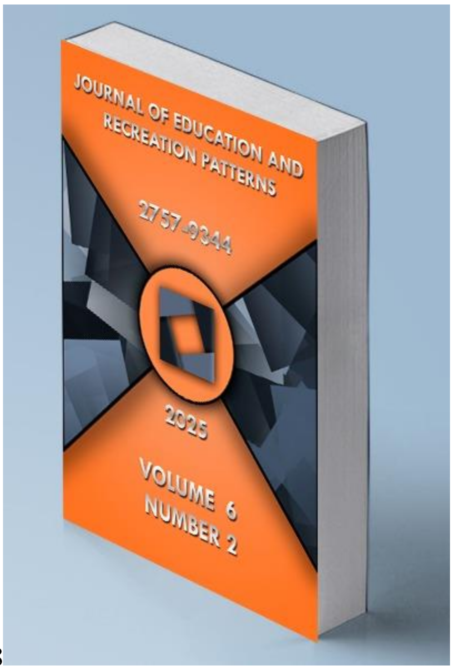

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Investigation of the Relationship Between Static Postural Sway Parameters and Explosive Power in Recreational Athletes via Digital Posturography

Sinan SEYHAN[1], Görkem AÇAR[2], Berkay ÜZÜMCÜ[3]

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[1] Department of Coaching Education, Faculty of Sport Sciences, Manisa Celal Bayar University, Türkiye; sinan.seyhan@cbu.edu.tr, https://orcid.org/0000-0002-4979-7992

[2] Department of Sport Science, Institute of Graduate Education, Manisa Celal Bayar University, Türkiye; gorkemacar2@gmail.com, https://orcid.org/0000-0002-0970-8625

[3] Cybernicx Health and Technology Company, 34720 Istanbul, Türkiye, berkayuzumcu59@gmail.com, https://orcid.org/0000-0002-6519-6273

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Investigation of the Relationship Between Static Postural Sway Parameters and Explosive Power in Recreational Athletes via Digital Posturography

Sinan Seyhan[1], Görkem Açar[2], Berkay Üzümcü[3]

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ABSTRACT

This study aimed to determine whether bipedal static balance performance, assessed under eyes-open and eyes-closed conditions, contributes to countermovement jump (CMJ) performance when sex-related differences and postural stability parameters are statistically controlled. Sixty-four physically active adults (32 females and 32 males; aged 18–45 years) who regularly engaged in resistance-based exercise participated in the study. Static balance was evaluated in a standardized bipedal stance using the TecnoBody D-Wall system by quantifying center-of-pressure (CoP) ellipse area under eyes-open and eyes-closed conditions. CMJ performance was assessed using the same system, with jump height, flight time, total mechanical work, maximum force, and maximum absolute power recorded. Statistical analyses were performed using IBM SPSS Statistics. Data normality was assessed with the Shapiro–Wilk test. Sex-based differences in anthropometric variables were analyzed using independent samples t-tests or Mann–Whitney U tests, as appropriate. To examine the effect of sex on CMJ performance while controlling for static balance parameters, analysis of covariance (ANCOVA) models were applied, with eyes-open and eyes-closed CoP ellipse areas entered as covariates. ANCOVA results revealed significant main effects of sex on several CMJ outcomes, including flight time, total work, maximum force, and maximum absolute power ($p < 0.05$), with large effect sizes. Eyes-open static balance did not significantly influence any CMJ parameter. In contrast, the eyes-closed CoP ellipse area demonstrated a borderline significant effect on total mechanical work ($p = 0.050$), suggesting a limited contribution of proprioceptive-dominant postural control to mechanical work production independent of sex. These findings indicate that bipedal static balance, as quantified by CoP ellipse area, does not substantially explain variability in vertical jump performance beyond sex-related effects. This conclusion is specific to static balance conditions and should not be generalized to dynamic balance or functional stability tasks. Overall, static postural control and explosive jump performance appear to represent largely independent motor capacities, underscoring the importance of task-specific assessment and training strategies in athletic populations.

Keywords: Countermovement Jump, Digital Posturography Technologies, Static Balance.

