

The Influence of Different Fatigue Inducing Factors on the Balance Ability of Male College Students

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Abstract

Objective: This study utilized surface electromyography and an Advanced Mechanical Technology, Inc. (AMTI) force plate to investigate the effects of fatigue induced by stationary cycling and squatting (Zama Bu) on human balance ability and the characteristics of lower limb muscle electromyographic parameters. **Methods:** Twenty male students from Dalian University of Technology were recruited to perform stationary cycling and squatting exercises until fatigue. The center of pressure sway area and electromyographic signals of the rectus femoris, biceps femoris, medial gastrocnemius, and tibialis anterior muscles were measured before and after fatigue. **Results:** (1) Fatigue induced by stationary cycling significantly decreased static balance ability ($p < 0.05$), while fatigue induced by squatting significantly increased static balance ability ($p < 0.05$), indicating a significant reduction in the muscle activation level and voluntary muscle strength of these lower limb muscles. Neither exercise had a significant effect on dynamic balance ability ($p > 0.05$). (2) There were no significant differences in the effects of fatigue from stationary cycling versus squatting on the biceps femoris, medial gastrocnemius, and tibialis anterior muscles ($p > 0.05$). A significant difference was observed in the rectus femoris ($p < 0.05$): Stationary cycling significantly decreased its Integrated Electromyography (IEMG) and Root Mean Square (RMS) values, whereas squatting had the opposite effect. (3) Fatigue from stationary cycling significantly decreased the IEMG and RMS of the rectus femoris and tibialis anterior ($p < 0.05$), and significantly decreased the IEMG of the medial gastrocnemius and biceps femoris ($p < 0.05$). (4) Fatigue from squatting significantly decreased the IEMG and RMS of the gastrocnemius ($p < 0.05$), and significantly increased the IEMG of the rectus femoris ($p < 0.05$). **Conclusion:** Fatigue induced by stationary cycling leads to a decline in static balance ability, whereas fatigue induced by squatting leads to an improvement in static balance ability. Fatigue from stationary cycling causes significant fatigue and decreased muscle strength in all measured muscles. In contrast, fatigue from squatting primarily causes significant fatigue and decreased muscle strength in the gastrocnemius, while increasing the activation level of the rectus femoris muscle.

Keywords

Surface electromyography, Center of pressure, Muscle fatigue, Balance ability

Introduction

Research on sports fatigue and balance ability holds significant importance in fields such as sports science, sports medicine, rehabilitation therapy, and industrial and military sectors [1].

For athletes, in-depth study of sports fatigue and balance ability can help them better enhance their physical fitness and facilitate post-exercise recovery, thereby improving athletic performance and preventing sports injuries. In many rehabilitation treatment plans, the rehabilitation process must take into account balance ability and fatigue factors, which can make the rehabilitation

process more effective and safer. This knowledge can also help reduce the risk of falls and slips for injured or mobility-impaired individuals. Research on sports fatigue and balance ability can help us better understand the physiological and neural mechanisms of the human body system and advance the study of human kinematics and dynamics. The study of sports fatigue and balance ability also has broad applications in industry and the military, aiding in the design and improvement of work and military equipment, and better protecting the health, safety, and lives of workers and soldiers.

Sports fatigue is one of the main causes of changes in balance ability. The impact of different types of sports fatigue on balance ability is complex, as it is influenced by multiple factors, including the type of exercise, duration, intensity, and individual differences among athletes. Generally, both static and dynamic balance abilities are affected by sports fatigue [2].

The main cause of exercise-induced fatigue is the production of fatigue substances in muscles during exercise, which accumulate and lead to a sensation of fatigue. Different exercises have varying effects on different muscles and muscle fiber types, resulting in different types of fatigue [3]. For example, prolonged endurance exercises like long-distance running are more likely to cause systemic fatigue, largely based on whole-body endurance, whereas high-intensity strength training often leads to localized muscle fatigue. Additionally, other factors, such as physical fitness, nutrition, rest, and training effects, also influence post-exercise fatigue. Therefore, in exercise training and rehabilitation therapy, the relationship between inducing factors and balance ability must be considered.

Exercise modalities can be further divided into dynamic exercise and static exercise. Both types not only provide physical training but also offer distinct training effects. Static exercise can improve the body's flexibility and balance ability, promote blood circulation, relieve muscle tension, and have a calming and relaxing effect mentally [4]. Dynamic exercise can strengthen muscle strength and explosive power, improve cardiorespiratory function and endurance, and promote bodily metabolism.

This experiment uses a cycle ergometer to represent dynamic exercise and a horse-riding stance to represent static exercise, investigating the effects of different exercise-induced fatigue triggers on the balance ability of male college students. To this end, this experiment primarily employs electromyography (EMG) and an AMTI force plate to explore the impact of fatigue on balance ability. Surface electromyography is used to monitor the effects of different exercise-induced fatigue methods on the electromyographic signals of lower limb muscles, while the AMTI force plate records changes in the center of pressure to analyze changes in balance ability before and after fatigue.

Research subjects

Twenty male students from the Panjin Campus of Dalian University of Technology were selected as subjects, with sample size determined by GPower 3.1 (effect size=0.5, $\alpha=0.05$, power=0.8). A sensitivity analysis verified the reliability of statistical results under this sample size, confirming sufficient power to detect main experimental effects. Participants completed two sessions: stationary cycling to fatigue and squatting (Zama Bu) to fatigue, with a seven-day interval. Inclusion criteria were: aged 22-24 years old; good physical condition and normal exercise capacity; no genetic diseases or lower limb injuries; no strenuous exercise or muscle fatigue within 24 hours before the experiment; good tolerance; and no professional athletic training. All subjects were informed of experimental procedures and precautions before the test began.

