Mechanism of Bafa Wubu of Tai Chi Promoting Lower Extremity Exercise: A Cross-sectional Study Based on an AnyBody Musculoskeletal Model

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Abstract

Background: This paper aimed to explore the scientific training methods and technical characteristics of Bafa Wubu, as well as its contribution to comprehensive exercise of the lower extremities, by analyzing the biomechanical characteristics of the lower extremities of participants who practice Bafa Wubu at different levels and by comparing their femur loading during Bafa Wubu and walking.

Methods: A total of 16 male participants were recruited and divided into an amateur group (N=8) and a professional group (N=8).Data were collected by a BTS 3D infrared-based motion capture system, Kistler 3D force plate and BTS surface electromyography. The kinematic and kinetic parameters of the lower extremities were captured by AnyBody 7.2 simulation modeling and finite element analysis of the femur was performed with an ANSYS 19.2 workbench.

Results: During Elbowing and leaning sideways with steps sideways (ELS), the ground reaction force of the professional group was significantly higher than that of the amateur group in the sagittal, vertical and frontal axes ($P<0.01$). During six sets of motions (except Standing knee raises:SKR), the knee flexion/extension angle of the professional group was significantly larger than that of the amateur group ($P<0.01$). During actions with back steps, the ankle flexion/extension angle of the professional group was significantly larger than that of the amateur group ($P<0.01$). During actions with steps sideways, hip flexion/extension angle and rotation angle significantly larger than that of the amateur group ($P<0.01$). During stepping forward, backward and sideways, the loading of the professional group's joints at the hip, knee, and ankle was always higher in the vertical direction ($P<0.01$). Furthermore, during Warding off with steps forward (WOF), Laying with steps forward (LF) and Rolling back with steps backward (RBB), hip joint loading increased in the med–lat direction. During actions with steps backward and sideways, the ankle flexion/extension torque and hip abduction/rotation torque of the professional group were significantly larger than those of the amateur group ($P<0.01$). Different actions in Bafa Wubu activate muscles to different degrees, whereas the iliacus is mainly responsible for stabilizing postures when practitioners perform standing knee lifting motions. Comparing femur loading during walking to the seven sets of motions in Bafa Wubu, when performing Bafa Wubu, participants' femur loading increases while threshold loading and maximum loading point vary with the actions. Therefore, continuously practicing the seven sets of motions can stimulate the femur in a comprehensive way.

Conclusions: Bafa Wubu of Taichi is composed of core techniques of Tai Chi Chuan, characterized by movements in five directions. When performing Bafa Wubu, performers display increased joint angle and joint load at hip, knees, and ankles, consequently enhancing their joint proprioception. Besides, different motions activate muscles of different types at different levels. Also, the threshold of femur load and maximum loading point always change when seven sets of motions in Bafa Wubu are completed coherently. Therefore, it can be concluded that muscles, joints, and bones of the lower extremity can obtain comprehensive and balanced exercise through Bafa Wubu.

Introduction

As an ancient Chinese martial art, Tai Chi Chuan's role in fitness and health has been a topic of interest to many scholars. Past studies have shown that practicing Tai Chi Chuan can strengthen the lower extremities(Ge Y et al.,2019), reduce bone density loss(Liye Z et al.,2017), improve balance(Wang L et al.,2021), and prevent falls(Li et al.,2021). Considering that Tai Chi Chuan of the traditional form is difficult for the elderly, simplified and personalized versions have been developed for certain groups(Pjc et al.,2020). Hence, the General Administration of Sport of China promoted a more user-friendly routine of Tai Chi Chuan based on the 24-form simplified Tai Chi, called Bafa Wubu. It integrates eight essential forms called Peng (warding off), Lv (rolling back), Ji (pressing), An (pushing), Cai (plucking), Lie (laying), Zhou (elbowing), Kao (leaning sideways), and five steps called Jin (advancing), Tui (retreating), Gu (shifting left), Pan (shifting right), and Ding (central equilibrium), which are the core patterns of Tai Chi Quan. Compared with the 24-form simplified version, Bafa Wubu is even simpler and takes less time and energy(Lyu et al.,2020). Therefore, it is of great value to probe into Bafa Wubu's role and mechanism of promoting fitness. Tsang (Tsang, W.,2012) found that by practicing Tai Chi, elderly individuals enhance their proprioception, promote their vestibular function and strengthen their lower extremities, subsequently improving their dynamic and static balance. Likewise, some scholars believe Bafa Wubu improves the foot center of pressure (COP) and foot arch tactile sense more than knee proprioception so that the elderly have enhanced balance capacity and a reduced risk of falls(Hu xiu et al.,2021). Additionally, some studies have focused on the typical actions of Bafa Wubu and reported its characteristics, such as the motions have bilateral symmetry, proximal muscles work before the distal ones, and the lower extremity muscles play a major role in performing Bafa Wubu(Lv xunlu.,2020). According to the literature, Bafa Wubu of Tai Chi was launched relatively recently, and its biomechanical research is limited.

In this paper, AnyBody finite element modeling was utilized to biomechanically analyze the lower extremity characteristics of Bafa Wubu practitioners at different levels and discover the activation and mobilization of different motions on the lower extremity muscles. Meanwhile, femur loading changes were also revealed by finite element analysis. The purpose of this paper was to investigate the biomechanical principles of Bafa Wubu in strengthening of the lower extremities, muscles and bones to provide scientific guidance for primary practitioners and improve their training efficiency.

Materials And Methods

Participants

A total of 16 male volunteers were recruited as subjects. Half served as the professional group, while the other half served as the amateur group. Only professional athletes who had achieved both national level titles and placed in the top three in domestic Tai Chi Chuan competitions were qualified for the professional group, and male teenagers practicing Bafa Wubu for more than one year were qualified for the amateur group. Then, 5 national master's sportsmen and 3 athletes at the national level were recruited from Beijing Sport University, making up the professional group. The amateur group was recruited from students attending Beijing Normal University. All subjects were in good health with no history of lower limb injury in the past six months, and everyone's dominant leg was on the right side. There were no significant differences in physical dimensions between the two groups based on the subjects' records, including age, height, weight, BMI, leg length, hip width, knee width, or ankle width. All participants provided written informed consent and understood the experimental process and purpose. All methods in this study were carried out in accordance with the 'Declaration of Helsinki' relevant guidelines and regulations, and This study was reviewed and approved by the Ethics Committee of China National Rehabilitation Center. The participants' basic information is listed in Table 1.

Table 1. Basic information of all participants (mean ± SD)

Body parameters	Groups		T value	P value
	Amateur group（N=8）	**Professional group（N=8）**		
Age(y)	21.50±2.14	20.50±1.60	1.058	0.31
Height(cm)	174.44±4.95	175.00±5.24	-0.221	0.83
Weight(kg)	70.25±6.20	70.75±3.77	-0.195	0.85
BMI	23.10±2.05	23.13±1.49	-0.038	0.97
Leg length(cm)	86.25±0.71	85.94±2.40	0.354	0.73
Hip width(cm)	22.50±1.85	23.13±1.96	-0.656	0.52
knee width(cm)	9.50±0.65	9.94±0.68	-1.313	0.21
Ankle width(cm)	7.25±0.60	7.38±0.52	-0.447	0.66

*p> 0.05 represents insignificant differences among the basic information of the two groups.

Methods

Instrumentation

In this study, all motion data were collected by 8 high-precision infrared motion capture systems (BTS SMART DX 700, BTS Bioengineering, Italy), whose parameters are as follows: frequency of 250 Hz, resolution of 640 d×480 pixels, precision of 400 mm×300 mm×300 mm. Three 3D force plates (928E, Kistler, Switzerland) were used to measure the ground reaction force with a frequency of 1000 Hz and a static detection error of less than 0.5%. Surface EMG was measured by a BTS surface EMG system with a frequency of 1000 Hz, which was synchronized with the infrared motion-capture acquisition.

Bafa Wubu of Tai Chi

Bafa Wubu, a primary routine of Tai Chi, includes 5 types of footwork called Jin, Tui, Gu, Pan, and Ding, which respectively mean moving forward, backward, left, right, and standing still. As shown in Fig. 1, by combining the five types of footwork and eight essentials, Bafa Wubu can be divided into seven sets of motions: WOF (warding off with steps forward), LF (laying with steps forward), RBB (rolling back with steps backward), PB (plucking with steps backward), PPS (pushing and pressing with steps sideways), ELS (elbowing and leaning sideways with steps sideways), and SKR (standing knee raises). Namely, WOF and LF move forward, RBB and PB move backward, PPS and ELS move sideways, and SKR is a balanced and motionless posture. These motions include the 13 fundamental techniques at the core of Tai Chi Chuan with different features in the directions of displacement, strength generation methods and exercise effects; therefore, the seven sets of motions above were selected as the subject of this research.

AnyBody simulation

A musculoskeletal simulation model is established through software anybody 7.2 (AnyBody Technology, German) to process 3D motion-capture dynamics. Validated by many experiments, Anybody 7.2 software runs with high reliability and precision(Saraswat et al.,2010; Damsgaard et al.,2006). The musculoskeletal model established in AnyBody is a standard multibody dynamic model, which consists of rigid parts (such as the human skeleton or external objects), kinematic actuators (such as body motion), and force/torque actuators (such as muscles). Generally, forces and torques are simulated by means of multibody dynamics simulation.

