J Musculoskelet Neuronal Interact 2023; 23(2):215-222

Journal of Musculoskeletal and Neuronal Interactions JMNI

Original Article

Effects of acute lower limb and trunk fatigue on balance, performance, and skin temperature in healthy males

Ozan Bahadir Turkmen[1], Seher Ozyurek[2], Arzu Genc[2]

[1]Department of Physiotherapy and Rehabilitation. Bandirma Onyedi Eylul University, Turkey;
[2]Faculty of Physical Therapy and Rehabilitation, Dokuz Eylul University, Izmir, Turkey

Abstract

Objective: It is unclear whether lower limb and trunk fatigue leads to different effects. Although some studies have compared the effects of muscle fatigue on balance and performance in healthy individuals, little is known about its effects on skin temperature. This study aimed to compare the effects of lower limb and trunk fatigue on balance, performance, and skin temperature in healthy males. **Methods**: Twenty participants performed trunk and lower limb fatigue protocols on two separate days. Balance (Y-Balance Test-YBT), trunk performance (plank test), lower limb performance (Single-Leg Triple Hop-SLTH and Countermovement jump-CMJ), and skin temperature were assessed pre-fatigue and post-fatigue. Infrared Thermography assessed the skin temperatures of the trunk and lower limb. **Results**: Compared with trunk fatigue, the lower limb fatigue protocol had a more significant adverse effect on reducing YBT score, CMJ parameters, and SLHT distance ($p<0.05$). Both fatigue protocols resulted in lower plank test times and trunk skin temperature ($p<0.05$). The changes in plank times and skin temperature were similar between protocols ($p>0.05$). **Conclusions**: Taken together, these results suggest that lower limb fatigue adversely affected balance and lower limb performance more than trunk fatigue. Trunk performance and trunk skin temperatures decreased after both fatigue protocols. Lower limb and trunk fatigue-induced changes in trunk performance and skin temperatures were similar.

Keywords: Assessment, Exhaustion, Infrared Thermography, Skin Temperature, Thermal Imaging

Introduction

At the beginning of the exercise, increased blood flow causes cutaneous vasoconstriction in the contracted muscle[1]. However, as exercise is extended and body temperature rises, heat removal through the skin and vasodilation are controlled by the central regulatory mechanisms[2]. These mechanisms decreases muscle power output throughout the exercise, resulting in muscle fatigue[3]. Fatigue can be defined decrease in the power generation capacity of the muscles from the beginning of the movement[4]. This can negatively affect an individual's overall performance[5]. When assessed separately, muscle fatigue, such as in the lower limbs or trunk, has been shown to affect balance[5-8] and performance[5,9]. It has been stated that lower limb fatigue reduces performance and may increase the risk of injury by decreasing neuromuscular control[10,11]. However, there is no consensus on the effect of lower limb fatigue on balance. Although some studies show that it affects balance negatively[8,12], there are also studies that it does not affect balance[5,11]. Previous studies have shown that as trunk fatigue increases, it causes a decrease in postural control and negatively affects balance and performance[7]. However, fatigue protocols, protocol termination criteria, and demographic characteristics of the participants (such as age, gender, and physical activity level) differ in these studies. To our knowledge, only one study has examined the effects of the trunk and lower limb fatigue on the balance and performance of the same individuals[12].

There are many methods to measure fatigue, but most have some disadvantages. For example, some biomarkers (like blood and bone) are invasive and challenging, making them difficult to manage during training[13]. Infrared Thermography

The authors have no conflict of interest.

Corresponding author: Ozan Bahadir Turkmen, PhD Candidate, Yeni Mahalle Sehit Astsubay Mustafa Soner Varlik Caddesi No:77, 10200 Bandirma/ Balikesir, Turkey
E-mail: oturkmen@bandirma.edu.tr
ORCID: 0000-0002-1799-3286

Edited by: G. Lyritis
Accepted 29 March 2023

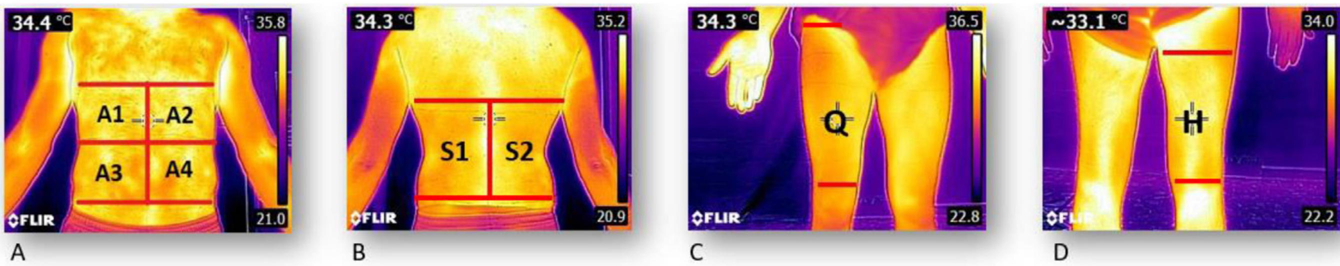

Figure 1. Trunk and lower limb skin temperature. A) Abdominal skin temperature. B) Back skin temperature. C) Quadriceps skin temperature. D) Hamstring skin temperature.