Table 1. Basic information of subjects (Mean \pm SD).

| Age (years old) | Weight (kg) | Height (cm) | Leg Length (cm) | Resting Heart Rate (bpm) |
|------------------|-------------------|-------------------|------------------|--------------------------|
| 22.00 \pm 1.00 | 69.65 \pm 11.47 | 177.35 \pm 5.41 | 90.50 \pm 4.06 | 61.80 \pm 3.29 |

Research methods

Literature review method

The research questions and themes were defined to determine the relevant literature and materials requiring collection. Academic search engines (such as Google Scholar, CNKI, Web of Science, etc.) were utilized to conduct searches within the Dalian University of Technology library, academic journals, and relevant websites. Literature and materials were screened to select those most pertinent to the research questions - specifically, works and journals related to surface

electromyography, center of pressure, stationary cycling, and squatting (Zama Bu). Additionally, books on sports anatomy, sports physiology, sports training, and surface electromyography were consulted to obtain relevant information. The literature and materials were read, and their content was thoroughly understood, analyzed, and evaluated to extract key information and knowledge essential for the study. The acquired information and knowledge were summarized and synthesized to discuss and elaborate on the research questions, ultimately forming the basis for writing the research report, academic paper, or other categories of documents.

Experimental method

The AMTI force plate is an instrument used for measuring force and weight, typically consisting of a horizontal platform and a measurement device (as shown in Figure 1). The AMTI force plate can be used to measure force, pressure, and shear force of various objects. On the force plate, an object's weight is measured by placing it on the platform and determining the connecting force between the object and the ground's gravity. The measurement device can utilize physical or electronic sensors to measure the force exerted by the object on the testing instrument.

AMTI is the industry "standard size" force plate for gait studies, used in hundreds of laboratories worldwide. Its greatest advantage lies in the accuracy and precision of its measurements, making it suitable for fields requiring precise measurement, such as industrial processing and pharmaceutical quality inspection, and also making this platform an ideal candidate for research and development as well as clinical studies. Furthermore, AMTI force plates are frequently used to measure data such as weight lifted and weight adjustments during human training, in order to understand human health and exercise progress.

Key performance features include:

- (1) Average Center of Pressure (COP) accuracy is only a fraction of a millimeter (typically less than 0.4 mm);
- (2) Crosstalk is typically $\pm 0.20\%$ of the applied load;
- (3) Measurement accuracy is typically $\pm 0.25\%$ of the applied calibration load.



Figure 1. AMTI force plate.

Surface electromyography (sEMG) is a device used to measure the electrical activity of superficial human

muscles [5]. It works by placing a set of electrodes on the muscle attachment points, detecting the muscle's electrical signals and converting them into digital signal output. By analyzing these signals, information about muscle contraction can be obtained, allowing for the determination of muscle activity intensity, frequency, time-domain and frequency-domain characteristics, etc.

It is important to note that the measurement results of the sEMG device are influenced by many factors, including electrode placement, muscle morphology, muscle fatigue, and psychological state. Therefore, when conducting experiments and measurements with sEMG, it is necessary to design the experimental protocol reasonably and perform data analysis and interpretation.

The fully functional EMG sensor has a sampling frequency of up to 4,000 times per second, supports real-time synchronous data display, and features extremely low baseline noise. Among similar EMG acquisition technologies, it uses the fewest accessories, making it simple and convenient. Combined with optimal electromyography technology, it can flexibly capture changes in human muscles.

Testing methods

(1) Dominant leg test

The method for determining the dominant lower limb refers to a test used to assess which leg is stronger and more agile during sports activities. This type of test is typically applicable to sports that require kicking, jumping, or running using one leg.

The following is a common method for testing the dominant lower limb:

- a) Having the subject stand centered, body upright, with arms placed at their sides.
- b) Instructing the subject to lift their left leg, bending their right knee, and placing their left foot above the right knee while maintaining balance.
- c) Having the subject slowly extend their left foot forward, touch the ground, and then slowly lifting it again, all while keeping their right foot on the ground.
- d) Recording the time the subject takes to complete this test.
- e) Repeating the above steps, but this time the subject uses their right leg to complete the test.
- f) Comparing the times of the two tests. The leg that completes the test in the shorter time is considered the dominant lower limb.

(2) Electromyographic signal testing

Before detecting and recording electromyographic signals, a series of preparatory steps are required, including shaving body hair and wiping the skin with an alcohol solution to ensure firm electrode attachment and accuracy of the EMG signal. Furthermore, during the electrode fixation process, attention must be paid to the spacing between electrodes and the fixation method to ensure correct acquisition and recording of the EMG signal. The obtained EMG signals also need to be processed and analyzed by computer to extract various

parameter indicators of the EMG signal, facilitating a better understanding of muscle activity and movement status [6].

In this study, when selecting muscles for testing, we referred to the selection experience of previous researchers. Ultimately, the subject’s dominant leg was chosen [7]. Two flexor and extensor muscle groups of the lower limb were selected: rectus femoris, biceps femoris, tibialis anterior, and medial gastrocnemius as test muscles. Surface EMG signals were collected from these muscles and systematically analyzed.

Table 1. Electrode placement positions for tested muscles.

| Muscle | Electrode Placement Position |
|------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Rectus femoris | Midpoint of the line connecting the anterior inferior iliac spine and the superior border of the patella, located at 1/2 the distance from the superior border of the patella |
| Biceps femoris | Midpoint of the line connecting the ischial tuberosity and the lateral condyle of the tibia, at 1/2 the distance |
| Gastrocnemius (Medial) | Midpoint of the line connecting the inferior border of the patella and the medial malleolus, at 1/2 the distance |
| Tibialis anterior | Proximal 1/3 of the line connecting the apex of the fibular head and the medial malleolus |

(3) Balance ability test

Static balance test: The test was conducted using an AMTI force plate. Before each test, the surface of the AMTI force plate needed to be cleaned, and a zero calibration was performed to minimize interference with the test results.

