AMERICAN JOURNAL OF BIOCHEMISTRY AND BIOTECHNOLOGY

RESEARCH ARTICLE

MRI Observation and Analysis of Muscle Activity During Exercise

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Abstract: While conventional biomechanical testing techniques are able to determine the mechanical characteristics of muscle tissue, they do not offer precise insight into how muscle metabolism and microstructure change in response to various types of exercise activities over the course of time. Using Magnetic Resonance Imaging (MRI) analysis of muscle tissue allows researchers to examine how different levels of intensity affect muscle activity during the time period of physical testing. This study involves 120 healthy adults who were grouped into three categories based on their exercise intensity (low, medium, and high), with 40 subjects assigned to each group. The MRI images will be interpreted by two qualified imaging professionals. The MRI imaging results provide detailed evaluations of the muscle activity levels among the different exercise groups. The results show that with various exercise intensities, significant differences exist in the start time of muscle activation of the volunteers' tibialis anterior, gastrocnemius muscle, and rectus femoris ($P<0.05$). MRI technology provides images with high clarity and good image quality, with 85% meeting the standards of very high and relatively high clarity. This paper uses high-precision data from MRI technology to study the effects of exercise on muscles and their related physiological mechanisms.

Keywords: Exercise Process, Muscle Activity, Magnetic Resonance Imaging, Exercise Intensity, Perceived Exertion

Received: 14-01-2026 | **Revised:** 26-05-2026 | **Accepted:** 09-06-2026 | **DOI:** 10.3844/ajbbsp.2026.22.02.031

Introduction

Physical Exercise plays an important role in how people function, as well as being a primary cause of muscle contraction [1-3]. The amount of influence each muscle has on a person depends on their ability and stability. Several different imaging techniques have been developed to look at the way muscles operate; however, MRI has gained a lot of attention because of its ability to provide a very clear picture of muscle activity without having to open the person's skin. MRI has become an important tool for studying muscle activity and performance. Many other mechanical and electrical techniques have also been designed to aid in understanding how the muscles work; however, these tools are less reliable than MRI in determining what is going on in the muscle at the cellular level. MRI works by using large magnetic fields and radio waves non-invasively to create very detailed images of someone's body parts. The main component of the MRI technology is that the images of each part are created by using a computer program to detect and analyze the radio wave energy signals that come from the hydrogen isotopes' nuclei when they return to their lowest energy state. Using MRI, it is now possible to see inside someone's body without surgery [4-6].

DOI: 10.3844/ajbbsp.2026.22.03.031

Muscles change over time while exercising by going through multiple contractions and relaxations. Through MRI, we're able to accurately observe those changes in all dimensions of how our bodies work through the use of various imaging techniques. MRI is therefore an excellent means to observe and study how muscles act throughout the different phases of exercise. In addition to providing an accurate representation of how much strength and endurance a muscle exhibits during a particular phase of training, Comprehensive Medical Imaging can also help better understand what causes an injury due to overtraining or excessive training, so that scientific training methodologies and injury prevention strategies can be based on this knowledge to help better protect the health of athletes (and for anyone else who performs exercise regularly).

A very complicated and delicate process occurs when an individual begins exercising, and the brain sends signals to the muscles through the nervous system. After the muscles receive the signal from the brain, they contract and produce force [7-9] 's research focused on the changes in the electromyogram (EMG) amplitude recorded from the limbs of 17 experienced cyclists during three different levels of exercise intensity. The results of her study indicated that there was a substantial increase in the amplitude of the EMG signal recorded from each cyclist when exercising at the highest levels of intensity examined. The secondary muscles play a vital role in shoulder stability. [10] selected twenty healthy subjects to perform prone external rotation exercises and measured muscle activity during each shoulder external rotation exercise using surface electromyography. Muscle activity of the gluteus maximus and hamstrings plays a vital role in hip joint stability during various functional activities, including the prone hip joint extension exercise. [11]'s study aimed to investigate gluteus maximus and hamstring muscle activities in healthy individuals during three different bridge exercises. Given that the canter of the thoroughbred is an asymmetric gait, either the forelimb or the hindlimb may affect muscle activity. [12] studied the effects of speed and leading edge on surface electromyography during running and found that different muscles responded differently to speed and leading side. Eccentric training is associated with several specific physiological adaptations, and the flywheel machine is one of the simplest ways to perform eccentric overload training. [13] compared muscle activities during knee extension exercises with a flywheel versus a weight machine in patients with severe hemophilia. They found benefits of moderate-intensity knee extension exercises with a flywheel. [14] aimed to analyze and compare the muscle activities of plank exercise and togu-jumper and selected 10 males without upper or lower limb musculoskeletal disorders as subjects. The togu-jumper was used on the upper limbs to maximize core training performance during the plank exercise.

