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Randomized controlled trial of whole body vibration training on lower limb muscle strength in sub elite short track speed skaters

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This randomized controlled trial aimed to examine the effects of whole-body vibration training (WBVT) at different frequencies on lower-limb muscular strength in sub-elite short-track speed skaters. This study employed a randomized controlled trial methodology. Subsequent to the screening process, a total of 75 male sub-elite short track speed skaters were selected from the Shenyang Sport University. Participants were randomly allocated to one of three groups ($n = 25$ per group): 30 Hz WBVT, 50 Hz WBVT, or a non-vibration control group. The intervention was administered twice weekly for four weeks, with three groups participating on each occasion. The intervention lasted four weeks, with an amplitude of 2 mm. Each session comprised 30 s of whole-body vibration training. The control group comprised 25 participants who performed the same duration and posture of semi-squatting movement on the vibration platform, but without additional vibration stimulation. Maximal strength, rapid force, and muscular endurance during concentric contractions of the knee flexors and extensors were assessed using an IsoMed 2000 isokinetic dynamometer system pre- and post-intervention. The results indicate that after four weeks of WBVT, significant improvements were observed in knee flexor and extensor strength among sub-elite short-track speed skaters ($p < 0.01$). A 50 Hz frequency was more effective than 30 Hz (at 2 mm amplitude) in enhancing maximal and power, particularly for bilateral knee flexors and the left extensor ($p < 0.05$), and also improved strength endurance, especially in the left knee flexors ($p < 0.01$).

Keywords Whole-body vibration training, Different frequencies, Short-track speed skaters, Lower limb muscular strength

Short-distance speed skating, also known as short track speed skating, is a discipline requiring high levels of physical proficiency, particularly within speed-strength sports. The competitive abilities of athletes in this field are significantly influenced by their physical fitness, technical abilities, and strategic proficiency. To excel in this sport, athletes require rapid neural conduction, high levels of strength, and the ability to adapt to the rapid movements and frequent changes in direction on the ice. Therefore, a strong foundation of lower limb muscular strength is essential for short-track speed skating athletes to achieve optimal performance[1].

Whole-body vibration training (WBVT) involves standing on a vibrating platform with adjustable parameters (frequency, amplitude, duration) to mechanically stimulate muscles and enhance neuromuscular function. Its physiological effects are often attributed to the tonic vibration reflex (TVR), which enhances muscle activation and motor unit recruitment through reflexive pathways[2]. WBVT has been shown to improve muscular strength[3], explosive power[4], balance[5], and proprioceptive function[6,7] in a relatively short time. Typically applied at frequencies ranging from 20 to 50 Hz[8],the primary objective of WBVT is to enhance maximum strength and explosive power. The efficacy of different frequencies in muscular strength training has been the subject of considerable research. While studies have demonstrated the effectiveness of a range of frequencies, including both medium and high frequencies and low frequencies, the optimal frequency for developing strength remains a topic of ongoing investigation[9]. The frequencies of 30 Hz (medium-low) and 50 Hz (medium-high) were selected to represent distinct points within the commonly used WBVT range. This selection allows for a comparison of potential differential effects on muscular strength parameters, as different frequencies are hypothesized to engage neuromuscular structures differently[10].

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In this experiment, the vibration frequencies of medium-low (30 Hz) and medium-high (50 Hz) were used to conduct a four-week[5] training intervention under the condition of 2 mm amplitude. The aim was to compare the changes in lower limb muscular strength before and after the training in order to investigate the effects of whole-body vibration training on sub-elite athletes of short-track speed skating. This study aims to provide both theoretical insights and practical guidance for coaches and athletes, potentially informing training periodization and injury prevention strategies in short-track speed skating.

Participants and methods

Participants

The required sample size was calculated using G*Power 3.1. With a significance level (α) of 0.05 and a statistical power (1 − β) of 0.85, a one-way analysis of variance (ANOVA) was selected as the statistical approach. A priori power analysis was conducted for the primary outcome of peak torque at 60°/s, indicating a minimum of 72 participants was needed for the three groups. The results indicated that a minimum of 72 participants was needed for the three groups. Initially, 80 sub-elite short-track speed skaters were recruited. Following the screening process, 75 male short-track speed skating sub-elite athletes[11] from the Shenyang Sport University were selected as the experimental participants (Table 1). Female athletes were not included in this study. All 75 participants who were randomly assigned completed the entire 4-week intervention and both pre- and post-testing assessments, resulting in a 0% dropout rate. This high adherence rate may be attributed to the short duration of the study and the closely supervised nature of all training sessions.

