Effect of Lower Limb Muscle Fatigue on Dynamic Balance Performance in Healthy Young Adults: Role of Arm Movement

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ABSTRACT

There is evidence that balance performance deteriorates due to exercise-induced muscle fatigue. However, it is unknown if free arm movement during balance testing can compensate for, or restricted arm movement can amplify these performance degradations. Thus, the objective of this study was to compare the effects of free versus restricted arm movement on balance performance under non-fatigued and fatigued conditions. Fifty-two healthy participants (men = 31, women = 21; age = 22.6 ± 1.6 years) were assessed for their dynamic balance (reach distances for the Y Balance Test – Lower Quarter) under non-fatigued and fatigued (repetitive vertical bipedal box jumps until failure) conditions using two different arm positions: free (move the arms freely) and restricted (keep the arms akimbo) arm movement. Restriction of arm movement (all $p < 0.001$; $0.48 \le \eta_p^2 \le 0.79$) and application of fatigue ($p \le 0.003$; $0.16 \le \eta_p^2 \le 0.28$) independently, but not the interaction between the two (except for the posteromedial reach direction: $p = 0.046$; $\eta_p^2 = 0.08$), resulted in significantly deteriorated lower limb reach distances. These findings suggest that free arm movement and thus the use of an 'upper body strategy' has no compensatory effect on muscle fatigue-induced balance deteriorations.

Introduction

Motor performance fatigue is defined as a reversible exercise-induced reduction in neuromuscular performance [1–3] and can lead to a range of negative outcomes, including reduced postural control [4]. For example, Pau et al. [5] investigated fatigue-induced changes in static balance performance and reported significantly increased sway values during bipedal and unipedal stance following a repeated sprint ability test (i. e. 6 repetitions of maximal 2 × 15-m shuttle sprints). Moreover, Johnston et al. [6] compared dynamic balance performance before and after a modified 60-s

Wingate fatiguing protocol and showed significantly reduced reach distances for the Y Balance Test–Lower Quarter (YBT–LQ). In addition, Zech et al. [7] examined the effects of i) a whole-body fatiguing exercise (i. e. treadmill running) and ii) a localized muscle fatigue exercise (i. e. unilateral barbell step-ups) on measures of static and dynamic balance. Irrespective of fatigue protocol, sway values during unipedal stance but not reach distances in the YBT–LQ were negatively affected.

While exercise-induced muscle fatigue leads to deteriorated static and dynamic balance performance, there is evidence that the use of arm movements can contribute to stabilise balance. More specifically, recent studies [8, 9] showed better static and dynamic balance performance in non-fatigued conditions when the arms were used freely to when they were constrained (i. e. keep the arms akimbo). This can be explained by the fact that arm movements can be used to increase the moment of inertia [10], generate restoring torques to reduce angular momentum of the body [11], and act as counterweight to shift the centre of mass away from the direction of instability [12]. However, it is unclear whether the compensatory use of free arm movement observed under non-fatigued conditions is also evident following exercise-induced muscle fatigue. The investigation of this question has particular practical relevance, as falls occur more frequently [13] and injury risk increases [14] in fatigued when compared to non-fatigued situations.

The objective of this study was to determine how arm movement influences dynamic balance performance during non-fatigued and fatigued conditions. Thus, we compared the effects of free versus restricted arm movement on dynamic balance performance during non-fatigued and fatigued (repetitive vertical bipedal box jumps until failure) conditions in healthy young adults. We hypothesised that lower limb muscle fatigue and restricted arm movement would lead to deteriorated dynamic balance performance. However, the fatigue-induced performance decrements would be less pronounced when participants are allowed to use their arms during balance testing.