MRI is a medical imaging technology that uses magnetic resonance to capture high-definition images of the internal structure of muscles. In the study of muscle activities, MRI can display the static structural information of muscles and reveal the activities of muscles under different exercise states through dynamic scanning [15-18] believed that the genetic diagnosis of muscular dystrophy is guided by clinical presentation, muscle biopsy, and muscle MRI data, and machine learning can help doctors diagnose muscular dystrophy by analyzing muscle fat in MRI. Gastrointestinal MRI provides rich spatiotemporal data on food movement within the stomach but does not directly report muscle activity in the gastric wall. [19] described a new approach to characterize the motility of the gastric wall, which drives volume changes in the gastric wall. Investigating the relationship between short-term and long-term physical activity and degenerative changes in the thoracic and lumbar spine, [20] used data on physical inactivity and back pain in volunteers over 14 years and quantified thoracic and lumbar disc degeneration using magnetic resonance imaging and found that the degree of physical inactivity was strongly correlated with intervertebral disc degeneration in the thoracic and lumbar spine. [21] mainly analyzed the clinical effect of MRI diagnosis in knee meniscus injury. Patients with knee meniscus injury were selected as the research subjects. All patients underwent magnetic resonance imaging, surgery, and arthroscopy. [22] examined 72 athletes to investigate the connections between the structures of the Achilles tendon using a precise weighted gradient echo sequence with very short echo times in MRI images and their functional properties.

Materials and Methods

Research Subjects and Groups

Between July 2023 and April 2024, 120 healthy volunteers were selected to participate in the study, 60 males and 60 females. Their basic information, such as name, age, and gender, was collected through a questionnaire. The volunteers were randomly assigned to three exercise groups: low-intensity, medium-intensity, and high-intensity, with 40 people in each group and balanced genders. All participants provided detailed medical and imaging data and signed informed consent before the start of the study. Inclusion criteria are as follows:

1. Aged between 18 and 40, in good health, without prominent chronic diseases or movement disorders

2. Without lower limb trauma, surgery, or disease affecting exercise ability in the past six months
3. Able to withstand medium-intensity exercise and suitable for MRI examination. Exclusion criteria are as follows
4. With the presence of a nervous system or muscle system disease that affects muscle function
5. With cardiovascular disease, respiratory disease, or other health problems that may affect exercise tolerance
6. Pregnant or lactating women. Figure 1 presents the inclusion and grouping of cases

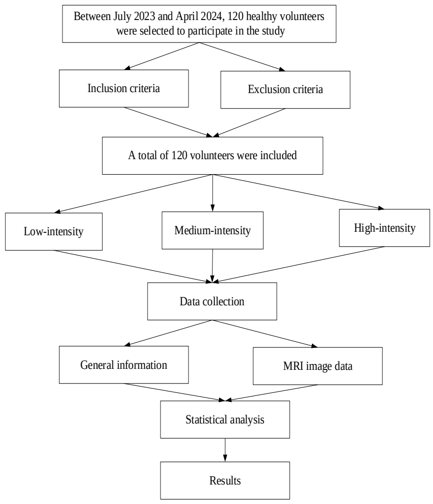

Fig. 1: Case inclusion and grouping

In order to control the potential confounding effects of baseline physical fitness level, body composition, daily physical activity, and training background on MRI measurement results of muscle activity, all volunteers were systematically evaluated before grouping in this study. The specific definitions and measurement methods of each evaluation index are as follows: the maximum oxygen uptake is indirectly calculated by the sub-extreme power bicycle test; the body fat rate and skeletal muscle mass are measured by bioelectricity impedance method; the daily physical activity level is quantified by the short version of the International physical activity questionnaire; the training background is collected through self-compiled questionnaires, and individuals who have systematically undergone resistance training or high-intensity interval training in the past three months are excluded. The detailed baseline data of the three groups of volunteers are shown in Table 1.

Table 1: Comparison of baseline characteristics of three groups of volunteers

Indicator	Low intensity group (n = 40)	Medium intensity group (n = 40)	High-strength group (n = 40)	P value
	Physical fitness level			
Maximum oxygen uptake (mL/kg/min)	39.2 ± 5.4	38.9 ± 5.1	39.5 ± 5.6	0.72
	Body composition			
Body fat rate (%)	22.6 ± 6.3	22.1 ± 5.8	22.8 ± 6.5	0.68
Skeletal muscle mass (kg)	29.8 ± 4.5	30.2 ± 4.2	29.6 ± 4.7	0.59
	Daily physical activity			
IPAQ score (MET-minutes/week)	1710 ± 540	1680 ± 510	1730 ± 560	0.64
Moderate and above intensity activity time (hours/week)	2.2 ± 0.9	2.1 ± 0.8	2.3 ± 0.9	0.71
	Training background			
History of system resistance training in the past three months (number of people, %)	0 (0%)	0 (0%)	0 (0%)	—
History of high-intensity interval training in the past three months (number of people, %)	0 (0%)	0 (0%)	0 (0%)	—
Years of regular exercise (years)	1.1 ± 1.3	1.0 ± 1.2	1.2 ± 1.4	0.83

DOI: 10.3844/ajbbsp.2026.22.03.031

Table 1 demonstrates that there were no statistically significant differences among the low-, middle-, and high-performance groups in key indicators such as physical fitness level (maximum oxygen uptake approximately 39 mL/kg/min), body composition (body fat percentage approximately 22%, skeletal muscle mass approximately 29–30 kg), daily physical activity (IPAQ score approximately 1700 MET-min/week, weekly activity duration approximately 2.1–2.3 hours), and training background (average years of regular exercise approximately 1.0–1.2 years; none reported recent systematic resistance or high-intensity interval training). The P-values ranged from 0.59 to 0.83, all exceeding 0.05. These results indicate that the three volunteer groups exhibited good baseline comparability regarding core confounding factors influencing muscle response to exercise. Consequently, observed differences in muscle activation time, BOLD signal changes, and muscle volume were primarily attributable to variations in exercise intensity across experimental conditions rather than intergroup imbalances in participants' physical fitness, body composition, daily activity levels, or training backgrounds, thereby providing robust methodological support for the validity of the study conclusions.