These sub-elite athletes were defined as competitors at the provincial level in China, with a minimum of 5 years of systematic speed skating training experience and currently training for approximately 20–30 h per week. Subsequently, a one-way ANOVA analysis was conducted on the participants' basic information and pre-test results. The obtained indexes demonstrated no significant difference between the groups. Subsequently, a random grouping was conducted using the random number generator in SPSS (the fixed value was 20231010), using a simple randomization procedure, resulting in the formation of three groups: a vibration frequency of 30 Hz group comprising 25 participants, a 50 Hz group comprising 25 participants, and a control group comprising 25 participants.

Participant flow through the stages of the study (enrollment, allocation, follow-up, and analysis) is detailed in Fig. 1 (CONSORT flow diagram). Inclusion criteria: (1) male provincial-level sub-elite short-track speed skaters with ≥ 5 years of systematic training; (2) aged 18–28 years; (3) weekly training volume of 20–30 h; (4) no history of cardiovascular, cerebrovascular, or musculoskeletal diseases (e.g., knee osteoarthritis, ligament tears) in the past 2 years; (5) no surgical procedures within 6 months prior to the study; (6) no prior experience with WBVT; (7) willingness to comply with the study protocol and provide informed consent. Exclusion criteria: (1) acute muscle/joint injuries (≤ 1 month prior to enrollment); (2) regular consumption of caffeine (> 400 mg/day), creatine, alcohol, or other stimulants; (3) use of anabolic drugs, protein powder, or other strength-enhancing supplements; (4) inability to complete isokinetic testing or WBVT due to physical limitations. The study was approved by the Ethics Committee of the Shenyang Sport University. All participants were novices in WBVT and provided informed consent prior to participation.

Methods

Experimental protocol

The study timeline spanned eight weeks from October to December 2023. Week 1 involved familiarization with the vibration platform and isokinetic testing procedures. All WBVT sessions were supervised by a certified fitness trainer. A washout period followed in Week 2. Pre-intervention isokinetic testing was conducted in Week 3. The 4-week WBVT intervention occurred between Weeks 4 and 7. Post-intervention testing was completed in Week 8.(Registration number: ChiCTR2300069975;Registration date:30/03/2023).

The intervention was conducted at the Fitness Center located on the first floor of the Badminton and Table Tennis Gymnasium, Shenyang Sport University. All assessments were performed in the isokinetic testing laboratory situated within the Science and Technology Building. The experimental equipment consisted of a Power Plate pro5 whole-body vibration platform which provides vertical vibration and an IsoMed 2000 isokinetic dynamometer.

Prior to the commencement of this study, the athletes underwent a training period of one week. This included familiarisation with the WBVT equipment, the movements to be performed, and pre-experimental testing of lower limb muscular strength. It has been demonstrated that the development of a whole-body vibration training programme must consider the impact of gender. Consequently, this experiment was conducted with male participants[12]. During WBVT, participants assumed a semi-squat position on the platform (knee angle ~ 120°), with the torso leaning naturally forward. In order to maintain the subject's head posture, the focus should

	30 Hz group ($n = 25$)	Group 50 Hz ($n = 25$)	Control group ($n = 25$)	F	p
Age(years)	23.80 ± 2.16	23.64 ± 2.16	23.88 ± 1.69	0.092	0.912
Height(cm)	1.79 ± 0.05	1.81 ± 0.05	1.81 ± 0.04	0.860	0.428
Weight(kg)	79.68 ± 7.85	83.12 ± 7.99	82.43 ± 9.77	1.122	0.331

Table 1. Participant characteristics (Data are presented as mean ± standard deviation). (Note: $p < 0.05$ indicates a significant difference between the pre-intervention groups, and $p < 0.01$ indicates a highly significant difference between the pre-intervention groups, same below.).

