

# Effects of Taekwondo Match-Simulated Fatigue on Static and Dynamic Balance Performance in Female Athletes

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## Research Article

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# Abstract

## Background

Balance is an important aspect of physical performance in taekwondo and can be affected by the high-intensity, intermittent, and repetitive movements carried out during a competition. This study investigated the effects of a taekwondo match-simulated fatigue protocol on static and dynamic balance performance in trained female taekwondo athletes.

## Methods

Eighteen trained female taekwondo athletes participated in a single-group repeated-measures study. Static and dynamic single-leg balance was assessed on the dominant leg at rest and immediately after a taekwondo-specific match-simulation protocol using the Biodex Balance System. The protocol comprised three 2-minute rounds separated by 1-minute rest intervals. Balance performance was evaluated using the Overall Stability Index, Anteroposterior Stability Index, and Mediolateral Stability Index. Separate  $2 \times 2$  repeated-measures ANOVAs were performed to examine the main effects of time and balance condition and their interaction, with partial eta squared ( $\eta^2$ ) reported as the effect-size measure.

## Results

No significant main effects of time or balance condition and no significant time  $\times$  balance condition interactions were found for the overall, anteroposterior, or mediolateral stability indices ( $p \geq .149$ ).

## Conclusions

Under the present protocol and assessment conditions, no statistically significant changes in static or dynamic single-leg balance performance were detected following the taekwondo match simulation. These findings should be interpreted with caution due to the small sample size, the absence of a control condition, and the lack of direct physiological or perceptual verification of fatigue.

## Trial registration

The trial was retrospectively registered at ClinicalTrials.gov with registration number (NCT07747064) and date (20260725).

## Introduction

Taekwondo is a modern Olympic combat sport that places substantial demands on physiological systems and is characterized by highly intensive, short-duration, and intermittent activity patterns. The sport involves dynamic technical and tactical actions that require considerable lower-limb flexibility, with kicking constituting the primary offensive strategy and accounting for approximately 98% of all attacks during a match [1, 2]. To execute and sustain these technical actions effectively, athletes must demonstrate elevated levels of physical fitness components, including muscular strength, power, flexibility, speed, and agility, to support movements such as kicking, punching, blocking, holding, pushing, and footwork. Consequently, optimal performance in taekwondo relies on both technical and tactical proficiency and the development of fitness components such as aerobic and anaerobic power, muscular strength, muscular power, flexibility, speed, agility, and balance [3]. The ability to maintain postural stability and control the center of gravity during rapid, complex movements is essential for executing offensive throws while simultaneously resisting an opponent's counterattacks [4]. Although fatigue can impair postural control, its effects may vary by direction of stability, with anteroposterior stability being more susceptible to fatigue than mediolateral stability in taekwondo athletes [5].

Human balance is a multidimensional concept that refers to an individual's ability to avoid falling. At the same time, postural control encompasses the processes of maintaining, achieving, or restoring balance during various postures or activities [6]. Balance is typically classified as either static, the capacity of the body or a body segment to remain stable in a specific posture [7], or dynamic, the ability to regulate body posture during movement [8]. Both static and dynamic balance are highly relevant in Taekwondo, where athletes must continuously adjust their body position and distance from opponents through multidirectional turning and stepping actions during both offensive and defensive maneuvers [3, 9].

Taekwondo kicking techniques often require athletes to maintain balance on a single supporting leg, underscoring the importance of postural stability for effective kick execution [10]. Dynamic kicking combinations demand strength, speed, stamina, flexibility, and coordination [11]. Inadequate postural balance can result in whole-body instability, excessive loading of passive musculoskeletal structures, and an increased risk of injuries and falls [10]. Roundhouse, spin roundhouse, side, and back kicks are fundamental techniques frequently employed in taekwondo competition, where kicks constitute approximately 80% of all techniques performed [12]. Due to the predominance of kicking, the strength and energy demands on the lower extremities may lead to fatigue during training and competition, which, in turn, can impair postural stability in taekwondo athletes [5]. Repeated high-intensity actions in taekwondo primarily engage anaerobic metabolism, and the resulting intracellular accumulation of hydrogen ions ( $H^+$ ) may contribute to muscular fatigue and diminished lower-extremity strength and power [13, 14]. These effects may alter the hamstring-to-quadriceps strength ratio, as the hamstrings' complex architecture, multi-joint function, and high proportion of fatigue-susceptible Type II fibers may render them particularly vulnerable to fatigue [15, 16]. The literature further suggests that both the absolute strength of the quadriceps and hamstring muscles and the balance between these muscle groups are associated with performance in balance tasks [17].

Taekwondo athletes often compete in four to five consecutive matches within a single day, with each match comprising three 2-minute rounds separated by 1-minute rest intervals. This schedule results in substantial cumulative physiological fatigue [2]. Lower-extremity muscle fatigue has been demonstrated to transiently increase postural sway and impair postural stability [18]. This phenomenon is particularly relevant in taekwondo, as the lower extremities represent the most frequently injured body region [19]. Furthermore, injury incidence has been reported to rise across rounds, from 7.5% in the first round to 43.1% in the second and 49.5% in the third, a trend attributed to fatigue [20]. Collectively, these findings indicate that cumulative fatigue during competition may impair balance control and increase the risk of injury.