Scanning Equipment and Scanning Parameters

In this study, a GE 3.0T scanner is used for MRI examination. Before the MRI examination, volunteers are informed in detail of the relevant precautions and contraindications and are required to remove all metal and dangerous items from their bodies. The feet-first posture is adopted. Hands are placed on both sides of the abdomen. Ears are plugged with cotton balls to reduce noise interference [23-25]. The center line of the scan is placed at the midpoint of the line connecting the greater trochanter of the femur and the upper edge of the patella. The study is conducted through T1WI (T1-weighted Imaging), T2WI (T2-weighted Imaging), and Diffusion Tensor Imaging (DTI) scans. Table 2 lists the scanning parameters, where the units are millimeters (mm) and milliseconds (ms). Part of the acquired image data is shown in Figure 2.

Table 2: MRI scan parameters

Parameter name	T1WI	T2WI	DTI
Scan sequence	TSE (Turbo Spin Echo)	TSE	EPI (Echo Planar Imaging)
Scan voxel (mm)	1.6*1.6*1.6	1.0*1.0*4.0	3.1*3.1*4.0
Echo time (ms)	120	76	85
Repetition time (ms)	2000	344	466
Number of scan layers	9	32	24
Layer thickness (mm)	1.6	4.0	4.0
Number of incentives	3	2	2
Field of view (mm)	400*400	400*400	400*400
Matrix	256*256	256*256	128*128
Layer spacing (mm)	0.8	0.8	-

The MRI scanning parameters of this study are detailed in Table 1, including the scanning sequence order for each protocol, voxel size, echo time, repetition time, slice thickness, slice spacing, matrix, and field of view. T1-weighted imaging (T1WI) was performed using the turbo spin-echo sequence, T2-weighted imaging (T2WI) used the TSE sequence, and Diffusion Tensor Imaging (DTI) employed the EPI sequence. All scans were conducted on a 3.0T scanner with patients in a supine position, hands placed bilaterally on the abdomen, and earplugs worn for noise reduction.

Fig. 2: Part of image data

DOI: 10.3844/ajbbsp.2026.22.03.031

MRI Image Preprocessing

When using MRI technology to observe and analyze muscle activities during exercise, the intensity distribution of the image may vary due to the use of different imaging sequences. This difference can lead to image inhomogeneity, which may increase the difficulty of subsequent analysis. Therefore, images must be standardized to ensure uniformity and comparability of image intensity. The original MRI images often contain many background areas that are irrelevant to the analysis, which not only affects the analysis efficiency but also may bring interference. Therefore, it is necessary to crop the image to remove these redundant background areas and retain only the muscle areas relevant to the analysis. In the preprocessing stage of MRI images, although the DICOM (Digital Imaging and Communications in Medicine) format is the standard format for medical images [26, 27], due to its large file size and slow processing speed, this paper chooses the more efficient and concise NIFTI (Neuroimaging Informatics Technology Initiative) [28] format for subsequent processing. For images with a spacing smaller than the template, pooling is used to select the maximum value in the area. For images with large layer spacing, interpolation operations are used to ensure image continuity [29, 31]:

$$W_n^* = \frac{W_n - \frac{1}{M}\sum W_n}{\sqrt{\frac{1}{M}\sum \left(W_n - \frac{1}{M}\sum W_n\right)^2}} \quad (1)$$

Among them, W_n represents the voxel value of sample n. M is the number of samples. W_n^* represents the voxel value of sample n after normalization. Figure 3 shows the specific effects.

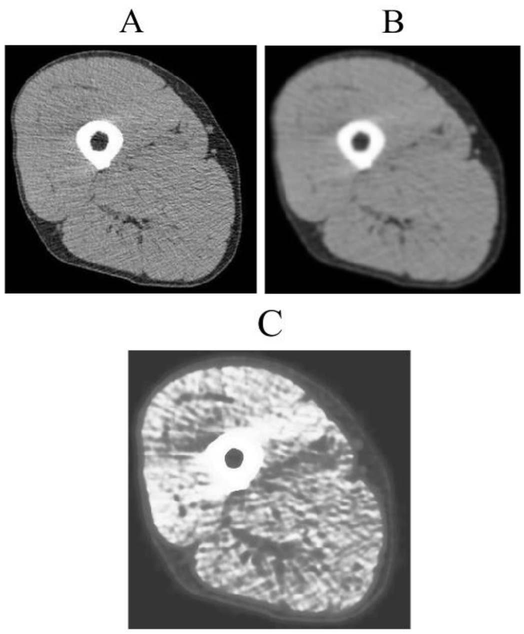

Fig. 3: MRI image preprocessing effects

In Figure 3, A is the original image; B is the processed image; C is the image after denoising. It can be found in Figure 3 that the image has been significantly improved after denoising.