Materials and Methods

Participants and sample size estimation

Fifty-two healthy young female ($n = 21$) and male ($n = 31$) adults aged 19 to 29 years volunteered to participate in this study. Participants' characteristics are presented in ▶ **Table 1**. Using G*Power 3.1.9.8 [15], an a priori power analysis ($f = 0.25$, $\alpha = 0.05$, $1\text{-}\beta = 0.80$, number of groups: $n = 1$, number of measurements: $n = 4$, drop-out rate: 10 % due to reasons not attributable to experimental procedure) was conducted for measures of dynamic balance performance [6, 16]. The analysis revealed that $N = 41$ participants would be sufficient to detect statistically significant repeated measures analysis of variance (ANOVA) effects. All participants did not report any musculoskeletal dysfunction, neurological impairment, or orthopaedic disorder that might have affected their ability to execute the experimental procedure. Before the start of the study, participants were familiarised with the procedure. Participants' written informed consent was obtained prior to the start of the study. The study protocol was approved through an institution affiliated with one of the authors.

▶ **Table 1** Characteristics of the study participants ($N = 52$).

Characteristic	Value
Gender (n)	31 men; 21 women
Age (years)	22.6 ± 1.6
Body height (cm)	175.9 ± 9.5
Body mass (kg)	74.0 ± 12.6
Body mass index (kg/m^2)	23.8 ± 3.0
Leg length (cm)	92.8 ± 5.9

Note: Values are means ± standard deviations.

Experimental procedure

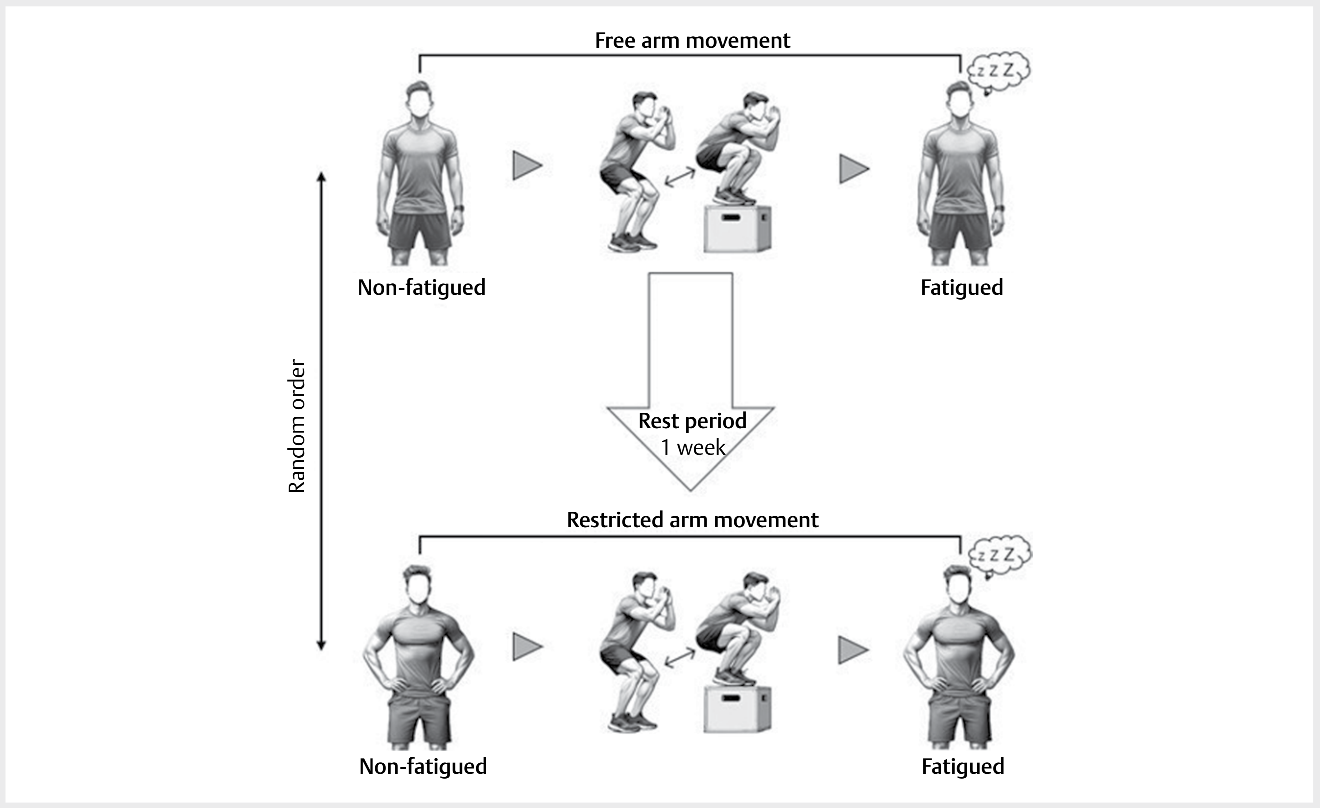
A single-group repeated-measures design including two sessions (1 week apart) was used to assess the effects of exercise-induced lower limb muscle fatigue on variables of dynamic balance performance (▶ **Fig. 1**). At the beginning of each testing session, participants received instructions on the specific procedure. Thereafter, a standardised warm-up protocol was conducted consisting of three minutes of rope skipping, two minutes of stretching, and two minutes of a familiarisation phase with submaximal single-leg reaching movements. Subsequently, the participants had to perform one set of three single leg reaches per reach direction that was followed by a rating of their initial perceived exertion. Afterwards, they performed the fatigue protocol, followed by another rating of their perceived exertion and a further set of three single-leg reaching movements per reach direction. This procedure was repeated one week later. The permission to use (free) or not to use (restricted) arm movements while performing the single leg reaches before and after the fatigue protocol was randomised between participants to avoid potential bias. For the free arm movement condition, participants were instructed to move their arms freely and to their advantage. For the restricted arm condition, participants were asked to keep their arms akimbo and compliance was visually monitored.