Examining the effects of match-related fatigue on postural stability is essential due to its physiological and performance implications. While previous research has demonstrated that fatigue impairs postural stability in taekwondo athletes, one study utilized an incremental maximal Bruce treadmill test to induce fatigue rather than a taekwondo-specific protocol [5]. This method does not accurately replicate the repeated kicking actions and intermittent activity characteristic of taekwondo competition. To address this limitation, Chuang et al. [2] developed a match-simulated protocol involving 10-second bouts of maximal kicking alternated with 10-second periods of low-intensity bouncing. Employing a match-simulated kicking protocol may therefore offer a more task-specific evaluation of the effects of fatigue on postural stability. The primary objective of the present study was to investigate the effects of a simulated taekwondo match on static and dynamic balance performance in female taekwondo athletes.

## Methods and Materials

### Participants

The study sample consisted of accessible female taekwondo athletes who met the inclusion criteria during the research period and volunteered to participate in the study. For this reason, the sample size was not determined in advance using a priori power analysis. Eighteen female taekwondo athletes participated in a single-group repeated-measures study. All participants volunteered, possessed more than three years of taekwondo experience, and were actively competing in official events. Based on the classification framework by McKay et al. [21], these athletes were classified as Tier 2 (trained) due to their consistent training and competitive backgrounds. Weight category was excluded as an analytical variable. Data collection was conducted during the competition period to ensure that athletes were engaged in official competitions. The mean age of participants was  $18.9 \pm 1.05$  years, mean height was  $165.6 \pm 5.32$  cm, mean body mass was  $56.9 \pm 5.06$  kg, and mean body mass index (BMI) was  $20.7 \pm 1.24$  kg/m<sup>2</sup>.

Participants refrained from eating for at least one hour prior to testing and were permitted to consume only water. None of the participants had a musculoskeletal injury or condition affecting lower extremity function within three months preceding the study. All balance assessments included in the data analysis were performed during the second visit within a single testing session. No adverse events were reported

during either visit. Participants received information about the study procedures in advance and provided written informed consent prior to participation. The study was approved by the Ethics Committee of the Faculty of Sport Sciences at Selçuk University (Protocol No: 279, 11 December 2025, Konya, Turkey) and was conducted in accordance with the Declaration of Helsinki. The study was retrospectively registered at ClinicalTrials.gov (NCT07747064, on July 25, 2026).

## Research Design

A single-group, two-visit repeated-measures design was employed in this study, with a 48-hour interval between visits. The first session served to familiarize participants with the study procedures and balance assessments. Practice trials of static and dynamic balance tests were conducted using the Biodex Balance System (Biodex Medical Systems, Shirley, NY, USA); data from these trials were excluded from analysis. During the second session, participants performed a five-minute warm-up consisting of low-intensity bouncing and stretching exercises. Static and dynamic balance performance was then assessed under rested conditions. All balance tests were conducted on the dominant leg, defined as the leg preferred for kicking a ball. The sequence of static and dynamic balance tests was randomly assigned for each participant and maintained before and after the exercise protocol. Following the rested balance assessments, participants completed a taekwondo-specific match-simulated kicking protocol adapted from Chuang et al. [2]. Balance testing commenced within one minute after completion of the protocol, and these results were recorded as post-protocol balance values (Fig. 1). All assessments were conducted between 09:00 and 11:00 under controlled environmental conditions (temperature: 22–24°C; relative humidity: 50–55%). Device settings and test procedures remained consistent throughout the study, and the same researcher performed all measurements. Rested and post-protocol balance results were compared to evaluate acute changes in static and dynamic balance following the taekwondo-specific match simulation. This study was conducted in accordance with the CONSORT 2025 guidelines. The completed CONSORT checklist is provided as an additional file, and the study flow chart is presented in Fig. 1.

## Taekwondo-Specific Fatigue Protocol

The taekwondo-specific match-simulated kicking protocol, adapted from Chuang et al. [2], served as a high-intensity, sport-specific exercise stimulus. Chuang et al. [2] documented elevated heart rate, perceived exertion, and post-exercise blood lactate concentrations in elite taekwondo athletes during this protocol. The protocol employed a single-match format comprising three 2-minute rounds, each separated by a 1-minute rest period. The protocol took place in an 8 × 8-meter octagonal competition area with a rubberized floor. Athletes wore standard competition equipment throughout the protocol. During each 2-minute round, athletes performed consecutive sidekicks, reverse sidekicks, and roundhouse kicks at maximal speed and effort for 10 seconds, followed by 10 seconds of active recovery with low-intensity bouncing movements. This cycle of 10-second kicking and 10-second active recovery was repeated throughout each round, maintaining a 1:1 work-to-recovery ratio. This protocol

was chosen based on evidence that it elicits heart rate, blood lactate, and perceived exertion responses similar to those observed during simulated taekwondo competition [2]. Additionally, its non-contact design enabled athletes to perform high-intensity, taekwondo-specific kicking movements without direct physical contact.

## Static and Dynamic Balance Tests

The Biodex Balance System (Biodex Medical Systems Inc., Shirley, NY, USA) was employed to assess participants' static and dynamic balance performance. Balance was evaluated using a single-leg stance test under two conditions: eyes-open (EO) and eyes-closed (EC). For the EO condition, platform stability was set to level 5, whereas a static level was applied for the EC condition. The order of static and dynamic balance assessments was randomized for each participant to minimize potential order effects. All assessments were performed barefoot on the dominant lower extremity, defined as the foot the participant preferred when kicking a ball.