Exercise Process Design

This study evaluates three different exercise intensities by monitoring heart rate and uses this to determine an individual's maximum oxygen uptake range [32, 33]. Before the maximal oxygen uptake test, the subject's height and weight are measured. Before the test begins, volunteers with similar heart rates in a resting state are selected to ensure the accuracy and comparability of the experimental results. To ensure the subjects are in a non-fatigued state, they are asked to avoid high-intensity exercise within 48 hours before the test. The Rating of Perceived Exertion (RPE) scale, also known as the subjective fatigue rating scale, is an assessment tool used to quantify an individual's feelings of fatigue after physical activity [34-36]. It requires participants to rate the intensity of exercise based on their perception, thereby subjectively assessing physical exertion. The scale covers multiple levels, from extremely easy to extremely strenuous, and participants can choose the value

DOI: 10.3844/ajbbsp.2026.22.03.031

that best represents their experience based on their immediate feelings after exercise [37, 38]. The RPE values of the subjects after fatigue are recorded in Table 3.

Table 3: RPE values of volunteers

RPE	Subjective exercise feeling	Corresponding heart rate	RPE	Subjective exercise feeling	Corresponding heart rate
6	Quiet		14	Slightly strenuous	140
7	Extremely easy	70	15	Strenuous	150
8	Extremely easy	80	16	Strenuous	160
9	Very easy	90	17	Very strenuous	170
10	Very easy	100	18	Very strenuous	180
11	Easy	110	19	Extremely strenuous	190
12	Easy	120	20	Extremely strenuous	Maximum heart rate
13	Slightly strenuous	130			

For low-intensity exercise tasks, activities that last long and have a light load can be chosen, such as slow gait or slow cycling, to observe the basic activation patterns of muscles at low heart rates. High-intensity exercise involves fast exercises with high loads, such as fast running, high-speed cycling, or climbing hills, for 3 to 5 minutes. Table 4 displays the correspondence between exercise intensity and heart rate intensity.

Table 4: Correspondence between exercise intensity and heart rate intensity

Exercise intensity	Maximum individual oxygen uptake (%)	Heart rate intensity (beats/minute)	Exercise intensity (kilometer/hour)
Low-intensity	68	144	10
Medium-intensity	74	158	13
High-intensity	86	171	15

In Table 4, the individual maximum oxygen uptake corresponding to low-intensity exercise is 68%, and the heart rate is 144 beats/minute. The maximum oxygen uptake during high-intensity exercise is 86%, and the heart rate increases to 171 beats/minute. Through this progressive intensity setting, the activation status of muscles under different loads and their changing trends can be effectively observed and recorded.

The low-intensity exercise protocol involves jogging at 10 km/h for 30 minutes; the moderate-intensity protocol requires running at 13 km/h for 20 minutes; and the high-intensity protocol entails running at 15 km/h for 5 minutes. Each exercise session includes 5 minutes of warm-up and 5 minutes of cool-down activities. Rest intervals between sessions are set at 48 hours to prevent fatigue accumulation. Exercise intensity is monitored through real-time heart rate tracking (target heart rate ranges are provided in Table 3) and post-exercise RPE ratings, ensuring that participants' actual exertion levels meet the specified group requirements.

All MRI scans were performed uniformly 30 minutes after the completion of the exercise task. This timing was determined based on pre-experimental observations to allow partial resolution of acute hyperemia and edema effects while preserving signals of sustained metabolic and structural changes associated with exercise intensity. Consequently, low-intensity exercise did not induce significant volumetric changes, whereas moderate-to-high-intensity exercise produced markedly increased measurements, reflecting genuine differences in muscle responses that go beyond short-term perfusion effects.

Image Analysis

Two imaging diagnostic experts, one of whom is an experienced attending physician and the other is a senior deputy chief physician, are invited to jointly be responsible for the MRI image analysis of muscle activity during exercise. Each expert separately and thoroughly analyzes the imaging data during this period. If there are differences in opinion on how to interpret an image, the two experts engage in extensive discussion and consultation with each other to arrive at one common interpretation. This cooperative and consensus approach has vastly improved the reliability of the results produced from examining the images, significantly decreased the degree of variation created through individual subjective analyses, and created a much better and more accurate foundation for further data mining and conclusion/formulation activities.

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In order to evaluate the consistency of the MRI image analysis results of the two image interpretation experts, the weighted Kappa coefficient was used for reliability testing in this study. The evaluation indicators include muscle activation start time, BOLD signal change classification, and muscle volume measurement values. The results showed that the weighted Kappa coefficient of the two experts on all evaluation indicators was 0.86, and the 95% confidence interval was 0.81 to 0.91, indicating that the interpretation results are extremely consistent. In addition, the image quality evaluation adopts a double-blind independent scoring method, and the two experts rate each image without understanding the imaging method and grouping information.

Level A is defined as the muscle edges are clear, there is no artifact interference, and the internal structure is legible; Level B is the muscle edges are basically clear, there are slight artifacts, but it does not affect interpretation; Level C is the edges are blurred, or the artifacts are obvious; Level D is unable to be used for diagnosis. The Kappa coefficient of consistency between the two experts in the image quality score is 0.84, and the mean is taken when the scores are inconsistent. The above results jointly confirm the reliability and repeatability of the image interpretation and quality evaluation process.

Statistical Analysis

SPSS (Statistical Product and Service Solutions) version 22.0 software is used for statistical data analysis. The measurement data are expressed as X±S. The correlation test is performed using the P-value. When $P<0.05$, it indicates significance.