Fatigue protocol

Muscular fatigue of the lower extremities was individually induced by repeated vertical box jumps (▶ **Fig. 1**). Specifically, participants were instructed to perform as many metronome-paced (70 beats per minute) repetitive bipedal box jumps (box height: 40 cm) as possible until failure [17]. Failure was defined as the time when the participants were unable to keep up with the pace of the metronome. The number of repetitions in the first set was used as reference (i. e. 100 %) for the following set. During this set, participants were again asked to perform as many repetitions as possible until failure. If at least 60 % of the first set was attained [17], another set followed, otherwise the fatigue protocol was terminated. A one-minute rest was provided between sets. The number of repetitions per set was manually recorded.

Assessment of anthropometric variables

Body height was measured to the nearest 0.1 cm using a Seca 217 linear measurement scale (Seca, Basel, Switzerland). The participants were asked to stand straight and upright without shoes for the measurement. Body mass was determined to the nearest 100 g using a Seca 803 electronic scale (Seca, Basel, Switzerland). The



▶ **Fig. 1** Schematic diagram of the experimental procedure showing the fatigue and arm movement conditions and the fatiguing protocol (i. e. metronome-paced repetitive bipedal vertical jumps until failure).

participants wore light sportswear but no shoes. The body mass index was calculated by dividing the body mass by the body height squared (kg/m^2).

Assessment of dynamic balance performance

The Y Balance Test kit (Functional Movement Systems, Chatham, VA, USA) was used to assess dynamic balance performance. Precisely, participants were asked to stand without shoes with the dominant leg (determined by self-report based on the following question: "Which foot do you use to kick a ball?") on the central foot plate and to move the reach indictor with their non-dominant leg as far as possible along three pipes with centimetre markings representing anterior (AT), posteromedial (PM), and posterolateral (PL) directions. One set of three data-collection trials were performed per reach direction and the absolute maximal reach distance (cm) was noted on a score sheet. In accordance with Plisky et al. [18], a trial was discarded and repeated if the participant a) lost balance (i. e. touched the ground with the reach leg), b) stepped on top of the reach indicator for weight support, c) kicked the reach indicator to achieve a greater distance, d) failed to return the reach leg to the central foot plate, or e) released the arms from hips during restricted arm movement condition. The obtained values were normalised by dividing the absolute maximal reach distance (cm) by leg length (LL in cm) and then multiplying by 100. Moreover, the normalised (% LL) composite score (CS) was calculated as the sum of the absolute maximal reach distance (cm) per reach direction divided by three times LL (cm) and then multiplied by 100 [19]. The lower limb length of each participant was determined from the anterior superior iliac spine to the most distal aspect of the medial malleolus [18]. The YBT–LQ test is a valid (discriminative and predictive) and reliable (moderate to excellent) tool to assess dynamic balance performance in healthy young adults [20].