Prior to testing, the optimal foot position for each participant was established using an adjustable platform that enabled modification of the supporting foot's placement to maximize stability. This position was recorded by the system and maintained throughout all testing sessions. During assessments, participants stood on one leg with their arms folded across their chests. The non-supporting leg was positioned away from the test leg without contact, with the hip aligned, slightly abducted, and the knee flexed at 90 degrees. Each balance test lasted 20 seconds. The dynamic balance test was performed with eyes open (EO), while the static balance test was conducted with eyes closed (EC). For the dynamic balance test, participants focused on a fixed point located approximately 1 meter ahead at eye level. To prevent visual feedback on performance, the device display remained concealed during all measurements. Three familiarization trials were administered before data collection and were excluded from analysis. Upon completion of each test, the system automatically calculated three balance indices: the Overall Stability Index (OSI), the Anteroposterior Stability Index (APSI), and the Mediolateral Stability Index (MLSI) [22]. Higher index values correspond to poorer balance performance [23].

## Statistical Analysis

The arithmetic mean  $\pm$  standard deviation were calculated for the participants' physical and demographic characteristics. The Shapiro–Wilk test was conducted to assess normality, and all parameters were found to be normally distributed. In order to look at the effects of time (at rest as compared with after fatigue) and of the balance condition (dynamic as opposed to static) on balance, a separate 2×2 repeated-measures ANOVA (time × balance condition) was carried out for each balance index. The effect sizes obtained from the ANOVA were given as partial eta squared ( $\eta^2$ ) and were interpreted as negligible ( $< .01$ ), small ( $.01$  to  $< .06$ ), medium ( $.06$  to  $< .14$ ), or large ( $\geq .14$ ) according to Cohen's (1988) criteria [24]. All analyses were performed using SPSS version 27, and statistical significance was set at  $p < 0.05$ .

# Results

Table 1 provides descriptive statistics (mean  $\pm$  SD) for overall, anteroposterior, and mediolateral balance parameters obtained from dynamic and static balance tests conducted under both resting and post-fatigue conditions.

Table 1  
Descriptive Statistics for Dynamic and Static Balance Parameters

| Balance condition | Parameter       | Resting         | Post-fatigue    |
|-------------------|-----------------|-----------------|-----------------|
|                   |                 | Mean $\pm$ SD   | Mean $\pm$ SD   |
| Dynamic balance   | Overall         | 2.29 $\pm$ 0.72 | 2.06 $\pm$ 0.56 |
|                   | Anteroposterior | 1.71 $\pm$ 0.90 | 1.39 $\pm$ 0.45 |
|                   | Mediolateral    | 1.17 $\pm$ 0.43 | 1.19 $\pm$ 0.44 |
| Static balance    | Overall         | 2.29 $\pm$ 0.79 | 2.49 $\pm$ 0.67 |
|                   | Anteroposterior | 1.81 $\pm$ 0.82 | 1.82 $\pm$ 0.67 |
|                   | Mediolateral    | 1.22 $\pm$ 0.19 | 1.37 $\pm$ 0.36 |

Data presented as mean  $\pm$  SD.

Table 2  
Results of the 2  $\times$  2 Repeated-Measures ANOVA for Balance Parameters

| Parameter               | Effect                          | <i>F</i> (1, 17) | <i>p</i> | $\eta^2$ |
|-------------------------|---------------------------------|------------------|----------|----------|
| Overall balance         | Time                            | 0.020            | 0.890    | 0.001    |
|                         | Balance condition               | 1.809            | 0.196    | 0.096    |
|                         | Time $\times$ Balance condition | 2.198            | 0.156    | 0.114    |
| Anteroposterior balance | Time                            | 0.998            | 0.332    | 0.055    |
|                         | Balance condition               | 2.280            | 0.149    | 0.118    |
|                         | Time $\times$ Balance condition | 1.152            | 0.298    | 0.063    |
| Mediolateral balance    | Time                            | 1.098            | 0.309    | 0.061    |
|                         | Balance condition               | 1.135            | 0.302    | 0.063    |
|                         | Time $\times$ Balance condition | 0.809            | 0.381    | 0.045    |

Time = resting (pre-fatigue) and post-fatigue measurements; balance condition = dynamic and static balance conditions; Time  $\times$  balance condition = interaction effect indicating whether the change from resting to post-fatigue differs between balance conditions;  $\eta^2$  = partial eta squared.

Table 2 shows that repeated-measures ANOVAs did not reveal statistically significant main effects of time, balance condition, or their interaction for overall balance ( $p = 0.890$ ,  $p = 0.196$ , and  $p = 0.156$ , respectively). No significant main effects of time or balance condition, nor a significant time by balance condition interaction, were observed for anteroposterior balance ( $p = 0.332$ ,  $p = 0.149$ , and  $p = 0.298$ , respectively). Mediolateral balance also demonstrated no significant main effects or interaction effects ( $p = 0.309$ ,  $p = 0.302$ , and  $p = 0.381$ , respectively).

Figure 2 shows the individual and group-level responses obtained when going from the resting to the post-fatigue states under both dynamic and static balance conditions. The thinner colored lines indicate individual participants' responses, while the larger outlined circles, together with the error bars, show the group means and 95% confidence intervals. The  $p$  values given above each panel relate to the separate  $2 \times 2$  repeated-measures ANOVAs and reflect the main effects of time and balance condition as well as the interaction between time and balance condition. For all the stability indices, no significant main effects or interactions were found ( $p > .05$ ).