(IRT), another method frequently used to assess muscle fatigue in recent years, is a radiation-free, non-contact, safe, and non-invasive technology that monitors physiological variables by controlling skin temperature[14]. This technology can study the relationship between muscle contraction and skin temperature. During exercise, muscles can increase or decrease skin temperature depending on the exercise's intensity[15].

In light of this information, fatiguing the trunk or lower limb muscles may provide a better understanding of the cause-effect of each muscle group on sports performance. Therefore, we hypothesized that fatiguing the lower limb or the trunk would affect balance, performance, and skin temperature differently.

Materials and Methods

Design

This study was carried out on two separate visits in a cross-over design. Participants completed one of two fatigue protocols to fatigue either trunk or lower limb muscles. The order of the two protocols was randomized using a sealed envelope method. A minimum of 2 and a maximum of 7 days break period was required between visits to ensure that fatigue was eliminated, and the two protocols would not affect each other. Pre-fatigue and post-fatigue tests were performed at the same hour of the day (± 1 hour) to avoid performance differences depending on variability in circadian rhythms on testing days[12].

Participants

Twenty-five participants who fit the criteria were included in the study. However, five participants were excluded from the study because they could not be taken to the second evaluation due to the Covid-19 pandemic after the first-day evaluation. Finally, a total of 20 healthy participants (20 male; age 24.1±3.87 years; body mass 76.1±9.52 kg; height 179.25±0.06 m) completed the study. This study was conducted in the School of Physical Therapy and Rehabilitation at Dokuz Eylul University between October 2020 and March 2021. Inclusion criteria were determined as being male, having a Body Mass Index (BMI) between 18-29.9 kg/cm^2, and exercising regularly (at least three days a week for a 90-minute duration). The sample group in the study was decided, as in similar studies, to have a homogeneous sample in terms of physical activity level[12]. Exclusion criteria from the study were drug use known to affect balance, history of injury in the lower limb or trunk, and acute pain in the lower limb or trunk in the last six months. Pain status was assessed with The Nordic Musculoskeletal Questionnaire (NMQ). Kahraman et al.'s study indicated that the Turkish version of the NMQ has appropriate psychometric properties, including satisfying test-retest reliability, inner consistency, and construct validity[16]. Each participant's anthropometrics (age, height, and body mass) were recorded, and the test procedure was explained to the participants[5,12].

Procedures

Participants underwent the same test procedure on each testing day before and after the fatigue protocol. The test was consistently applied in chronological order, as explained below. Other than the time required for changing the testing device, no rest was given, and avoid any recovery during testing.

Thermographic Assessment

Thermal imaging was performed to assess the trunk and anterior and posterior lower limb skin temperature (Figure 1). Similar to Chudecka et al.[17], skin temperature was evaluated by thermal imaging in a room without sunlight and airflow, with an average ambient temperature of 22.5°C and humidity of 31.5%. Participants were asked to participate in the assessment with shorts, t-shirts, and sneakers. Measurements were made after the participants were kept in the evaluation room for 10 minutes to adapt to the environmental conditions. The FLIR E6-XT® Thermal Camera (FLIR Systems AB, Sweden) with 240x180 IR resolution pixels was used for thermal imaging, and the Color Palette iron was chosen to display the images. The auditor took the measurements from 0.5 m from the participants[18]. Average skin temperature in degrees was recorded. On each test day, the first imaging was done just before the start of the warm-up exercises, and the final imaging was done just after all the exercises were finished. Twelve thermal camera images were taken, six of which were before and after fatigue.

The average of each rectangular region of interest (ROI) was collected using FLIR Tools software (FLIR Systems AB, Sweden). The configuration of the rectangles was determined using anatomical landmarks such as seen a) the abdominal ROIs, from the xiphoid process to 5 cm below the umbilicus, divided into four segments (A1, A2, A3, and A4); as seen c) thigh ROI was measured from 5 cm above the upper border of the patella to the groin line. Relevant points on the back of the body were marked using a tape measure surrounding the examined area parallel to the floor. Figure 1 shows images taken of a single participant with labeled ROIs[18].