Rating of perceived exertion

A 6–20 Borg scale was used to assess the level of subjectively perceived exertion immediately before and after the fatigue protocol with 6 indicating "very, very light" if at all and 20 indicating "very, very hard" [21].

Statistical analyses

Prior to the performance of parametric analyses, normal distribution (Kolmogorov–Smirnov test) and variance homogeneity (Mauchly's test) were checked and confirmed. Data were presented as group mean value ± standard deviation (SD). For the balance-related measures, a series of 2 (fatigue level: non-fatigued, fatigued) × 2 (arm movement: free, restricted) repeated measures ANOVA were performed. If a significant fatigue level by arm movement interaction occurred, Bonferroni-adjusted post-hoc tests (i. e. paired *t*-tests) were applied. For the fatigue-related measures, the Wilcoxon test was used since the rating of perceived exertion represents ordinal scaled variables. The significance level was a priori

▶ **Table 2** Dynamic balance outcomes separated by fatigue and arm movement condition.

Outcome	Non-fatigued		Fatigued	
	Free	**Restricted**	**Free**	**Restricted**
Anterior reach distance (% leg length)	77.6 ± 14.5	71.8 ± 12.8	75.3 ± 11.4	69.8 ± 10.0
Posteromedial reach distance (% leg length)	122.5 ± 13.3	114.3 ± 12.5	119.4 ± 11.6	112.9 ± 11.1
Posterolateral reach distance (% leg length)	119.4 ± 14.0	110.4 ± 14.2	116.2 ± 13.8	107.8 ± 12.4
Composite score (% leg length)	106.5 ± 13.2	98.8 ± 12.6	103.6 ± 11.5	96.8 ± 10.5

Note: Values are means ± standard deviations.

▶ **Table 3** Inference statistics for the main and interaction effects of the repeated measures ANOVA for all dynamic balance outcomes.

Outcome	Main effect: fatigue		Main effect: arm movement		Interaction effect: fatigue × arm movement	
	$F_{(1,51)}$	p (η_p^2)	$F_{(1,51)}$	p (η_p^2)	$F_{(3,153)}$	p (η_p^2)
Anterior reach distance (% leg length)	9.878	0.003 (0.16)	47.483	< 0.001 (0.48)	0.192	0.663 (0.01)
Posteromedial reach distance (% leg length)	12.936	< 0.001 (0.20)	150.287	< 0.001 (0.75)	4.170	**0.046 (0.08)**
Posterolateral reach distance (% leg length)	18.692	< 0.001 (0.27)	195.925	< 0.001 (0.79)	0.416	0.522 (0.01)
Composite score (% leg length)	19.365	< 0.001 (0.28)	177.516	< 0.001 (0.78)	1.892	0.175 (0.04)

Note: The bold value indicates a statistically significant interaction effect ($p < 0.05$). Threshold values for the η_p^2 value were $0.02 \leq \eta_p^2 \leq 0.12$ = small, $0.13 \leq \eta_p^2 \leq 0.25$ = medium, and $\eta_p^2 \geq 0.26$ = large.

set at $\alpha < 0.05$. For the ANOVA, effect size was calculated as partial eta-squared (η_p^2) and reported as small ($0.02 \leq \eta_p^2 \leq 0.12$), medium ($0.13 \leq \eta_p^2 \leq 0.25$), or large ($\eta_p^2 \geq 0.26$) [22]. For the paired *t*-test, effect size was calculated as Cohen's *d* and stated as small ($0 \leq d < 0.50$), medium ($0.50 \leq d < 0.80$), or large ($d \geq 0.80$) [22]. All analyses were performed using SPSS version 28.0 (IBM Inc., Armonk, NY, USA).