## Discussion

The primary objective of this study was to evaluate the effects of a simulated taekwondo match on static and dynamic balance performance in female taekwondo athletes. The  $2 \times 2$  repeated-measures ANOVA indicated no significant main effects of time or balance condition, nor any interaction between time and balance condition for any stability indices. These findings suggest no overall change in balance performance from pre- to post-experiment and no difference between static and dynamic conditions. This outcome contrasts with the findings of Erkmen et al. [22], who reported decreased balance performance following prolonged exercise under specific experimental conditions. The absence of significant time effects may be attributed to postural adaptations and compensatory mechanisms developed through training, or to the specific type, intensity, and duration of the fatigue protocol employed [25]. In conclusion, balance control did not exhibit a measurable decline under the match-simulation protocol.

The lack of significant effects in the present study should not be taken as proof that exercise-induced fatigue does not affect postural control. Meta-analytic evidence indicates that exercise-induced fatigue typically leads to increased postural sway and a deterioration in postural control in healthy young adults. However, the magnitude of these effects varies widely depending on the exercise protocol and the postural task [26, 27]. The way in which post-exercise postural sway depends on the protocol and characteristics of the balance task might account for the different results found in various studies [28]. When conditions differed from those in the present study, Hyun et al. [5] found that fatigue induced by an incremental maximal treadmill test increased anteroposterior COP displacement, COP area, and dynamic postural stability indices, while reducing vertical jump performance in taekwondo athletes. Match-induced fatigue had a significant negative impact on both static and dynamic balance in elite young female wrestlers [29]. Similarly, acute fatigue impaired dynamic balance, particularly the overall and anteroposterior stability indices, in trained female judokas, whereas static balance was unaffected [4].

Therefore, the lack of significant effects should be attributed to the specific protocol and task rather than as evidence that balance is generally maintained in the presence of fatigue. In trained female taekwondo athletes, the match-simulated kicking protocol produced no significant main effects of time or balance condition, and no time  $\times$  balance condition interactions, for the overall, anteroposterior, or mediolateral stability indices measured during the single-leg Biodex tests 1 minute after exercise (Table 2). The difference with the findings of Hyun et al. [5] may be due to methodological differences between their treadmill-based fatigue protocol with force-plate measurements and our sport-specific kicking protocol, as well as the use of Biodex stability indices. Along with the inconsistent results in wrestling and judo, these results indicate that fatigue responses may be sport- and task-specific. Hence, the absence of significant effects could be due to training-related compensatory strategies or to the limited sensitivity of the selected measures in detecting subtle changes after fatigue.

The absence of significant time-related effects indicates that trained female taekwondo athletes were able to maintain their single-leg balance performance after performing the match-simulated kicking procedure. This result could be due to compensatory neuromuscular strategies, as global dynamic balance performance remains unchanged even when muscle activation patterns change following exercise [30]. The lack of significant fatigue-related effects in the current study is consistent with findings that static and conventional dynamic balance indices do not change after karate-specific fatigue. Nevertheless, some of the limits-of-stability measures did change, and the 10–30-minute delay before the assessment may have affected the results [31]. Similarly, Özer (2019) found no significant differences before and after fatigue in either the static or dynamic Biodex indices among elite male Greco-Roman wrestlers. This implies that standard balance results may remain unaltered after certain laboratory-based fatigue protocols in well-trained combat-sport athletes [32].

A possible explanation lies in the nature of the fatigue protocol. Even though the model created by Chuang et al. [2] is specific to sport and is based on the timing of an Olympic taekwondo match, it is still a non-contact simulation. It produced heart rate, lactate, and perceived exertion responses similar to those seen in competition, but caused less muscle damage, inflammation, and catabolic stress. Therefore, the results of the present study should be interpreted in the context of a competition-structured protocol that may not fully replicate the physiological and contact-related demands of a real taekwondo match. The current study used a sport-specific kicking model simulating a match, with the structure following the timing of an Olympic bout [2]. Taekwondo consists of short periods of high-intensity activity alternating with lower-intensity defensive actions, and regular training can enhance dynamic balance in elite female athletes [33]. It is therefore possible that familiarity with these sport-specific demands has contributed to the maintenance of the balance response, even though compensatory mechanisms were not directly assessed. Despite the importance of investigating postural responses under conditions that closely mimic the demands of a particular sport, sport-specific fatigue protocols have been used sparingly [25]. A second explanation is that balance tests may react differently when an individual is fatigued. Zech et al. [34] observed that fatigue increased static COP sway but had no effect on dynamic SEBT performance, showing that static and dynamic tests evaluate different aspects of postural control. A similar pattern has also been reported in trained female judokas, whose

static balance did not change. In contrast, their dynamic balance, particularly the overall and anteroposterior indices, declined following acute fatigue [4]. In contrast, the present study found no significant main or interaction effects related to fatigue, which could indicate a protocol-specific preservation of balance or limited sensitivity of the indices used to detect subtle changes after fatigue. A third explanation is that the preservation of balance scores can coexist with changes in neuromuscular control. Global dynamic balance may have remained unchanged despite decreased soleus activation, with compensation due to increased stiffness [30]. People might also employ different neuromuscular and kinematic strategies in response to fatigue [35], and local and general fatigue can lead to different muscle activation and co-activation responses [36]. Hence, the maintained Biodex indices might indicate successful compensation rather than the absence of fatigue-related effects, although this explanation remains speculative, as neuromuscular activity was not measured.