INTRODUCTION

Athletic performance is a multidimensional construct arising from the interaction of neuromuscular power, coordination, and postural control. Among these components, jumping ability is widely regarded as a key indicator of lower-extremity power and has been consistently linked to sport-specific performance outcomes such as sprint speed, acceleration, and running performance across different competitive distances (Fatouros et al., 2000; Luebbers et al., 2003; Robinson et al., 2004; Chaouachi et al., 2014; Farkas et al., 2024). Vertical jump performance, particularly during the countermovement jump (CMJ), reflects an athlete's capacity to rapidly generate force and efficiently utilize the stretch–shortening cycle (SSC), making it a commonly used marker of explosive performance in both research and applied sport settings (Luebbers et al., 2003; Chaouachi et al., 2014).

Balance, defined as the ability to maintain the body's center of mass within the base of support, constitutes another essential determinant of athletic performance. Effective postural control allows athletes to stabilize the body during static positions and regulate movement during dynamic actions, particularly in sports involving repetitive jumping, rapid deceleration, and changes of direction (Chaouachi et al., 2014; Alhashimi et al., 2024; Suzuki et al., 2024). Balance performance relies on the integration of visual, vestibular, and somatosensory inputs and is commonly categorized as static or dynamic, each reflecting distinct aspects of sensorimotor control and neuromuscular regulation (Hrysomallis, 2011).

From a biomechanical perspective, a potential mechanistic link between balance and vertical jump performance may be explained through force transmission efficiency during the SSC. The CMJ begins with an eccentric loading phase, during which the ankle, knee, and hip joints must remain sufficiently stabilized to allow effective storage and subsequent release of elastic energy. Insufficient joint stabilization may result in force dissipation through non-vertical planes, leading to so-called "lateral force leaks" and a reduction in net vertical impulse (Chaouachi et al., 2014; Christensen & Nordstrom, 2008). In this context, postural stability can be considered a prerequisite for directing generated force along the intended movement axis and optimizing jump performance.

In addition to mechanical stability, proprioceptive input represents a shared neuromuscular mechanism underlying both balance and explosive power production. Sensory feedback from muscle spindles, Golgi tendon organs, and joint mechanoreceptors provides continuous information regarding muscle length, tension, joint position, and movement velocity. This afferent input plays a crucial role in regulating muscle stiffness, intermuscular coordination, and timing of motor unit recruitment during both postural control and jumping tasks (Šimek Šalaj et al., 2007; Struzik et al., 2017). A well-functioning proprioceptive system minimizes postural sway during stance and contributes to optimized neuromuscular activation patterns during the rapid eccentric–concentric transition of the SSC (Christensen & Nordstrom, 2008; Struzik et al., 2017). Consequently, it has been proposed that superior balance ability may support explosive performance by enhancing neuromuscular efficiency and force application.

Importantly, these neuromuscular mechanisms may operate differently in male and female due to sexual dimorphism in musculoskeletal and neural control characteristics. Female generally exhibit greater joint range of motion and ligamentous laxity, which may favor postural adaptability but reduce joint stiffness and peak force transmission capacity during explosive movements. In contrast, male typically possess a stiffer muscle–tendon unit and greater absolute force-generating capacity, which may enhance vertical jump performance but potentially compromise fine postural control under static conditions (Chaouachi et al., 2014; Hrysomallis, 2011). These sex-specific neuromuscular strategies suggest that the relationship between balance and jumping performance may differ between males and females, and that analyses pooling both sexes may obscure meaningful physiological patterns.

Despite these theoretical considerations, empirical findings regarding the relationship between balance and jumping performance remain inconsistent. While some studies have reported positive associations—particularly when balance is assessed under challenging sensory conditions or via dynamic and unilateral tasks—others have demonstrated weak or non-significant relationships between static balance parameters and vertical jump performance (Chaouachi et al., 2014; Goktepe et al., 2016; Cooper et al., 2020; Suzuki et al., 2024). These discrepancies may stem from methodological differences, including the type of balance assessment employed (static vs. dynamic), task difficulty, athlete population, sensory manipulation (eyes open vs. closed), and failure to account for sex-related neuromuscular differences.