This study employed one-way ANOVA to compare differences among the three groups for various indicators. For multiple comparisons involving multiple muscle groups (6 muscles) and multiple imaging parameters (activation time, BOLD signal, volume changes), the Bonferroni correction was applied, with the corrected significance threshold set at $P < 0.05/18 \approx 0.0028$. All P-values reported in this paper represent the corrected results.

Results

Comparison of General Data of Research Subjects

In this study, 120 volunteers were chosen and split into three groups based on the level of activity. These three volunteer groups' fundamental data are compared in Table 5.

Table 5: General information on volunteers

Indicator	Group				
	Low-intensity	Medium-intensity	High-intensity	F-value	P-value
Age (years old)	26.8±4.8	25.7±5.1	26.4±4.6	0.58	0.64
Height (cm)	168.3±8.6	169.4±7.3	168.8±8.1	0.73	0.49
Weight (kg)	60.8±7.4	61.3±7.6	60.4±7.1	0.33	0.18
Body Mass Index	22.6±1.6	23.1±2.1	22.8±1.8	0.19	0.23
Blood oxygen saturation	98.6±1.9	99.1±1.6	98.4±2.1	0.24	0.86
History of diabetes (%)	25	20	22.5	0.37	0.33
History of hypertension (%)	15	15	12.5	0.11	0.71

Table 5 shows that there were no significant differences ($P>0.05$) between the comparison groups regarding the selected indicators, and therefore, the basic indicators did meet the criteria for experimental design. The average ages of the three comparison groups are: 26.8, 25.7, and 26.4 years old. Thus, the average ages of all three groups are similar, and there is no significant difference in average age ($P = 0.64 > 0.05$). The average heights of the three comparison groups are: 168.3 cm, 169.4 cm, and 168.8 cm, and there is no significant difference between the three groups ($P = 0.49 > 0.05$). The average weights of the three comparison groups are: 60.8 kg, 61.3 kg, and 60.4 kg; while there are slight differences in weight among groups, these differences were not statistically significant ($P = 0.18 > 0.05$). When considering the proportions of individuals in each comparison group with either a history of diabetes or hypertension, there were no significant differences in the distribution of either medical history within each exercise intensity comparison group.

DOI: 10.3844/ajbbsp.2026.22.03.031

Comparison of Muscle Activation Start Time at Different Exercise Intensities

Volunteers' muscles have different activation times when exercising at different intensity levels. Activation patterns and activation time for each muscle at a variety of exercise intensities have been demonstrated by MRI images. The MRI scans are an excellent way to see how muscle activity responds to exercise intensity. For the specific findings of this project, see Table 6.

Table 6: Comparison of muscle activation start time at different exercise intensities (unit: seconds)

Indicator	Group				
	Low-intensity	Medium-intensity	High-intensity	F-value	P-value
Tibialis anterior	6.25±1.68	3.13±1.41	1.22±1.09	10.6	0.000
Gastrocnemius muscle	9.86±1.83	5.29±1.67	3.43±1.34	6.8	0.008
Rectus femoris	8.38±1.26	4.84±1.11	2.88±0.94	7.7	0.002
Biceps femoris muscle	5.92±0.83	3.48±0.67	1.16±0.55	11.8	0.000
Gluteus maximus	10.67±2.25	6.38±2.01	2.07±1.64	8.5	0.002
Adductor muscle	12.71±2.69	7.87±2.13	2.69±1.87	8.1	0.008
Soleus	10.11±2.17	4.43±1.91	1.24±1.37	9.8	0.000

Table 6 shows the significant associations between different exercise intensities and muscle responses. The study found a difference in muscle activation onset time based on exercise intensity, with low-intensity exercise causing muscle groups to activate at a slower rate than higher-intensity exercises. The tibialis anterior and gastrocnemius muscles activated at 6.25 and 9.86 seconds, respectively, while participating in the low-intensity group of exercises. In contrast, the moderate exercise group saw a significant decrease in muscle group activation times, particularly with the tibialis anterior activating at 3.13 seconds after beginning moderate exercise. In addition to this, the high-intensity group experienced activation of the muscle groups even faster, with the tibialis anterior activating at only 1.22 seconds. The muscle groups of the high- and moderate-intensity group showed similar patterns of muscle group activation rates. The differences in activation time between the groups were statistically significant ($P<0.05$). This evidence demonstrates that increased levels of exercise intensity will stimulate muscle groups' response rates at a faster rate than lower levels of exercise intensity. These findings will contribute to the understanding of the role of exercise intensity on muscle coordination and how to develop optimal training and rehabilitation protocols.

BOLD Signal and Muscle Volume Changes Under Different Exercise Intensities

MRI technology can be used to visually assess the level of activation in the thigh muscles during exercise, thus providing a greater understanding of how muscle volume reacts to varying exercise intensities. The BOLD (Blood Oxygen Level Dependent) signal is a strong measurement of metabolic activity and oxygen use in the muscles during exercise and provides insight into the changing dynamic between these variables [39, 40]. In the investigation of muscle response to various intensities of exercise, this information aims to highlight the long-lasting effects of varying exercise intensities upon muscle training. The findings are listed in Table 7.

