Original Article

Comparison Thigh Skeletal Muscles between Snowboarding Halfpipe Athletes and Healthy Volunteers Using Quantitative Multi-Parameter Magnetic Resonance Imaging at Rest

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Abstract

Background: Magnetic resonance (MR) imaging provides a unique, noninvasive diagnostic platform to quantify the physiological and biochemical variables of skeletal muscle at rest. This study was to investigate the difference in thigh skeletal muscles between snowboarding halfpipe athletes and healthy volunteers via multiparametric MR imaging.

Methods: A comparative study was conducted between 12 healthy volunteers and 14 snowboarding halfpipe athletes. MR scanning targeted the left leg at the level of the proximal thigh on a 3.0T MR system. The measured parameters compared between the two groups included T1, T2, T2* relaxation times, fat fraction (FF), and cross-sectional area (CSA) of the quadriceps femoris and the hamstring muscles. Statistical analysis was carried out using independent sample *t*-test. Interrater reliability was also assessed with intraclass correlation coefficients (ICCs).

Results: It was statistically equivalent between two groups in age, body mass index, thigh circumference, calf circumference, systolic blood pressure, and resting heart rate (all $P > 0.05$). However, the T1 and T2 values of the hamstring muscles in the athlete group were found to be significantly shorter than those in control group (T1: 1063.3 ± 24.1 ms vs. 1112.0 ± 38.2 ms in biceps femoris, 1050.4 ± 31.2 ms vs. 1095.0 ± 39.5 ms in semitendinosus, 1053.1 ± 31.7 ms vs. 1118.4 ± 40.0 ms in semimembranosus, respectively; T2: 33.4 ± 0.7 ms vs. 36.1 ± 1.9 ms in biceps femoris, 34.6 ± 2.0 ms vs. 37.0 ± 1.9 ms in semitendinosus, 36.9 ± 1.5 ms vs. 38.9 ± 2.4 ms in semimembranosus, respectively; all $P < 0.05$) although T2* relaxation time was detected with no significant difference. The FF of the hamstring muscles was obviously less than the control group (5.5 ± 1.9% vs. 10.7 ± 4.7%, $P < 0.001$). In addition, the quadriceps' CSA in the athlete group was substantially larger than the control group (8039.0 ± 1072.3 vs. 6258.2 ± 852.0 mm^2, $P < 0.001$). Interrater reliability was excellent (ICC: 0.758–0.994).

Conclusion: Multiple MR imaging parameters indicated significant differences between snowboarding halfpipe athletes and healthy volunteers in the thigh skeletal muscles.

Key words: Cross-sectional Area; Fat Fraction; Quantitative Magnetic Resonance Imaging; Relaxation Time

Introduction

Skeletal muscles provide the main strength to maintain the stability and the mobility of bones and joints,[1] in which sports' medicine researchers have the center of interest, along with the studies of their structures, fiber composition, and physiological and biochemical variables. In the past, invasive muscle biopsy technique was applied to detect their anatomical and structural features which were the key

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characteristics in the athletic performance.[2] Recently, with the prospective algorithms, magnetic resonance (MR) has displayed its favorable results in the quantitative evaluation of skeletal muscles after the technical limitations were eliminated in the muscle component assessments. The noninvasive MR imaging techniques enable to capture the information of changes in microstructure and perfusion at the cellular or fascicular level.[3-5] These quantitative MR imaging techniques include T1-mapping, T2-mapping, and multi-echo mDixon-Quant imaging, from which parameters (T1, T2, and T2*) derived are the characteristic indicators of the tissue composition and the metabolic changes; both fat fraction (FF) and cross-sectional area (CSA) of the muscle are two quantitative markers of the muscular strength and damage.[6-8] We hypothesized that these quantitative MR imaging techniques could reflect structural and functional changes at the microscopic level of skeletal muscles. Therefore, the purpose of this study was to quantitatively investigate the difference in the thigh skeletal muscles at rest between snowboarding halfpipe athletes and healthy volunteers via multiparametric MR imaging.

Methods

Ethical approval

The study was conducted in accordance with the *Declaration of Helsinki* and was approved by the Ethics Committee of the Shengjing Hospital of China Medical University (2017PS028K). Informed written consent was obtained from all participants before their enrollment in this study.