The literature in this area indicates that fatigue can affect postural control via both peripheral and central mechanisms. Possible factors include decreased force generation, altered proprioceptive input, impaired mechanoreceptor function, hyperventilation, and disrupted central integration of sensory information [28, 37, 38]. Both localized and general fatigue can lead to different postural adjustments. Localized neuromuscular fatigue appears to have a longer-lasting impact on postural control, possibly due to altered proprioceptive feedback, whereas general fatigue tends to elicit only temporary compensatory responses [36]. These mechanisms may be pertinent to taekwondo, as athletes often compete in four or five matches in a single day, thereby incurring considerable physiological fatigue [33]. Furthermore, competition injuries have been found to occur more often in the second and third rounds than in the first, a situation which may be linked to fatigue [20]. It has also been demonstrated that taekwondo-specific fatigue increases reaction time and reduces the impact of the roundhouse kick, indicating that sport-specific performance can decline even though global balance indices do not change [39].

One of the main advantages of this study is that it employs a sport-specific, competition-based fatigue protocol together with an assessment immediately after fatigue in trained female taekwondo athletes. This approach helps counter the fact that sport-specific protocols have so far been used sparingly in research examining exercise-induced changes in postural control [25]. It is also valuable to focus solely on female athletes, as women have received little attention in this area of research and fatigue-related balance and neuromuscular responses may vary between the sexes [37, 38].

The main limitations of this study were the relatively small sample size, which was not determined by an a priori power analysis, the lack of a no-fatigue control condition, the assessment of only the dominant leg, and the decision to conduct post-protocol testing only at the immediate recovery stage. The limited sample size may have reduced the study's statistical power, particularly in detecting small effects. Since no physiological or perceptual indicators of fatigue—such as heart rate, blood lactate levels, or the rating of perceived exertion—were recorded, it was not possible to verify the amount of fatigue caused in each participant. Moreover, neither the menstrual cycle phase nor the use of hormonal contraceptives was recorded or controlled, so their potential effects on variability in fatigue and balance responses could not be evaluated [38]. Although the protocol mimicked the temporal pattern and the requirement for

intermittent kicking associated with competition, the non-contact nature of the laboratory setting did not fully capture opponent interaction, tactical decision-making, or psychological stress. Additionally, the use of Biodex stability indices might have hindered the identification of minor neuromuscular or movement-specific adaptations. As postural control disturbances can persist or change for 10 to 30 minutes after exercise, a single assessment immediately after exercise may not adequately capture the full recovery response [31, 40]. Future studies should include a larger number of female participants, introduce a no-fatigue control condition, conduct bilateral testing, use both objective and perceptual measures of fatigue, monitor menstrual cycles and contraceptive use, and make repeated assessments during the recovery period. Combining balance indices with measures of neuromuscular function, inter-limb asymmetry, and landing biomechanics could identify fatigue-related adaptations that standard balance tests fail to detect [41, 42].

## Conclusion

The present study found no statistically significant deterioration in single-leg static or dynamic balance performance following a taekwondo match-simulation protocol in trained female taekwondo athletes. No significant time-related effects or time  $\times$  balance condition interactions were observed for the overall, anteroposterior, or mediolateral stability indices. Under the current protocol and assessment conditions, match-simulated fatigue did not result in measurable changes in Biodex balance performance. Future research should incorporate objective fatigue verification alongside neuromuscular and biomechanical assessments to clarify whether these findings reflect effective postural compensation or subtle alterations that the stability indices employed fail to detect.

## Declarations

### **Ethics approval and consent to participate**

Participants received information about the study procedures in advance and provided written informed consent prior to participation. The study was approved by the Ethics Committee of the Faculty of Sport Sciences at Selçuk University (Protocol No: 279, 11 December 2025, Konya, Turkey) and was conducted in accordance with the Declaration of Helsinki.

### **Consent for publication**

Not applicable.

## Competing interest

The authors declare no competing interests.

# Declarations of generative AI and AI-assisted technologies in the writing process

Generative AI was used exclusively for language and grammatical refinement of the manuscript, as well as for improving the visual quality and presentation of the figures. The author(s) solely developed the conceptualization, content, structure, and original design of all figures.

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## Author Contribution

B.L., Y.K., and A.T. conceptualized the study. H.G. and A.T. performed the experiments and analyzed the data. A.T. validated and finalized the data. B.L., Y.K., and A.T. supervised the study. Y.K., H.G., and A.T. drafted the original version of the manuscript. B.L. and A.T. reviewed, revised, and finalized the manuscript. All authors have read and approved the final version of the manuscript.

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## Data Availability

Raw data supporting the results of this article will be provided by the corresponding author upon request.

## References

1. Bridge CA, Ferreira da Silva Santos J, Chaabène H, Pieter W, Franchini E. Physical and physiological profiles of taekwondo athletes. *Sports Med.* 2014;44(6):713–33. 10.1007/s40279-014-0159-9.
2. Chuang SJ, Sung YC, Chen CY, Liao YH, Chou CC. Can match-mimicking intermittent practice be used as a simulatory training mode of competition using Olympic time frame in elite taekwondo athletes? *Front Physiol.* 2019;10:244. 10.3389/fphys.2019.00244.
3. Boyanmış AH, Uslular A, Korkmaz C, Demir A, Doğaner S, Akın M. The Effect of Taekwondo Training on Static and Dynamic Balance Development: A Brief Review. *Afr J Biol Sci.* 2024;6(6):7500–9.
4. Taskuyu E, Yavuz SC. Investigation of the effect of acute muscle fatigue on static and dynamic balance performances in female judokas. *Sportive.* 2025;8(1):200–9. 10.53025/sportive.1635494.