Balance

The Y-balance test (YBT) (Functional Movement Systems, VA, USA) was used to assess dynamic balance. Participants viewed an instructional video that explained and demonstrated the testing procedures. After the demonstration, participants placed the most distal end of the longest toe of the test leg at the red line on the platform on the test kit. Participants reached anterior, 135° posteromedial, and 135° posterolateral directions, with the other leg pushing the box as far as possible while maintaining a single-leg stance on the test leg. Trials were discarded and repeated if the participant: 1) not returning to the starting position, 2) put the reaching leg anywhere to increase the reaching distance, 3) raised or moved the stance leg during the test, or kicked the indicator box with the reaching foot to gain more distance[19]. Reach distances have been standardized based on the anatomical length of the legs and expressed as a percentage of the length of the legs (reach distance/length of the limbs) X 100. The composite standardized reach distance was calculated for each leg as (ANT + PM + PL) / (3 X limb length) X 100. Reach distance differences between right and left were calculated in cm (reach distance difference = [maximum right reach distance − maximum left reach difference]), and the total reach asymmetry was calculated as the sum of the three-reach direction differences[20].

Performance

Trunk and lower limb performance were evaluated using prone plank test, Countermovement Jump, and Single-Leg Triple Hop Test for Distance.

Prone Plank Test

A prone plank test was used to evaluate trunk performance. At the start of the test, participants held a prone bridge with forearm and foot support. Participants were asked to maintain this static position for as long as possible and were given verbal cues to promote adherence to the position for test validity. When the participant assumed the correct position, the researcher started the stopwatch. The test was terminated if: (1) the participant became fatigued or voluntarily stopped the test, (2) the participant failed to maintain the correct position, (3) the participant reported adverse effects from the test (e.g., shoulder pain not related to fatigue), or (4) the researcher occurred when two consecutive corrective prompts given to the participant did not fulfill. At the end of the test, each participant's test time was recorded[21].

Counter Movement Jump (CMJ)

The participants began the test upright with their feet placed shoulder-width apart and hands on their hips. Once the evaluator gave the command to start, the participants made an initial downward movement via flexion of their hips and knees, then immediately extended their hips and knees again to jump off the ground vertically. Participants were asked to jump as high as possible with both feet. During the test, the participants were instructed to maintain their hands on their hips. A wireless motion detection device (G-Walk, BTS Bioengineering SpA, Italy), a valid and reliable method for CMJ testing, attached using a strap, was attached to the individual's waist (at L4-L5). G-walk is a reliable device for assessing jump[22]. The data transmitted from the motion detection device to the computer via Bluetooth were recorded. Participants performed three CMJ tests.

Single-Leg Triple Hop Test for Distance (SLTH)

Participants began by standing on the designated test foot with their toes on the starting line. Participants performed three consecutive maximum hops forward with the designated leg when ready. The distance between the start line and the landing point of the participant's heels was measured. The test performed upper limb movement without restriction. For the test to be successful: 1) the participant did not shift or rotate the landing foot, 2) the other foot was not contacted with the ground for support on landing, and 3) the participant had to complete the stop within one second of landing. Participants attempted no more than three practice trials to avoid fatigue before the test for each lower limb fatigue[23]. The average distance of three hoops was recorded as a test score.

Fatigue Protocol for Lower Limb

Three exercises were performed to fatigue the lower limb muscles. Participants began the fatigue protocol with three exercises - one set of 50 step-ups, 50 squats, and ten vertical jumps[24]. The step height was 30 cm. Participants stepped up with the dominant lower limb fatigue and down with the non-dominant lower limb fatigue or vice versa. Participants were considered fatigued if their hop distance was reduced to 80% of their average distance. If participants could hop further than this distance, they performed fatigue protocol and were retested until they met fatigue criterion[24].

Table 1. Y-Balance Test of Trunk and Lower Limb Fatigue.

	Trunk Fatigue				Lower Limb Fatigue				
YBT Composite score, % limb length	Pre-Fatigue Mean ± SD	Post-Fatigue Mean ± SD	Δ	ᵃp	Pre-Fatigue Mean ± SD	Post-Fatigue Mean ± SD	Δ	ᵃp	ᵇp
Dominant	104.95±1.37	105.34±1.24	0.19	0.472	103.61±1.64	99.83±2.21	-4.31	**0.002***	**0.008***
Non-dominant	104.76±1.49	101.83±1.42	-1.09	0.112	105.34±1.60	99.18±2.34	-5.17	**0.005***	0.070

SD: Standard Deviation; YBT: Y-Balance Test, ᵃp: Wilcoxon Test: Pre-fatigue and post-fatigue intra-group comparison, ᵇp: Mann Whitney U test: comparison of differences (Δ) between the trunk and lower limb fatigue, Δ: variable difference between pre- and post-fatigue.