Results

Fatigue-related measures

Participants completed between two to four sets of bipedal box jumps until failure. This corresponds to an average jump number of 17.9 ± 7.4, 16.4 ± 6.3, and 14.0 ± 8.3 for the second, third, and fourth set, respectively, and resulted in a significant increase in the level of perceived exertion in both arm movement conditions from "very light" to "very hard" (free: non-fatigued = 9.4 ± 1.5; fatigued = 17.0 ± 1.4; $Z = -6.293$, $p < 0.001$; restricted: non-fatigued = 8.6 ± 1.8, fatigued = 16.7 ± 1.6; $Z = -6.289$, $p < 0.001$).

Balance-related Measures

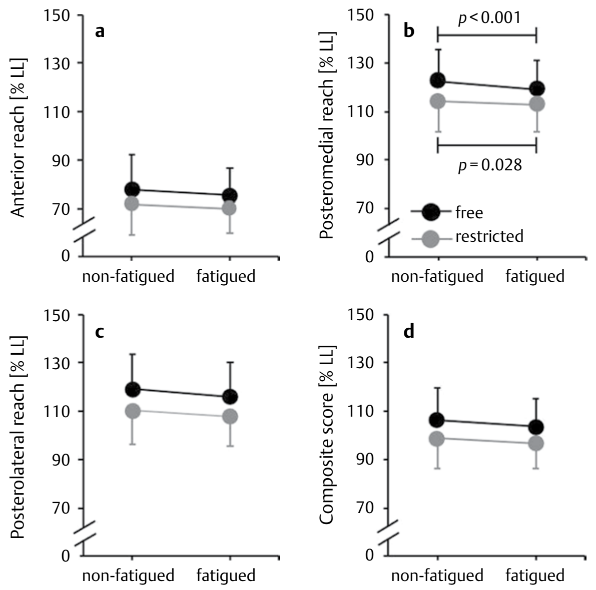
The results of the descriptive and inference statistics are shown in ▶ **Table 2** and ▶ **3**, respectively. In addition, lower limb reach values by fatigue (non-fatigued vs. fatigued) and arm movement (free vs. restricted) condition are illustrated in ▶ **Fig. 2 a–d**. Irrespective of outcome, there were significant main effects of fatigue ($p \leq 0.001$–0.003; $0.16 \leq \eta_p^2 \leq 0.28$) and arm movement (all $p < 0.001$; $0.48 \leq \eta_p^2 \leq 0.79$). However, there were no significant interactions between the two except for the PM reach direction ($p = 0.046$, $\eta_p^2 = 0.08$). Post-hoc tests revealed significant decreases in PM reach distance from the non-fatigued to the fatigued condition during free ($t_{(1,51)} = 3.867$, $p < 0.001$, $d = 0.24$) and restricted ($t_{(1,51)} = 1.961$, $p = 0.028$, $d = 0.11$) arm movement. Additionally performed gender-adjusted sub-analysis did not reveal any significant interaction effects (data not shown), indicating that both genders show the same responses to fatigue and arm movement condition.

Discussion

We aimed to elucidate the effect of exercise-induced lower limb muscle fatigue and the role of arm movement on dynamic balance performance in healthy young adults. The following major novel findings emerged from this study: a) in accordance with our hypothesis, the application of lower limb muscle fatigue and the restriction of arm movement resulted in deteriorated dynamic balance performance; b) contrary to our assumption, the fatigue-induced balance deteriorations were not compensated by the use of arm movements.