5. Hyun SH, Kim YP, Ryew CC. Effects of fatigue induction on ground reaction force components, postural stability, and vertical jump performance in taekwondo athletes. *Korean J Appl Biomech.* 2016;26(2):143–51. 10.5103/KJSB.2016.26.2.143.
6. Pollock AS, Durward BR, Rowe PJ, Paul JP. What is balance? *Clin Rehabil.* 2000;14(4):402–6. 10.1191/0269215500cr342oa.
7. Xie K, Han X, Lu J, Xu X, Hu X. Prediction model of all-cause death based on balance ability among middle-aged and older Chinese adults of overweight and obesity. *Front Public Health.* 2022;10:1039718. 10.3389/fpubh.2022.1039718.
8. Yin R, Zhu G, Liu A, Wang M, Li L, Dai S. The impact of additional visual tasks in physical exercise on balance ability among 9–10-year-old children: the mediating effect of visual acuity. *Front Public Health.* 2024;11:1270947. 10.3389/fpubh.2023.1270947.
9. Pieter W, Heijmans J. *Scientific Coaching for Olympic Taekwondo.* 2nd ed. Oxford, UK: Meyers and Meyers Sport; 2000.
10. Zhang J, Kim Y, Qu Q, Kim S. Effects of different Taekwondo practices on biomechanics of balance and control during kick technique. *Ann Hum Biol.* 2025;52(1):2461132. 10.1080/03014460.2025.2461132.
11. Lystad RP, Pollard H, Graham PL. Epidemiology of injuries in competition taekwondo: a meta-analysis of observational studies. *J Sci Med Sport.* 2009;12(6):614–21. 10.1016/j.jsams.2008.09.013.
12. Serina ER, Lieu DK. Thoracic injury potential of basic competition taekwondo kicks. *J Biomech.* 1991;24(10):951–60. 10.1016/0021-9290(91)90173-k.
13. Lopes-Silva JP, Da Silva Santos JF, Artioli GG, Loturco I, Abbiss C, Franchini E. Sodium bicarbonate ingestion increases glycolytic contribution and improves performance during simulated taekwondo combat. *Eur J Sport Sci.* 2018;18(3):431–40. 10.1080/17461391.2018.1424942.
14. Machado CF, Nakamura FY, Fortes RP, Trapaga ID, Brusco CM, Pinto MD, Pinto RS. Changes in knee flexion-extension performance and hamstring-to-quadriceps ratio during a fatiguing isokinetic protocol in male professional futsal players. *Int J Perform Anal Sport.* 2023;23(4):249–63. 10.1080/24748668.2023.2221501.
15. Hamada T, Sale DG, MacDougall JD, Tarnopolsky MA. Interaction of fibre type, potentiation and fatigue in human knee extensor muscles. *Acta Physiol Scand.* 2003;178(2):165–73. 10.1046/j.1365-201X.2003.01121.x.
16. Dastjerdi AS, Esmaeili H, Sadeghi M, Bashiri B. Effect of simulated handball match-induced fatigue on isokinetic hamstring-to-quadriceps ratio and evertor-to-invertor ratio in professional players. *PLoS ONE.* 2025;20(5):e0323978. 10.1371/journal.pone.0323978.
17. Yilmaz S, Erdemir İ. The influence of quadriceps and hamstring strength on balance performance. *Phys Educ Students.* 2023;27(3):112–7. 10.15561/20755279.2023.0303.
18. Harkins KM, Mattacola CG, Uhl TL, Malone TR, McCrory JL. Effects of 2 Ankle Fatigue Models on the Duration of Postural Stability Dysfunction. *J Athl Train.* 2005;40(3):191–4.

19. Kazemi M, Shearer H, Choung YS. Pre-competition habits and injuries in Taekwondo athletes. *BMC Musculoskelet Disord.* 2005;6(26):1–9. 10.1186/1471-2474-6-26.
20. Hssin N, Ouergui I, Haddad M, Paunescu C, Paunescu M, Chamari K. Injuries in Taekwondo. In: Haddad M, editor. *Performance Optimization in Taekwondo: From Laboratory to Field.* USA: OMICS Group; 2014. pp. 1–14.
21. McKay AKA, Stellingwerff T, Smith ES, Martin DT, Mujika I, Goosey-Tolfrey VL, Sheppard J, Burke LM. Defining training and performance caliber: a participant classification framework. *Int J Sports Physiol Perform.* 2022;17(2):317–31. 10.1123/ijsp.2021-0451.
22. Erkmen N, Taskin H, Kaplan T, Sanioglu A. Balance performance and recovery after exercise with water intake, sport drink intake and no fluid. *J Exerc Sci Fit.* 2010;8(2):105–12. 10.1016/S1728-869X(10)60016-0.
23. Costa PB, Graves BS, Whitehurst M, Jacobs PL. The acute effects of different durations of static stretching on dynamic balance performance. *J Strength Cond Res.* 2009;23(1):141–7. 10.1519/JSC.0b013e31818eb052.
24. Cohen J. *Statistical power analysis for the behavioral sciences.* 2nd ed. Hillsdale, NJ: Lawrence Erlbaum; 1988. 10.1016/0198-9715(90)90050-4.
25. Zemková E. Physiological mechanisms of exercise and its effects on postural sway: Does sport make a difference? *Front Physiol.* 2022;13:792875. 10.3389/fphys.2022.792875.
26. Paillard T. Effects of general and local fatigue on postural control: a review. *Neurosci Biobehav Rev.* 2012;36(1):162–76. 10.1016/j.neubiorev.2011.05.009.
27. Penedo T, Vuillerme N, Chardon M, Dos Santos PR, Barbieri FA. Exercise-induced fatigue effects on postural control in young adults: A systematic review and meta-analysis. *J Biomech.* 2026;198:113189. 10.1016/j.jbiomech.2026.113189.
28. Zemková E, Hamar D. Physiological mechanisms of post-exercise balance impairment. *Sports Med.* 2014;44(4):437–48. 10.1007/s40279-013-0129-7.
29. Iri R, Aktug ZB, Koc M, Sahin I, Murathan F. The effect of fatigue in elite young female wrestlers upon balance performance and reaction time. *Biomed Res.* 2016;27(4):1166–70.
30. Marcolin G, Cogliati M, Cudicio A, Negro F, Tonin R, Orizio C, Paoli A. Neuromuscular Fatigue Affects Calf Muscle Activation Strategies, but Not Dynamic Postural Balance Control in Healthy Young Adults. *Front Physiol.* 2022;13:799565. 10.3389/fphys.2022.799565.
31. Güler M, Gülmez I, Yilmaz S, Ramazanoglu N. The evaluation of balance performance for elite male karate athletes after fatigue. *Int J Sport Exerc Train Sci.* 2017;3(4):161–8. 10.18826/useeabd.336577.
32. Özer Ö. Investigation of the Effect of Acute Muscular Fatigue on Static and Dynamic Balance Performances in Elite Wrestlers. *J Educ Learn.* 2019;8(5):179–84. 10.5539/jel.v8n5p179.
33. Khazaei L, Parnow A, Amani-Shalamzari S. Comparing the effects of traditional resistance training and functional training on the bio-motor capacities of female elite taekwondo athletes. *BMC Sports Sci Med Rehabil.* 2023;15:139. 10.1186/s13102-023-00754-9.