Research subjects

Twenty-six male individuals were recruited to participate in this MR research. Athlete group included 14 snowboarding halfpipe athletes (average age 18.5 years, ranging from 18 to 22 years) from the snowboarding halfpipe sports team of Shenyang. Twelve age-matched healthy student volunteers (average age 19.3 years, ranging from 18 to 21 years) were tested as controls. The exclusion criteria were: (1) general MR contraindications and (2) history of lower limb surgery, neurological disorders or acute trauma.

Before the imaging session, the demographic and physiological information for participants were collected: the participants' height and weight were measured with their indoor clothes on but no shoes. Their waistline, hip circumference, thigh circumference, and calf circumference were also measured by the measuring tape in this way. Their systolic blood pressure, diastolic blood pressure, and heart rate were recorded by a wrist sphygmomanometer at their rest. In addition, all the athletes were interviewed with a designed questionnaire, which reflects their career length of being professional athletes and their weekly training time.

Magnetic resonance imaging protocol

MR scanning targeted the left leg (nondominant leg) at the level of the proximal thigh on a 3.0T MR system (Philips Ingenia, Philips Medical System, The Netherlands). Each individual was examined in a supine position with a phased-array body coil. The scanning ranged from the lower edge of the pubic symphysis to the distal 20 cm. The scan protocol consisted of the axial T1-weighted turbo spin-echo sequence (repetition time [TR]/echo time [TE] = 260/15 ms, slice thickness = 4 mm, slice gap = 0.4 mm, matrix = 512 × 486, field of view [FOV] = 400 mm × 381 mm), the coronal short T2 inversion recovery sequence (TR/TE = 2275/20 ms, thickness = 4 mm, slice gap = 0.4 mm, matrix = 512 × 486, FOV = 352 mm × 329 mm), and the quantitative sequences, which included the axial T1-mapping (TR/TE = 2.2/1.01, slice thickness = 4 mm, matrix = 204 × 148, FOV = 410 mm × 298 mm), the axial T2-mapping (TR/TE = 2010/*n* × 20, slice thickness = 4 mm, matrix = 140 × 229, FOV = 414 mm × 250 mm), and the axial mDixon-Quant sequence (TR/TE/delta TE = 9.3/1.5/1.2, flip angle = 3°, echo number = 6, matrix = 384 × 254, FOV = 420 mm × 280 mm). All images were obtained at the same section locations as transverse anatomic T1-weighted image (T1WI).

Quantitative measurements

The DICOM data of T1WI and all quantitative sequences were loaded into IntelliSpace Portal 8.0 (Philips Medical System, The Netherlands) for the evaluation. The T2* and FF map were acquired from the mDixon-Quant sequence. For each individual, the last slice (20 cm from the lower [inferior] edge of the pubic symphysis) on T1WI was chosen for drawing region of interests (ROIs) (area 50 mm^2). The quadriceps femoris (rectus femoris, vastus intermedius, vastus medialis, and vastus lateralis) and the hamstring (long head of biceps femoris, semitendinosus, and semimembranosus) of the left leg were manually segmented [Figure 1], avoiding muscle fasciae and large vessels. Then, all ROIs were copied to T1, T2, and T2* maps to record the relaxation times [Figure 2]. FF and CSA of the muscles were calculated on the same slice of quadriceps femoris and the hamstring muscles. The outline of drawing was strictly along the edge of the quadriceps femoris and the

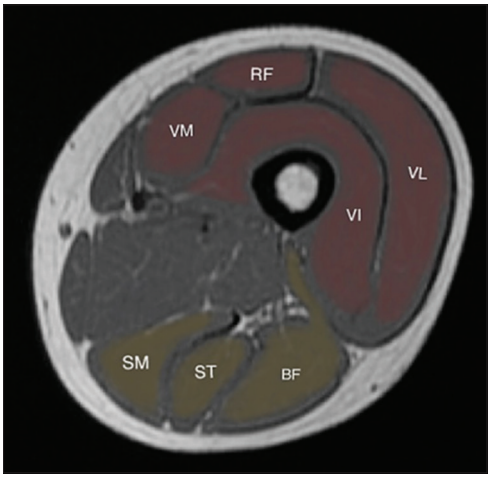

Figure 1: Representative region of interest in the left mid-thigh muscles of a 21-year-old healthy volunteer on T1-weighted magnetic resonance image. VL: Vastus lateralis; VI: Vastus intermedius; RF: Rectus femoris; VM: Vastus medialis; BF: Biceps femoris; ST: Semitendinosus; SM: Semimembranosus.