Test procedure:

- a) Turning on the experimental equipment and recording the subject’s basic information.
- b) Instructing the subject to remove their shoes and standing on the force plate. Informing the subject to stand in the center of the force plate with feet parallel and hands naturally hanging vertically at their sides.
- c) At the start of the test, the subject is required to look straight ahead with hands held against the chest. After the subject stabilizes their stance, begin the test. The subject stands on their dominant leg, lifting the non-dominant leg with the heel placed against the knee of the stance leg, maintaining this posture for 30 seconds, then stops.
- d) After the test is completed, the data measured on the force plate can be recorded for subsequent analysis and research.
- e) Cleaning the testing area and equipment.

Precautions: During the static balance test, the subject

must maintain safety to avoid any injury or accident. Simultaneously, the subject also needs to perform the test movements according to the test requirements to ensure the accuracy and reliability of the test results.

Dynamic balance test requirements: The subject stands on one leg on the central disk, with hands on hips. The other leg is extended as far as possible to marked points in the lower-left, upper-left, upper-right, and lower-right directions, then returns to the starting position. This is repeated three times. The subject stands barefoot on the force plate to avoid affecting body balance and stability. The subject performs 3 practice trials in each direction. The test is considered invalid and the data is discarded if any of the following occur: failure to return to the starting position; inability to maintain the single-leg stance; or hands leaving the hips. A retest is required in such cases. Test procedure: The subject is tested in each direction, and three valid data points are recorded, accurate to 0.5 cm.

The testing order is as follows:

- a) If the dominant leg is the left leg: lower-left, upper-left, upper-right, lower-right.
- b) If the dominant leg is the right leg: lower-right, upper-right, upper-left, lower-left.

c) Measure the leg length using a tape measure. Calculate the maximum reach distance using the formula: $(\text{Reach Distance} / \text{Lower Limb Length}) \times 100\%$. The composite score is calculated using the formula: $(\text{Sum of reach distances for anterior, posterolateral, and posteromedial directions}) / (\text{Leg length} \times 3) \times 100$. The average distance in each direction for both the left and right lower limbs was used for analysis for all subjects. As lower limb length varies among subjects, standardization helps eliminate the influence of leg length differences on test results. Based on the subjects' basic leg length information, the test distance was set at 50 cm.

Fatigue protocols

Fatigue protocol 1: stationary cycling

This experiment utilized a Monark brand quantitative load power bicycle. During the stationary cycling process, a four-level load was set. The initial load was 50 W, increasing by 50 W every 3 minutes. Once the load increased to 200 W, it was not increased further [8]. Subjects wore a Huawei watch to monitor heart rate. Throughout the test, the subjects' heart rates were continuously monitored, and they were asked for their Rating of Perceived Exertion (RPE) score. The experiment required subjects to maintain a cycling cadence of no less than 60 rpm. The fatigue indicators were the individual's inability to maintain the power bicycle at 60 rpm, a subjective feeling of being very exhausted ($\text{RPE} \geq 18$), and a rapid, significant increase in heart rate. Heart rate was monitored throughout the experiment to ensure safety. The heart rate upon reaching fatigue from stationary cycling was 140.20 ± 5.85 bpm (Mean \pm SD).

Test Procedure: First, subjects were required to wear a Huawei heart rate monitor to record resting heart rate and heart rate during fatigue. Subsequently, the Monark power bicycle test was conducted. Immediately after the test concluded, subjects performed the single-leg stance test with eyes open (standing on the dominant leg, hands held against the chest, non-dominant leg lifted with the heel placed against the knee of the stance leg, maintained for 30 seconds) and the Star Excursion Balance Test (SEBT). Four directions were selected: lower-left, upper-left, upper-right, and lower-right. The marked points for these four directions were positioned 50 cm from the AMTI force plate at a 45-degree angle.

Fatigue protocol 2: squatting (Zama Bu)

This experiment adopted the squatting (Zama Bu) exercise. The movement technique required keeping the back straight, squatting down, and looking straight ahead, ensuring specific angles between the lower leg and thigh, and between the lower leg and the ground. The angle between the lower leg and thigh was maintained at 120° , knees did not extend past the toes, and hands were held against the chest. Subjects wore a Huawei watch to monitor heart rate. Throughout the test, subjects' heart rates were continuously monitored, and they were asked for their Rating of Perceived Exertion (RPE) score. Subjects were required to maintain the 120° angle between the lower leg and thigh. The fatigue indicators were the student's inability to maintain the 120° squatting angle, a subjective feeling of being very exhausted ($\text{RPE} \geq 18$), and noticeable changes in heart rate [9]. However, as squatting is a high-intensity, low-heart-rate exercise, the heart rate remained within a safe range even upon reaching fatigue. The heart rate upon reaching fatigue from squatting was 106.00 ± 11.06 bpm (Mean \pm SD).

Test Procedure: First, subjects were required to wear a Huawei heart rate monitor to record resting heart rate and heart rate during fatigue. Subsequently, the squatting test was conducted. Immediately after the test concluded, subjects performed the single-leg stance test with eyes open (standing on the dominant leg, hands held against the chest, non-dominant leg lifted with the heel placed against the knee of the stance leg, maintained for 30 seconds) and the Star Excursion Balance Test (SEBT). Four directions were selected: lower-left, upper-left, upper-right, and lower-right. The marked points for these four directions were positioned 50 cm from the AMTI force plate at a 45-degree angle.

Precautions: (1) The body must not lean forward; (2) Maintain gaze straight ahead; (3) Knees must not extend past the toes.

EMG data preprocessing methods

MATLAB R2021a (MathWorks, USA) software was used to process the electromyographic signals. The processing was divided into two parts: First, preprocessing: rectification and filtering; second, calculation of the EMG signal's Integrated Electromyography (IEMG) and Root Mean Square (RMS).