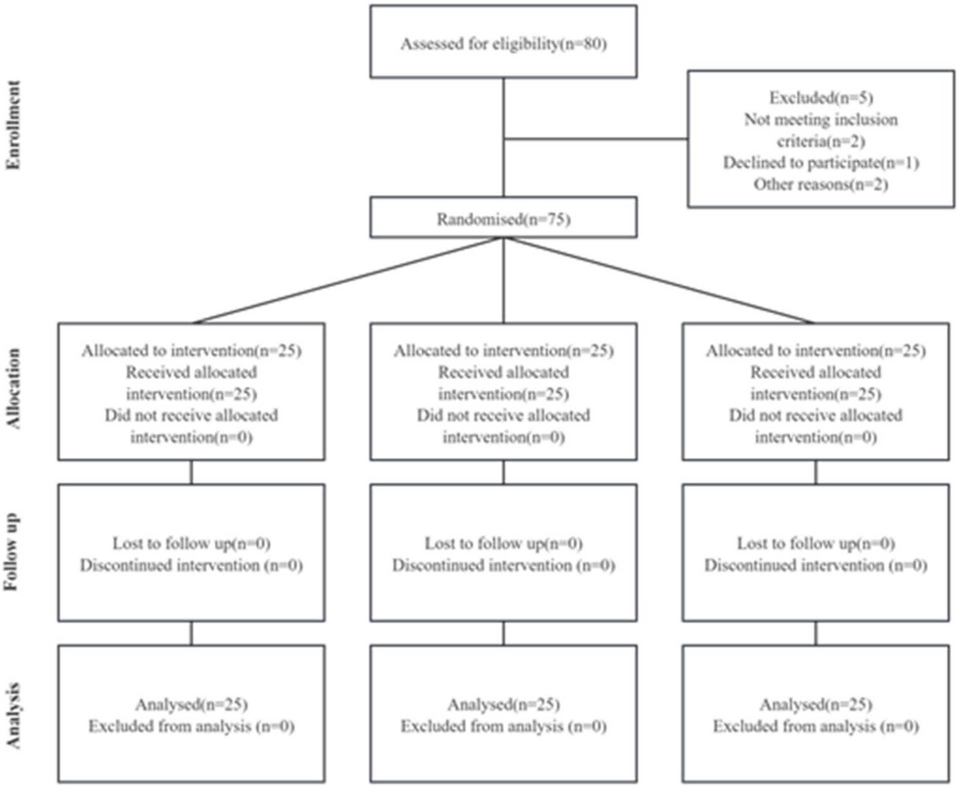

Fig. 1. CONSORT flow diagram.

score	post-intervention (judgement on this training)	pre-intervention (judgement of last training)	score
1	Feeling very heavy.	No recovery, very tired, sore muscles	1
2	feel heavy	Tiredness, muscle stiffness	2
3	Feels comfortable and just right	A little tired, about to recover	3
4	relaxed	resumption	4
5	It feels so easy.	full recovery	5

Table 2. Active fatigue Scale - Level 5 score Scale. (Note: Total score: 2–4 points reduce the intensity of practice; 5–7 points continue to practice according to the programme; >7 points increase the intensity of practice appropriately.).

be on the sign in front of the mark point, with the hands lightly holding the handrails, the two feet wider than the shoulder, the whole foot on the ground with the toes slightly outwardly spread.

Each training session consisted of three sets, with each set comprising three repetitions. The vibration frequency is 30 Hz for the first group of 25 people and 50 Hz for the second group of 25 people. Each vibration time is 30 s. The frequencies of 30 Hz (medium-low) and 50 Hz (medium-high) were selected to represent distinct points within the commonly used WBVT range, allowing for a comparison of potential differential effects on muscular strength parameters. The control group of 25 people performs the same length and posture of the semi-squat posture on the vibration platform, but without additional vibration stimulation. The semi-squat posture was chosen for its relevance to the skating position and to standardize the intervention.

The 4-week intervention period was selected to investigate the short-term adaptive responses to WBVT, as previous studies have reported significant neuromuscular changes within this timeframe[8]. The three groups of participants undergo sub-intervals of 1–3 min, with an intergroup interval of 5 min. Prior to and following the training period, the participants engaged in a 10-minute warm-up and relaxation routine, with each session lasting approximately 40 min. Following each WBVT session, the "Active Fatigue Scale - Level 5 Score Scale" (Table 2) was administered to promptly evaluate the participants' physical state. Based on individual scores, individualized adjustments were made to the subsequent training load and protocol. All participants maintained their regular sport-specific training (20–30 h/week) throughout the study. Although training logs were not systematically collected, participants reported no major changes in their routines during the intervention period. This lack of standardized control over external training load is acknowledged as a study limitation.

A single assessor, blinded to group allocation, conducted all isokinetic strength tests. Participants were instructed not to reveal their group assignment, and the assessor was not involved in training delivery. However, complete blinding was not feasible due to the audible and tactile cues of the vibration platform, which represents a methodological limitation. The tests were performed at angular velocities of 60°/s and 180°/s, with 2–3 min of rest between trials. Participants were seated during testing, with 0° defined as full knee extension. The range of motion was set from 0° to 130°. This standardized testing protocol, including participant positioning, joint alignment, and range of motion, is consistent with established procedures for isokinetic assessment of knee musculature[13]. Rest periods of 2–3 min between trials were provided to minimize fatigue. The axis of rotation was aligned with the femoral condyles, and the reference point was placed at the top of the joint space, superior to the fibular head. After positioning, participants performed 2–3 practice repetitions before formal data collection. One leg was tested followed by the other. Following a four-week intervention period, the impact of the intervention was evaluated through a data analysis.