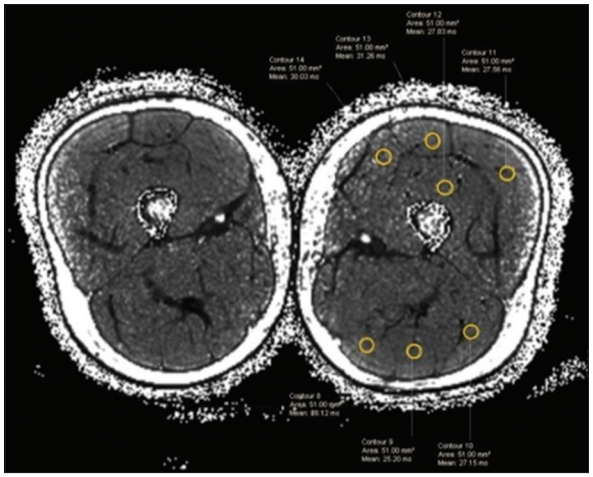

Figure 2: The quadriceps femoris and the hamstring muscles of region of interest in an 18-year-old athlete were segmented on T2* map for generation and calculation. T2* value as follows: VL = 27.56 ms, VI = 27.83 ms, RF = 31.26 ms, VM = 30.03 ms, BF = 27.15 ms, ST = 25.20 ms, SM = 28.12 ms. VL: Vastus lateralis; VI: Vastus intermedius; RF: Rectus femoris; VM: Vastus medialis; BF: Biceps femoris; ST: Semitendinosus; SM: Semimembranosus.

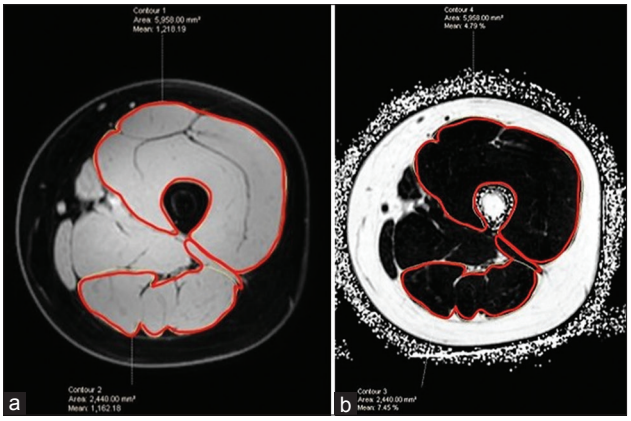

Figure 3: Measurements of FF and CSA in the quadriceps femoris and the hamstring muscles of a 19-year-old athlete. (a) Anatomical T1-FFE-weight derived from mDixon-Quant sequence was used to outline muscle. (b) The muscle groups of the interest were copied to FF map to calculate FF and CSA. The FF of the quadriceps femoris and hamstrings muscles were 4.8% and 7.5%, respectively, and the CSA were 5958 mm^2 and 2440 mm^2, respectively. FF: Fat fraction; CSA: Cross-sectional area; FFE: Fast field echo.

hamstring muscles [Figure 3]. All numerical measurements were averaged over three times.

Statistical analysis

The data analysis was conducted using SPSS version 22.0 (IBM, Chicago, IL, USA). The Shapiro-Wilk test was used to evaluate the normality of measure variables. All continuous variables were presented as mean ± standard deviation (SD). Two independent sample *t*-test was used to compare the difference in the muscle's T1, T2, T2* relaxation times, and FF and CSA between two groups. The interrater reliability between two visits was assessed with intraclass correlation coefficients (ICCs) on 10 out of 12 control group images. The degree of the agreement was interpreted as follows: <0.40, poor; 0.40–0.59, fair; 0.60–0.74, good; and 0.75–1.00, excellent. A $P < 0.05$ was considered statistically significant.

Results

Subject demographics

Table 1 shows the demographic and physiological characteristics of two groups. The athlete group demonstrated significantly lower waistline, hip circumference, and diastolic blood pressure than the controls (all $P < 0.05$). No significant differences in the age, body mass index, thigh circumference, calf circumference, systolic blood pressure, and resting heart rate were found between two groups. In the athlete group, their mean career length of athletic professional was 4.5 ± 2.7 years and their mean weekly training hours was 28.2 ± 2.9 h.

Interrater reliability

All interrater reliability for multiparametric MR imaging measures was excellent in the quadriceps femoris and the hamstring muscles. ICC was as follows: T1 value ranged from 0.758 to 0.975; T2 value ranged from 0.842 to 0.994; T2* value ranged from 0.763 to 0.963.