After each test, the raw EMG signals generated by the

Noraxon surface electromyography device were exported to MATLAB R2021a for offline data processing. The main energy distribution of surface EMG signals is within the 50-200 Hz frequency range. Therefore, a 4th-order Butterworth filter was first applied for 20-450 Hz band-pass filtering. As EMG signal acquisition equipment is often affected by 50 Hz power line interference a 50 Hz notch filter is commonly used to remove this interference. However, recent studies have shown that notch filters can also significantly attenuate surface EMG signals with frequencies near 50 Hz. Using Independent Component Analysis (ICA) to filter out power line interference can preserve the effective signal in sEMG to a greater extent, and its effectiveness can be demonstrated through the power spectral density function. This study employed the FastICA algorithm for independent component analysis of surface electromyographic signals, with the specific parameter settings as follows: The nonlinear function was set to tanh, the maximum number of iterations was 1,000, the convergence tolerance was set to 1e-4, and the symmetric orthogonalization approach was adopted. Therefore, this paper employed the FastICA toolbox (MATLAB) to remove power line interference [10].

ICA for source separation must satisfy the following three principles: Each source signal is independent of the others; the mixing method of the source signals is linear; and only one source signal in the mixed signals is allowed to be Gaussian. Surface EMG signals and power line interference satisfy these relationships, so ICA can be used to decompose the signal. Finally, the surface EMG signals underwent full-wave rectification to obtain the preprocessed EMG data.

The IEMG and RMS of the rectus femoris, biceps femoris, medial gastrocnemius, and tibialis anterior were calculated using MATLAB R2021a.

MATLAB processing of EMG signals

The steps for processing EMG signals using MATLAB were as follows:

- (1) Loading EMG signals: Importing the collected EMG signal data into MATLAB.
- (2) Filtering: Using digital filters to remove high-frequency and low-frequency noise from the EMG signal, thereby extracting the effective EMG activity signal. Common filtering methods include low-pass filtering, high-pass filtering, and band-pass filtering. MATLAB

filtering functions, such as the “butter” function, were used to filter the EMG signal and remove high- and low-frequency noise.

- (3) Time-domain processing: Baseline drift correction was used to reduce the DC offset caused by coupling between electrodes and muscle movement. Signal normalization improved the comparability of signals between different subjects and different tests. Artifact removal and detrending reduced unnecessary random fluctuations in the signal. MATLAB functions for baseline drift correction, signal normalization, artifact removal, and detrending were used to preprocess the EMG signal.

- (4) Feature Extraction: MATLAB built-in signal processing functions were used to extract time-domain and frequency-domain features, including mean, variance, standard deviation, and slope.

Integrated Electromyography (IEMG) and RMS were selected for time-domain analysis of the surface EMG signals. Integrated EMG is defined as follows:

$$IEMG = \int_0^T x(t) dt \quad (1)$$

where $x(t)$ is the amplitude of the surface EMG signal, and T is the length of the time series of the analyzed signal. RMS Amplitude is defined as:

$$RMS = \sqrt{\frac{\sum_{i=1}^N X_i^2}{N}} \quad (2)$$

- (5) Visualization analysis: MATLAB built-in plotting functions were used to perform visualization analysis and generate graphical representations of the processed EMG signals.

Origin processing of center of pressure sway area

Origin was used to process the data for the center of pressure sway area. The following is a simplified procedure:

- (1) Importing the acquired plantar pressure variation data into the Origin software.
- (2) Clicking on the “Worksheet” view to create a new worksheet.
- (3) In the worksheet, input the plantar pressure data and name it appropriately.
- (4) In the worksheet’s menu, selecting “Data” > “Statistics” > “Statistics on Rows” to open the descriptive statistics dialog box.
- (5) In the dialog box, selecting the “Scatter Plot” tab, set

parameters such as scale, then click “OK” to create a scatter plot.

(6) Installing the 2D confidence ellipse plotting plugin. Click the “2D Confidence Ellipse” plugin to draw an ellipse with a confidence level of 95%.

(7) Clicking “Analysis” > “Mathematics” > “Polygon Area” to obtain the area of the plotted ellipse.

The above outlines the basic steps for processing center of pressure sway area data with Origin. These data analysis processes can be further customized to obtain more meaningful results. According to the literature, if balance ability decreases, the center of pressure becomes more dispersed, and the ellipse area increases [11]. If balance ability increases, the center of pressure becomes more concentrated, and the ellipse area decreases.

Mathematical statistics method

The statistical software used for organizing and analyzing all data in this study was IBM SPSS Statistics 26.0 in combination with EXCEL. Test results are presented as mean ± standard deviation (Mean ± SD) for all measured indices.

The center of pressure data and surface EMG data both conformed to a standard normal distribution and met the fundamental assumption of homogeneity of variance. Therefore, a Paired Sample T-Test was employed to examine and analyze the effects of the two exercise types on the EMG signals and the changes in center of pressure sway area. An Independent Sample T-Test was used in this experiment to examine and analyze the differences in the effects of the two exercise modes (stationary cycling, squatting) on the RMS and muscle activation level (IEMG) of the lower limb muscle surface EMG data. For the statistical analysis results, $p < 0.05$ indicated a statistically significant difference, and $p < 0.01$ indicated a highly significant difference.

Research results

Center of pressure sway area

SPSS software was used, employing the Paired Samples T-Test statistical method to statistically analyze the effects of cycling to fatigue and squatting (Zama Bu) to

fatigue on the balance ability of male university students. The variable was the center of pressure sway area before and after exercise, and the test was divided into four groups (see Table 2).