The muscle actuating system, usually containing more muscles than is necessary to drive the joints, is usually solved by the central nervous system (CNS), which is responsible for muscle activation and recruitment. To simulate how the CNS works, the AnyBody modeling simulation system provides a standard mechanism for selecting the optimal muscle recruitment system. Specific methods of muscle recruitment are demonstrated in the following optimization formula:

$Minimize\ G(f^{(M)})$ (1)

$Cf = d$ (2)

$0 \le f_i^{(M)} \ge N_i,\ i \in \{1, \ldots, n^{(M)}\}$ (3)

where G is an objective function assuming the CNS's distribution strategy to muscle force with the muscle force $f_i^{(M)}$ as the dependent variable. $f_i^{(M)}$ refers to the muscle force of the external equilibrium load; cf = d is the dynamic equilibrium equation of the human muscle model with equation matrix *C* and is the sum of the inertia force and external force *d*. N_i refers to the muscle strength to be calculated.

The formula for the muscle recruitment methods is:

$$G\left(f^{(M)}\right) = \sum_{i=1}^{n^{(M)}} \left(\frac{f_i^{(M)}}{N_i}\right)^p \quad (4)$$

where *P* is a polynomial power series of (p≥1). Set P to different values. When the power series is larger, the number of muscles balancing the external force is more extensive, and the synergy effect is significant. When the muscle model or human physiological system reaches a balance, the maximum relative load of the different muscles must be minimized due to a collective protection mechanism, where muscle activity is minimal to avoid muscle strain from excessive stress:

$$\max\left(\frac{f_i^{(M)}}{N_i}\right), i = 1,2,3, \ldots, n^{(M)} \quad (5)$$

Testing protocols

This experiment was completed in the sports biomechanics laboratory of Beijing Normal University. We set BTS infrared motion capture cameras at intervals of more than 200 mm and at a height of 300 mm. The cameras were placed in a semiarc around the test center. Before the experiment, the global coordinates and force plate coordinates were calibrated to ensure that each camera could capture the participants' motions and bodies. We turned on the surface EMG system and connected it to the infrared action system to select the surface EMG. A VIXTA recording camera was used to record the whole experiment.

Participants wore uniform shorts and black socks to reduce errors due to clothing shaking and other variables. According to the requirements of the plugin Gait, marker set LowerExtremity model in AnyBody 7.2, 25 marker points were attached to the bone marker points of the subjects. The positions of marker points included the left and right anterior head, left and right posterior head, sternum, clavicle joint, tenth thoracic vertebra, sternal xiphoid process, left and right anterior superior iliac spine, left and right posterior superior iliac spine, left and right lateral lower 1/3 of the thigh, left and right external epicondyle of the fibula, right lateral lower 1/3 of the calf, left lateral lower ½ of the leg, left and right heel, left and right lateral malleolus, left and right first metatarsal, and left and right fifth metatarsal(Welke et al.,2013;Manders et al.,2008). Four surface muscles were selected during surface EMG data collection: vastus lateralis, biceps femoris, tibialis anterior, and gastrocnemius. To avoid interference, the hair on the muscle belly was shaved, and the sebum was removed with 75% alcohol on a cotton swab. The largest area of each muscle belly was selected for attachment of the electrodes.

Data collection and analysis

Since all participants were right-side dominant and the motions are symmetric and periodic in Bafa Wubu of Tai Chi, this experiment mainly investigated the characteristics of motions when the force of the knee joint in the vertical direction reaches the maximum in the stance phase of the right lower extremity, which lasts from heel strike to toe off(Babaee et al.,2018).

Kinematic and dynamic data of the lower extremities

We used BTS SMART Capture software and eight BTS SMART Dx 700 cameras to shoot the motion data of the reflective markers and then delineated their moving paths by the BTS tracker. When the process was finished, the C3D file of kinematic data was imported into AnyBody 7.2 simulation software to establish a musculoskeletal simulation model of the seven sets of Tai Chi motions (Fig. 2).

The calculation process of the body simulation is as follows: optimizing the reflective markers, conducting the dynamics computation, and conducting inverse dynamics computation. Then, the kinematic and dynamic data were calculated. The joint angle corresponded to the maximum state when a certain motion was completed. Standardized processing was accomplished after the calculated dynamic indices were imported into Excel. In addition, joint force, joint torque, and muscle strength were divided by body weight (unit: N/BW)(Walter et al.,2017), where joint forces were defined to be both positive and negative values between the joints(Wu, G et al.,2005).

Skeleton finite element model processing

The skeleton finite element model in this experiment was established based on CT scans of the femur of a healthy young man (171 cm, 75 kg). In Mimics 20.0 (Materialise, Leuven, Belgium), the original CT image was converted into tetrahedrons and exported in STL format. Then, the bone and the retrograde mesh were restored in Geomagic Wrap 2013 (Geomagic company, Research Triangle Park, NC, USA), where the holes were filled and the sharp corners were repaired. The IGES format was exported after the treatment was completed. Finally, in ANSYS 19.2 workbench (Cybernet Systems Co., Ltd., Tokyo workbench, Japan), Young's modulus and Poisson's ratio of femur were added(Toyohara et al.,2020), where the greater trochanter was fixed, and the net joint force was loaded to the end of the medial and lateral condyle, and then the force of the femur was analyzed.

Force plate and electromyography data processing

The force plate and electromyography data were processed by a BTS SMART Analyzer. We determined the range of the force plate according to the data and determined its maximum values from periods processing of force in the X, Y and Z axes. In addition, the original EMG signals were corrected and filtered (20~4400 Hz), and then the iEMG was calculated with a truncation frequency of 20 Hz(Liu, Q et al.,2008).

Statistical analysis

In this study, data were analyzed with statistical analysis software (SPSS 26.0), and the results are displayed as the mean value and standard deviation (mean ± SD). T tests were used to analyze the kinematic and dynamic data of the lower extremities of Bafa Wubu practitioners at different levels. P ≤0.05 indicates a statistically significant difference. P<0.05 represents a significant difference. P<0.01 represents an extremely significant difference. The correlation analysis between the surface EMG data and the muscle force data from the AnyBody simulation was conducted using the Pearson method.

Results

3.1 Comparison of the ground reaction forces

As shown in Table 2 and Fig. 3, during ELS, the GRF of the professional group was significantly higher than that of the amateur group in the vertical, anterior–posterior (ant–post), and medial–lateral (med–lat) directions (P<0.01).

Table 2. Mean and standard deviation (mean ± SD) of the maximum ground reaction force (GRF) during seven sets of motions. Units: N/BW

	Groups	WOF	LF	RBB	PB	PPS	ELS	SKR
F(x)	Amateur	0.43 ±0.08	0.38 ±0.11	0.50 ±0.15	0.61 ±0.23	0.99 ±0.83	0.80 ±0.85	0.26 ±0.07
	Professional	0.51 ±0.10	0.42 ±0.12	0.45 ±0.06	0.51 ±0.11	1.71 ±1.04	2.03 ±1.00**	0.36 ±0.21
F(y)	Amateur	9.47 ±2.53	10.03 ±1.13	10.89 ±0.83	10.73 ±1.02	12.23 ±1.53	10.71 ±2.10	5.56 ±0.45
	Professional	9.73 ±0.77	10.13 ±0.37	10.20 ±0.28	10.12 ±0.56	11.29 ±1.18	13.05 ±1.66**	5.74 ±1.84
F(z)	Amateur	1.20 ±0.28	1.15 ±0.33	1.11 ±0.42	1.29 ±0.57	1.45 ±0.40	1.39 ±0.32	0.89 ±0.15
	Professional	1.42 ±0.21	1.15 ±0.30	1.03 ±0.25	0.92 ±0.26	1.95 ±0.67	2.22 ±0.67**	0.96 ±0.94

∗∗ P<0.01 and ∗P<0.05 represent the comparison between the professional group and the amateur group; the X-axis is the sagittal axis, the Y-axis is the vertical axis, and the Z-axis is the frontal axis.

3.2 Comparisons of three joint angles of the lower extremities

As shown in Table 3 and Fig. 4, during WOF, the knee flexion/extension angle, hip flexion/extension angle, hip abduction and rotation angle of the professional group were significantly larger than those of the amateur group (P<0.01).

During LF, the knee flexion/extension angle, hip abduction and rotation angle of the professional group were significantly larger than those of the amateur group (P<0.01), while the hip flexion/extension angle of the professional group was also larger (P<0.05).

During RBB, the ankle flexion/extension angle and knee flexion/extension angle of the professional group were significantly larger than those of the amateur group (P<0.01).

During PB, the ankle flexion/extension angle, knee flexion/extension angle and hip rotation angle of the professional group were significantly larger than those of the amateur group (P<0.01).

During PPS, the knee flexion/extension angle was significantly larger than that of the amateur group (P<0.01).

During ELS, the knee flexion/extension angle and hip rotation angle of the professional group were significantly larger than those of the amateur group (P<0.01).

During SKR, the hip flexion/extension angle of the professional group was significantly larger than that of the amateur group (P<0.01).