Table 2. Performance Tests of Trunk and Lower Limb Fatigue.

	Trunk Fatigue				Lower Limb Fatigue				
	Pre-Fatigue Mean ± SD	Post-Fatigue Mean ± SD	Δ	ᵃp	Pre-Fatigue Mean ± SD	Post-Fatigue Mean ± SD	Δ	ᵃp	ᵇp
Plank (sec)	56.33±5.21	26.33±3.41	-22.00	**<0.001****	55.17±4.19	28.66±3.32	-21.99	**<0.001****	0.561
SLTH									
Dominant (cm)	545.33±13.48	476.17±14.15	-31.67	**<0.001****	550.50±9.32	426.66±10.89	-121.50	**<0.001****	**<0.001****
Non-dominant (cm)	526.67±13.17	489.50±12.60	-25.17	0.003	530.99±10.20	412.83±10.37	-110.50	**<0.001****	**<0.001****
CMJ									
Jump Height (cm)	30.03±0.95	29.11±0.82	-0.98	0.380	31.05±1.08	27.18±1.07	-3.45	**<0.001****	**<0.001****
Take of Force (kN)	1.07±0.43	1.07±0.46	0.01	0.856	1.07±0.43	1.07±0.38	-0.02	0.955	0.705
Impact Force (kN)	1.65±0.18	1.54±0.17	-0.04	0.077	1.66±0.16	1.60±0.11	-0.22	**0.016***	0.358
MCP	4.24±4.17	4.21±3.99	-0.05	0.563	4.12±3.84	3.94±1.43	-0.25	0.117	0.351
Average Speed Concentric Phase (m/sec)	1.52±0.03	1.49±0.04	-0.03	0.140	1.46±0.05	1.43±0.05	-0.09	**<0.001****	**0.036***
Peak Speed (m/sec)	2.79±0.05	2.72±0.05	-0.02	0.588	2.78±0.05	2.66±0.05	-0.12	**0.004***	**0.044***
Take off Speed (m/sec)	2.7 ±0.05	2.63±0.05	-0.01	0.823	2.70±0.05	2.59±0.05	-0.11	**0.009***	0.086

SD: Standart Deviation; SLTH: Single Lower Limb Triple Hop, CMJ: Counter Movement Jump, cm: centimeters, kN: Kilonewtons. ᵃp: Wilcoxon Test: Pre-fatigue and post-fatigue intra-group comparison, ᵇp: Mann Whitney U test: comparison of differences (Δ) between the trunk and lower limb fatigue, Δ: variable difference between pre-fatigue and post-fatigue.

Table 3. Thermographic Assessment of Trunk and Lower Limb Fatigue.

	Trunk Fatigue				Lower Limb Fatigue				
	Pre-Fatigue Mean ± SD	Post-Fatigue Mean ± SD	Δ	^{a}p	Pre-Fatigue Mean ± SD	Post-Fatigue Mean ± SD	Δ	^{a}p	^{b}p
Quadriceps/°C									
Dominant	31.76±0.32	31.71±0.26	-0.12	0.601	32.21±0.25	32.33±0.30	0.29	0.232	0.255
Non-dominant	32.00±0.28	31.85±0.22	-0.48	0.687	32.21±0.26	32.61±0.25	0.48	**0.038***	0.320
Hamstrings/°C									
Dominant	32.15±0.33	32.05±0.29	-0.30	0.232	32.30±1.16	32.49±1.29	32.80	0.372	0.144
Non-dominant	32.15±0.32	32.25±0.29	0.00	0.663	32.28±1.17	32.36±1.29	32.45	0.409	0.507
Trunk Anterior (Abdominal)/°C									
A1	33.80±0.30	31.85±0.27	-1.10	**0.017***	34.05±0.32	32.20±0.28	-1.70	**<0.001****	0.239
A2	33.80±0.30	31.85±0.26	-1.00	**0.005***	34.20±0.32	32.05±0.30	-1.95	**<0.001****	0.185
A3	33.25±0.33	31.45±0.25	-1.15	**0.004***	33.15±0.35	31.50±0.33	-1.45	**0.003***	0.394
A4	33.4±0.33	31.75±0.27	1.05	**0.017***	33.65±0.35	31.60±0.35	-1.65	**0.002***	0.208
Trunk Posterior (Back)/°C									
B1	33.45±0.34	31.45±1.24	-1.40	**0.002***	33.35±0.33	32.30±0.28	-1.40	**0.016***	0.337
B2	33.65±0.34	31.45±0.28	-1.60	**0.005***	33.65±0.34	32.55±0.26	-0.95	**0.038***	0.151

SD: Standard Deviation; °C: Degrees Celsius; A and B ROI are described in Figure 1, ^{a}p: Wilcoxon Test: Pre-fatigue and post-fatigue intra-group comparison, ^{b}p: Mann Whitney U test: Comparison of differences (Δ) between the trunk and lower limb fatigue, Δ: variable difference between pre-fatigue and post-fatigue.