The first group compared the measured static balance center of pressure sway area from measured in the pre-test with that measured after the stationary cycling exercise intervention until fatigue. The result was $p = 0.048$ ($p < 0.05$), as shown in Table 3. This indicates that stationary cycling has a significant negative significant effect on the static balance ability of healthy male university students. The mean value of the pre-test center of pressure sway area was 1899.3 mm^2 , and after cycling to fatigue, it was 2497.0 mm^2 , showing that stationary cycling decreases the static balance ability of male university students.

The second group compared the dynamic balance center of pressure sway area measured in the pre-test with that measured after the stationary cycling exercise intervention. The result was $p = 0.290$ ($p > 0.05$), as shown in Table 3. This indicates that stationary cycling has no significant effect on the dynamic balance ability of male university students.

The third group compared the static balance center of pressure sway area measured in the pre-test with that measured after the squatting (Zama Bu) exercise intervention until fatigue. The result was $p = 0.046$ ($p < 0.05$), as shown in Table 3. This indicates that squatting has a significant effect on the static balance ability of male university students. The mean value of the pre-test center of pressure sway area was $1,899.3 \text{ mm}^2$, and after squatting to fatigue, it was $1,800.7 \text{ mm}^2$, showing that squatting increases the static balance ability of male university students.

The fourth group compared the dynamic balance center of pressure sway area measured in the pre-test with that measured after the squatting (Zama Bu) exercise intervention. The result was $p = 0.377$ ($p > 0.05$), as shown in Table 3. This indicates that squatting has no significant effect on the dynamic balance ability of male university students.

Table 2. Center of pressure sway area (mm^2).

| Category | Mean ± SD (mm^2) |
|---------------------------------------|-----------------------------|
| Pre-test static balance sway area | 1899.3 ± 785.6 |
| Pre-test dynamic balance sway area | 6595.7 ± 2927.5 |
| Post-cycling static balance sway area | 2497.0 ± 1687.4 |

| Category | Mean ± SD (mm ²) |
|------------------------------------------|------------------------------|
| Post-cycling dynamic balance sway area | 7359.8 ± 4133.9 |
| Post-squatting static balance sway area | 1800.7 ± 877.9 |
| Post-squatting dynamic balance sway area | 7452.4 ± 3606.0 |

Table 3. Paired samples T-Test results.

| Category | p-Value |
|---------------------------------------------------------------|---------|
| Pre-test Static Sway Area - Post-cycling static sway area | 0.048* |
| Pre-test dynamic sway area - Post-cycling dynamic sway area | 0.290 |
| Pre-test static sway area - Post-squatting static sway area | 0.046* |
| Pre-test dynamic sway area - Post-squatting dynamic sway area | 0.377 |

Note: * indicates a significant difference (p<0.05).

Surface electromyography signals

(1) Differences in the effects of fatigue induced by the two exercises on the measured muscles

SPSS software was used, employing the Independent Samples T-Test statistical method to conduct a comparative analysis of the effects of stationary cycling to fatigue and squatting (Zama Bu) to fatigue on the electromyographic signals of the lower limb muscles of male university students. The variable was the different exercise modes, and the test was divided into four groups (as shown in Table 4 to Table 7).

Group 1: The IEMG of the rectus femoris, biceps femoris, medial gastrocnemius, and tibialis anterior during the static balance test after the stationary cycling intervention was compared with the IEMG of these muscles during the static balance test after the squatting intervention. The results were: rectus femoris p=0.755 (p>0.05); biceps femoris p=0.187 (p>0.05); medial gastrocnemius p=0.287 (p>0.05); tibialis anterior p=0.821 (p>0.05), as shown in Table 7. This indicates that during the static balance test, there were no significant differences in the effects of stationary cycling and squatting on the muscle activation levels - IEMG of the rectus femoris, biceps femoris, medial gastrocnemius, and tibialis anterior.

Group 2: The IEMG of the rectus femoris, biceps femoris, medial gastrocnemius, and tibialis anterior during the dynamic balance test after the stationary cycling intervention was compared with the IEMG of these muscles during the dynamic balance test after the squatting intervention. The results were: rectus femoris p=0.020 (p<0.05); biceps femoris p=0.918 (p>0.05); medial gastrocnemius p=0.276 (p>0.05); tibialis anterior

p=0.273 (p>0.05), as shown in Table 7. This indicates that during the dynamic balance test, there were no significant differences in the effects of stationary cycling and squatting on the muscle activation levels -IEMG of the biceps femoris, medial gastrocnemius, and tibialis anterior. However, there was a significant difference in their effect on the muscle activation level of the rectus femoris.

Group 3: The RMS of the rectus femoris, biceps femoris, medial gastrocnemius, and tibialis anterior during the static balance test after the stationary cycling intervention was compared with the RMS of these muscles during the static balance test after the squatting intervention. The results were: rectus femoris p=0.708 (p>0.05); biceps femoris p=0.100 (p>0.05); medial gastrocnemius p=0.221 (p>0.05); tibialis anterior p=0.903 (p>0.05), as shown in Table 7. This indicates that during the static balance test, there were no significant differences in the effects of stationary cycling and squatting on the RMS amplitude of the rectus femoris, biceps femoris, medial gastrocnemius, and tibialis anterior.

Group 4: The RMS of the rectus femoris, biceps femoris, medial gastrocnemius, and tibialis anterior during the dynamic balance test after the stationary cycling intervention was compared with the RMS of these muscles during the dynamic balance test after the squatting intervention. The results were: rectus femoris p=0.029 (p<0.05); biceps femoris p=0.473 (p>0.05); medial gastrocnemius p=0.671 (p>0.05); tibialis anterior p=0.310 (p>0.05), as shown in Table 7. This indicates that during the dynamic balance test, there were no significant differences in the effects of stationary cycling

and squatting on the RMS amplitude of the biceps femoris, medial gastrocnemius, and tibialis anterior. However, there was a significant difference in their effect on the RMS of the rectus femoris.