Table 3. Mean and standard deviation (mean ± SD) of the maximum joint angle of the hip, knee and ankle during the seven sets of motions. Units: N/BW

Joint angle	Group	WOF	LF	RBB	PB	PPS	ELS	SKR
Ankle flex/ext	Amateur	18.35 ±8.47	14.65 ±6.24	13.27 ±5.57	7.97 ±5.43	17.90 ±10.04	13.02 ±9.09	12.65 ±8.34
	Professional	21.87 ±13.00	17.51 ±11.08	28.42 ±12.72**	21.29 ±13.10**	17.42 ±10.31	12.57 ±7.77	14.76 ±7.74
Knee flex/ext	Amateur	52.34 ±18.15	63.29 ±14.26	81.37 ±12.67	72.33 ±18.97	71.02 ±16.31	61.11 ±18.12	59.99 ±31.69
	Professional	75.80 ±13.52**	97.49 ±19.76**	109.07 ±10.96**	98.53 ±16.75**	90.89 ±14.76**	84.20 ±11.86**	75.08 ±30.57
Hip flex/ext	Amateur	26.08 ±13.04	41.57 ±11.12	23.80 ±16.93	23.87 ±10.71	32.45 ±9.82	33.98 ±11.42	41.97 ±15.02
	Professional	50.46 ±17.75**	54.35 ±13.14*	36.44 ±11.09	31.79 ±10.52	36.25 ±11.38	45.58 ±11.88	70.28±20.25**
Hip abduction	Amateur	10.51 ±5.54	16.59 ±5.62	17.53 ±9.24	15.81 ±6.14	29.71 ±5.16	24.94 ±9.23	14.26 ±9.38
	Professional	30.54 ±16.04**	23.68 ±5.90**	24.53 ±6.50	19.55 ±7.24	32.92 ±9.69	31.61 ±4.73	17.40 ±10.74
Hip rotation	Amateur	11.02 ±10.41	19.15 ±11.68	23.44 ±12.55	23.41 ±11.52	27.43 ±9.75	17.56 ±6.88	13.40 ±6.36
	Professional	33.26 ±10.85**	37.97 ±15.90**	35.20 ±8.17	36.78 ±8.63**	34.91 ±12.47	35.77 ±11.17**	18.97 ±10.04

∗∗ P<0.01 and ∗P<0.05 represent comparisons of the amateur group and professional group. flex/ext: flexion/extension

3.3 Comparisons of the net joint reaction force of the three joints of the lower extremities

The joint reaction forces exerted on the ankle, knee and hip joints are shown with peak values in Table 4 and Fig. 5, where the X, Y, and Z axes represent the med–lat, vertical, and ant–post directions, respectively.

In terms of hip joints, during SKR, the hip joint reaction force of the professional group in the med–lat direction was higher than that of the amateur group (P<0.05); during WOF, LF, and RBB, the hip joint reaction forces of the professional group were significantly higher than that of the amateur group in both the vertical and ant–post directions (P<0.01).

In terms of knee joints, during LF, RBB, PB, PPS, and ELS, the knee joint reaction force of the professional group was significantly higher than that of the amateur group in the vertical direction (P<0.01), whereas no significant differences existed in the med–lat and ant–post directions.

In terms of ankle joints, during RBB, PB, and PPS, the ankle joint reaction forces of the professional group were significantly higher than that of the amateur group in the vertical direction (P<0.01), whereas no significant differences existed in the med–lat and ant–post directions.

Table 4. Mean and standard deviation (mean ± SD) of the maximum joint force of the hip, knee and ankle during the seven sets of motions. Units: N/BW

Joint force		Group	WOF	LF	RBB	PB	PPS	ELS	SKR
Hip	X-axis	Amateur	-0.77 ±0.48	-1.02 ±0.70	-0.62 ±0.34	-0.57 ±0.26	-0.73 ±0.27	-1.22 ±0.98	4.96 ±3.46
		Professional	-0.12 ±0.09	-0.75 ±0.46	-0.47 ±0.28	-0.75 ±0.98	-0.67 ±0.42	-0.55 ±0.57	10.69 ±5.51*
	Y-axis	Amateur	30.69 ±16.19	29.95 ±13.20	30.06 ±15.55	57.49 ±24.09	87.98 ±53.09	51.98 ±23.40	14.16 ±8.60
		Professional	74.62 ±39.66**	76.95 ±41.47**	117.53 ±99.00**	75.37 ±26.89	101.67 ±63.09	70.97 ±27.00	23.95 ±12.77
	Z-axis	Amateur	4.10 ±3.90	3.56 ±3.43	2.41 ±1.83	13.50 ±9.17	23.48 ±20.15	9.35 ±5.52	1.93 ±0.95
		Professional	20.75 ±14.30**	21.28 ±6.39**	27.41 ±12.58**	27.00 ±14.12	32.86 ±19.21	12.99 ±3.87	2.85 ±1.47
Knee	X-axis	Amateur	-2.18 ±3.63	-1.73 ±0.85	-0.82 ±0.42	-0.90 ±0.41	-0.46 ±0.21	-3.96 ±1.18	-1.35 ±0.64
		Professional	-0.56 ±2.37	-1.15 ±0.32	1.80 ±1.14	-1.03 ±1.16	0.05 ±0.02	0.46 ±0.13	-3.77 ±1.79
	Y-axis	Amateur	2.83 ±1.46	2.39 ±1.39	4.70 ±3.03	3.85 ±2.24	7.43 ±3.91	6.56 ±3.54	0.81 ±0.17
		Professional	3.73 ±3.11	7.32 ±2.95 **	10.85 ±4.80**	8.07 ±3.92 **	11.58 ±1.91**	11.24 ±3.92**	1.69 ±1.15
	Z-axis	Amateur	-0.99 ±1.05	-0.49 ±0.85	-0.02 ±0.01	-0.04 ±0.03	0.10 ±0.01	-5.57 ±4.53	-0.37 ±0.43
		Professional	0.32 ±0.43	0.15 ±0.11	-0.05 ±0.03	-0.26 ±0.14	0.11 ±0.07	0.02 ±0.02	-1.59 ±1.21
Ankle	X-axis	Amateur	1.26 ±1.06	1.76 ±1.52	4.25 ±1.83	4.58 ±1.88	3.72 ±1.29	3.01 ±1.79	6.95 ±2.67
		Professional	3.13 ±2.86	3.54 ±2.90	4.74 ±1.67	3.91 ±2.55	4.35 ±1.24	5.40 ±3.49	6.52 ±0.95
	Y-axis	Amateur	13.65 ±5.81	13.42 ±4.37	19.11 ±10.25	18.62 ±7.78	90.45 ±28.76	60.94 ±22.12	21.48 ±17.27
		Professional	18.29 ±8.06	18.37 ±13.23	34.77 ±15.92**	23.07 ±13.20**	148.97 ±30.94**	87.42 ±33.65	10.65 ±7.90
	Z-axis	Amateur	-1.04 ±1.44	-1.31 ±1.09	-0.08 ±0.11	-0.15 ±0.10	-0.08 ±0.10	-8.87 ±2.05	-0.05 ±0.10
		Professional	-0.11 ±0.20	-0.20 ±0.21	-0.05 ±0.09	-0.37 ±0.74	-0.07 ±0.18	-6.17 ±2.14	-2.39 ±6.92

∗∗ P<0.01 represents comparisons between the amateur group and the professional group. The X-axis is the sagittal axis, the Y-axis is the vertical axis and the Z-axis is the frontal axis.

3.4 Comparisons of net joint torque of the three joints in the lower extremities

As shown in Table 5 and Fig. 6, during RBB, hip abduction torque, hip flexion/extension torque and knee flexion/extension torque of the professional group were significantly larger than those of the amateur group (P<0.01), while hip rotation torque of the professional group was larger, but not significantly, than that of the amateur group (P<0.05).

During PB, the hip abduction torque, hip flexion/extension torque and ankle flexion/extension torque of the professional group were significantly larger than those of the amateur group (P<0.01).

During ELS, the hip flexion/extension torque and knee flexion/extension torque of the professional group were significantly larger than those of the amateur group (P<0.01).

During the remaining four sets of motions, there were no significant differences between the two groups’ net joint torque of the three joints.

Table 5. Mean and standard deviation (mean ± SD) of the maximum joint torque of the hip, knee and ankle during the seven sets of motions. Units: N/BW

Joint torque	Group	WOF	LF	RRB	PB	PPS	ELS	SKR
Hip abduction	Amateur	0.28±0.10	0.28±0.22	0.61±0.23	0.55±0.26	1.00±0.23	0.89±0.36	0.27±0.12
	Professional	0.41±0.13	0.53±0.27	1.26±0.76**	0.90±0.26**	1.25±0.71	1.04±0.21	0.21±0.10
Hip rotation	Amateur	0.19±0.08	0.21±0.14	0.10±0.09	0.11±0.09	0.32±0.18	0.25±0.11	0.09±0.04
	Professional	0.34±0.24	0.20±0.07	0.35±0.19*	0.08±0.04	0.51±0.23	0.42±0.21	0.08±0.04
Hip flex/ext	Amateur	0.40±0.17	0.39±0.37	0.30±0.17	0.32±0.24	0.64±0.33	0.09±0.07	0.38±0.13
	Professional	0.38±0.14	0.36±0.23	1.37±1.06**	0.59±0.25**	0.81±0.42	0.88±0.83**	0.37±0.04
Knee flex/ext	Amateur	0.39±0.24	0.28±0.20	0.10±0.01	0.09±0.01	0.20±0.11	0.36±0.29	0.29±0.19
	Professional	0.53±0.46	0.33±0.26	0.54±0.08**	0.18±0.12	0.22±0.10	0.44±0.45**	0.34±0.26
Ankle flex/ext	Amateur	0.32±0.28	0.44±0.36	0.90±0.38	0.57±0.21	0.94±0.24	0.70±0.29	0.66±0.14
	Professional	0.55±0.34	0.57±0.45	0.91±0.23	0.76±0.09**	0.86±0.21	0.92±0.38	0.51±0.36

∗∗ P<0.01 and ∗ P<0.05 represent comparisons of the amateur group and the professional group.

3.5 Comparisons of lower extremity muscle strength

Table. 6 and Fig. 7 compared the lower extremity muscle strength between two groups during seven sets of motions.

During WOF, the professional group showed significantly more strength than the amateur group for the tibialis anterio, tibialis posterior, and gastrocnemius (P<0.01).