Effect of exercise-induced muscle fatigue on postural control

In line with our hypothesis and in accordance with previous literature [6, 23, 24], exercised-induced muscle fatigue resulted in significantly reduced lower limb reach movements for each direction and the CS under restricted and free arm movement conditions. In this regard, Hill et al. [24] compared dynamic balance performance using the YBT-LQ before and immediately after a fatiguing exercise (5 × 20 drop jumps)



► **Fig. 2** Dynamic balance performance by fatigue (non-fatigued vs. fatigued) and arm movement (free vs. restricted) condition for **a**) anterior reach direction, **b**) posteromedial reach direction, **c**) posterolateral reach direction, and **d**) composite score. *Note.* Black filled circles mean free arm movement condition and grey filled circles mean restricted arm movement condition. LL, leg length.

in 16 recreationally active men (mean age: 24.8 ± 5.0 years) and 10 women (mean age: 21.0 ± 1.6 years). They observed that the fatiguing exercise protocol induced significant reductions in all three reach directions and the CS. Further, Johnston et al. [6] investigated 20 female and male physically active young adults (mean age: 23.8 ± 4.8 years) who performed the YBT-LQ prior and following the completion of a modified 60-s Wingate fatiguing protocol. The authors reported significant fatigue-related performance decrements for all three reach directions. Lastly, Cooper et al. [23] studied dynamic balance performance using the Biodex Balance System in 24 recreationally trained young adults (age range: 21–28 years) before and after the Bosco fatigue test (i. e. continuous maximal-effort squat jumps for 60 seconds). Following fatigue, they found significantly greater sway values for single leg dynamic balance performance. The observation of deteriorated dynamic balance in the fatigued compared to the non-fatigued condition could be attributed to several factors related to exercise-induced reductions in neuromuscular performance [1–3]. Precisely, we applied repetitive vertical bipedal box jumps to induce fatigue effects on the lower extremities. As a consequence, this may lead to the accumulation of metabolic by-products (e. g. lactic acid) that decreases the afferent sensorimotor input and muscle fibre conduction velocity [25, 26], resulting in impaired neuromuscular control.

Role of arm movement for postural control

In accordance with our hypothesis and consistent with previous literature [8, 9, 27, 28], the restriction of arm movement resulted in significantly reduced lower limb reach movements for each reach direction and the CS under non-fatigued and fatigued conditions. For instance, Cug [27] examined 25 young female and male adults (mean age: 20.3 ± 2.4 years) and reported significantly worse YBT-LQ performances (i. e. all reach directions and CS) for the restricted compared to the free arm movement condition. Moreover, Hébert-Losier [8] investigated 46 young men and women (age range: 20–38 years) who performed the YBT-LQ with hands on hips and hands free to move and found significantly lower reach distances for all three reach directions as well as the CS when the arms were restricted compared to when they were used freely. Finally, Sogut et al. [9] studied young adults aged 22.7 ± 1.9 years and again detected significantly lower YBT-LQ performances (i. e. PM and PL reach distances and CS) during arms restricted versus arms free condition. Several mechanical mechanisms may account for the deteriorated dynamic balance performance observed during restricted arm movement conditions. Specifically, the arms cannot a) act as a counterweight to shift the body centre of mass away from the direction of instability [12], b) generate restoring torque to reduce angular momentum of the body [11], and c) increase the moment of inertia [10].

Compensatory effect of arm movements on fatigue-induced decrements in postural control