T1, T2, and T2* relaxation times between two groups

The T1, T2, and T2* relaxation times of two groups in the quadriceps femoris and hamstring muscles are shown in Table 2. The T1 and T2 relaxation times of the hamstring muscles were found to be significantly shorter in the athlete group than those in control group (T1: 1063.3 ± 24.1 ms vs. 1112.0 ± 38.2 ms in biceps femoris, 1050.4 ± 31.2 ms vs. 1095.0 ± 39.5 ms in semitendinosus, 1053.1 ± 31.7 ms vs. 1118.4 ± 40.0 ms in semimembranosus, respectively; T2: 33.4 ± 0.7 ms vs. 36.1 ± 1.9 ms in biceps femoris, 34.6 ± 2.0 ms vs. 37.0 ± 1.9 ms in semitendinosus, 36.9 ± 1.5 ms vs. 38.9 ± 2.4 ms in semimembranosus, respectively; all $P < 0.05$), while there was no significant difference in the quadriceps femoris between two groups ($P > 0.05$). The T2* relaxation time was detected without significant differences in all muscles between two groups ($P > 0.05$).

Fat fraction and cross-sectional area of the muscle between two groups

The FF and CSA of the muscles in two groups are shown in Table 3. The FF of the hamstring muscles in the athlete group was apparently less than that of control group (5.5 ± 1.9% vs. 10.7 ± 4.7%, $P < 0.001$), while the FF of the quadriceps femoris did not show significant difference between two groups ($P = 0.153$). In contrast, the CSA of the quadriceps femoris in the athlete group was substantially larger than that of control group (8039.0 ± 1072.3 mm^2 vs. 6258.2 ± 852.0 mm^2, $P < 0.001$), while CSA of the hamstring muscles had no significant different between two groups ($P = 0.179$).

Discussion

The results of this study demonstrated that there were significant differences in a number of MR imaging

Table 1: Demographic and physiological characteristics of all participants in this study

Characteristics	Control group (n = 12)	Athlete group (n = 14)	t	P
Age (years)	19.3 ± 1.1	18.5 ± 1.2	1.760	0.091
BMI (kg/m^2)	24.5 ± 4.2	21.7 ± 2.8	2.027	0.057
Waistline (cm)	86.2 ± 5.5	76.4 ± 8.2	3.513	0.002
Hip circumference (cm)	100.1 ± 3.1	94.5 ± 7.9	2.303	0.031
Thigh circumference (cm)	56.1 ± 2.1	53.5 ± 5.4	1.566	0.064
Calf circumference (cm)	38.4 ± 2.5	36.7 ± 2.8	1.621	0.119
Rest SBP (mmHg)	125.3 ± 12.8	119.2 ± 9.0	1.422	0.168
Rest DBP (mmHg)	82.6 ± 8.2	73.9 ± 7.1	2.901	0.008
Resting heart rate (beats/min)	76.0 ± 7.4	76.8 ± 11.5	−0.207	0.857

The data are shown as mean ± SD. BMI: Body mass index; SBP: Systolic blood pressure; DBP: Diastolic blood pressure; SD: Standard deviation.

Table 2: T1, T2, and T2* relaxation times of volunteers and athletes in the quadriceps femoris and hamstring muscles

Items	T1 value (ms)				T2 value (ms)				T2* value (ms)			
	Control group (n = 12)	Athlete group (n = 14)	t	P	Control group (n = 12)	Athlete group (n = 14)	t	P	Control group (n = 12)	Athlete group (n = 14)	t	P
Vastus lateralis	1036.1 ± 33.5	1030.9 ± 39.5	0.358	0.712	35.5 ± 3.6	34.3 ± 1.4	1.153	0.252	30.8 ± 1.5	30.2 ± 2.5	0.726	0.475
Vastus intermedius	1061.6 ± 29.9	1060.5 ± 28.6	0.096	0.922	34.3 ± 1.2	34.2 ± 1.2	0.212	0.844	28.4 ± 1.7	28.9 ± 1.7	−0.748	0.462
Rectus femoris	1071.2 ± 25.0	1068.5 ± 34.2	0.226	0.816	35.5 ± 2.6	35.2 ± 2.1	0.326	0.747	30.6 ± 1.9	30.6 ± 2.2	0.059	0.953
Vastus medialis	1083.2 ± 24.6	1077.7 ± 23.6	0.581	0.554	38.4 ± 2.1	37.2 ± 1.7	1.611	0.118	29.8 ± 1.7	29.9 ± 2.5	−0.036	0.972
Biceps femoris	1112.0 ± 38.2	1063.3 ± 24.1	3.948	<0.001	36.1 ± 1.9	33.4 ± 0.7	4.953	<0.001	29.2 ± 1.8	28.2 ± 1.9	1.370	0.183
Semitendinosus	1095.0 ± 39.5	1050.4 ± 31.2	3.216	0.003	37.0 ± 1.9	34.6 ± 2.0	3.121	0.004	26.9 ± 1.8	26.6 ± 1.5	0.464	0.647
Semimembranosus	1118.4 ± 40.0	1053.1 ± 31.7	4.644	<0.001	38.9 ± 2.4	36.9 ± 1.5	2.765	0.011	29.2 ± 1.2	29.1 ± 2.4	0.131	0.897