Importantly, many studies reporting stronger balance–performance relationships have employed dynamic or functional balance tests, such as the Star Excursion Balance Test or sport-specific instability assessments, which challenge the limits of postural control (Goktepe et al., 2016). In contrast, bipedal static stance tests primarily reflect baseline postural sway and neural noise, potentially limiting their sensitivity in well-trained populations (Hrysomallis, 2011). Nevertheless, instrumented static balance measures, such as equilibrium ellipse area derived from digital posturography, offer objective and highly reliable quantification of postural control and may provide insight into baseline sensorimotor stability under controlled conditions.

Accordingly, the present study aimed to examine whether baseline static postural stability, quantified via equilibrium ellipse area under eyes-open and eyes-closed conditions, is associated with detailed vertical jump performance parameters obtained from an instrumented assessment system, while explicitly accounting for sex-related differences. The originality of this study lies in its integration of sensory-specific static balance conditions, comprehensive CMJ performance metrics, and sex-based analytical considerations to clarify conflicting findings in the literature.

Based on theoretical and empirical considerations, the following hypotheses were formulated:
(H1) Static balance performance under eyes-closed conditions would demonstrate a stronger association with vertical jump parameters compared to eyes-open conditions, due to increased reliance on somatosensory and vestibular input.

(H2) The relationship between static balance performance and vertical jump outcomes would differ between females and males due to sex-specific neuromuscular control strategies.

(H3) Individuals exhibiting superior static balance performance would demonstrate better vertical jump performance outcomes.

METHOD

Ethics

Çankırı Karatekin University Ethics Committee, Institutional Review Board, granted the study's ethical approval under protocol number 2024-09-18 (743df7c398de482b). The study adhered to the principles of the Declaration of Helsinki. All participants provided informed consent, with written consent obtained from each individual.

Participants

Participants were eligible for inclusion if they were between 18 and 45 years of age, engaged in regular resistance-based exercise for approximately 90 minutes on at least three days per week for a minimum of the past six months, and voluntarily consented to participate in the study. This definition was intended to identify regularly exercising individuals rather than elite or sport-specific athletes. All participants were required to be free from any condition that could directly affect balance control or explosive lower-extremity performance.

Exclusion criteria included the presence of any current or recent musculoskeletal injury affecting the lower extremities or spine, diagnosed orthopedic disorders, structural foot deformities such as pes cavus or pes planus, a history of lower-extremity or spinal surgery within the previous six months, and any known neurological, vestibular, or systemic condition that could impair postural control or neuromuscular function. Participants reporting chronic pain, balance disorders, or the use of medications known to influence neuromuscular performance were also excluded from the study.

The sporting background or primary exercise discipline of the participants was not restricted, and individuals may have engaged in different types of physical activities (e.g., resistance training, recreational sports, or general fitness exercise). Therefore, the sample represents a heterogeneous group of physically active adults rather than a homogeneous athletic population from a single sport discipline.

Participant characteristics and sex-based comparisons are presented in Table 1. No statistically significant difference was observed between females and males in terms of age ($p = .520$). In contrast, significant sex-related differences were identified for anthropometric variables. Male participants exhibited significantly greater height, body weight, and body mass index (BMI) compared with female participants (all $p < .001$). These findings indicate clear sex-related differences in body composition and anthropometric profiles, while age distribution was comparable between groups.

Table 1

Participant Characteristics and Sex Comparisons

Variable	Females (n = 32) Mean ± SD	Males (n = 32) Mean ± SD	p
Age (years) ^{u}	29.9 ± 6.3	31.8 ± 6.7	.520
Height (cm) ^{t}	162.8 ± 4.4	178.6 ± 4.3	< .001***
Weight (kg) ^{u}	56.8 ± 4.5	80.1 ± 10.0	< .001***
BMI (kg/m²) ^{u}	21.6 ± 1.7	25.2 ± 2.5	< .001***

u; Mann–Whitney U test, t;Independent t-test, cm; centimetre, kg; kilogram, BMI; Body mass index, SD; Standard deviation

Evaluations

Static balance assessment was performed using the TecnoBody D-Wall system (TecnoBody®, Bergamo, Italy) in a bipedal stance. To ensure protocol standardization and minimize variability related to base of support, all participants were instructed to stand with their feet positioned at shoulder-width distance, with both feet parallel and evenly loaded. Hand position was standardized by placing the hands alongside the body throughout the balance tests.