We further hypothesised that the fatigue-induced performance decrements in dynamic balance performance would be less pronounced when participants are allowed to use their arms to correct postural control during balance testing. However, we only detected fatigue by arm movement interaction for the PM reach distance. Although this interaction effect was only small under both arm movement conditions (restricted: $d = 0.11$; free: $d = 0.24$), the performance deteriorations were larger in the latter than the former, which is contrary to our hypothesis. This result suggests that free arm movement and thus the use of an ‘upper body strategy’ has no compensatory effect on fatigue-induced dynamic balance deteriorations. From a practical perspective, this finding indicates that the recommendation to use the arms freely cannot compensate for decreases in dynamic balance performance emanating/resulting from lower limb muscle fatigue. Instead, a rest period should be provided for neuromuscular recovery. Indeed, Johnston and colleagues [6] showed that performance in the YBT-LQ was restored 10 minutes (AT reach distance) and 20 minutes (PM reach distance) after fatigue (i. e. modified 60-s Wingate protocol). Therefore, future studies should examine whether these rest periods are also valid for our fatigue protocol (i. e. repetitive vertical bipedal box jumps until failure) and can be shortened by free arm movement during balance testing.

Limitations

The findings of the present study should be interpreted considering the study limitations. Firstly, we did not measure body kinematics or muscle activation, which limits our insights on how arm movements contribute to postural control during exercise-induced muscle fatigue. Secondly, a subjective (i. e. 6–20 Borg scale) but no objective (e. g. lactic acid) measure of muscle fatigue was used. Thirdly, our study was limited to healthy young adults and therefore our findings are only generalisable to this but no younger (i. e. children, adolescents) or older (i. e. seniors) age groups. Maturational and biological aging processes of the neuromuscular system may make young and older individuals more reliant on arm movement for balance control during fatigue.

Conclusion

In the present study we compared the effects of free versus restricted arm movement on balance performance under non-fatigued and fatigued conditions. We found that application of exercise-induced lower limb muscle fatigue and the restriction of arm movement independently resulted in decrements in dynamic balance performance. However, we could not prove the assumed compensatory effect of free arm movement on dynamic postural stability when fatigued. Since the fatigue-related performance deteriorations could not be compensated for by arm movement (i. e. 'upper body strategy'), rest periods seem to be necessary to restore the functionality of the neuromuscular system. Thus, future studies should explore whether the combination of rest periods and arm movement could help to compensate for lower limb fatigue effects on dynamic balance performance.

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Conflict of Interest

The authors declare that they have no conflict of interest.

References

[1] Ament W, Verkerke GJ. Exercise and fatigue. Sports Med 2009; 39: 389–422. DOI: 10.2165/00007256-200939050-00005

[2] Enoka RM, Baudry S, Rudroff T et al. Unraveling the neurophysiology of muscle fatigue. J Electromyogr Kinesiol 2011; 21: 208–219. DOI: 10.1016/j.jelekin.2010.10.006

[3] Behrens M, Gube M, Chaabene H et al. Fatigue and human performance: An updated framework. Sports Med 2023; 53: 7–31. DOI: 10.1007/s40279-022-01748-2

[4] Paillard T. Effects of general and local fatigue on postural control: a review. Neurosci Biobehav Rev 2012; 36: 162–176. DOI: 10.1016/j.neubiorev.2011.05.009

[5] Pau M, Ibba G, Attene G. Fatigue-induced balance impairment in young soccer players. J Athl Train 2014; 49: 454–461. DOI: 10.4085/1062-6050-49.2.12

[6] Johnston W, Dolan K, Reid N et al. Investigating the effects of maximal anaerobic fatigue on dynamic postural control using the Y-Balance Test. J Sci Med Sport 2018; 21: 103–108. DOI: 10.1016/j.jsams.2017.06.007

[7] Zech A, Steib S, Hentschke C et al. Effects of localized and general fatigue on static and dynamic postural control in male team handball athletes. J Strength Cond Res 2012; 26: 1162–1168. DOI: 10.1519/JSC.0b013e31822dfbbb

[8] Hebert-Losier K. Clinical implications of hand position and lower limb length measurement method on Y-Balance test scores and interpretations. J Athl Train 2017; 52: 910–917. DOI: 10.4085/1062-6050-52.8.02

[9] Sogut B, Harput G, Tunay VB. Star excursion balance test scores under different conditions: Effects of arms position and shoe-wear. J Bodyw Mov Ther 2022; 30: 17–22. DOI: 10.1016/j.jbmt.2021.10.011