Fatigue Protocol for the Trunk

A fatigue protocol consisting of back extension, trunk flexion, side plank, and prone plank exercises were applied to fatigue the trunk muscles of the participants[7]. The four exercises in this fatigue protocol were performed in a cycle. During the exercises in the cycle, the participants were asked to maintain the isometric position until complete exhaustion[7], and after each cycle, the participants were asked to rate the Modified BORG scale. The cycle continued until the modified BORG scale score was eight and above. No rest time was allowed between exercises and cycles. In total, it took 20 to 30 minutes for each participant.

Statistical Analysis

Statistical analysis was performed using IBM SPSS Statistic software for Windows (Version 23.0. Armonk, NY: IBM Corp). The study's sample size was calculated with the G-Power software (Version 3.1.9.2, University of Dusseldorf, Dusseldorf, Germany) (95). According to the primary outcome measure, Vertical Jump Height (VJH), there should be at least 20 participants with a power of 0.99, an alpha error probability of 0.05, and a large effect size (1.5)[25]. The Shapiro-Wilk test was used to check whether the data fit the normal distribution, and it was found that the data were not normally distributed. The delta (Δ) value, difference scores across the pre-fatigue and post-fatigue measurements, was calculated for each dependent variable. Wilcoxon Signed-Rank Test analysis was performed to compare dependent variables before and after fatigue, and the Mann-Whitney U test compared intra-group changes in lower limb and trunk fatigue. The significance level for all tests was accepted as $p<0.05$.

Results

Trunk Fatigue

It was found that trunk fatigue decreased the prone plank test and SLTH results statistically significantly ($p<0.05$) but did not change CMJ parameters and balance score ($p>0.05$) (Table 1 and Table 2). After trunk fatigue, trunk skin temperatures (abdominal and back) decreased ($p<0.05$), while lower limb skin temperatures (quadriceps and hamstring) did not change ($p>0.05$) (Table 3).

Lower Limb Fatigue

The decrease in CMJ parameters (Jump Height (JH), Ave. Speed Concentric Phase (ASCP), Impact Force (IF), Peak Speed (PS) and Take of Speed (TS)), prone plank test time, SLHT, composite score, non-dominant hamstring skin temperature, and trunk skin temperature was more significant than the pre-fatigue ($p<0.05$) (Table 1 and Table 2). There was no change in the non-dominant leg skin temperature (except non-dominant quadriceps skin temperature) ($p>0.05$) (Table 3).

Trunk Fatigue vs. Lower Limb Fatigue

Pairwise comparison between the trunk and lower limb showed a more significant effect on lower limb fatigue performance tests and balance results than trunk fatigue, excluding the prone plank test. Fatiguing lower limb muscles cause a more severe loss of performance and balance than fatiguing trunk muscles (Table 1 and Table 2). After both fatigue protocols, there were no statistically significant differences in the trunk and lower limbs' skin temperature (Δ values) ($p>0.05$). Compared with trunk fatigue, lower limb fatigue protocol showed a more adverse effect on Y balance score, CMJ parameters, and reduced SLHT distance (Table 1 and Table 2). Both fatigue protocols were found to cause similar decreases in plank test times and trunk skin temperature (Table 1, Table 3).

Discussion

This study aimed to investigate the effects of trunk and lower limb fatigue on balance, performance, and skin temperature. Our results found that lower limb fatigue negatively affected balance and lower limb performance more than trunk fatigue. However, trunk fatigue did not affect balance. This result did not support the common opinion that balance performance would significantly reduce post-exercise-induced trunk muscle fatigue. Trunk performance was similarly reduced after both fatigue protocols. In addition, this study is the first to examine the effect of both fatigue protocols on skin temperature. Trunk skin temperature decreased similarly after both fatigue protocols. However, changes in lower skin temperatures were similar and unchanged.