All data were shown as mean ± SD. SD: Standard deviation.

Table 3: FF and CSA of the quadriceps femoris and hamstring muscles in two groups

Items	Quadriceps femoris				Hamstring muscles			
	Control group (n = 12)	Athlete group (n = 14)	t	P	Control group (n = 12)	Athlete group (n = 14)	t	P
FF (%)	3.3 ± 1.6	2.6 ± 1.0	1.477	0.153	10.7 ± 4.7	5.5 ± 1.9	3.767	<0.001
CSA (mm^2)	6258.2 ± 852.0	8039.0 ± 1072.3	−4.631	<0.001	2770.4 ± 307.5	3029.9 ± 583.5	−1.382	0.179

All data were shown as mean ± SD. FF: Fat fraction; CSA: Cross-sectional area; SD: Standard deviation.

quantitative parameters between snowboarding halfpipe athletes and healthy volunteers in thigh skeletal muscles at rest. It found that the T1 and T2 values of the hamstring muscles in athletes were shorter than those of volunteers, which was inconsistent with the results of Le Rumeur *et al*.'s study.[9] They found that no differences in T1 and T2 were observed in the three thigh muscles at rest among untrained men, soccer players, and triathletes. It was considered that the differences in the experimental conditions, subject selection, and training methods might cause the differences in results. The previous studies about skeletal muscle have reported that the cause for variety of relaxation time included muscle fiber composition, intracellular and extracellular water content, perfusion, lipids, and other conditions in the case of the same external environment, especially the present of water and fat of tissue.[10-12] Moreover, bound water which was associated with intracellular protein, glycogen, and other macromolecules slowed down the resonance frequency closer to the Larmor frequency, causing more efficient longitudinal and transverse relaxation, thereby shortening both T1 and T2 relaxation times of water. In this study, the T1 and T2 relaxation times in the hamstring muscles in the athletes were lower than those of the volunteers, while there were no significant differences in quadriceps femoris between two groups. This result might be due to the increase in protein synthesis and glycogen reserve of athletes in the hamstring muscles. Long-term muscle contraction training will lead to increased muscular strength and muscle hypertrophy. Training-induced muscle hypertrophy stems from enhanced protein synthesis within the muscle fibers, mainly myofibrillar.[13] Moreover, according to the results of biochemical studies, the levels of glycogen (66%), creatine phosphate (22%), and ATP (18%) rose at rest after a 5-month strength training on muscles.[14] These macromolecules gathered in intracellular raised bound water and shorten T1 and T2 relaxation times.

The T2* value of skeletal muscle is an index of muscle perfusion and peripheral microvascular function, which increases with exercise whereas decreases with ischemia.[15-17] Consistent with the results of previous studies, this study showed that no statistically significant differences in all

muscles were found between two groups. Since this study was completed at rest and no vigorous exercise was performed within 24 h, there was no significant difference in blood flow between two groups either. However, it was believed that postexercise MR imaging might acquire different results of T2* value, because, as the study of Varghese *et al*.[6] demonstrated, in comparison to the resting level, T2* value was significantly and differentially increased immediately after postexercise and recovered to near the baseline within 30–40 min among the leg muscle groups. Therefore, further MR perfusion studies of athletes in postexercise state will be required to support this hypothesis.