During LF, the professional group showed significantly more strength than the amateur group for the rectus femoris, vastus lateralis, vastus medialis, gluteus minimus, tibialis anterio, and gastrocnemius (P<0.01).

During RBB, the professional group showed significantly more strength than the amateur group for the rectus femoris, vastus medialis, biceps femoris, iliacus, gluteus maximus, gluteus minimus, and adductor longus (P<0.01).

During PB, the professional group showed significantly more strength than the amateur group for the iliacus and sartorius (P<0.01).

During PPS, the professional group showed significantly more strength than the amateur group for the rectus femoris, vastus lateralis, vastus medialis, iliacus, and gluteus minimus (P<0.01).

During ELS, the professional group showed significantly more strength than the amateur group for the biceps femoris, iliacus, adductor longus, and sartorius (P<0.01).

During SKR, the professional group showed significantly more strength than the amateur group for the iliacus (P<0.01).

Table 6. Mean and standard deviation (mean ± SD) of muscle strength during the seven sets of motions. Units:N/BW

Muscles	Group	WOF	LF	RBB	PB	PPS
Rectus femoris	Amateur	3.28±1.31	2.77±1.47	8.27±3.59	7.05±2.10	8.47±2.64
	Professional	3.95±2.14	5.85±3.50**	11.86±3.07**	8.55±3.05	13.10±2.8
Vastus lateralis	Amateur	10.86±4.70	10.19±5.50	25.50±11.30	24.53±8.18	28.82±10.
	Professional	11.70±9.51	23.73±10.35**	36.25±12.75	29.58±14.26	44.81±6.4
Vastus medialis	Amateur	5.63±2.74	5.04±2.73	13.15±6.81	12.92±2.86	15.18±5.3
	Professional	7.10±5.37	12.09±4.59**	22.16±7.14**	15.86±8.69	24.97±4.3
Biceps femoris	Amateur	3.12±2.28	4.72±2.95	2.10±0.79	3.66±2.90	5.38±3.46
	Professional	5.12±2.29	5.11±2.96	10.92±10.17**	4.83±2.66	8.29±5.02
Iliacus	Amateur	2.65±1.58	2.17±1.05	2.29±1.36	1.59±0.99	3.75±4.26
	Professional	2.43±1.19	2.15±0.66	7.61±6.09**	3.15±0.88**	7.76±2.98*
Gluteus maximus	Amateur	7.99±4.74	8.20±4.45	3.72±2.23	8.76±7.09	15.75±8.1
	Professional	11.50±5.61	13.47±7.32	18.65±15.01**	11.53±18.03	18.89±8.3
Gluteus minimus	Amateur	1.77±1.03	1.87±1.77	3.73±1.99	3.30±1.06	5.88±1.88
	Professional	2.89±1.06	3.84±1.87**	8.29±3.41**	3.93±2.91	9.21±3.83*
Sartorius	Amateur	1.83±0.91	1.55±1.28	1.38±0.41	1.35±0.74	2.14±1.74
	Professional	1.85±0.51	2.04±0.51	2.54±0.55	5.00±1.24**	3.43±2.59
Adductor longus	Amateur	0.68±0.76	0.95±0.70	0.70±0.39	0.66±0.44	2.00±1.45
	Professional	1.11±0.88	0.40±0.26	3.57±2.82**	1.24±0.71	2.67±0.95
Tibialis anterior	Amateur	0.81±0.53	1.94±1.64	0.16±0.10	0.21±0.13	5.42±4.12
	Professional	4.87±4.30**	4.85±2.71**	0.80±1.32	0.39±0.27	4.85±1.32
Tibialis posterior	Amateur	0.05±0.01	0.62±0.49	1.43±0.67	0.22±0.41	1.30±0.90
	Professional	0.50±0.46**	0.89±0.73	1.98±1.11	0.54±0.27	1.42±1.32
Gastrocnemius	Amateur	1.86±0.31	3.49±2.53	19.35±10.79	16.27±7.26	14.03±5.0
	Professional	12.25±3.38**	11.32±3.10**	23.76±13.65	19.64±12.28	17.59±9.06

∗∗ P<0.01 represent comparisons of the amateur group and the professional group.

3.6 Comparisons of femur load during Bafa Wubu of Tai Chi and walking

As shown in Fig. 8 and Fig. 9, there was no significant difference in femur load during SKR and walking, whereas femur load is more significant during other six sets of actions than that during walking. The femur load in descending order was ELS, PPS, PB, LF, WOF, RBB, SKR, and walking. The maximum loading point was located at the greater trochanter of the femur during walking, while it shifted to the body of the femur during the seven sets of actions. Femur stress was the largest during ELS, mainly located on the outer side of the body of the femur, whereas the maximum loading point shifts to the inner side of the body of the femur during PPS, to the posterior inner-side of the body of the femur during PB, to the inner side of the body of the femur during WOF, to the neck of the femur during PB, to the posterior outer-side of the body of the femur and the neck of the femur during LF, to the inner side of the body of the femur during SKR. During the training process of Bafa Wubu, the stress constantly changes during the actions and is distributed evenly on the femur, which indicates Bafa Wubu's capacity to stimulate femur effectively.

3.7 Verification of the lower extremity muscle strength from the AnyBody simulation

To verify the effectiveness of the AnyBody simulation data, a correlation analysis of EMG and the simulated muscle strength of the lower extremities of AnyBody was conducted. As demonstrated in Fig. 10, there is a strong correlation (r>0.7) between the simulated muscle strength and the EMG of the lower extremities, which proves that the AnyBody simulation is reliable.

Discussion

4.1 Ground reaction force activity analysis

As an essential metric in biomechanics, ground reaction force (GRF) covers the parameters of loading rate (LR), first impact peak, second impact peak, and the transition between the first and second impact peaks in heel strike runners(Yu et al.,2021). Based on the observed peak of GRF, it was found that among the seven sets of motions, the GRF of the professional group was significantly higher than that of the amateur group in the vertical, anterior–posterior (ant–post), and medial–lateral (med–lat) directions. Matijevich et al. concluded that increases in GRF metrics could not indicate increases in tibial bone load or the overuse injury risk(Matijevich et al.,2019), In contrast it is possibly related to muscle strength, muscle contributions and mechanical arrangement(Gao et al.,2020). Bafa Wubu of Tai Chi integrates firmness and softness so that starting and landing should be gentle like a catwalk and powerful(Zhu et al.,2021). During ELS, the center of gravity is shifted from the left leg to the right leg when the body moves sideways. In the first stage, the pressure on the ground is slowly released. In the next stage, where elbowing is rapidly released from within, the muscle strength of the lower extremity becomes downward and outward so that GRF increases in the vertical, med–lat and ant–post directions. Joints of the lower extremities receive multidirectional stimulation from such a comprehensive activity(Zhang et al.,2021).

4.2 Lower extremity joint activity analysis

Bafa Wubu of Tai Chi is a slow-to-fast and fast-to-slow sport where many motions are based on half squats so that the knee flexion/extension angle of the professional group is much larger than that of the amateur group. During Bafa Wubu of Tai Chi, half squats effectively exercise the muscles around the knee joints, thereby improving the stability and proprioception of the knee joints(Zhou et al.,2016); however, further studies are needed to investigate whether such a continuous flexion and extension movement would result in increasing fatigue of the knee joints. In addition, Bafa Wubu of Tai Chi is characterized by a flexible combination of an empty gait and solid gait, during which the center of gravity shifts between the lower extremities and the slow landing of the ankles, since they are the closest joints to the ground and support the entire body. The ankle flexion/extension angle of the professional group was significantly larger than that of the amateur group during motions with back steps. When practitioners increase their ankle flexion/extension angle appropriately, it allows their body to land more effectively over a prolonged time and strengthens their personal control of their ankles(Liye et al.,2017;Kou et al.,2021). In addition, during Bafa Wubu of Tai Chi, the practitioners' waist and hip set the lower extremity in motion, which is evident when the motions are started from the legs and manipulated by the waist, and the lower extremity moves smoothly in five directions during the control of the hip joints(Mao et al.,2006). Therefore, it is concluded that Tai Chi training is beneficial for enhancing the ability of the hips to control the lower extremity(Ko et al.,2020). It is noteworthy that amateurs are likely to display an excessive flexion/extension angle of the lower extremities and an insufficient capacity to control the abduction and rotation of the hip joints when performing Bafa Wubu of Tai Chi.

Zhu, Q(Zhu Q et al.,2016) reported that Tai Chi training could increase joint loading of the lower extremities due to the angles of joints of the lower extremities and the exercise methods of Tai Chi. In this experiment, the joint loading of professional participants was found to be greater than that of amateur participants. For Bafa Wubu performers, the center of gravity is expected to be low and smooth, and the motions are expected to be gentle and slow in a coherent continuum. Coherence means that stress on the lower extremities is first exerted at the heel, then is transmitted to the calf through the ankles, and rises to the knee, then the hip through rotation, finally forming a penetrating force of the three joints of the lower extremities, which positively stimulates them. Apart from moving forward, motions with steps backward and sideways help increase joint loading in the horizontal and vertical directions and enrich the exercise activities of the lower extremities. Due to its uniqueness, Bafa Wubu training refines the performers' capacity for postural control.