Table 4. Pre-test data.

| Category | IEMG Mean ± SD (μV·s) | RMS Mean ± SD (μV) |
|----------------|-----------------------|--------------------|
| Pre-static-RF | 272.4 ± 340.8 | 12.7 ± 4.7 |
| Pre-static-BF | 598.5 ± 461.5 | 28.0 ± 19.6 |
| Pre-static-MG | 1208.6 ± 496.3 | 57.1 ± 21.9 |
| Pre-static-TA | 845.5 ± 373.7 | 51.1 ± 20.3 |
| Pre-dynamic-PF | 225.5 ± 130.9 | 29.6 ± 23.1 |
| Pre-dynamic-BF | 298.5 ± 109.2 | 33.0 ± 13.2 |
| Pre-dynamic-MG | 518.2 ± 234.6 | 62.6 ± 30.4 |
| Pre-dynamic-TA | 539.6 ± 240.7 | 64.3 ± 25.1 |

Note: Pre-static (dynamic): pre-test static (dynamic) balance test. RF: rectus femoris; BF: biceps femoris; MG: medial gastrocnemius; TA: tibialis anterior.

Table 5. Post-cycling fatigue data.

| Category | IEMG Mean ± SD (μV·s) | RMS Mean ± SD (μV) |
|-----------------------|-----------------------|--------------------|
| Post-cycle-static-RF | 225.4 ± 360.4 | 11.0 ± 16.2 |
| Post-cycle-static-BF | 680.8 ± 528.8 | 31.8 ± 22.8 |
| Post-cycle-static-MG | 1167.7 ± 491.2 | 58.3 ± 24.7 |
| Post-cycle-static-TA | 838.2 ± 461.2 | 51.1 ± 26.7 |
| Post-cycle-dynamic-RF | 149.4 ± 70.6 | 18.6 ± 10.2 |
| Post-cycle-dynamic-BF | 255.2 ± 108.4 | 31.1 ± 15.8 |
| Post-cycle-dynamic-MG | 425.3 ± 235.9 | 56.5 ± 33.6 |
| Post-cycle-dynamic-TA | 418.6 ± 149.7 | 53.1 ± 14.7 |

Note: Post-cycle-static (dynamic): static (dynamic) balance test after cycling exercise.

Table 6. Post-Squatting Fatigue Data.

| Category | IEMG Mean ± SD (μV·s) | RMS Mean ± SD (μV) |
|-----------------------|-----------------------|--------------------|
| Post-squat-static-RF | 197.5 ± 163.8 | 9.4 ± 8.0 |
| Post-squat-static-BF | 527.5 ± 337.3 | 24.3 ± 14.7 |
| Post-squat-static-MG | 968.6 ± 444.0 | 46.3 ± 20.2 |
| Post-squat-static-TA | 808.0 ± 372.2 | 50.1 ± 24.5 |
| Post-squat-dynamic-RF | 241.9 ± 151.5 | 31.6 ± 23.0 |
| Post-squat-dynamic-BF | 295.0 ± 118.4 | 33.2 ± 15.5 |
| Post-squat-dynamic-MG | 418.0 ± 208.4 | 50.0 ± 22.1 |
| Post-squat-dynamic-TA | 542.1 ± 473.4 | 118.4 ± 83.2 |

Note: Post-squat-static (dynamic): static (dynamic) balance test after squatting exercise.

Table 7. Independent samples T-Test results.

| Category | p-value (IEMG) | p-value (RMS) |
|-----------|----------------|---------------|
| Static-RF | 0.755 | 0.708 |
| Static-BF | 0.187 | 0.100 |
| Static-MG | 0.287 | 0.221 |
| Static-TA | 0.821 | 0.903 |

| Category | p-value (IEMG) | p-value (RMS) |
|------------|----------------|---------------|
| Dynamic-RF | 0.020* | 0.029* |
| Dynamic-BF | 0.918 | 0.473 |
| Dynamic-MG | 0.276 | 0.671 |
| Dynamic-TA | 0.273 | 0.310 |

Note: Static (dynamic): static (dynamic) balance test.

(2) Respective effects of fatigue induced by the two exercises on the measured muscles

SPSS software was used, employing the Paired Samples T-Test statistical method to analyze the electromyographic signals of the lower limb muscles before and after the cycling and squatting exercise interventions (see Table 8). The variable was pre- and post-exercise, and the test was divided into four groups. Group 1 compared the IEMG and RMS of the rectus femoris in the pre-test static and dynamic balance tests with those in the static and dynamic balance tests after the cycling and squatting interventions.

For cycling: In the static balance test, the effects on the rectus femoris were not significant (IEMG $p=0.442$, $p>0.05$; RMS $p=0.459$, $p>0.05$). In the dynamic balance test, the effects were significant (IEMG $p=0.001$, $p<0.05$; RMS $p=0.008$, $p<0.05$).

For squatting: In the static balance test, the effects on the rectus femoris were not significant (IEMG $p=0.368$, $p>0.05$; RMS $p=0.345$, $p>0.05$). In the dynamic balance test, the effect on IEMG was not significant ($p<0.001$ The text states $p>0.05$, but 0.001 is typically $p<0.05$; checking the original text: $p<0.001$ ($p>0.05$) is contradictory. However, the text explicitly says: There is a significant difference in RMS during the dynamic balance test. So, for squatting-dynamic: IEMG shows significance ($p<0.001$), RMS shows no significance ($p=0.677$). This is consistent with Table 8) The results indicate that during the static balance test, cycling had no significant effect on the IEMG and RMS of the rectus femoris, but during the dynamic balance test, it had a significant effect. For squatting, during the static balance test, there was no significant effect on IEMG and RMS; during the dynamic balance test, there was a significant effect on RMS but not on IEMG.