In Table 7, BOLD signals indicate that increased levels of exercise intensity significantly increase the volume and BOLD signal in all muscle groups ($P<0.05$). The rate of signal change in the muscle groups at low-Intensity levels showed a relatively smooth pattern. At High Intensity, the signal change is substantially accelerated due to an increase in the metabolic activity of the muscle via oxygen consumption and muscle metabolism. Compared with Low-Intensity levels, BOLD signals in the following muscle groups at High Intensity have dramatically increased: Tibialis Anterior = 25.94 %, Gastrocnemius = 22.18 %, Rectus Femoris = 28.47 %, Biceps Femoris = 23.81 %, and Soleus = 24.97 %. BOLD signal percentage increases at low intensity versus high intensity were 13.35%, 9.84%, 15.26%, 12.59%, and 10.45%, respectively ($P < 0.05$). Results of this study support the utility of BOLD signals in determining muscle metabolism and highlight increased metabolic demand of muscle during high-intensity exercise training. Compared to low-intensity exercise, high-intensity exercise results in significantly larger changes in skeletal muscle volume (P<0.05). Furthermore, results from this study support the idea that exercise intensity affects skeletal muscle volume and that high-intensity exercise is beneficial for promoting hypertrophy. Using Magnetic Resonance Imaging technology to examine and analyze muscle data has allowed for better insight into how exercise intensity affects the metabolism and volume of skeletal muscles and has established a scientific foundation for the link between exercise intensity and the training effect.

Table 7: Effects of different exercise intensities on BOLD signals and muscle volume changes in human muscle groups

Indicator		Group				
		Low-intensity	Medium-intensity	High-intensity	F-value	P-value
BOLD signal change (%)	Tibialis anterior	13.35±2.64	18.28±2.87	25.94±3.42	14.3	0.008
	Gastrocnemius muscle	9.84±2.13	14.67±2.46	22.18±3.18	15.2	0.006
	Rectus femoris	15.26±3.51	20.68±3.16	28.47±3.42	18.1	0.001
	Biceps femoris muscle	12.59±2.27	17.11±2.34	23.81±2.08	14.5	0.011
	Soleus	10.45±1.66	16.48±1.28	24.97±2.37	13.6	0.018
Volume change (cm^3)	Tibialis anterior	180.4±20.8	326.3±23.5	482.9±0.9	19.4	0.001
	Gastrocnemius muscle	208.1±22.1	382.3±26.2	523.6±31.5	20.3	0.000
	Rectus femoris	226.5±18.6	311.3±21.9	467.4±26.1	15.8	0.009
	Biceps femoris muscle	174.4±15.7	289.7±18.6	436.7±25.6	16.7	0.007
	Soleus	193.9±21.9	265.3±24.3	418.4±30.5	14.6	0.012

Changes in Thigh and Calf Muscle Volume Before and After Exercise

The muscles are stimulated by exercise, producing a physiological response at the time the muscle is being used and an adaptive response to long-term, repeated exercise. By examining how muscle responds to various types of exercises with different levels of intensity, we may better understand the finer details of the mechanisms whereby muscle adapts physiologically. MRI allows us to visualize precisely how muscle is utilized and the spatial and volumetric changes that occur in the muscle during the exercise. The specific findings related to this research can be found in Table 8.

Table 8: Study on the changes in human muscle volume at different exercise intensities

Group	Observation indicators	Before exercise	After exercise	F-value	P-value
Low-intensity	Thigh muscle volume (cm^3)	4822±126.3	5634±137.8	2.4	0.15
	Calf muscle volume (cm^3)	1980±98.8	2142±112.5	1.6	0.29
Medium-intensity	Thigh muscle volume (cm^3)	4883±124.8	5968±200.4	6.7	0.011
	Calf muscle volume (cm^3)	2012±99.3	2756±165.9	6.1	0.014
High-intensity	Thigh muscle volume (cm^3)	4906±125.8	8144±234.3	10.6	0.001
	Calf muscle volume (cm^3)	1993±99.7	3342±181.6	10.3	0.001

In Table 8, the thigh and calf muscle volumes increase after low-intensity exercise, but these changes are not statistically significant (P>0.05), mainly reflecting short-term physiological responses. The volume of thigh muscles increases significantly from 4883cm^3 to 5968 cm3, and the volume of calf muscles increases significantly from 2012cm^3 to 2756cm^3, when exercise was performed at a moderate level of intensity (P<0.05). The volume of both the thigh and calf muscles shows significant increases (P<0.05), resulting from acute physiological changes caused by medium intensity exercise and chronic adaptations to medium intensity exercise such as significant increases in muscle volume. This illustrates the significant effect of exercise on muscle. In contrast, High-intensity exercise creates an even stronger effect on muscle, resulting in larger increases in both the thigh and calf muscle volumes and more pronounced differences between them than in low or moderate intensity exercise (P<0.05). The combination of both moderate and high intensity exercise also appears to stimulate the deeper physiological mechanisms within the muscle; therefore leading to a greater increase in muscle mass due to increased thickness and size of the muscle fibre.

DOI: 10.3844/ajbbsp.2026.22.03.031

Comparison of Image Quality of Different Imaging Technologies

The collected images are classified into grades A-D. Grade A implies the image is very clear; grade B implies the image is relatively clear; grade C implies the image is fuzzy; grade D implies the image is unclear. The images generated using MRI are compared with those generated based on Computed Tomography (CT) and Ultrasound Imaging (US). The 120 volunteers are divided into three groups using three methods, with 40 people in each group. Figure 4 presents the specific comparison results.

