PT groups ($p > 0.14$). It was observed that at baseline, compared to PT, the D-TTS in the CT group is significantly greater ($p = 0.003$), and no significant difference in other outcomes was observed ($p > 0.13$). Therefore, we included the baseline D-TTS as a covariate into the model that compared the effects between CT and PT on D-TTS.

3.1. The effects of combined training on the time to stability

The primary two-way repeated-measures ANOVA models showed significant effects of time ($p < 0.001$, Confidence interval (CI) 95 %: (−0.435, −0.184)), but not group ($p = 0.27$) or interactions between group and time on N-TTS ($p > 0.70$); and no significant effects of time ($p = 0.15$), group ($p = 0.20$), or their interactions ($p = 0.80$) on D-TTS. The exploratory analysis showed that within CT group, the N-TTS [$F_{(1,15)} = 14.755$, $p = 0.001$, partial $\eta^2 = 0.345$, CI 95 %: (−0.511, −0.156)] was significantly decreased (i.e., better performance) as compared to pre-intervention, while no significant change in D-TTS ($p = 0.34$) from pre- to post-intervention was observed; and within PT group, both D-TTS [$F_{(1,15)} = 27.61$, $p < 0.001$, partial $\eta^2 = 0.496$, CI 95 %: (−0.753, −0.331)] and N-TTS [$F_{(1,15)} = 10.8$, $p = 0.003$, partial $\eta^2 = 0.278$, CI 95 %: (−0.463, −0.107)] were significantly decreased (i.e., better performance) after

Table 2
The TTS and COP in CT group and PT groups before and after the 6-week training.

	CT (N = 8)		PT (N = 8)		P-value of interaction
	Pre	Post	Pre	Post	
D-TTS	0.68 ± 0.05	0.76 ± 0.19	1.01 ± 0.29	0.68 ± 0.07$^{\#}$	0.802
N-TTS	0.76 ± 0.16	0.58 ± 0.87$^{\#}$	0.88 ± 0.13	0.71 ± 0.11$^{\#}$	0.702
D-COP$_{AP}$ (cm)	90.28 ± 16.39	65.95 ± 6.51*	95.15 ± 12.65	88.27 ± 8.28$^{\#}$	0.014
N-COP$_{AP}$ (cm)	99.18 ± 14.64	69.00 ± 5.36*	102.66 ± 14.89	93.67 ± 11.62$^{\#}$	0.021
D-COP$_{ML}$ (cm)	72.97 ± 11.99	60.55 ± 6.23$^{\#}$	81.90 ± 10.30	74.81 ± 2.73	0.441
N-COP$_{ML}$ (cm)	84.43 ± 13.39	66.41 ± 5.11*	92.86 ± 7.67	83.96 ± 8.16$^{\#}$	0.026
D-COP$_{PL}$ (cm)	131.60 ± 22.10	109.70 ± 18.56$^{\#}$	137.27 ± 15.39	132.19 ± 11.17	0.180
N-COP$_{PL}$ (cm)	143.78 ± 19.49	107.11 ± 12.81	148.37 ± 16.22	131.42 ± 20.29	0.121

Note: *Statistically significant difference as compared to all the other pre- and post-intervention, $p < 0.05$. #Statistically significant difference within CT or PT group, $p < 0.05$. COP, the center of pressure. TTS, time to stabilization.

intervention as compared to pre (Table 2).

3.2. The effects of combined training on the center of pressure characteristics

The secondary two-way repeated-measures ANOVA models showed significant main effects of time, group, and interactions between group and time on D-COP_{AP}, N-COP_{AP} and N-COP_{ML} (time: $p < 0.001$; group: $p = 0.001$–0.003; interaction: $p = 0.014$–0.026), but not on D-COP_{ML}, D-COP_{PL} and, N-COP_{PL} ($p = 0.121$–0.441). The post-hoc analysis revealed that D-COP_{AP} [$F_{(1,15)} = 14.774$, $p = 0.001$, partial $\eta^2 = 0.345$, CI 95 %: (-34.218, -10.426)], N-COP_{AP} [$F_{(1,15)} = 16.228$, $p < 0.001$, partial $\eta^2 = 0.367$, CI 95 %: (-37.211, -12.124)] and N-COP_{ML} [$F_{(1,15)} = 26.851$, $p < 0.001$, partial $\eta^2 = 0.490$, CI 95 %: (-32.868, -14.244)] were significantly greater after CT as compared to the outcomes of all the other pre- and post-intervention (Table 2). The exploratory analysis showed that within the CT group, N-COP_{PL} [$F_{(1,15)} = 17.659$, $p < 0.001$, partial $\eta^2 = 0.387$, CI 95 %: (-54.556, -18.799)] was significantly improved as compared to pre-intervention. Marginally significant change in D-COP_{ML} ($p = 0.015$, CI 95 %: (-22.287, -2.557)) and D-COP_{PL} ($p = 0.017$, CI 95 %: (-39.593, -4.197)) from pre- to post-intervention was also observed within this group (Table 2). Within the PT group, no such significant changes in COP outcomes were observed from pre- to post-intervention ($p > 0.062$).