Consistent with the results of previous studies, this study found that the CSA of quadriceps femoris in the athletes was substantially larger than that of the volunteers. Ema *et al*.[18,19] found greater CSA of the quadriceps femoris in experienced cyclists or oarsmen compared with untrained individuals. This change resulted from the muscle hypertrophy caused by regular training. Muscle training could induce muscle fiber hyperplasia and protein synthesis enhancement, resulting in an increased muscle physiological CSA, which was proportional to the muscular strength and reflected the muscle mobility.[20] However, no statistical difference in the CSA of hamstring muscles between two groups in this study might be owing to the measurement at mid-thigh level where the CSA of hamstring muscles is relatively small. The CSA measurement using MRI was proved superior to other force test system, with the advantages of noninvasive, simple, quantitative, and not affected by the external environment.[21] Therefore, as an indicator of muscle strength, CSA is a potential biomarker to measure athletic muscle activities.

Age-related or disease-related increase in the intramuscular fat accumulation has been illustrated in the previous studies.[22,23] Only few researches were conducted on the correlation between exercise or training and intramuscular fat content. Fischmann *et al*.[24] found that the FF of each vastus muscle was reduced after squats exercise using two-point Dixon technique. This view was slightly discrepant from this study. In this study, it was showed that the FF of the hamstring muscles in the athletes was remarkably less than that of controls, while the FF of the quadriceps femoris did not show any significant difference between two groups. It was considered that a possible cause for the reduced FF after long-term training is physiological increased bound water which was also related to the shorter T1 and T2 values of hamstrings muscles. Another possible reason is that the exercising muscle might consume intramyocellular lipids. In addition, this study used the seven-fat-peak model of multi-echo Dixon technology to measure FF, which was more accurately than two-point or three-point Dixon. The muscle fat content reflected the muscle density, which was associated with protein synthesis and not related to muscle strength.[25,26] Therefore, the FF of muscle might be one of the indicators to reflect the effect of muscle training.

This study had several limitations. The sample number was evidently small and the athletes were only derived from and restricted to single snowboarding halfpipe athletes. Due to these reasons, the evaluation of cross-section of thigh images was limited to a certain level.

In conclusion, the noninvasive, multiparameter MR imaging techniques could quantitatively evaluate the changes in muscle structure, function, and metabolism at cellular and microstructure levels. Shorter T1 and T2 values and lesser FF of the hamstring muscles and larger CSA of quadriceps femoris could be found in the athlete group, which might due to the changes in muscle physiology and biochemistry caused by long-term athletic training. Moreover, these parameters might become biomarkers to guide and assess the athlete's training level and performance in the further research.

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Conflicts of interest

There are no conflicts of interest.

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利用定量多参数磁共振成像对比静息状态下单板滑雪运动员与健康志愿者大腿骨骼肌的差异

摘要

背景：磁共振成像提供一个唯一无创的诊断平台来量化骨骼肌在静息状态时的生理和生化改变。本研究旨在通过多参数磁共振成像研究单板滑雪运动员与健康志愿者之间大腿骨骼肌的差异。

方法：12名健康志愿者和14名单板滑雪运动员进行比较研究。扫描在3.0T磁共振系统，定位为左大腿近端水平。比较两组股四头肌和腘绳肌的T1，T2，T2 *弛豫时间和脂肪分数及肌肉横截面积等定量参数。利用独立样本t检验进行统计分析。评判间信度用组内相关系数进行评估。

结果：两组在年龄、身体质量指数、大腿围、小腿围，收缩压和静息心率中无统计学差异。然而，在运动员组中，发现腘绳肌的T1和T2值显著短于志愿者组（T1值: 股二头肌为1063.3±24.1 ms vs. 1112.0±38.2 ms, 半腱肌为1050.4±31.2 ms vs.1095.0±39.5 ms, 半膜肌为1053.1±31.7 ms vs. 1118.4±40.0 ms；T2值: 股二头肌为33.4±0.7 ms vs. 36.1±1.9 ms,半腱肌为34.6±2.0 ms vs. 37.0±1.9 ms，半膜肌为36.9±1.5 ms vs. 38.9±2.4 ms；所有$P<0.05$）。T2*值并没有统计学差异在所有肌肉中。腘绳肌的脂肪分数显著少于对照组（5.5±1.9% vs. 10.7±4.7%, $P<0.001$）。此外，运动员组股四头肌的横截面积显著大于志愿者组（8039.0±1072.3 mm^2 vs. 6258.2±852.0 mm^2, $P<0.001$）。评判间信度的可靠性非常好（组内相关系数为0.758–0.994）。

结论：磁共振多参数在单板滑雪运动员与健康志愿者大腿骨骼肌之间存在显著差异。