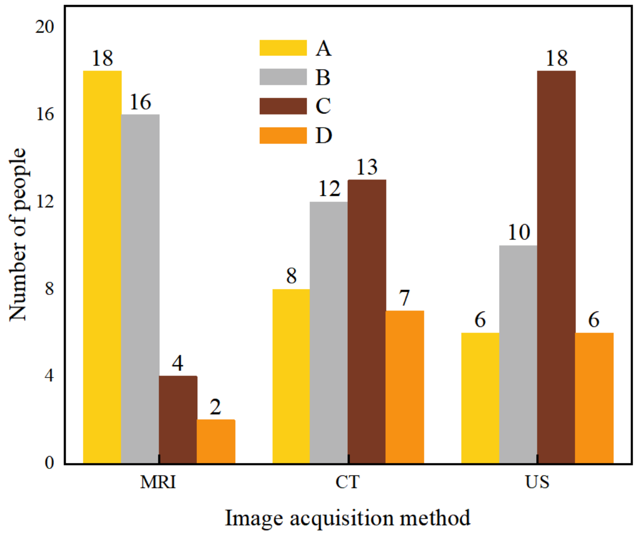

Fig. 4: Comparison of image quality of different muscle imaging technologies

In Figure 4, MRI technology demonstrates excellent performance in terms of image quality. Among the 40 volunteers who undergo MRI examinations, 18 obtain the highest grade A images, accounting for 45%, and 16 volunteers' images are rated grade B, meaning that a total of 85% of the images meet the standards of being very clear and relatively clear. The results clearly illustrate the major benefits of using MRI for acquiring high-resolution, high-quality images for observing and studying subtle changes in muscle activity during exercise. Of the 40 volunteers examined by CT, just 8 received Grade A images (20%), 12 received Grade B images (i.e., 50% of images were of high and moderate clarity), while 13 received Grade C. Although CT has a distinct advantage over MRI for showing detailed anatomic structures, it does not have high clarity capabilities for capturing dynamic changes occurring in muscles. Of the 40 volunteers examined by US, only 6 received Grade A images (15%), and an additional 10 received Grade B images (40% of images). While ultrasound (US) is frequently utilized in clinical applications because of its ability to provide images in real-time, MRI technology has advantages in terms of image clarity and can produce images that are more accurate for determining the muscle activity state of individuals performing exercise than ultrasound. The image clarity produced by MRI is superior to that produced by CT or ultrasound and thus shows that in all cases these imaging modalities are inferior to MRI.

Based on the qualitative grading of image quality, this study further calculated the "proportion of high-quality images" (the sum of Grade A and Grade B images as a percentage of total images) for the three imaging techniques. The proportion of high-quality images was 85% (34/40) for MRI, 50% (20/40) for CT, and 40% (16/40) for ultrasound. MRI demonstrated a 35% and 45% higher proportion compared to CT and ultrasound, respectively, further highlighting MRI's superior clarity in muscle activity imaging.

Discussion

MRI technology allows for the real-time measurement of muscle activation, metabolism, and structure during different intensities of exercise. Because MRI is able to collect a large amount of data with excellent resolution, it provides researchers with a detailed picture of the physiological effects of sports training on muscles, which in turn supports scientific recommendations to improve athletic performance through training. MRIs have distinct advantages over other tools when tracking microstructure changes and the physiological function of muscles in general. Muscles must not only carry out immediate biomechanical functions while in exercise but must continue to adapt to the demands of exercise to recover and build energy reserves as well. The effect of the intensity of exercise on muscle is not confined to immediate activation but also alters the volume, strength, and microstructure of muscle over time. In this study, MRI has been used to determine if different intensities of exercise affected the time it took for the muscles of volunteers to become activated. In high intensity, the amount of time taken for muscles to become activated was decreased significantly, and their time to respond was faster than that of the lower intensity exercise. This creates the opportunity to develop optimal methods of training and rehabilitation of muscles. When rehabilitating patients with slow muscle reaction times, they should be started at low intensity and gradually advanced to higher levels, allowing for the gradual reconstruction and recovery of the muscle. For athletes who wish to develop muscle strength and power, high-intensity exercises should be advocated.

This research utilized MRI technology to analyze how physical activity at varying levels of intensity affects muscle mass and muscle adaptations in response to training. The study employed trained people on an exercise program and used MRI to examine all of the major muscle groups (thighs) twice (before-and-after) to detect the subtle differences between each subject's muscle volume before/after training. Results indicated that muscle volume difference was significantly greater in the group performing high-intensity exercise. High-intensity exercise activates the muscle fibre (contracting/stretching) at an increased level, which leads to increased synthesis and deposition of muscle protein, increased remodelling of the internal microstructure of muscles, and a resulting rapid increase in muscle volume and a significant increase in strength.