34. Zech A, Steib S, Hentschke C, Eckhardt H, Pfeifer K. Effects of localized and general fatigue on static and dynamic postural control in male team handball athletes. *J Strength Cond Res*. 2012;26(4):1162–8. 10.1519/JSC.0b013e31822dfbbb.
35. Dury J, Ravier G, Michel F. Hip abductor muscle fatigue induces different strategies during disrupted postural control. *Front Sports Act Living*. 2022;4:918402. 10.3389/fspor.2022.918402.
36. Nardon M, Piscitelli F, Alessandro C, Tam E, Bertucco M. Effects of localized and general fatigue on postural adjustments coupling during predictable external perturbations. *Eur J Appl Physiol*. 2025;125(9):2539–61. 10.1007/s00421-025-05760-y.
37. Hill M, Rosicka K, Wdowski M. Effect of sex and fatigue on quiet standing and dynamic balance and lower extremity muscle stiffness. *Eur J Appl Physiol*. 2022;122(1):233–44. 10.1007/s00421-021-04831-0.
38. Tornero-Aguilera JF, Jiménez-Morcillo J, Rubio-Zarapuz A, Clemente-Suárez VJ. Central and peripheral fatigue in physical exercise explained: a narrative review. *Int J Environ Res Public Health*. 2022;19(7):3909. 10.3390/ijerph19073909.
39. Sant'Ana J, Franchini E, da Silva V, Diefenthaler F. Effect of fatigue on reaction time, response time, performance time, and kick impact in taekwondo roundhouse kick. *Sports Biomech*. 2017;16(2):201–9. 10.1080/14763141.2016.1217347.
40. Dickin DC, Doan JB. Postural stability in altered and unaltered sensory environments following fatiguing exercise of lower extremity joints. *Scand J Med Sci Sports*. 2008;18(6):765–72. 10.1111/j.1600-0838.2007.00760.x.
41. Ye B, Zhang B, He Z, Sheng C, Liu G, Zhu H, Meng G. Exercise-induced fatigue affects lower limb biomechanics in high-risk backhand smash landings among female badminton players. *Iscience*. 2026;29(4):115261. 10.1016/j.isci.2026.115261.
42. Choudhary PK, Choudhary S, Saha S, Rajpoot YS, Ciocan VC, Nicolae-Lucian V, Pavel SI, Șufaru C. Lower-Limb Biomechanical Adaptations to Exercise-Induced Fatigue During Running: A Systematic Review of Injury-Relevant Mechanical Changes. *Life (Basel)*. 2026;16(2):272. 10.3390/life16020272.