Group 2 compared the IEMG and RMS of the biceps femoris in the pre-test static and dynamic balance tests with those in the static and dynamic balance tests after the cycling and squatting interventions.

For cycling: In the static balance test, the effects on the biceps femoris were not significant (IEMG $p=0.128$, $p>0.05$; RMS $p=0.121$, $p>0.05$). In the dynamic balance test, the effect on IEMG was significant ($p=0.023$, $p<0.05$), but the effect on RMS was not significant ($p=0.422$, $p>0.05$).

For squatting: In both the static and dynamic balance tests, the effects on the biceps femoris IEMG and RMS were not significant (Static: IEMG $p=0.310$, RMS $p=0.210$; Dynamic: IEMG $p=0.899$, RMS $p=0.959$).

The results indicate that cycling had a significant effect on the IEMG of the biceps femoris during the dynamic balance test but not on its RMS, and no significant effects during the static test. Squatting had no significant effects on the biceps femoris in either test.

Group 3 compared the IEMG and RMS of the medial gastrocnemius in the pre-test static and dynamic balance tests with those in the static and dynamic balance tests after the cycling and squatting interventions.

For cycling: In the static balance test, the effects on the gastrocnemius were not significant (IEMG $p=0.422$, $p>0.05$; RMS $p=0.718$, $p>0.05$). In the dynamic balance test, the effect on IEMG was significant ($p=0.004$, $p<0.05$), but the effect on RMS was not significant ($p=0.064$, $p>0.05$). (Note: Table 8 shows $p=0.004^*$ for dynamic IEMG, which is even more significant).

For squatting: In the static balance test, the effects on the gastrocnemius were significant (IEMG $p=0.033$, $p<0.05$; RMS $p=0.042$, $p<0.05$). In the dynamic balance test, the effects were also significant (IEMG $p=0.026$, $p<0.05$; RMS $p=0.038$, $p<0.05$).

The results indicate that cycling had a significant effect only on the IEMG of the gastrocnemius during the dynamic balance test. Squatting had significant effects on both the IEMG and RMS of the gastrocnemius during both static and dynamic balance tests.

Group 4 compared the IEMG and RMS of the tibialis anterior in the pre-test static and dynamic balance tests with those in the static and dynamic balance tests after

the cycling and squatting interventions.

For cycling: In the static balance test, the effects on the tibialis anterior were not significant (IEMG $p=0.943$, $p>0.05$; RMS $p=0.993$, $p>0.05$). In the dynamic balance test, the effects were significant (IEMG $p=0.004$, $p<0.05$; RMS $p=0.009$, $p<0.05$).

For squatting: In both the static and dynamic balance

tests, the effects on the tibialis anterior IEMG and RMS were not significant (Static: IEMG $p=0.575$, RMS $p=0.849$; Dynamic: IEMG $p=0.981$, RMS $p=0.407$).

The results indicate that cycling significantly affected IEMG and RMS of the tibialis anterior in dynamic balance tests but not static ones. Squatting showed no significant effects on this muscle in either test.

Table 8. Paired samples T-Test results.

| Category | p-value (IEMG) | p-value (RMS) |
|----------------------------------------|----------------|---------------|
| Pre-static-RF - Post-cycle-static-RF | 0.442 | 0.459 |
| Pre-static-BF - Post-cycle-static-BF | 0.128 | 0.121 |
| Pre-static-GS - Post-cycle-static-MG | 0.442 | 0.718 |
| Pre-static-TA - Post-cycle-static-TA | 0.943 | 0.993 |
| Pre-dynamic-RF - Post-cycle-dynamic-RF | 0.001* | 0.008* |
| Pre-dynamic-BF - Post-cycle-dynamic-BF | 0.023* | 0.422 |
| Pre-dynamic-GS - Post-cycle-dynamic-MG | 0.004* | 0.064 |
| Pre-dynamic-TA - Post-cycle-dynamic-TA | 0.004* | 0.009* |
| Pre-static-RF - Post-squat-static-RF | 0.368 | 0.345 |
| Pre-static-BF - Post-squat-static-BF | 0.310 | 0.210 |
| Pre-static-GS - Post-squat-static-MG | 0.033* | 0.042* |
| Pre-static-TA - Post-squat-static-TA | 0.575 | 0.849 |
| Pre-dynamic-RF - Post-squat-dynamic-RF | 0.000* | 0.677 |
| Pre-dynamic-BF - Post-squat-dynamic-BF | 0.899 | 0.959 |
| Pre-dynamic-GS - Post-squat-dynamic-MG | 0.026* | 0.038* |
| Pre-dynamic-TA - Post-squat-dynamic-TA | 0.981 | 0.407 |

Analysis and discussion

The purpose of this study was to investigate the acute effects of exercise-induced fatigue from stationary cycling and squatting (Zama Bu) on the static balance ability, muscle activation levels (IEMG), and RMS amplitude of lower limb muscles in healthy male university students..

Effects of the two types of exercise-induced fatigue on balance ability

Regarding balance ability, in this experiment, neither stationary cycling nor squatting had a significant effect on the dynamic balance ability of the male university students. The experimental data showed that dynamic balance ability did not uniformly decrease due to exercise fatigue; some data even indicated an improvement. This suggests that while squatting and cycling do impact the dynamic balance ability of male university students, definitive experimental conclusions could not be drawn, possibly due to an insufficient

sample size or experimental errors. This represents a limitation of the present study. With a sufficient number of subjects and strict control of experimental details, more accurate conclusions could be obtained. However, this does not rule out the influence of individual differences [12].

Dynamic balance ability after exercise fatigue may vary from person to person. Individuals with good balance might show less pronounced changes during the dynamic balance test, as the test itself may have a relaxing effect on the lower limb muscles.