Additionally, joint torque is a key element of muscle activities around joints(Yu H et al.,2021), which plays a pivotal role in motion. In the transition of actions, performers should maintain a relatively low center of mass to increase the joint torque of the lower extremities(Nok-Yeung et al.,2014). The joint torque on the knee and hip joints significantly increases during motions with steps backward and sideways. Tai Chi performers are required to generate force from the foot and transmit it through the ankles. As a result, during RBB and ELS, the ankle flexion/extension angle of professional participants was significantly larger than that of amateur participants in that professional athletes strengthened their kinesthesia and muscle activation at the knees after receiving long-term training. Cheng and Liang's experiment(Cheng et al.,2017) verified that 24 weeks of Tai Chi training improves kinesthesia of knee flexion and extension, and 48 weeks of Tai Chi training significantly improves kinesthesia of knee and ankle flexion and extension. It can be summarized that performing Tai Chi in the long term contributes to improving the joint torque of the lower extremities and kinesthesia of the knees and ankles(Shaffer et al.,2007; Hu X et al.,2019).

4.3 Lower extremity muscle activity analysis

Tai Chi is slow in movement with a large joint load, which indicates that more muscles are involved in active exercise(Xian et al.,2017). The WOF and LF depicted in this paper involve a slow landing from heel off to toe off, which results in significantly longer and more frequent activation of the plantar flexor and dorsiflexors at the ankle, as well as greater stimulation of the muscles of the lower extremities(Wang et al.,2016). The WOF and LF are known to be forward-moving, but the LF contains a force of external rotation in addition to forward force. When the hip joints generate a force forward, their external rotation is complemented at the same time, which can be proven by the professional participants' greater muscle strength of the vastus lateralis, vastus medialis, and gluteus minimus. Bafa Wubu is characterized by rotation and twisting such that knee extensor and flexor muscles and hip abductors are responsible for stepping forward, whereas beginners tend to ignore the added strength of rotation.

When professional participants step backward, hip abductors, hip adductors and knee extensor and flexor muscles are responsible for providing strength. Since both RPB and PB require force backward, downward, and outward with the center of gravity shifting between the lower extremities, the joints of the hip and knees are extended and flexed, while the lower extremity muscles undergo repeated concentric and eccentric contractions(Hill et al.,2020). Hence, Bafa Wubu is of great value to increase the muscle strength of the lower extremities(Zhang et al.,2017).

In addition, Bafa Wubu of Tai Chi contains special motions in the med-lat direction. This study found that the hip abductors and hip adductors of the professional participants, including the adductor longus, vastus lateralis, vastus medialis, sartorius, and gluteus minimus, displayed significantly more strength than amateur ones. This proves that lateral movements effectively exercise muscles on both sides of the thigh and strengthen the hip abductors and hip adductors, which activates the lateral nerves and muscles and improves the lateral balance capacity(Chen et al.,2021). During SKR, participants must stand unassisted on one leg with another knee raised and remain balanced. The professional participants' iliacus of the raised leg exerted the most force during SKR, which may result from the height of the raised leg. The iliacus, controlling the abduction and rotation of the hip joints, plays an essential role in balancing the body postures(Alam et al.,2018), so it is responsible for single leg balance. For beginners, SKR training contributes to strengthening the iliacus and efficiently improving their physical balance.

4.4 Lower extremity femur stress analysis

Bafa Wubu of Tai Chi and walking are gait cycle movements with many similar biomechanical characteristics(Yan et al.,2019). In Fig. 8 and Fig. 9, the femur load in descending order was ELS, PPS, PB, LF, WOF, RBB, SKR, and walking. The maximum loading point was located at the greater trochanter of the femur while walking and it shifted to the body of the femur during Bafa Wubu. Furthermore, the maximum loading point also changed with strength generation. For instance, the maximum loading point shifted onto two sides of the body of the femur when practitioners stepped sideways. Bafa Wubu involves motions in five directions, which consequently adjusts the stress zone so that the femur receives omnidirectional stimulus. Previous studies have discovered that changes in the bones are mainly attributed to external forces so that when bone stress increases, bone trabeculae grow more densely, more osteoblasts are activated, and bone density increases(Wu et al.,2020). This finding exactly complies with the findings that Bafa Wubu training improves bone density and reduces bone loss because femur stress gets enhanced(Pang et al.,2021). Bafa Wubu training is a continuum where the femur stress and loading point move during the motions.

Conclusions

During ELS, the ground reaction force of the professional group was significantly higher than that of the amateur group in the vertical, anterior–posterior, and medial–lateral directions.

The professional group performed Bafa Wubu with a larger knee flexion/extension angle during the whole process, a larger ankle flexion/extension angle while stepping backward, and a larger hip abduction and rotation angle while stepping sideways.

Whether stepping forward or backward, hip joint reaction forces in the vertical and ant–post directions, knee joint reaction force in the vertical direction, and ankle joint reaction force in the vertical direction were significantly higher in the professional group. Additionally, they displayed a significantly higher joint reaction force at the ankle and knee in the vertical direction when moving in the medial–lateral direction.

During backward stepping, the hip abduction/rotation/flexion/extension torque, knee flexion/extension torque, and ankle flexion/extension torque of professional participants were all significantly larger than those of amateur participants. Motion with steps sideways exerted a greater impact on joint flexion/extension torque at the hip and knee.

Different actions activate muscles of different types at different levels. During SKR, the professional group generated greater iliacus strength than the amateur group.

Through stress analysis of the femur, we found that femur stress during Bafa Wubu was significantly larger than that during walking. In addition, the femur head mainly bore the load during walking, while it shifted to the body of the femur during Bafa Wubu. Meanwhile, the threshold of the load and maximum loading point changed during the movements.

Suggestions

Beginners are likely to encounter problems in Bafa Wubu training. For instance, the flexion/extension angle of their lower limb joints is excessive, the strength of their joints is insufficient, and their capacity to control their hip abduction and rotation is inadequate. Hence, practitioners are encouraged to appropriately increase their knee flexion/extension angle and strengthen their control of their hip joints. Targeted muscles should be trained in response to strength generating modes of action. In addition, the iliacus should be strengthened for standing knee raises in that it plays an essential role in stabilizing the lower extremity balance. Otherwise, beginners may stagger or even fall due to a lack of iliacus strength. In brief, to achieve optimal effects, practitioners are encouraged to pursue normative and continuous technical training of Bafa Wubu so that the femur can be comprehensively stimulated.

Abbreviations

BMI: Body mass index;WOF: Warding off with steps forward;LF: Laying with steps forward; RBB: Rolling back with steps backward; PB: Plucking with steps backward; PPS: Pushing and pressing with steps sideways; ELS: Elbowing and leaning with steps sideways; SKR: Standing knee raises; flex/ext: flexion/extension;

Declarations

Authors' contributions

Haojie Li conceived the study. Ji Zhongqiu and Shaojun Lyu designed the study protocol. Data collection was conducted by Fang Peng, Xiongfeng Li, and DanDanielle Guo. Haojie Li and Fang Peng performed statistical analysis. Shunze Shen contributed to the recruitment of subjects. Haojie Li contributed to writing and revising the manuscript. All authors assisted in drafting manuscript and approved the final manuscript. Authors were responsible for their personal contributions.

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Availability of data and materials

The datasets generated during the present study are available from the cor-responding author upon request.

Ethics approval and consent to participate

All methods in this study were carried out in accordance with the 'Declaration of Helsinki' relevant guidelines and regulations. This study was reviewed and approved by the Ethics Committee of the China National Rehabilitation Center (No. S20220206). The participants provided written informed consent to participate in this study. The potential risks and benefts of participation in this study were explained to each participant in advance. All participants provided signed informed con-sent before participation.

Consent for publication

All participants provided signed informed consent for the publication of this study.

Competing interests

All authors have no conficts of interest to declare.

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Figures

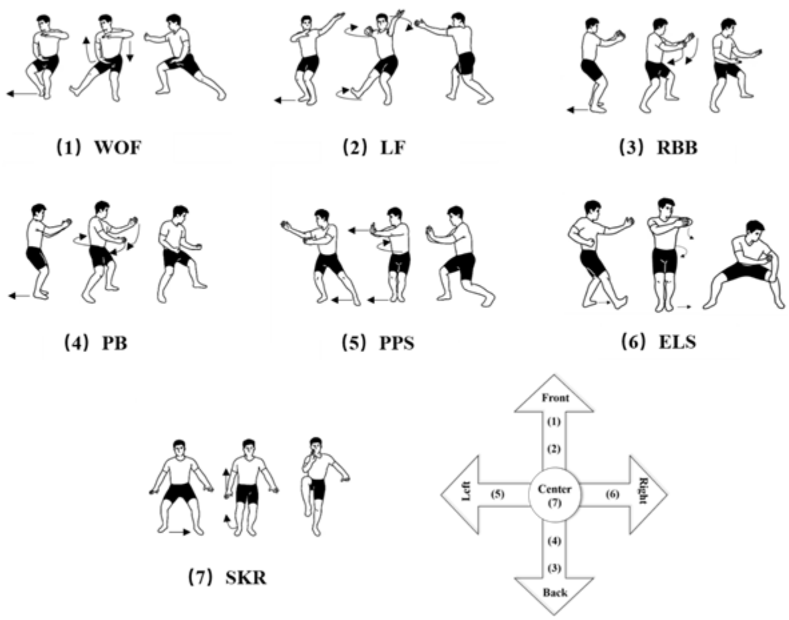

Figure 1

Illustration of the seven sets of motions in Bafa Wubu of Tai Chi: (1) WOF: Warding off with steps forward, (2) LF: Laying with steps forward, (3) RBB: Rolling back with steps backward, (4) PB: Plucking with steps backward, (5) PPS: Pushing and pressing with steps sideways, (6) ELS: Elbowing and leaning with steps sideways, (7) SKR: Standing knee raises.