The observed increase in muscle volume in this study may partially include exercise-induced acute congestion and edema rather than purely structural hypertrophy. To distinguish between these two phenomena, MRI scans were performed at least 30 minutes after exercise to minimize short-term perfusion effects. Furthermore, the volume changes in the moderate and high-intensity groups were not entirely parallel to the amplitude of BOLD signal changes, suggesting that, in addition to blood flow perfusion, genuine structural adaptations mediated by muscle fiber recruitment and enhanced metabolic activity were indeed present. This finding underscores the unique benefits of high-intensity exercise in promoting muscle growth and indicates that exercise intensity is a contributing factor to muscular adaptive changes.MRI uses the manipulation of hydrogen nuclei (hydrogen) in the human body to create detailed images of the human body's internal structure. MRI technology can provide high-definition images that allow for the detailed documentation of muscle fiber fine structure and dynamic changes that occur during muscle contraction and relaxation. MRI provides researchers with information regarding muscle activity during exercise, including changes caused by muscle contraction and relaxation, which occur mainly as a result of exercise.

The Change in blood in human muscle groups during low-intensity exercise results in a relatively small change in the Blood-Oxygenation-Level-Dependent (BOLD) Signal. Because low-intensity exercise does not require the same degree of muscular stimulation as other types of exercise, Muscle Fiber Contractions and Metabolism are minimal. Therefore, low-intensity exercise BOLD Signal changes will show minimal to no variation in blood oxygen content. As exercise intensity increases, so will the level of stimulation on the Muscles, leading to increased Muscle Fiber Contractions, Metabolic Processes, and Blood Oxygen Level fluctuations. Therefore, medium-intensity exercise BOLD Signal changes will show a considerable increase from Low Intensity BOLD Signals due to increased muscle metabolic activity and oxygen utilization. During high-intensity exercise, BOLD Signal changes; the stimulation of the Muscles is at its greatest, with a corresponding increase in metabolism and oxygen consumption.

BOLD signal enhancement primarily reflects the increased metabolic demand of muscles induced by exercise, leading to altered oxygen uptake and blood flow matching. During high-intensity exercise, increased muscle fiber recruitment and elevated metabolic rates result in a relative rise in deoxyhemoglobin, thereby enhancing BOLD contrast. Acute increases in muscle volume stem from fluid shift and congestion caused by muscle fiber contraction, while long-term increases are associated with upregulated muscle protein synthesis and enlarged muscle fiber cross-sectional area. Both phenomena exhibit a dose-response relationship with exercise intensity, reflecting the coupling between muscle metabolic activity and structural adaptation. This study focused on major active and antagonist muscles of the lower limbs, such as the tibialis anterior, which play critical roles in mechanical loading and metabolic responses during lower limb movement intensity variations. The findings are applicable to lower limb muscle groups engaged in periodic dynamic exercises but should not be directly generalized to upper limbs, the trunk, or isometric contraction-based movement patterns.

Although MRI offers high resolution in muscle activity studies, its widespread application is limited. Firstly, the equipment is costly, scans are time-consuming (typically 30–45 minutes per session), and subjects require strict compliance, making it difficult to implement in real-time motion scenarios or large-scale screening populations. Future developments should focus on creating portable MRI systems, shortening scan sequences, establishing standardized assessment criteria for key muscle functions, and reducing implementation barriers. This study employs a cross-sectional design, observing only immediate MRI changes post-isolated exercise intensities without enabling inference of long-term training effects. The recommendation that "high-intensity training promotes strength development while low-intensity training aids rehabilitation" represents a preliminary conclusion requiring validation through longitudinal intervention studies with sustained muscle tracking to provide reliable guidance. Although 60 male and 60 female participants were enrolled, gender subgroup analysis was not conducted due to insufficient sample size in each female group (approximately 13–14 individuals), compromising statistical power. While preliminary trends showed similar outcomes between genders, formal comparisons necessitate larger sample sizes; future research should incorporate gender-stratified analyses. Participants ranged from 18 to 40 years old, excluding middle-aged, elderly, and adolescents, warranting caution when generalizing findings to extreme age groups. Additionally, the single-center design limits sample diversity; future multicenter studies covering broader age ranges are essential to validate the results' generalizability.

Conclusion

In this study, Researchers use MRI technology to investigate how different levels of exercise intensity affect the amount of activity occurring within human muscle tissue. MRI images have high resolution and contrast between muscle and surrounding tissue, which makes this imaging technique ideal for studying changes within human muscles. By examining BOLD signals and changes in volume in the four main muscles located in the lower limbs, they determined that both the BOLD signal and volume of these four main muscles increased significantly with increasing levels of exercise intensity. Additionally, it was found that high levels of exercise intensity trigger rapid muscle activation, while low-level exercise is a much slower response. Therefore, researchers can assess how varying levels of exercise intensity will affect different muscle groups. Muscle volume also increased significantly during high-intensity exercises, indicating that the intensity of exercise positively impacts muscle growth. As a result, this information provides a scientific basis for understanding how different levels of exercise intensity influence muscle activity, while also providing a foundation for scientifically guided training methods, rehabilitation, and physical therapy. Thus, the effects of exercise intensity on BOLD signals and muscle volume are important findings that will provide future research with important references.

Acknowledgment

Thank you to the publisher for their support in the publication of this research article. We are grateful for the resources and platform provided by the publisher, which have enabled us to share our findings with a wider audience. We appreciate the efforts of the editorial team in reviewing and editing our work, and we are thankful for the opportunity to contribute to the field of research through this publication.

Funding Information

There is no funding information for the work in this paper.

Author's Contributions

Li-Chang Zou: Wrote the manuscript.
Hong-Wu Li: Analyzed the data.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved.

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