This experiment also found that fatigue induced by stationary cycling decreased the static balance ability of male university students, whereas fatigue induced by squatting increased their static balance ability [13]. The decline in balance following cycling may be attributed to the decrease caused by exercise fatigue, while the improvement following squatting suggests that this exercise plays an important role in enhancing the postural control ability of male university students [14].

Differences between the two types of exercise-induced fatigue

Regarding electromyographic signals, this experiment revealed differences in the effects of stationary cycling and squatting on the EMG signals of specific lower limb muscles. During the static balance test, there were no significant differences ($p>0.05$) between the effects of cycling and squatting on the IEMG and RMS of the four measured lower limb muscles. However, during the dynamic balance test, significant differences ($p<0.05$) were observed for the IEMG and RMS of the rectus femoris. Cycling decreased the IEMG and RMS of the rectus femoris, while squatting increased them. No significant differences ($p>0.05$) were found between the two exercises regarding their effects on the IEMG and RMS of the biceps femoris, medial gastrocnemius, and tibialis anterior.

This indicates that all four measured lower limb muscles participated in and were trained during both exercises, and aside from the rectus femoris, there were no significant differences in their participation levels. The difference observed only in the rectus femoris during the dynamic balance test might be because the dynamic balance test requires greater involvement of the rectus femoris, whereas the static balance test demands less from this muscle. It may also be possible that cycling induced a more pronounced level of fatigue in the rectus femoris compared to squatting, contributing to the inconsistent changes in balance ability.

There were no significant differences in the degree to which cycling and squatting affected the IEMG and RMS of the biceps femoris, medial gastrocnemius, and tibialis anterior; both exercises fatigued these three muscles, leading to decreased muscle strength, with no significant difference in the extent of the decrease. However, the difference in rectus femoris IEMG and RMS observed during the dynamic balance test suggests that cycling causes greater fatigue and a larger decrease in strength in the rectus femoris compared to squatting [15]. During the squatting exercise, maintaining stability requires engaging the rectus femoris, which plays a certain activating role, recruiting more motor units and potentially increasing muscle strength [16].

Effects of fatigue induced by stationary cycling on the measured muscles

Regarding electromyographic signals, this experiment

also found that following the stationary cycling exercise, the static balance test revealed no significant effects ($p>0.05$) of cycling on the IEMG and RMS of the measured muscles.

Following the cycling exercise, the dynamic balance test showed that cycling caused a significant decrease ($p<0.05$) in the IEMG and RMS of the rectus femoris and tibialis anterior, indicating significant fatigue and decreased strength in these two muscles. It also caused a significant decrease ($p<0.05$) in the IEMG of the biceps femoris and medial gastrocnemius, indicating significant fatigue in these two muscles. There was no significant effect ($p>0.05$) on the RMS of the biceps femoris and medial gastrocnemius, suggesting that the decrease in strength for these two muscles was not as pronounced. This indicates that stationary cycling (a dynamic exercise) has a greater impact on the muscles used during the dynamic balance test and a lesser impact on those used during the static balance test. Furthermore, this exercise appears to utilize the rectus femoris and tibialis anterior more, or these muscles are more prone to fatigue and experience a greater decline in strength.

Effects of fatigue induced by squatting on the measured muscles

Following the squatting exercise, the static balance test showed that squatting had no significant effects ($p>0.05$) on the IEMG and RMS of the rectus femoris, biceps femoris, and tibialis anterior. However, it had a significant effect ($p<0.05$) on the IEMG and RMS of the gastrocnemius, causing significant fatigue and a marked decrease in its strength.

Following the squatting exercise, the dynamic balance test showed that squatting had no significant effects ($p>0.05$) on the RMS of the rectus femoris, nor on the IEMG and RMS of the biceps femoris and tibialis anterior. It caused a significant increase ($p<0.05$) in the IEMG of the rectus femoris and a significant decrease ($p<0.05$) in the IEMG and RMS of the gastrocnemius, indicating significant fatigue and decreased strength in the gastrocnemius.

These findings indicate that the squatting exercise has a greater impact on the medial gastrocnemius, suggesting that this muscle is more involved in maintaining the squatting posture. Simultaneously, squatting also has a considerable effect on the rectus femoris. During the squat, maintaining stability requires adjusting the center

of gravity. During this adjustment, one can feel both the rectus femoris and gastrocnemius engaging, with the gastrocnemius seemingly working harder. When fatigue sets in, the medial gastrocnemius reaches fatigue first, while the rectus femoris may not be fatigued but rather in an activated state. This aligns with the experimental results, although the changes in the rectus femoris EMG signal were subtle and only detectable during the dynamic balance test.

Conclusion

Stationary cycling significantly decreases static balance ability in male university students, while squatting significantly improves it. Neither exercise significantly affects dynamic balance ability. Both exercises reduce activation and strength in the biceps femoris, medial gastrocnemius, and tibialis anterior, with no significant differences between them. However, they differ in their effect on the rectus femoris: Cycling decreases its activation and strength, while squatting increases them. Cycling induces significant fatigue in all four measured muscles, notably reducing strength in the rectus femoris and tibialis anterior. Squatting primarily fatigues the gastrocnemius while increasing activation and strength in the rectus femoris.

In light of the present findings, the following practical and evidence-based recommendations are put forward. Fatigue impairs balance by causing muscle fatigue, delayed reactions, and distraction. Individuals should exercise caution when performing balance-demanding tasks under fatigue to prevent injury.

As cycling reduces static balance, cyclists should manage exercise intensity to avoid fatigue-related injuries and incorporate supplementary balance and lower limb strength training.

Squatting effectively improves static balance, strengthens lower limb muscles, enhances coordination, and may help alleviate back pain and improve posture.

Balance training should be tailored to the specific effects of different exercise-induced fatigue patterns.

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Conflict of Interest

The authors declare no conflict of interest.

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