Fatigue and Balance

The balance score is expected to decrease after the muscles are fatigued. In previous studies, there was no consensus on the lower limb fatigue effect on balance[5,8,12,26-28]. Cooper et al.[5] found that lower extremity fatigue has no effect on balance. Cetin et al.[27] reported static balance is altered by the fatigue of lower extremity muscles while dynamic balance is altered partly by fatigue of lower extremity muscles. However, Simoneau et al.[28] and Roth et al.[12] that fatigue negatively affected the balance score. Our study results showed that balance decreased after lower limb fatigue. The explanation for the differences seems to be related to the study design, the type of balance measurements, and the fatigue protocol[5]. We also support this perspective.

The literature agrees that trunk fatigue adversely affects balance[6,7,29]. Our results did not support our hypothesis that balance performance would significantly reduce post-exercise-induced muscle fatigue. This difference may be due to the difference in trunk fatigue protocols and our use of the perceived fatigue level for completion.

The number of studies on the effect of the trunk and lower limb fatigue protocols on balance in the same sample is limited. Helbostad et al.[30] stated that reasonably consistent in that fatigue of the lower limb and trunk muscles impairs balance, despite differences in study design, populations, fatigue protocols, and outcome measures. Roth et al.[12] stated that lower limb fatigue affects balance more than trunk fatigue. Similar to the Roth et al.'s[12] study, our study showed that lower limb fatigue adversely affected balance more than trunk fatigue. The sequence of tests to be assessed after the acute fatigue protocols, the type of fatigue protocols, and the assessment of fatigue with more objective parameters (such as lactate levels) are essential for clinicians.

Fatigue and Performance

In this study, when lower limb and trunk fatigue were compared, we found that lower limb fatigue negatively affected performance test results more than trunk fatigue. (except for the prone plank test). This is explained by the fact that the lower limb muscles are particularly important for force generation, while the trunk muscles are activated to allow force transmission during kinetic chain movements and to provide central stability for distal mobility[12]. At the same time, it was stated that the reason for the decrease of the parameters in the CMJ test, which is one of the performance tests, after fatigue is due to the counter movement phase, which causes less contact with the ground as muscle fatigue increases[31,32]. The effect of fatigue on performance can be explained by reduced mechanical efficiency after exercise, possibly through reduced elastic energy storage and utilisation[9].

Fatigue and Skin Temperature

The balance between cutaneous vasodilation and vasoconstriction may differ depending on the role of the muscles[33,36]. The effects of long-term intense exercise on skin temperature have been reported in many studies[34-36]. Studies examining the effects of various fatigue protocols on skin temperatures show that body skin temperature is lower immediately after vigorous exercise compared to pre-exercise[14,37,38]. Hildebrandt et al.[14] showed that quadriceps skin temperature increased after aerobic exercise (0.7°C) and decreased after anaerobic exercise (-1.5°C). Neves et al.[39] support the conclusion that during high-intensity anaerobic exercise, the skin temperature of overactive muscles increases and slowly decreases after exercise. In addition, the skin temperature of overactive muscles decreased during low-intensity aerobic exercise and returned to normal within a few minutes.

However, Cerezci et al.[40] found no difference in skin temperature after anaerobic exercise in hamstring and quadriceps muscles in sailing athletes. Similarly, our study detected no changes in the lower limb skin temperatures (except non-dominant quadriceps) after both trunk and lower limb fatigue.

Dindorf et al.[37] reported that immediately after anaerobic exercise, trunk skin temperature diminished as perceived muscle fatigue increased. Similarly, our study found an adversely decrease in trunk skin temperature after both fatigue protocols. The reason suggested for this situation is a decrease in blood flow due to vasoconstrictor response and a decrease in mean skin temperature as exercise intensity increases[41]. Observing the existence and amount of fatigue to maximize performance and training adaptation is significant for applied sports scientists. Therefore, the thermal imaging method can be used by trainers to evaluate the dynamics of athletes' body temperatures and thus monitor the effectiveness of thermoregulation.

There are several limitations to the study. The population sample was limited to recreationally active males, so our results are only valid for this population. Using isokinetic devices for fatigue protocols and lactate tests for fatigue severity would provide a more objective result in future studies. Moreover, thermal images were recorded before and after exercise but not during exercise, limiting the interpretation of skin temperature dynamics. Despite the limitations noted above, since the number of studies examining the effects of both fatigue protocols on the same sample is limited, the contribution of our study to the literature may be valuable. In addition, to the best of our knowledge, this is the first study to examine the effect of fatigue protocols on skin temperature.

Conclusion

Our findings indicated that trunk and lower limb fatigue may affect motoric abilities differently. The detrimental effect on balance and lower limb performance of lower limb fatigue was higher than that of trunk fatigue. Balance is not affected following trunk fatigue. Trunk performance and trunk skin temperatures were similarly reduced after both fatigue protocols. The effects of fatigue during training and competition can be monitored using infrared thermography by coaches, athletic trainers, and physical therapists in athletes and individuals participating in high-intensity exercise. Further research should also include EMG analysis to check the results at different levels of loads to highlight the potential use of thermography in monitoring fatigue.