Statistical analysis

The data on lower limb muscular strength of sub-elite athletes in short track speed skating were entered into an Excel spreadsheet before and after the intervention of the training programme and subsequently analysed using the Statistical Package for the Social Sciences (SPSS) version 23.0. The data were tested for normal distribution using the Shapiro-Wilk test. Paired-samples t-tests were used for within-group pre-post comparisons, and one-way ANOVA with post-hoc LSD tests was applied for between-group comparisons of post-intervention values. No correction for multiple comparisons was applied, which increases the risk of Type I error; this is acknowledged as a statistical limitation. Data are presented as mean ± standard deviation; 95% confidence intervals (95% CI) for the mean differences are reported in the results text and are available in full upon request. The level of significance was set at 0.05, with a significant difference defined as $p < 0.05$ and a highly significant difference as $p < 0.01$.

Results

Changes in knee extensor peak torque at 60°/s Pre- and Post-Intervention

The primary outcome of this study was the peak torque of knee flexors and extensors at 60°/s, as it reflects maximal strength capacity most directly. As demonstrated in Table 3; Fig. 2, following four weeks of WBVT, the peak torque of the knee flexor and extensor muscle groups of both legs significantly increased compared to baseline measurements ($p < 0.01$). Except for the peak torque during right knee extension, no significant differences were observed in any other measurements between pre-intervention and post-intervention in the control group ($p > 0.05$). Table 4 reveals a significant difference ($p < 0.01$) in the peak torque of the flexor and extensor muscle groups of the knee joints of the three groups of participants after four weeks. The post-hoc test indicates that the enhancement of the peak torque of the flexor muscle groups of the knee joints on both sides was more pronounced when the vibration frequency was 50 Hz. In the left extensor knee joint, the peak torque of the experimental group were observed to be greater than those of the control group. However, no significant difference was identified between the training effects of the 50 Hz and 30 Hz frequencies. In the right extensor knee joint, the peak torque of the experimental group were found to be significantly greater than those of the control group. Additionally, the training effect of the 50 Hz frequency was identified to be significantly superior to that of the 30 Hz frequency.

	groups	pre-intervention	post-intervention	t	*p*	Cohen's d
Left knee flexion	30 Hz	99 ± 6.56	108.56 ± 6.51	−5.71	$<0.01^{\#\#}$	1.46
	50 Hz	98.56 ± 10.09	117.92 ± 5.94	−7.77	$<0.01^{\#\#}$	1.92
	control participants	95.08 ± 5.92	96.2 ± 6.10	−7.0	0.493	0.19
Right knee flexion	30 Hz	102.88 ± 5.31	114.08 ± 5.23	−6.81	$<0.01^{\#\#}$	2.11
	50 Hz	100.72 ± 9.03	118.64 ± 5.82	−10.50	$<0.01^{\#\#}$	1.98
	control participants	96.52 ± 6.36	98.64 ± 6.40	−1.11	0.277	0.33
Left knee extension	30 Hz	204.28 ± 8.35	214.68 ± 7.72	−4.90	$<0.01^{\#\#}$	1.25
	50 Hz	202.04 ± 23.15	214.84 ± 8.32	−2.53	$0.018^{\#}$	0.55
	control participants	205.36 ± 6.26	208.52 ± 6.70	−1.60	0.125	0.50
Right knee extension	30 Hz	203.36 ± 22.17	217.28 ± 10.53	−3.55	$0.002^{\#\#}$	0.63
	50 Hz	205.12 ± 9.18	222.08 ± 7.59	−6.85	$<0.01^{\#\#}$	1.85
	control participants	203 ± 6.53	204.92 ± 5.28	−2.69	$0.013^{\#}$	0.29

Table 3. Comparison of Pre- and Post-Intervention peak torque at 60°/s for the knee joint within the group (unit: N·m; M ± SD). (Note: "#" and "##" denote the results of paired-samples t-tests conducted within each group to compare pre- and post-intervention values. # $p < 0.05$ indicates a significant difference, and ## $p < 0.01$ indicates a highly significant difference. Cohen's *d* is provided as the effect size for within-group comparisons. According to conventional thresholds, Cohen's d values of 0.2, 0.5, and 0.8 represent small, medium, and large effect sizes, respectively.).