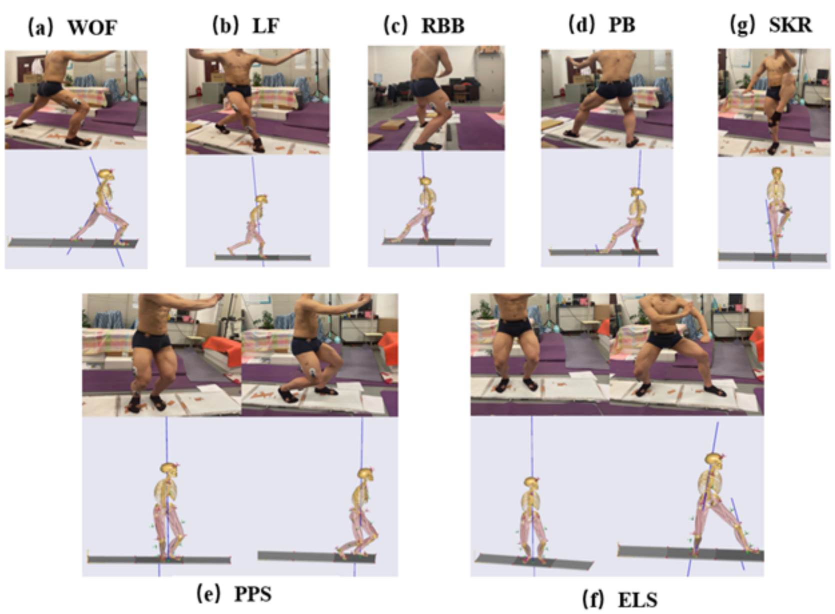

Figure 2

Musculoskeletal models of seven sets of motions in Bafa Wubu of Tai Chi: (a) WOF, (b) LF, (c) RBB, (d) PB, (e) PPS, (f) ELS, and (g) SKR.

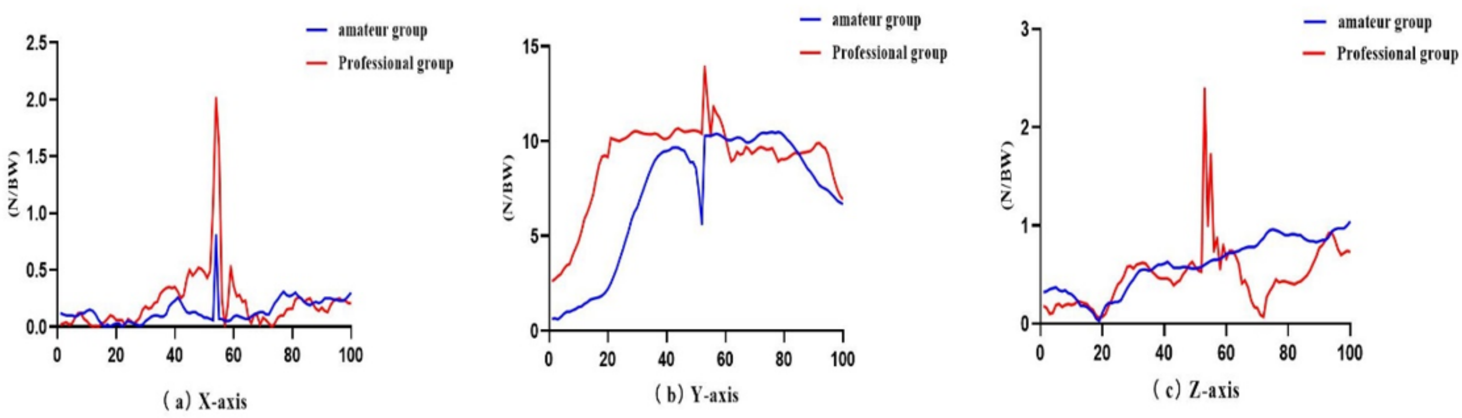

Figure 3

Comparisons of the GRF of the amateur group (blue line) and the professional group (red line) during ELS: (a) GRF on the X-axis, (b) GRF on the Y-axis, and (c) GRF on the Z-axis.

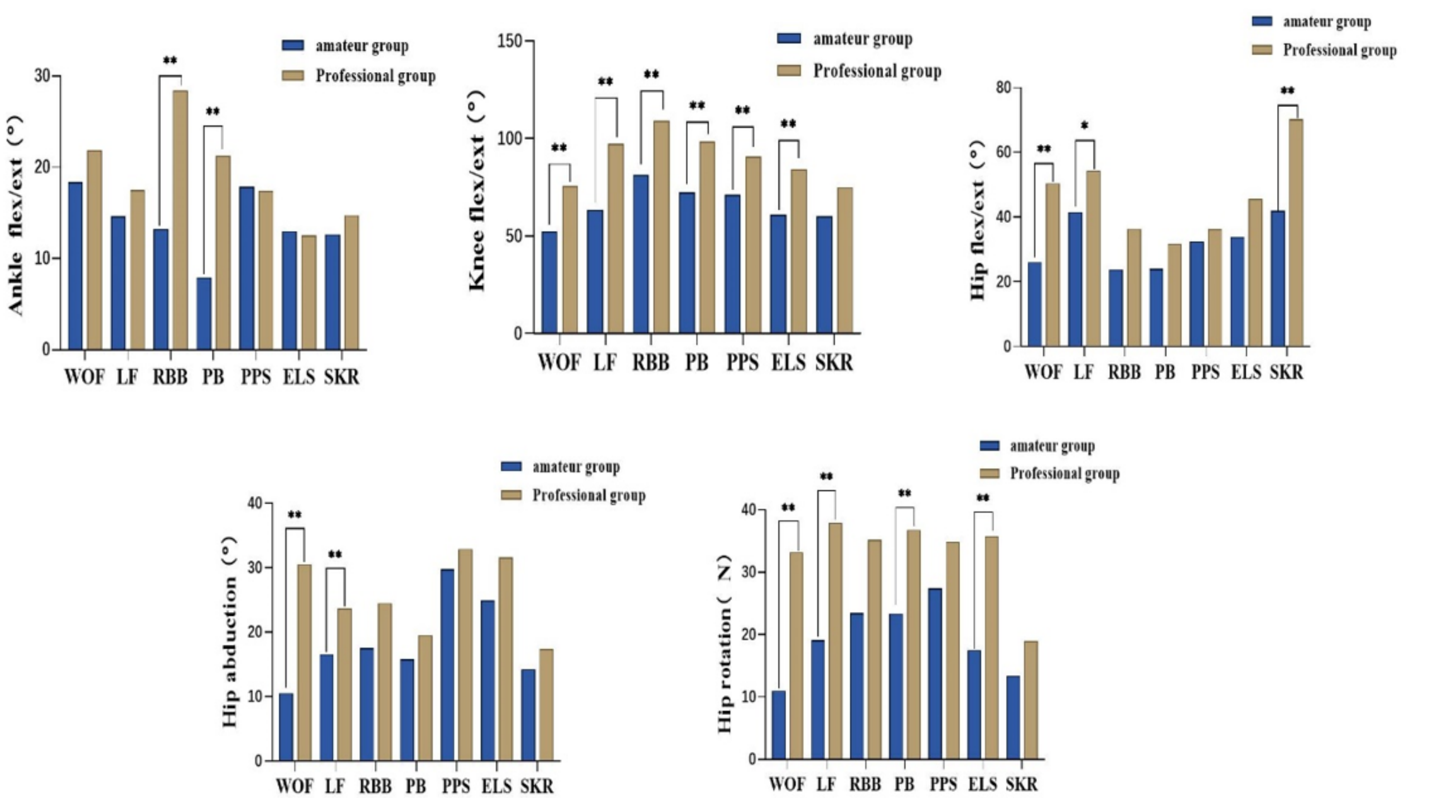

Figure 4

Comparisons of the joint angles of the hip, knee and ankle during the seven sets of motions between the amateur group (blue bar) and the professional group (yellow bar).