The static balance test consisted of two conditions: eyes open and eyes closed. Each condition was performed for 30 seconds, with a two-minute passive rest interval between conditions. During the eyes-open condition, participants were instructed to focus on a fixed visual target (a stationary cross) positioned at eye level on the screen in front of them. Importantly, no real-time center-of-pressure (CoP) or avatar-based visual biofeedback was provided, and participants were not instructed to actively control or adjust their posture based on screen information. This approach ensured that the eyes-open condition represented a true static balance task rather than a visual biofeedback exercise. During the eyes-closed condition, participants were asked to keep their eyes gently closed while maintaining the same standardized stance.

Static balance performance was quantified using the Center of Pressure (CoP) ellipse area (EA; mm^2) parameter derived from the D-Wall posturographic system, reflecting the spatial dispersion of postural sway during quiet standing.

Following completion of the balance assessments, participants rested passively for five minutes before performing the vertical jump evaluation. Vertical jump performance was assessed using the countermovement jump (CMJ) protocol on the same TecnoBody D-Wall device. Participants performed three maximal CMJ trials, and jump height (cm), maximum force (N), flight time (s), total work (J), and maximum absolute power (W) were recorded. Adequate rest was provided between trials to minimize fatigue, and the best performance among the three trials was used for subsequent analysis.

Anthropometric Measurements

This form consists of information such as gender, height, weight, education, etc. The participants' heights were measured using the TecnoBody D-Wall device. Body Mass Index (BMI) was calculated by dividing the weight in kilograms by the square of the height in meters (kg/m^2) (Norris et al., 2005).

Balance Measurement

TecnoBody has developed various devices used in the field of rehabilitation and sports sciences, one of which is the D-Wall device. D-Wall is an assessment and rehabilitation tool that provides auditory and visual feedback to help improve movement quality. It analyzes and trains postural structure during movement and assesses and improves segmental and global coordination and sensory-motor skills. During movement kinematics, the angles of the joints and biomotor characteristics (balance, agility, etc.) are measured. D-Wall supports each user's movement with immediate biological feedback (Üzümcü et al., 2024).

Countermovement Jump

Prior to the vertical jump assessment, all participants completed a standardized warm-up protocol consisting of 10 minutes of light jogging followed by dynamic stretching exercises targeting the lower extremities. After the warm-up, the athletes performed the countermovement jump test in front of the TecnoBody D-Wall device (Üzümcü et al., 2024). Participants executed the jump in a bipedal stance starting from approximately 90° of knee flexion, with their hands placed on their waists, and were instructed to jump as high as possible. Each athlete performed three maximal jump trials, with a 10-second rest interval provided between successive attempts to minimize fatigue effects. The highest value obtained from the three trials was selected for statistical analysis (Figure 1).

Figure 1

CMJ on TecnoBody D-Wall device

Eyes Open/Closed Balance

Athletes were positioned in front of the D-Wall device, with feet shoulder-width apart and pressure sensors underneath. Hands-free and eyes open and closed for 30 seconds each were used for static balance evaluations (Üzümcü et al., 2024).

Statistical Analysis

Statistical analyses were performed using IBM SPSS Statistics software (Version 26.0; IBM Corp., Chicago, IL, USA). Continuous variables were expressed as mean ± standard deviation, whereas categorical variables were reported as frequencies and percentages. The normality of continuous variables was assessed using the Shapiro–Wilk test. Based on the distribution characteristics, sex-related differences in anthropometric measurements were evaluated using the independent samples t-test for normally distributed variables and the Mann–Whitney U test for variables that did not meet the normality assumption.

To examine the effects of sex on CMJ performance while controlling for static balance parameters, analysis of covariance (ANCOVA) models were applied. In these models, sex was entered as a fixed factor, and eyes-open and eyes-closed center-of-pressure ellipse areas were included as covariates. For all statistical tests, a significance level of $p \leq 0.05$ was considered statistically significant.

The study's sample size was calculated using the G*Power 3.1.9.7 program. 64 people were calculated with 80% power (Goktepe et al., 2016).