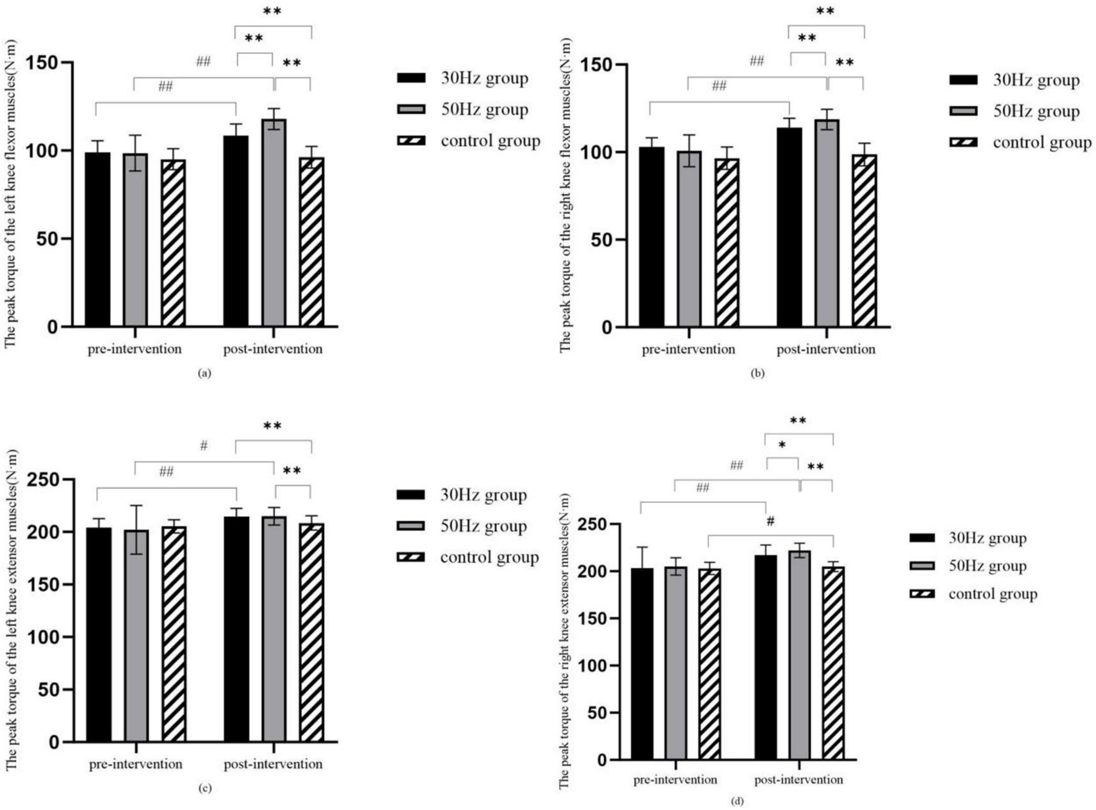

Fig. 2. Changes in Knee Extensor Peak Torque at 60°/s Pre- and Post-Intervention Across the Three Groups(Groups: 30 Hz, 50 Hz, Control).

	groups	pre-intervention	post-intervention	F	*p*	after-test	η_p^2
Left knee flexion	30 Hz(A)	99 ± 6.56	108.56 ± 6.51	77.46	$<0.01^{**}$	$C<A<B^{**}$	0.68
	50 Hz(B)	98.56 ± 10.09	117.92 ± 5.94				
	Control group (C)	95.08 ± 5.92	96.2 ± 6.10				
Right knee flexion	30 Hz(A)	102.88 ± 5.31	114.08 ± 5.23	80.74	$<0.01^{**}$	$C<A<B^{**}$	0.69
	50 Hz(B)	100.72 ± 9.03	118.64 ± 5.82				
	Control group (C)	96.52 ± 6.36	98.64 ± 6.40				
Left knee extension	30 Hz(A)	204.28 ± 8.35	214.68 ± 7.72	5.61	0.005^{**}	$A<B$; $C<A^{**}$; $C<B^{**}$	0.13
	50 Hz(B)	202.04 ± 23.15	214.84 ± 8.32				
	Control group (C)	205.36 ± 6.26	208.52 ± 6.70				
Right knee extension	30 Hz(A)	203.36 ± 22.17	217.28 ± 10.53	29.94	$<0.01^{**}$	$A<B^{*}$; $C<A^{**}$; $C<B^{**}$	0.46
	50 Hz(B)	205.12 ± 9.18	222.08 ± 7.59				
	Control group (C)	203 ± 6.53	204.92 ± 5.28				

Table 4. Between-Group comparison of knee joint peak torque at 60°/s Pre- and Post-Intervention (unit: N·m; M ± SD). (Note: $p<0.05$, $p<0.01$ indicate significant and highly significant differences, respectively, in post-hoc between-group comparisons. A, B, C denote the 30 Hz, 50 Hz, and Control groups, respectively. Notation such as "C < A < B" indicates the direction of differences.).