Ethics approval

Ethical approval was obtained from the Non-Invasive Research Ethics Committee of Dokuz Eylul University (No: 2020/02-30, Date: 20.01.2020), and all procedures were precisely implemented according to the Declaration of Helsinki.

Consent to participate

All participants gave verbal and written informed consent before data collection began.

References

1. Johnson JM. Exercise and the cutaneous circulation. Exercise and sport sciences reviews 1992;20:59-97.
2. Formenti D, Ludwig N, Gargano M, et al. Thermal imaging of exercise-associated skin temperature changes in trained and untrained female subjects. J Annals of Biomedical Engineering 2013;41(4):863-871.
3. Abbiss CR, Burnett A, Nosaka K, Green JP, Foster JK, Laursen PB. Effect of hot versus cold climates on power output, muscle activation, and perceived fatigue during a dynamic 100-km cycling trial. Journal of Sports Sciences 2010;28(2):117-125.
4. Davis MP, Walsh D. Mechanisms of fatigue. J J Support Oncol 2010;8(4):164-174.
5. Cooper CN, Dabbs NC, Davis J, Sauls NM. Effects of lower-body muscular fatigue on vertical jump and balance performance. The Journal of Strength & Conditioning Research 2020;34(10):2903-2910.
6. Parreira RB, Amorim CF, Gil AW, Teixeira DC, Bilodeau M, Da Silva RA. Effect of trunk extensor fatigue on the postural balance of elderly and young adults during unipodal task. J European Journal of Applied Physiology 2013;113(8):1989-1996.
7. Larson DJ, Brown SH. The effects of trunk extensor and abdominal muscle fatigue on postural control and trunk proprioception in young, healthy individuals. J Human Movement Science 2018;57:13-20.
8. Inoue K, Uematsu M, Maruoka H, et al. Influence of lower limb muscle fatigue on balance function. J Journal of Physical Therapy Science 2013;25(3):331-335.
9. Gathercole R, Sporer B, Stellingwerff T, Sleivert G. Alternative countermovement-jump analysis to quantify acute neuromuscular fatigue. International journal of sports physiology and performance 2015;10(1):84-92.
10. Bellew JW, Panwitz BL, Peterson L, Brock MC, Olson KE, Staples WH. Effect of acute fatigue of the hip abductors on control of balance in young and older women. Archives of physical medicine and rehabilitation 2009; 90(7):1170-1175.
11. Armstrong R, Brogden CM, Milner D, Norris D, Greig M. The influence of fatigue on star excursion balance test performance in dancers. Journal of Dance Medicine & Science 2018;22(3):142-147.
12. Roth R, Donath L, Zahner L, Faude O. Acute leg and trunk muscle fatigue differentially affect strength, sprint, agility, and balance in young adults. The Journal of Strength & Conditioning Research 2021;35(8):2158-2164.
13. Buchheit M, Racinais S, Bilsborough J, et al. Monitoring fitness, fatigue and running performance during a pre-season training camp in elite football players. Journal of science and medicine in sport 2013;16(6):550-555.
14. Hildebrandt C, Zeilberger K, Ring EFJ, Raschner C. The application of medical infrared thermography in sports medicine. INTECH Open Access Publisher; 2012.
15. Alfieri FM, Battistella LR. Body temperature of healthy men evaluated by thermography: A study of reproducibility. Technology and Health Care 2018; 26(3):559-564.
16. Kahraman T, Genç A, Göz E. The Nordic Musculoskeletal Questionnaire: cross-cultural adaptation into Turkish assessing its psychometric properties. Disabil Rehabil 2016; 38(21):2153-60.