RESULTS

Descriptive statistics of CMJ performance and static balance parameters stratified by sex are presented in Table 2. Female participants demonstrated lower values across all CMJ performance variables compared with males. Specifically, males exhibited greater bounce height, longer flight time, higher total mechanical work, greater maximal force, and higher maximal absolute power than females. With respect to static balance performance, females displayed smaller center-of-pressure (CoP) ellipse areas under eyes-open conditions compared with males, indicating reduced postural sway during visually guided stance. Under eyes-closed conditions, mean ellipse area values were comparable between sexes, although greater variability was observed in both groups. These findings suggest sex-related differences in explosive performance parameters, while static balance characteristics exhibited less pronounced differences between females and males.

Table 2

Descriptive Statistics of CMJ Performance and Static Balance Parameters by Sex

Variable	Female (n = 32) Mean ± SD	Male (n = 32) Mean ± SD
Bounce Height (cm)	24.6 ± 3.6	34.5 ± 6.9
Flight Time (s)	0.34 ± 0.05	0.43 ± 0.06
Total Work (J)	163.7 ± 31.0	274.9 ± 69.0
Max Force (N)	1179.5 ± 177.8	1528.6 ± 244.3
Max Abs. Power (W)	1906.3 ± 410.1	3117.3 ± 749.1
OE	116.6 ± 39.8	171.9 ± 94.9
CE	150.3 ± 70.7	164.2 ± 71.4

OE; Eyes open, CE; Eyes closed, EA; Ellipsis area, mm; minimetre, sec; second, cm; centimetre

Table 3

Results for the Effects of Sex and Static Balance Parameters on CMJ Performance

Dependent Variable	Source	df	F	p	ηp²
Jump Height (cm)	Sex	1, 6	5.60	.056	.48
	OE	1, 6	0.11	.753	.02
	CE	1, 6	3.49	.111	.37
Flight Time (s)	Sex	1, 6	7.27	.036*	.55
	OE	1, 6	0.11	.755	.02
	CE	1, 6	0.43	.534	.07
Total Work (J)	Sex	1, 6	22.42	.003**	.79
	OE	1, 6	0.01	.920	.00
	CE	1, 6	6.00	.050*	.50
Max Force (N)	Sex	1, 6	9.39	.022*	.61
	OE	1, 6	0.31	.598	.05
	CE	1, 6	0.22	.658	.03
Max Abs. Power (W)	Sex	1, 6	48.52	<.001***	.89
	OE	1, 6	0.77	.413	.11
	CE	1, 6	3.11	.128	.34

OE; Eyes open, CE; Eyes closed, EA; Ellipsis area, mm; minimetre, sec; second, cm; centimetre $p < .05$, * $p < .01$, ** $p < .001$***.

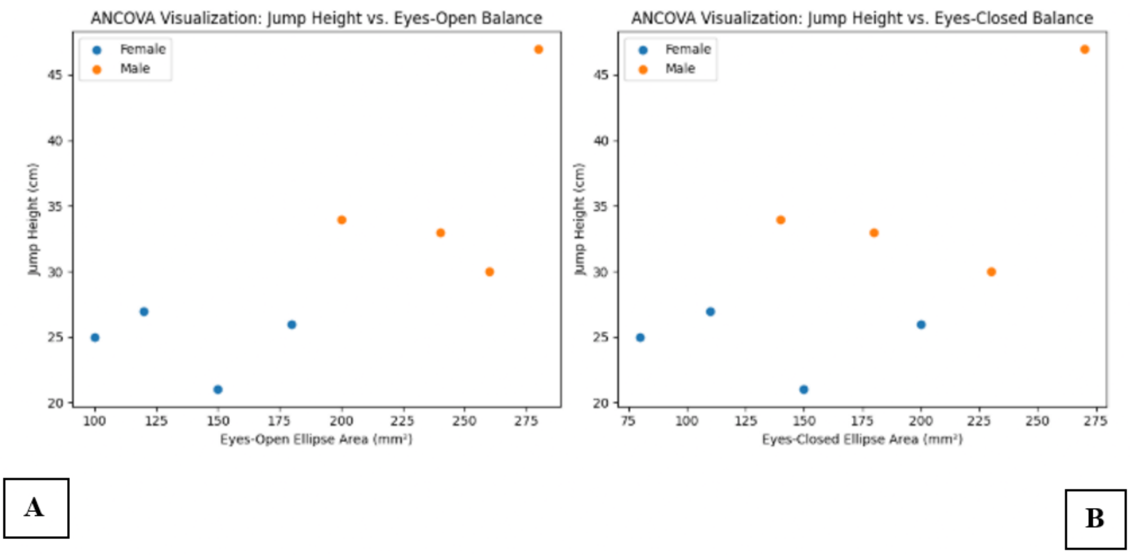
The effects of sex and static balance parameters on countermovement jump (CMJ) performance were examined using separate ANCOVA models for each dependent variable, with sex entered as a fixed factor and eyes-open (OE) and eyes-closed (CE) center-of-pressure ellipse areas included as covariates (Table 3).