## Figures

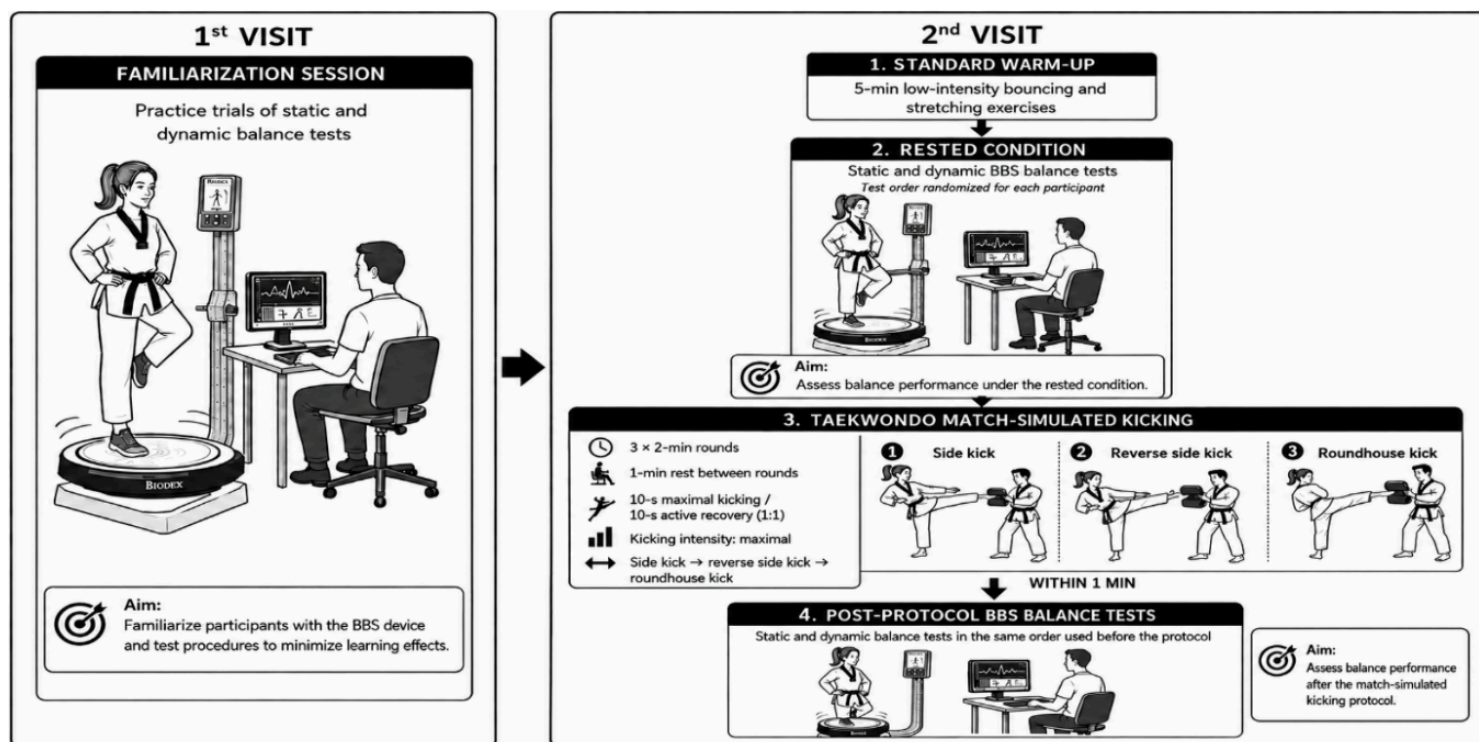


Figure 1

## Study Flowchart

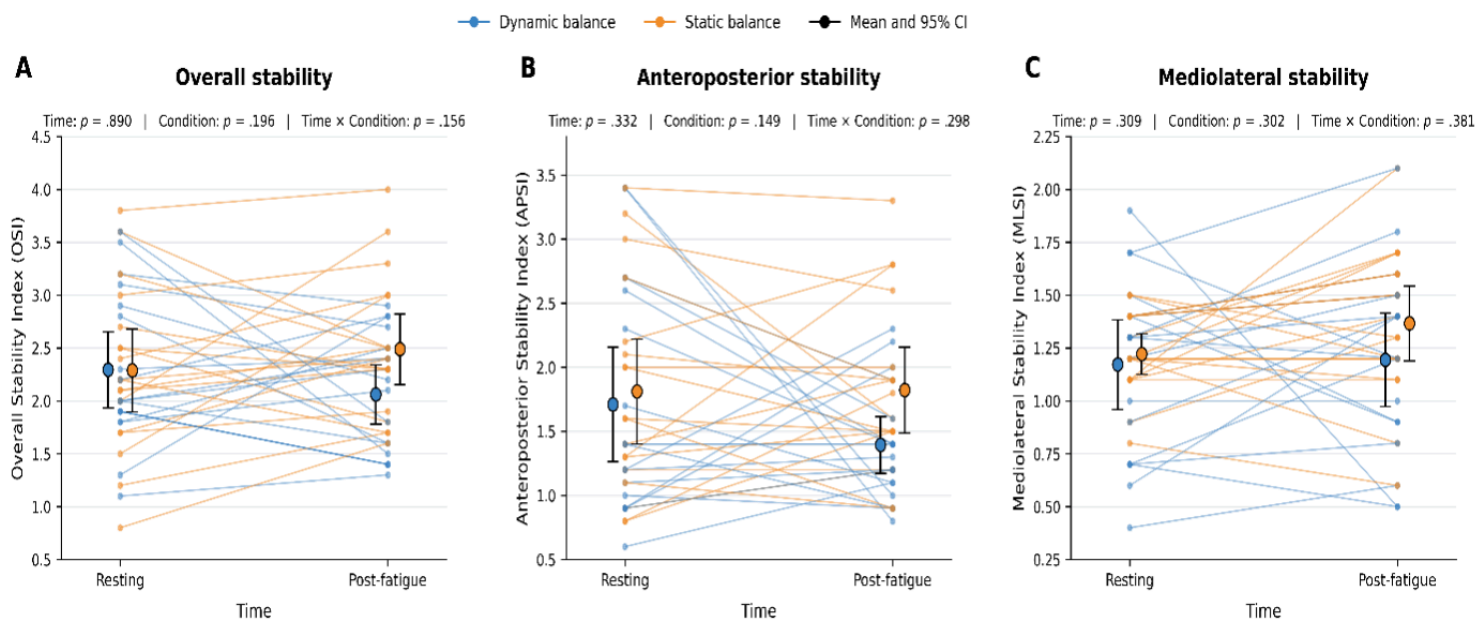


Figure 2

Changes in the Overall Stability Index (A), Anteroposterior Stability Index (B), and Mediolateral Stability Index (C) during dynamic and static balance tests under resting (pre-fatigue) and post-fatigue conditions.