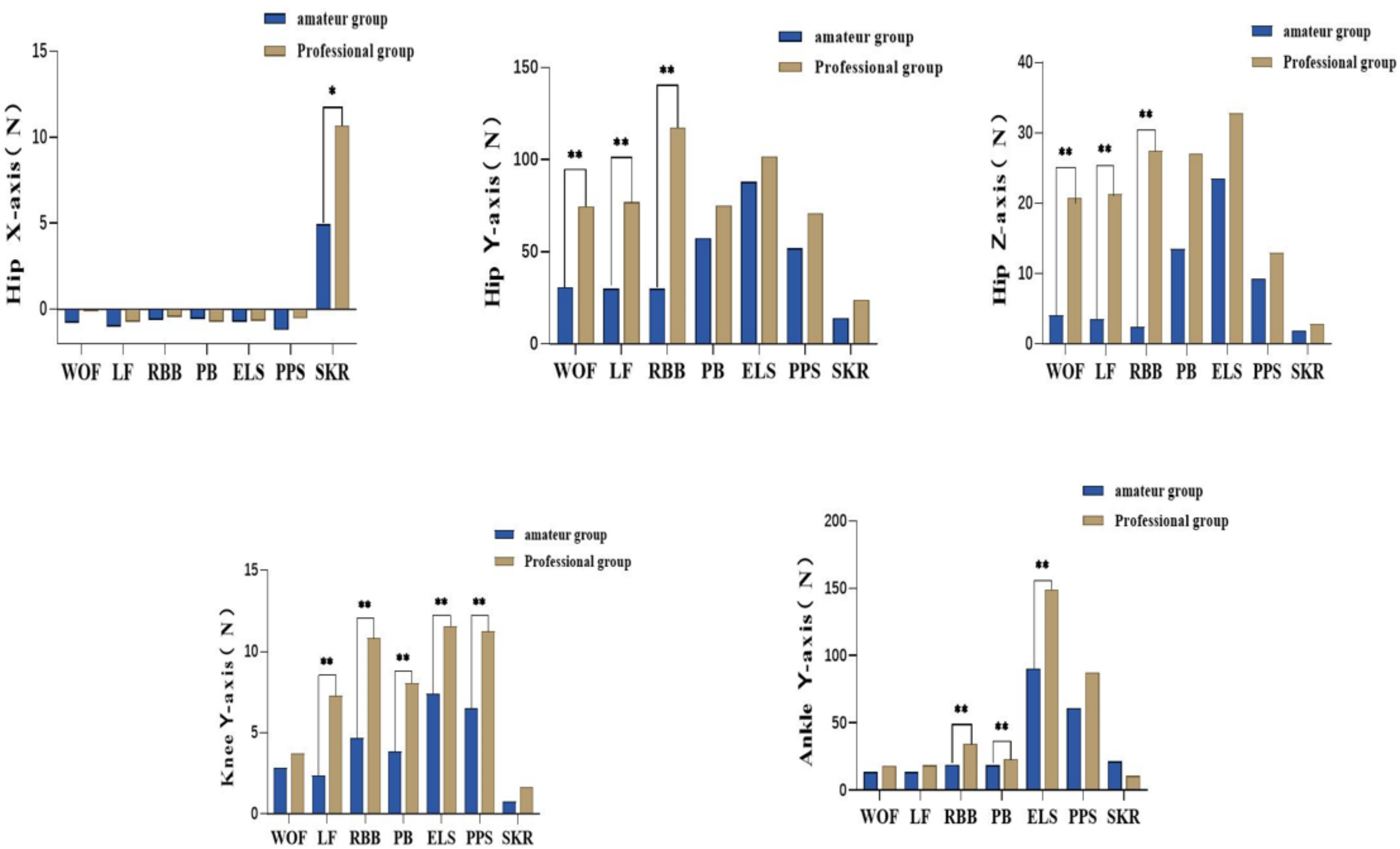

Figure 5

∗∗ P<0.01 and ∗P<0.05 represent comparisons of the joint angles of the hip, knee and ankle during the seven sets of motions between the amateur group (blue bar) and the professional group (yellow bar).

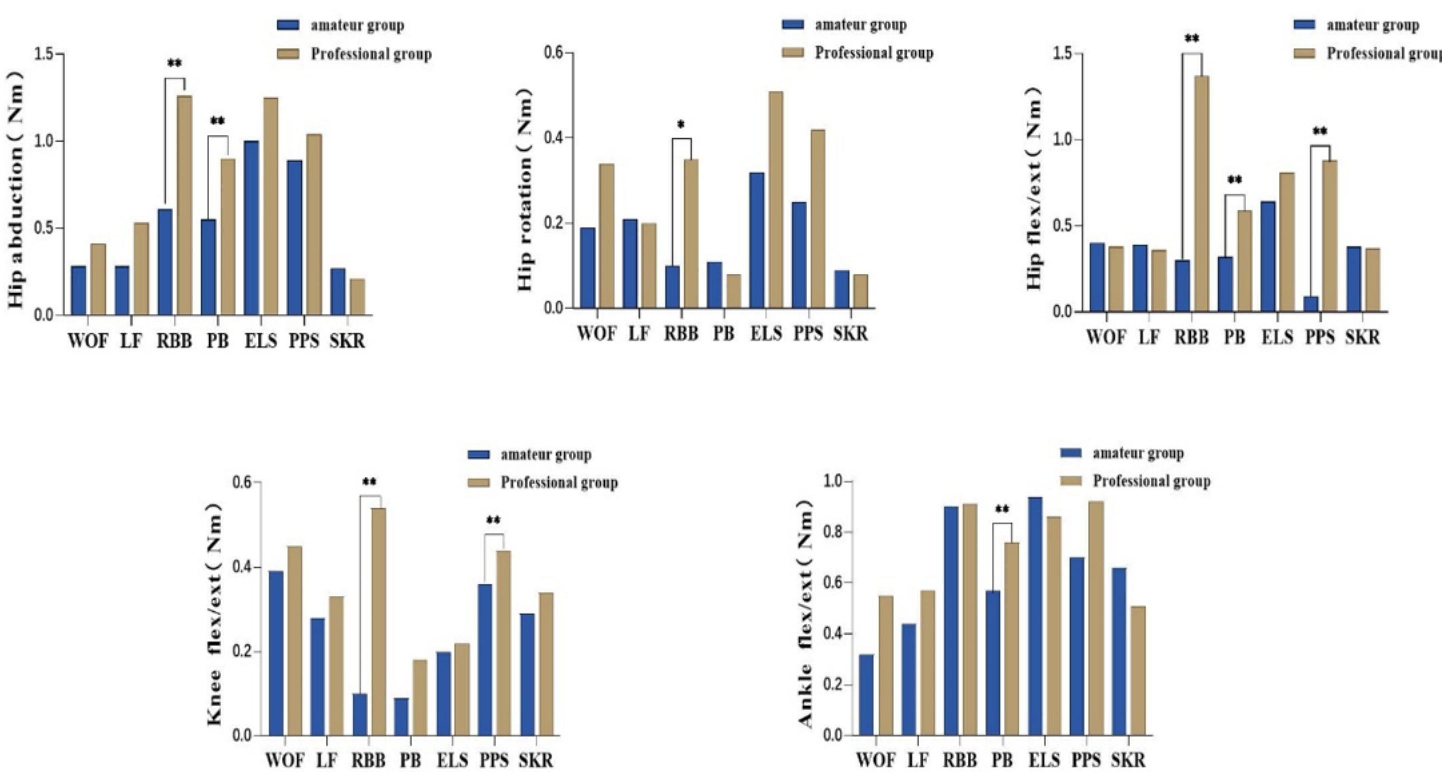

Figure 6

∗∗ P<0.01 and ∗P<0.05 represent comparisons of the joint torque of the hip, knee and ankle during the seven sets of motions between the amateur group (blue bar) and the professional group (yellow bar).

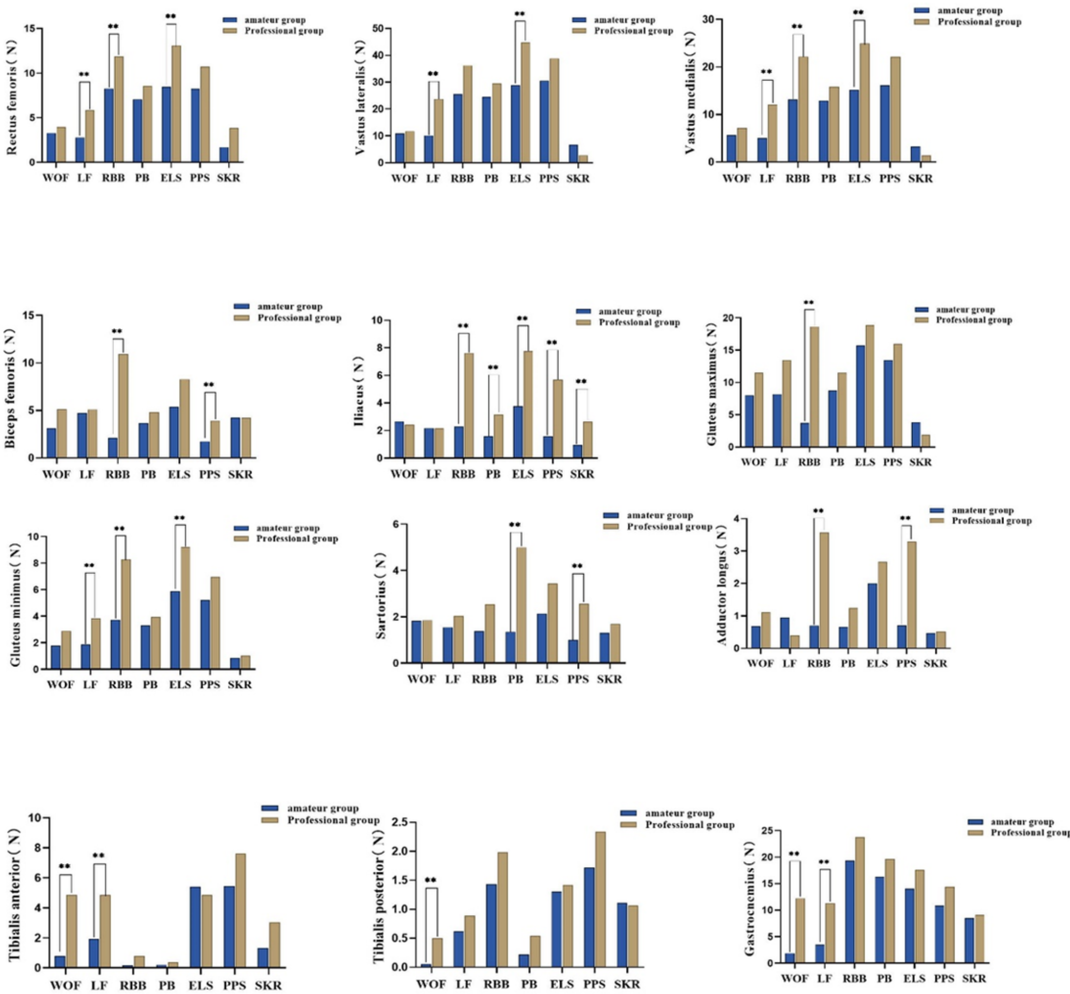

Figure 7

∗∗ P<0.01 and ∗P<0.05 represent comparisons of the muscle strength of the lower extremities during the seven sets of motions between the amateur group (blue bar) and the professional group (yellow bar).