4. Discussion

This pilot study demonstrated that, in comparison to PT, the 6-week CT induced comparable improvements in time to stabilization after the landing from single-leg jump, and significantly greater enhancements in related postural control performance (i.e., reduced postural sway). These observations suggest that this type of CT can effectively reduce the postural sway with at least similarly benefits for the capacity to restoring balance after landing from jumping in elite badminton athletes as compared to traditional PT.

It is observed that CT induced comparable improvements in the capacity to restoring balance after the single-leg jump with PT. The performance of TTS depends primarily upon the muscular strength of the lower limb and the stiffness of the ankle joint (e.g., During the descent phase, hip extension is employed to reposition the legs in preparation for landing [25]) of the support leg, as well as the capacity to quickly adjust the sway and movement of the body to the appropriate position (e.g., using visual cognition and knee proprioception [23]). The ankle stiffness and lower-limb muscular strength are the primary focus of PT. Studies have shown that, for example, PT can significantly reduce the time to adjust the ankle plantar flexor in response to the impact of a drop landing [26]. Therefore, we here observed that the CT consisting of the same PT protocol as the PT-only intervention induced similar improvements on TTS. Moreover, this result may indicate that the static balance training of CT we used here, which is additional to PT, which was primarily performed on a stable position, needs to be optimized for TTS. Previous studies have shown that the regulatory processes for static and dynamic balance are not entirely overlapped [27], and the preservation of a stable position following a dynamic task (e.g., jump) presents significantly greater challenges than static standing alone, as it involves destabilizing external forces and demands superior muscular coordination [21,27]. Additionally, it was suggested the training difficulty may interfere with its effects. For example, previous studies have demonstrated that greater difficulty in balance tasks, such as the manipulation of sensory inputs, can induce greater improvement in balance performance [28]. Therefore, strategies specifically targeting to the enhancement of dynamic postural control in a more challenging condition, such as the movement training on an unstable support (e.g., support of sand), may be more beneficial for capacity to restoring balance immediately after landing. Future studies are required to implement such protocols and examine their effects on the capacity to restoring balance.

Improved postural control of a single leg after a single-leg jump was significantly greater with CT compared to PT in our secondary analyses. These observations are consistent with previous studies [11,13,14] showing that CT can induce benefits for the performance of postural control. Postural control is dependent upon a complex regulation scheme consisting of multiple underlying neurophysiological procedures (e.g., the perception, processing and integration of vast sensory information, such as the visual and somatosensory inputs [29]). Therefore, strategies that simultaneously target these elements, especially the interactions between these elements, can be more appropriate for improving postural control performance. Specifically, compared to the PT protocol which targets primarily the functions of those components separately (e.g., the strength of lower limb), the CT consisting of balance training enhances the functionalities of multiple elements underlying the postural control simultaneously, such as the neural adaptation, recruitment and coordination of sensorimotor units (e.g., visual, vestibular, and proprioceptive inputs), and particularly, their interactions [30,31]. Still, it is worthwhile to explicitly measure those underlying elements and their interactions in future studies to provide direct evidence to the pathways underlying the benefits of CT for postural control performance when landing after the single-leg jump. These observations of this pilot study suggest that the CT intervention combining PT and balance training induces at least comparable improvements in the capacity of restoring balance and better postural control performance after a single-leg jump in badminton athletes as compared to PT only. It is highly demanded in future studies to confirm the findings of this pilot study, to optimize the CT with more appropriate protocols (e.g., incorporating balance training during position and movement changes), and then explore its benefits for badminton athletic performance.

5. Limitations

First, this pilot study has a relatively small sample size as it focuses only on male elite badminton players, thus limiting the generalizability of the findings. Future studies should include a larger and more diverse sample of participants, encompassing both males and females at various professional levels in badminton as well as other sports such as volleyball or soccer. And there is a high demand to examine and confirm the findings, as well as explore the clinical significance of this intervention in the study. The functional assessments used in this study primarily focused on postural control, it is thus needed to directly examine the effects of interventions on the on-court performance (e.g., batting success rate or accuracy in consecutive multiple shots). Meanwhile, it is worthwhile in future studies to characterize the dose-response relationship between the intervention and performance by completing multiple assessments throughout the intervention, of which the obtained knowledge will ultimately help optimize the design of CT protocol to maximize its benefits for the performance of athletes.

6. Conclusion

These observations of this pilot study suggest that the CT intervention combining PT and balance training induces at least comparable improvements in the capacity of restoring balance and better postural control performance after a single-leg jump in badminton athletes as compared to PT only. It is highly demanded in future studies to confirm the findings of this pilot study, to optimize the CT with more appropriate protocols (e.g., incorporating balance training during position and movement changes), and then explore its benefits for badminton athletic performance.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Luyu Zhang: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Limingfei Zhou:** Writing – review & editing, Resources, Methodology, Investigation, Data curation. **Wangcheng Gong:** Supervision, Investigation, Data curation. **Guole Jiang:** Writing – review & editing, Data curation. **Dapeng Bao:** Writing – review & editing, Funding acquisition, Conceptualization. **Brad Manor:** Writing – review & editing, Supervision, Investigation. **Junhong Zhou:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Luyu Zhang reports financial support was provided by the Fundamental Research Funds for the Central Universities. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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