Changes in knee joint peak power pre- and post-intervention

As demonstrated in Table 5; Fig. 3, the participants' knee flexor-extensor muscle groups exhibited a notable enhancement in peak power following four weeks of WBVT, when compared to the baseline measurements prior to training ($p<0.01$). In contrast, the control group showed no significant difference between pre- and post-intervention assessments, with the exception of a notable increase in the peak power of the right flexor knee ($p>0.05$). Table 6 reveals a significant difference in the peak power of the knee flexor and extensor muscle groups of the three subject groups after four weeks ($p<0.01$). Furthermore, the post hoc test revealed that the enhancement in peak power was more pronounced at 50 Hz for the bilateral knee flexors and the left knee extensors. For the right knee extensors, while both vibration groups improved significantly compared to their

	groups	pre-intervention	post-intervention	t	*p*	Cohen's d
Left knee flexion	30 Hz	75.32 ± 3.69	81 ± 2.78	−7.508	$<0.01^{\#\#}$	1.54
	50 Hz	76 ± 9.06	87.92 ± 7.63	−7.580	$<0.01^{\#\#}$	1.32
	control participants	79.84 ± 9.83	81.28 ± 8.01	−0.770	0.449	0.15
Right knee flexion	30 Hz	75.48 ± 4.85	82.32 ± 5.48	−6.282	$<0.01^{\#\#}$	1.41
	50 Hz	72.84 ± 3.56	87.08 ± 4.51	−12.374	$<0.01^{\#\#}$	4.00
	control participants	76.88 ± 6.23	77.64 ± 6.40	−2.282	$0.032^{\#}$	0.12
Left knee extension	30 Hz	128.68 ± 13.59	136.84 ± 10.09	−5.801	$<0.01^{\#\#}$	0.60
	50 Hz	133.16 ± 9.50	147.20 ± 9.70	−11.141	$<0.01^{\#\#}$	1.48
	control participants	131.24 ± 8.98	133.32 ± 8.25	−1.067	0.297	0.23
Right knee extension	30 Hz	129.40 ± 14.34	145.32 ± 9.93	−7.182	$<0.01^{\#\#}$	1.11
	50 Hz	132.52 ± 11.29	150.28 ± 8.32	−11.076	$<0.01^{\#\#}$	1.57
	control participants	130.24 ± 11.92	132.20 ± 10.05	−0.606	0.550	0.16

Table 5. Within-Group comparison of knee joint peak power at 180°/s Pre- and Post-Intervention (unit: W; M ± SD). (Note: "#" and "##" denote the results of paired-samples t-tests conducted within each group to compare pre- and post-intervention values. # $p < 0.05$ indicates a significant difference, and ## $p < 0.01$ indicates a highly significant difference. Cohen's *d* is provided as the effect size for within-group comparisons.According to conventional thresholds, Cohen's d values of 0.2, 0.5, and 0.8 represent small, medium, and large effect sizes, respectively.).

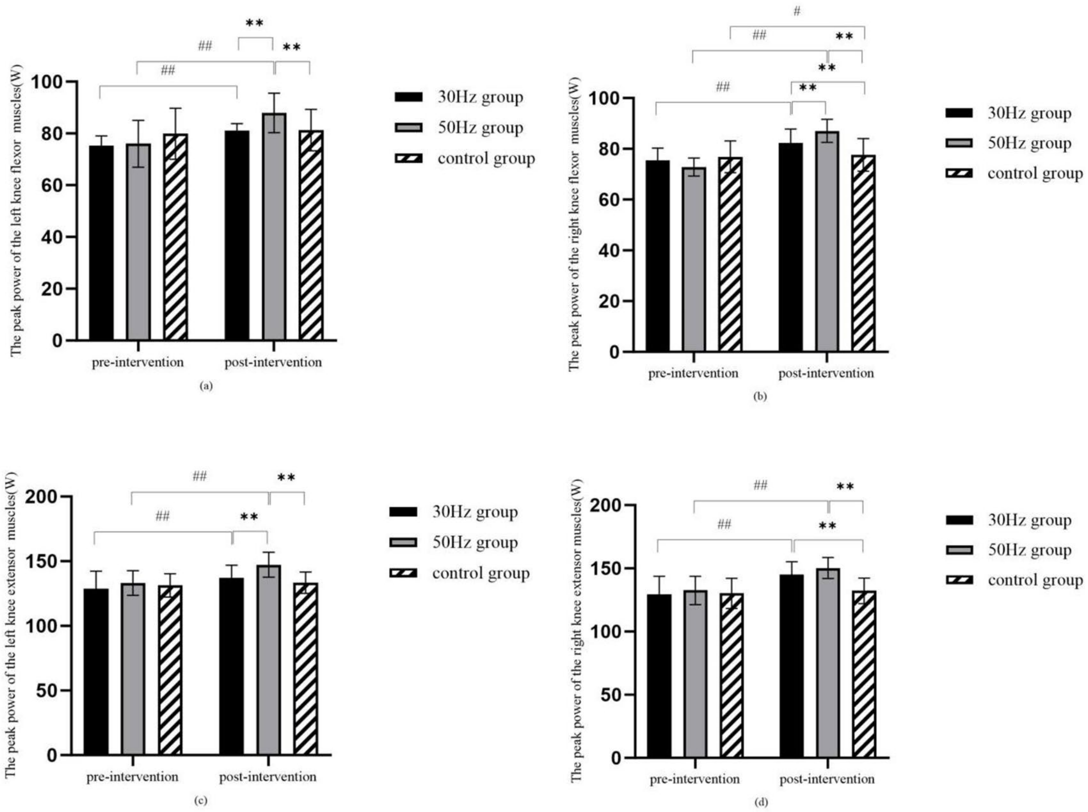

Fig. 3. Changes in Knee Joint Peak Power Pre- and Post-Intervention Across the Three Groups(Groups: 30 Hz, 50 Hz, Control).