Sex demonstrated a significant main effect on several CMJ performance variables. Specifically, significant sex effects were observed for flight time ($p = .036$), total work ($p = .003$), maximal force ($p = .022$), and maximal absolute power ($p < .001$), with large effect sizes ($\eta p^2 = .55–.89$). The effect of sex on jump height approached statistical significance ($p = .056$) and was associated with a large effect size ($\eta p^2 = .48$).

Regarding static balance parameters, eyes-open ellipse area did not show a significant effect on any CMJ performance variable ($p > .05$), with negligible effect sizes across models ($\eta p^2 \leq .11$). In contrast, eyes-closed ellipse area demonstrated a significant effect on total work ($p = .050$, $\eta p^2 = .50$), indicating a moderate-to-large contribution of balance performance under visual deprivation to mechanical work output. No significant effects of eyes-closed balance were observed for jump height, flight time, maximal force, or maximal absolute power ($p > .05$), although moderate effect sizes were noted in some models.

Figure 2

Scatter Plots Showing the Relationships between Jump Height and Center-Of-Pressure (CoP) Ellipse Area under (A) Eyes-Open and (B) Eyes-Closed Conditions, Stratified by Sex.



Scatter plots illustrating the relationships between jump height and static balance parameters measured as center-of-pressure (CoP) ellipse area under (A) eyes-open and (B) eyes-closed conditions, stratified by sex. Each data point represents an individual participant. The figures demonstrate sex-specific distribution patterns and visually support the ANCOVA findings, indicating that eyes-open static balance shows no apparent association with jump height, whereas eyes-closed balance reveals a trend toward higher jump performance in males, suggesting a potential contribution of proprioceptive-dominant postural control mechanisms, as shown in Figure 2.

DISCUSSION

The primary finding of the present study was that bipedal static balance performance, quantified via center-of-pressure (CoP) ellipse area under eyes-open and eyes-closed conditions, did not exhibit a robust association with countermovement jump (CMJ) performance variables when sex-related differences were statistically controlled. These findings suggest that static postural control and explosive jumping performance may represent largely independent motor components under the measurement conditions applied in this study.

Consistent with the existing literature, CMJ performance was strongly influenced by sex, with males demonstrating significantly greater flight time, total mechanical work, maximal force, and maximal absolute power compared with females. These differences are in line with well-documented sexual dimorphism in neuromuscular characteristics, whereby males typically exhibit greater muscle mass, higher muscle–tendon stiffness, and superior absolute force-producing capacity, while females often demonstrate greater joint range of motion and postural adaptability (Chaouachi et al., 2014; Hrysomallis, 2011). The large effect sizes observed across multiple CMJ outcomes reinforce the dominant contribution of sex-related neuromuscular factors to explosive performance.

From a mechanistic perspective, CMJ performance is primarily determined by the rapid generation of force, effective utilization of the stretch–shortening cycle, and neuromuscular synchronization across lower-extremity muscle groups (de Villarreal et al., 2011; Taipale et al., 2012). In contrast, static balance reflects the central nervous system's ability to integrate visual, vestibular, and somatosensory inputs to maintain postural stability with minimal sway (Hrysomallis, 2011). Although these performance domains share common sensorimotor substrates, the principle of task specificity suggests that they rely on distinct control strategies, particularly when balance is assessed under low-demand, bipedal static conditions.