[10] Hill MW, Wdowski MM, Pennell A et al. Dynamic postural control in children: Do the arms lend the legs a helping hand. Front Physiol 2019; 9: 1932. DOI: 10.3389/fphys.2018.01932

[11] Patel M, Buckwell D, Hawken M et al. Does outstretching the arms improve postural stability? Neurosci Lett 2014; 579: 97–100. DOI: 10.1016/j.neulet.2014.07.010

[12] Marigold DS, Bethune AJ, Patla AE. Role of the unperturbed limb and arms in the reactive recovery response to an unexpected slip during locomotion. J Neurophysiol 2003; 89: 1727–1737. DOI: 10.1152/jn.00683.2002

[13] Parijat P, Lockhart TE. Effects of lower extremity muscle fatigue on the outcomes of slip-induced falls. Ergonomics 2008; 51: 1873–1884. DOI: 10.1080/00140130802567087

[14] Chavarro-Nieto C, Beaven M, Gill N et al. Hamstrings injury incidence, risk factors, and prevention in Rugby Union players: a systematic review. Phys Sportsmed 2023; 51: 1–19. DOI: 10.1080/00913847.2021.1992601

[15] Faul F, Erdfelder E, Lang AG et al. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behav Res Methods 2007; 39: 175–191

[16] Wassinger CA, McKinney H, Roane S et al. The influence of upper body fatigue on dynamic standing balance. Int J Sports Phys Ther 2014; 9: 40–46

[17] Lesinski M, Prieske O, Demps M et al. Effects of fatigue and surface instability on neuromuscular performance during jumping. Scand J Med Sci Sports 2016; 26: 1140–1150. DOI: 10.1111/sms.12548

[18] Plisky PJ, Gorman PP, Butler RJ et al. The reliability of an instrumented device for measuring components of the star excursion balance test. N Am J Sports Phys Ther 2009; 4: 92–99

[19] Picot B, Terrier R, Forestier N et al. The Star Excursion Balance Test: an update review and practical guidelines. Int J Athletic Ther Train 2021; 26: 285–293. DOI: 10.1123/ijatt.2020-0106

[20] Plisky P, Schwartkopf-Phifer K, Huebner B et al. Systematic review and meta-analysis of the Y-Balance Test Lower Quarter: Reliability, discriminant validity, and predictive validity. Int J Sports Phys Ther 2021; 16: 1190–1209. DOI: 10.26603/001c.27634

[21] Borg G. Perceived exertion as an indicator of somatic stress. Scand J Rehabil Med 1970; 2: 92–98

[22] Cohen J. Statistical Power For The Behavioral Sciences. Hillsdale, NJ: Erlbaum; 1988

[23] Cooper CN, Dabbs NC, Davis J et al. Effects of lower-body muscular fatigue on vertical jump and balance performance. J Strength Cond Res 2020; 34: 2903–2910. DOI: 10.1519/JSC.0000000000002882

[24] 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: 233–244. DOI: 10.1007/s00421-021-04831-0

[25] Allen DG, Lamb GD, Westerblad H. Skeletal muscle fatigue: cellular mechanisms. Physiol Rev 2008; 88: 287–332. DOI: 10.1152/physrev.00015.2007

[26] Brody LR, Pollock MT, Roy SH et al. pH-induced effects on median frequency and conduction velocity of the myoelectric signal. J Appl Physiol (1985) 1991; 71: 1878–1885. DOI: 10.1152/jappl.1991.71.5.1878

[27] Cug M. Stance foot alignment and hand positioning alter star excursion balance test scores in those with chronic ankle instability: What are we really assessing? Physiother Theory Pract 2017; 33: 316–322. DOI: 10.1080/09593985.2017.1302028

[28] Objero CN, Wdowski MM, Hill MW. Can arm movements improve postural stability during challenging standing balance tasks? Gait Posture 2019; 74: 71–75. DOI: 10.1016/j.gaitpost.2019.08.010