own baselines, only the 50 Hz group showed a statistically greater improvement than the 30 Hz group in the between-group comparison.

Changes in knee joint total work pre- and post-intervention

As demonstrated in Table 7; Fig. 4, following four weeks of whole-body vibration training, the total work of both the knee flexor and extensor muscle groups of the participants exhibited a notable increase compared to the pre-

	groups	pre-intervention	post-intervention	F	*p*	after-test	η_p^2
Left knee flexion	30 Hz(A)	75.32 ± 3.69	81 ± 2.78	8.843	$< 0.01^{**}$	$C < B^{**}$; $A < B^{**}$	0.20
	50 Hz(B)	76 ± 9.06	87.92 ± 7.63				
	Control group (C)	79.84 ± 9.83	81.28 ± 8.01				
Right knee flexion	30 Hz(A)	75.48 ± 4.85	82.32 ± 5.48	18.319	$< 0.01^{**}$	$C < A < B^{**}$	0.34
	50 Hz(B)	72.84 ± 3.56	87.08 ± 4.51				
	Control group (C)	76.88 ± 6.23	77.64 ± 6.40				
Left knee extension	30 Hz(A)	128.68 ± 13.59	136.84 ± 10.09	14.793	$< 0.01^{**}$	$A < B^{**}$; $C < A$; $C < B^{**}$	0.29
	50 Hz(B)	133.16 ± 9.50	147.20 ± 9.70				
	Control group (C)	131.24 ± 8.98	133.32 ± 8.25				
Right knee extension	30 Hz(A)	129.40 ± 14.34	145.32 ± 9.93	24.345	$< 0.01^{**}$	$A < B$; $C < A^{**}$; $C < B^{**}$	0.40
	50 Hz(B)	132.52 ± 11.29	150.28 ± 8.32				
	Control group (C)	130.24 ± 11.92	132.20 ± 10.05				

Table 6. Between-Group comparison of knee joint peak power at 180°/s Pre- and Post-Intervention (unit: W; M ± SD). (Note: $p < 0.05$, $p < 0.01$ indicate significant and highly significant differences, respectively, in post-hoc between-group comparisons. A, B, C denote the 30 Hz, 50 Hz, and Control groups, respectively. Notation such as "C < A < B" indicates the direction of differences.).

	groups	pre-intervention	post-intervention	t	*p*	Cohen's d
Left knee flexion	30 Hz	84.56 ± 6.81	91.16 ± 5.74	−11.051	$< 0.01^{\#\#}$	0.97
	50 Hz	84.44 ± 4.42	93.40 ± 3.99	−13.141	$< 0.01^{\#\#}$	2.03
	control participants	83.60 ± 4.98	85.68 ± 4.41	−1.566	0.130	0.42
Right knee flexion	30 Hz	84.24 ± 7.87	93.80 ± 5.98	−14.99	$< 0.01^{\#\#}$	1.21
	50 Hz	85.20 ± 4.25	96.48 ± 4.58	−37.939	$< 0.01^{\#\#}$	2.65
	control participants	85.44 ± 3.00	87.80 ± 4.44	−2.293	$0.031^{\#}$	0.79
Left knee extension	30 Hz	136.20 ± 3.30	148.08 ± 6.08	−10.722	$< 0.01^{\#\#}$	3.60
	50 Hz	135.32 ± 2.87	149.20 ± 4.05	−22.101	$< 0.01^{\#\#}$	4.84
	control participants	135.64 ± 2.61	138.64 ± 2.66	−4.575	$< 0.01^{\#\#}$	1.15
Right knee extension	30 Hz	140.64 ± 9.57	151.64 ± 10.15	−15.016	$< 0.01^{\#\#}$	1.15
	50 Hz	136.52 ± 2.80	156.60 ± 3.92	−26.148	$< 0.01^{\#\#}$	7.17
	control participants	138.04 ± 3.30	139.60 ± 3.20	−1.615	0.119	0.47