Indeed, previous research has emphasized that the relationship between balance ability and athletic performance is highly dependent on the type of balance assessment employed (Hrysomallis, 2011). Studies reporting stronger associations between balance and jumping performance have predominantly used dynamic or unilateral balance tasks that challenge the limits of postural control. For example, Gualtieri et al. (2008) reported significant relationships between closed-eye balance performance and CMJ outcomes in amateur soccer players using more demanding proprioceptive tasks, while Wilczyński et al. (2021) demonstrated moderate associations between dynamic balance assessed via the Y-Balance Test and vertical jump performance. In contrast, bipedal static stance has been suggested to induce a ceiling effect in healthy and physically active individuals, thereby limiting its sensitivity to detect inter-individual differences (Hrysomallis, 2011). This methodological consideration likely explains the absence of strong associations between static balance and CMJ performance observed in the present study.

Importantly, although eyes-open static balance did not exert a significant effect on any CMJ variable, a borderline effect of eyes-closed balance on total mechanical work was identified. This finding warrants consideration from a neuromechanical perspective. Removal of visual input increases reliance on proprioceptive and vestibular systems, potentially amplifying the contribution of somatosensory feedback to postural regulation and force transmission (Hrysomallis, 2011). Efficient proprioceptive input may facilitate more stable joint positioning and improved force transfer through the kinetic chain during preparatory phases preceding force production. Previous studies have suggested that balance tasks imposing greater proprioceptive demands are more likely to reveal associations with strength and power outcomes (Gualtieri et al., 2008; Wilczyński et al., 2021). Therefore, the observed trend between eyes-closed balance and total work may reflect a subtle proprioceptive contribution to mechanical output that was insufficiently strong to reach conventional levels of statistical significance within the present sample.

Nevertheless, the overall lack of significant balance effects on CMJ performance supports the notion that eliminating visual input alone is not sufficient to meaningfully influence explosive force production in healthy, physically active individuals. Cooper et al. (2020)

reported that despite pronounced reductions in jump performance following lower-extremity fatigue, static balance parameters remained largely unchanged, further supporting the idea that static postural control and explosive power are governed by partially distinct neuromotor mechanisms. These findings are consistent with the present results.

While longitudinal studies have demonstrated that plyometric training can improve balance performance (Ramachandran et al., 2021), such findings primarily reflect training-induced adaptations rather than cross-sectional relationships. Consequently, the existence of long-term interactions between balance and jumping does not necessarily imply that these variables will be significantly associated in acute or cross-sectional assessments.

Overall, the findings of this study indicate that static balance and CMJ performance should be considered complementary yet largely independent components of athletic performance rather than interchangeable measures. This highlights the importance of employing multidimensional and task-specific assessment batteries when evaluating neuromuscular performance in physically active populations.

This study has several limitations. First, balance assessment was restricted to bipedal static conditions, and neither unilateral nor dynamic balance tests were included, which may have reduced sensitivity to detect balance–jump relationships. Second, the cross-sectional design precludes causal inferences. Finally, the absence of electromyographic or kinetic analyses limits direct evaluation of the neuromuscular mechanisms underlying the relationship between balance and jump performance. Future research should incorporate dynamic and unilateral balance tasks, longitudinal designs, and neuromuscular assessments to more comprehensively investigate the role of proprioception and postural control in explosive force production.

Conclusion

The present study demonstrated no statistically significant association between static balance performance and vertical jump performance, indicating that these capacities function as largely independent components of athletic performance. While both balance and explosive jumping are essential for sport success, they rely on distinct neuromuscular and motor control mechanisms and differ substantially in task demands. From a practical standpoint, these findings suggest that improvements in static balance alone are unlikely to translate directly into enhanced vertical jump performance under controlled conditions. Accordingly, training programs should avoid assuming automatic transfer effects between balance and explosive power. Instead, balance training should be primarily emphasized for postural control and injury prevention, whereas jump- and power-specific exercises should be prioritized to improve explosive performance. Coaches and practitioners are encouraged to implement complementary, task-specific training strategies that independently target balance and neuromuscular power to optimize overall athletic performance.

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