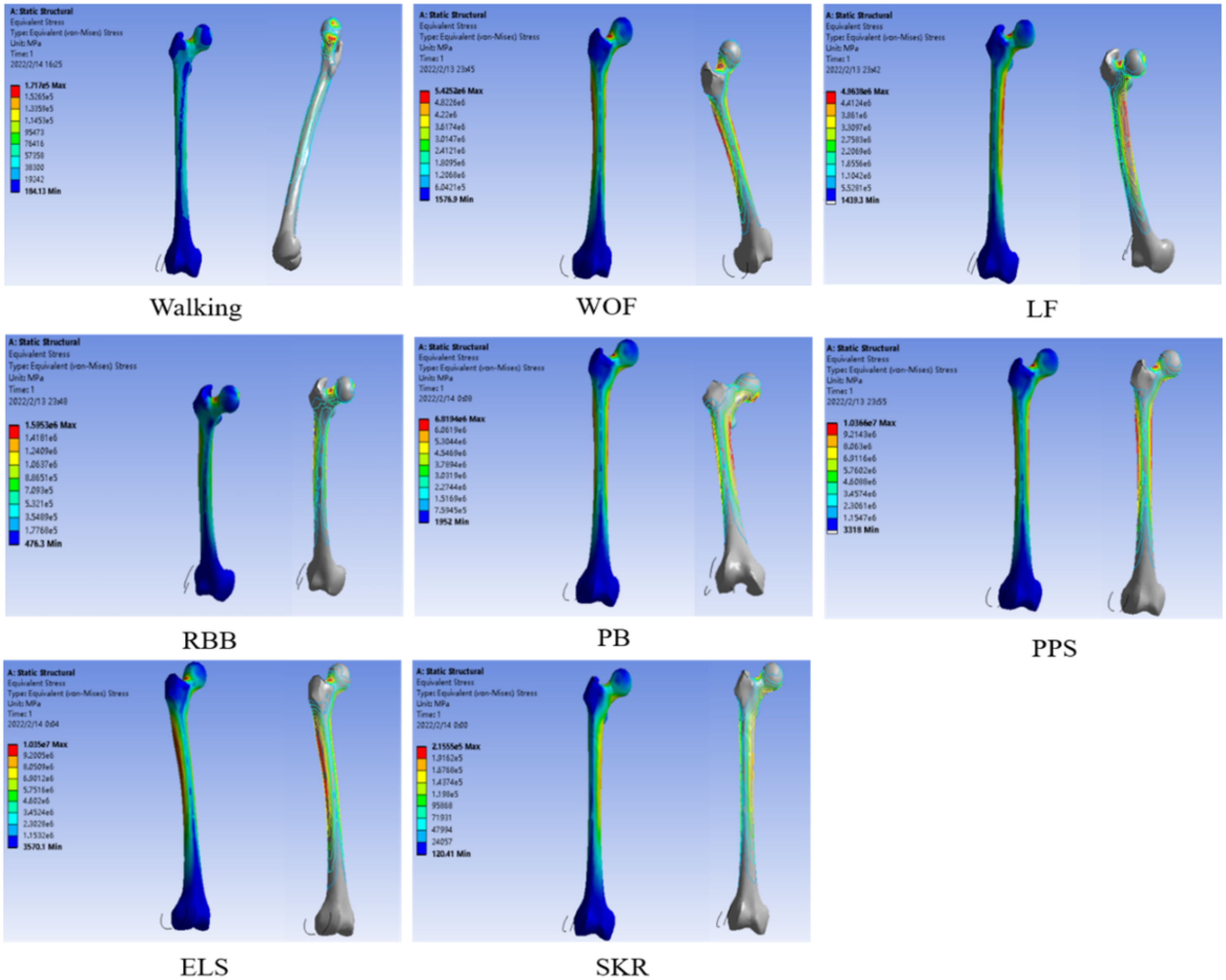

Figure 8

Equivalent stress distribution of the femur during Bafa Wubu and walking. The warmer the color is, the greater the stress. The red arrow indicates the maximum stress

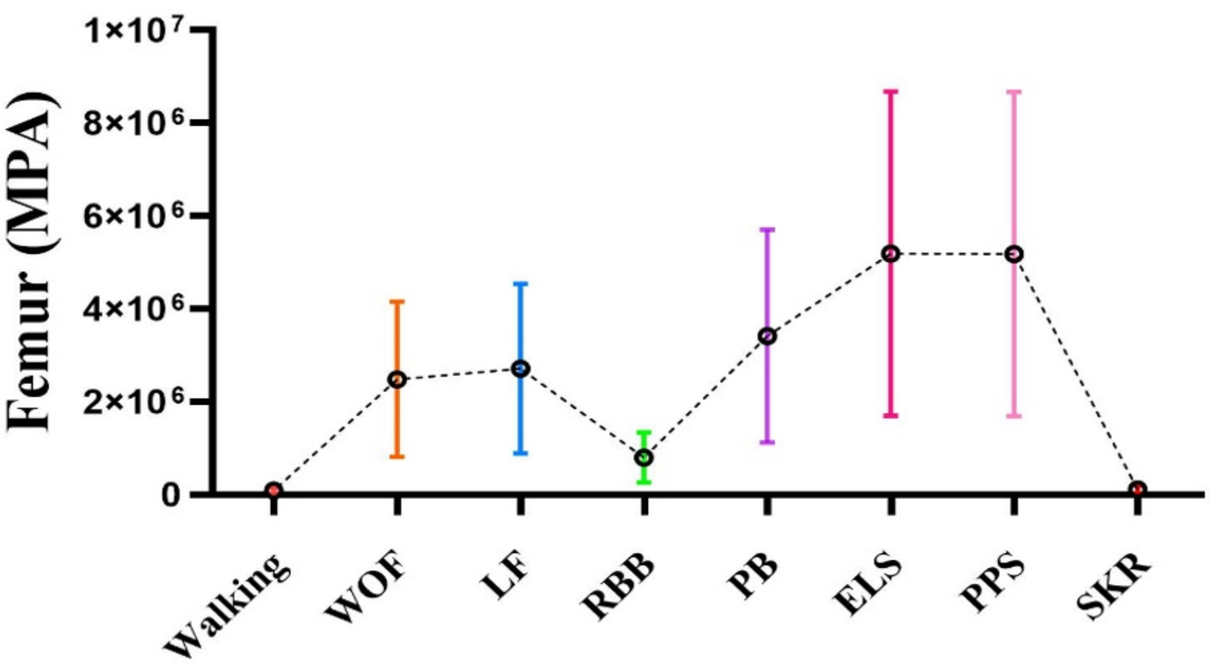

Figure 9

Change of mean values of femur stress distribution during Bafa Wubu and walking (walking in red; WOF in orange; LF in blue; RBB in green; PB in purple; ELS in rose; PPS in pink and SKR in red)

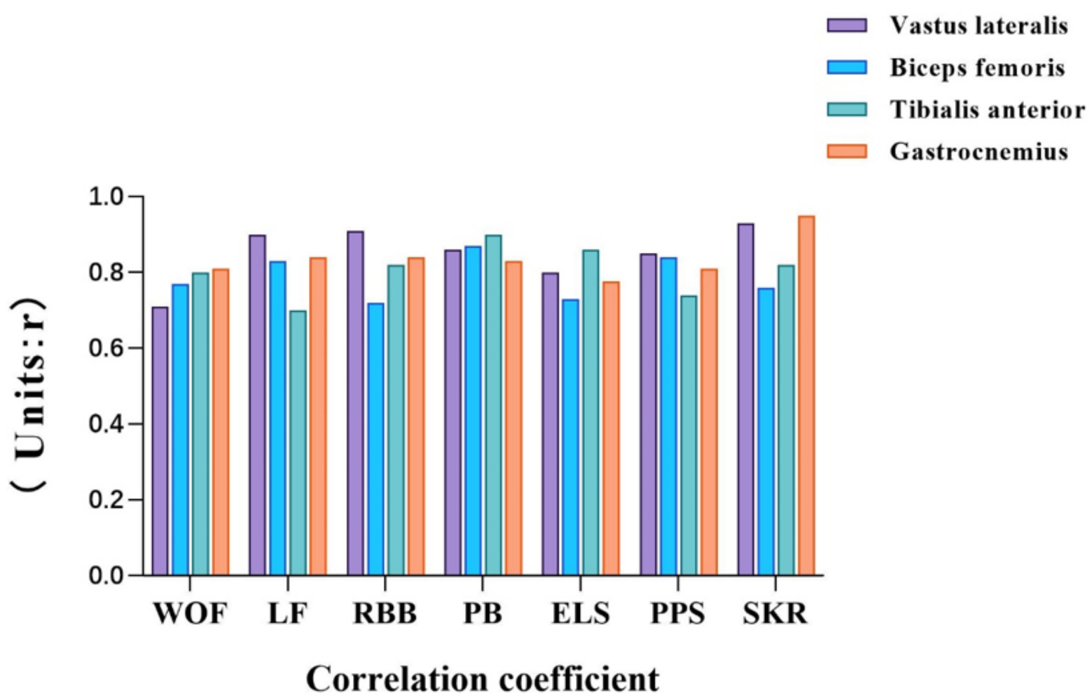

Figure 10

Correlation results of the AnyBody simulation muscle strength and IEMG. r>0.6 represents a strong correlation. r>0.8 represents an extreme correlation (vastus lateralis in purple; biceps femoris in blue; tibialis anterior in green and gastrocnemius in orange).