17. Chudecka M, Lubkowska A, Leźnicka K, Krupecki K. The use of thermal imaging in the evaluation of the symmetry of muscle activity in various types of exercises (symmetrical and asymmetrical). Journal of human kinetics 2015;49:141.
18. Marins JCB, Moreira DG, Cano SP, et al. Time required to stabilize thermographic images at rest. J Infrared Physics Technology 2014;65:30-35.
19. Coughlan GF, Fullam K, Delahunt E, Gissane C, Caulfield BM. A comparison between performance on selected directions of the star excursion balance test and the Y balance test. Journal of athletic training 2012;47(4):366-371.
20. Bulow A, Anderson JE, Leiter JR, MacDonald PB, Peeler J. The modified star excursion balance and y-balance test results differ when assessing physically active healthy adolescent females. Int J Sports Phys Ther 2019;14(2):192-203.
21. Strand SL, Hjelm J, Shoepe TC, Fajardo MA. Norms for an isometric muscle endurance test. Journal of human kinetics 2014;40:93.
22. Yazıcı G, Yazıcı MV, Çobanoğlu G, et al. The reliability of a wearable movement analysis system (G-walk) on gait and jump assessment in healthy adults. Journal of Exercise Therapy and Rehabilitation 2020;7(2):159-167.
23. Schmitt LC, Paterno MV, Hewett TE. The impact of quadriceps femoris strength asymmetry on functional performance at return to sport following anterior cruciate ligament reconstruction. journal of orthopaedic & sports physical therapy 2012;42(9):750-759.
24. Orishimo KF, Kremenic IJ. Effect of fatigue on single-leg hop landing biomechanics. Journal of applied biomechanics 2006;22(4):245-254.
25. Attia A, Dhahbi W, Chaouachi A, Padulo J, Wong DP, Chamari K. Measurement errors when estimating the vertical jump height with flight time using photocell devices: the example of Optojump. Biol Sport 2017; 34(1):63-70.
26. Bellew JW, Panwitz BL, Peterson L, Brock MC, Olson KE, Staples WH. Effect of acute fatigue of the hip abductors on control of balance in young and older women. J Archives of Physical Medicine Rehabilitation 2009;90(7):1170-1175.
27. Armstrong R, Brogden CM, Milner D, Norris D, Greig M. The influence of fatigue on star excursion balance test performance in dancers. J Journal of Dance Medicine Science 2018;22(3):142-147.
28. Simoneau M, Bégin F, Teasdale N. The effects of moderate fatigue on dynamic balance control and attentional demands. Journal of neuroengineering and rehabilitation 2006;3(1):1-9.
29. Cetin N, Bayramoglu M, Aytar A, Surenkok O, Yemisci OU. Effects of lower-extremity and trunk muscle fatigue on balance. J The Open Sports Medicine Journal 2008; 2(1):16-22.
30. Helbostad JL, Sturnieks DL, Menant J, Delbaere K, Lord SR, Pijnappels M. Consequences of lower extremity and trunk muscle fatigue on balance and functional tasks in older people: a systematic literature review. J BMC Geriatrics 2010;10(1):56.
31. McLellan CP, Lovell DI, Gass GC. The role of rate of force development on vertical jump performance. The Journal of Strength & Conditioning Research 2011;25(2):379-385.
32. Peterson MD, Alvar BA, Rhea MR. The contribution of maximal force production to explosive movement among young collegiate athletes. The Journal of Strength & Conditioning Research 2006;20(4):867-873.
33. Tanda G. Skin temperature measurements by infrared thermography during running exercise. Experimental Thermal and Fluid Science 2016;71:103-113.
34. Carpes FP, Mello-Carpes PB, Priego Quesada JI, Pérez-Soriano P, Salvador Palmer R, Ortiz de Anda RMC. Insights on the use of thermography in human physiology practical classes. Advances in Physiology Education 2018;42(3):521-525.
35. Hadžić V, Širok B, Malneršič A, Čoh M. Can infrared thermography be used to monitor fatigue during exercise? A case study. Journal of sport and health science 2019;8(1):89-92.
36. Hillen B, Pfirrmann D, Nägele M, Simon P. Infrared thermography in exercise physiology: the dawning of exercise radiomics. Sports Medicine 2020;50(2):263-282.
37. Dindorf C, Bartaguiz E, Janowicz E, Fröhlich M, Ludwig O. Effects of Unilateral Muscle Fatigue on Thermographic Skin Surface Temperature of Back and Abdominal Muscles - A Pilot Study. Sports 2022;10(3):41.
38. Formenti D, Ludwig N, Gargano M, et al. Thermal imaging of exercise-associated skin temperature changes in trained and untrained female subjects. Annals of biomedical engineering 2013;41(4):863-871.
39. Neves EB, Vilaca-Alves J, Antunes N, Felisberto IM, Rosa C, Reis VM. Different responses of the skin temperature to physical exercise: Systematic review. Annu Int Conf IEEE Eng Med Biol Soc 2015;2015:1307-10.
40. Cerezci Duygu S, Ozunlu Pekyavas N, Uzun A, et al. Muscle skin temperature responses for hamstring and quadriceps to aerobic and anaerobic test conditions in Turkish Olympic Sailing Athletes. Journal of Thermal Analysis and Calorimetry 2019;136(5):2125-2130.
41. Ludwig N, Trecroci A, Gargano M, et al. Thermography for skin temperature evaluation during dynamic exercise: a case study on an incremental maximal test in elite male cyclists. Applied optics 2016;55(34):D126-D130.