Table 7. Within-Group comparison of knee joint total work at 180°/s Pre- and Post-Intervention (unit: J; M ± SD). (Note: "#" and "##" denote the results of paired-samples t-tests conducted within each group to compare pre- and post-intervention values. # $p < 0.05$ indicates a significant difference, and ## $p < 0.01$ indicates a highly significant difference. Cohen's *d* is provided as the effect size for within-group comparisons.According to conventional thresholds, Cohen's d values of 0.2, 0.5, and 0.8 represent small, medium, and large effect sizes, respectively.).

training period ($p < 0.01$). Conversely, no statistically significant difference was observed in the total work of the left flexor and right extensor knees of the participants in the control group between the pre- and post-intervention periods ($p > 0.05$). Table 8 reveals a significant difference in the total work of the flexor-extensor muscle groups of both knees in all three groups of participants after four weeks ($p < 0.01$). However, no significant difference was observed in the effect of the frequencies of 30 Hz and 50 Hz on the total work of the flexor knee joints.

Discussion

The effects of 4-week WBVT at different frequencies on lower-limb maximum strength in sub-elite short-track speed skaters

Maximal voluntary contraction represents the highest force output capacity of a muscle. In this study, the peak torque is defined as the maximum moment value of the knee flexor and extensor muscle groups of short track speed skating students during exercise. This measurement can be used to assess the maximum muscular strength and absolute strength level of the knee muscle groups in these athletes. In this study, the peak torque measured at an angular velocity of 60°/s was employed to quantify the maximum strength of the knee muscles of the short track speed skating students. The athletes' training feedback was obtained through the "Active Fatigue Scale - Level 5 Score Scale".

Following a four-week WBVT programme, the peak torque of the knee flexors and extensors of both legs exhibited a significant increase compared to the pre-training measurements. In contrast, the control participants demonstrated no significant improvement in the peak torque of their knee joints before and after the training

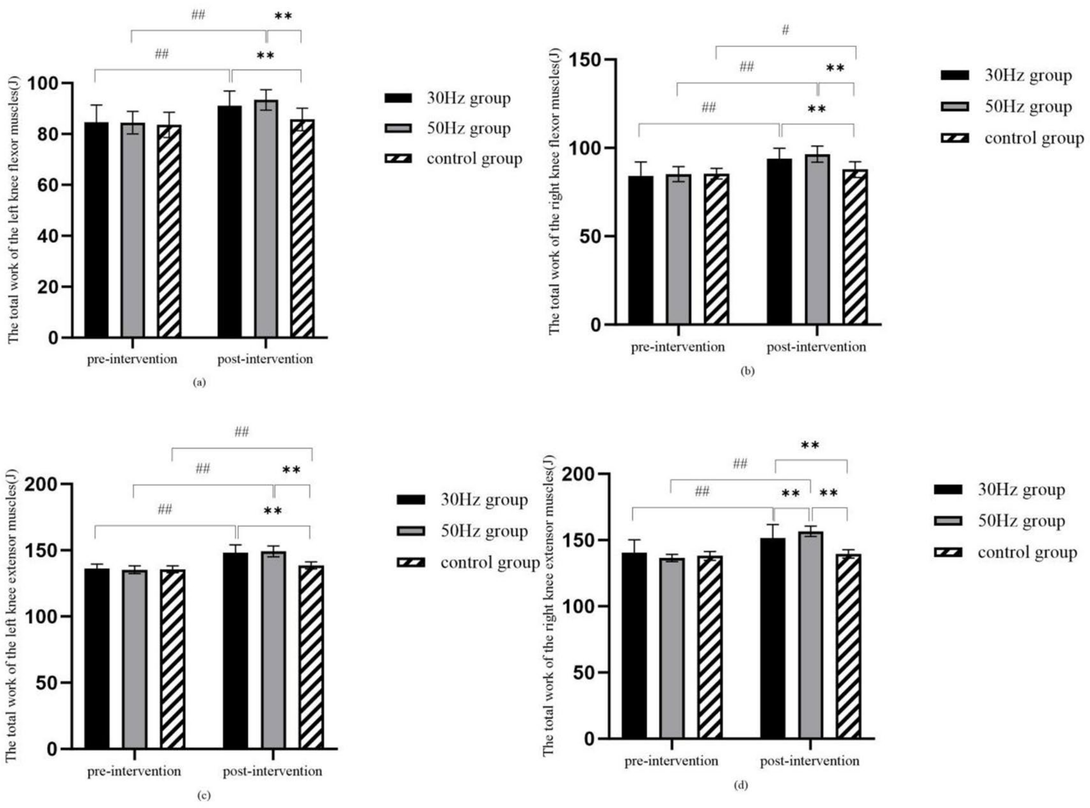

Fig. 4. Changes in Knee Joint Total Work Pre- and Post-Intervention Across the Three Groups(Groups: 30 Hz, 50 Hz, Control).

	groups	pre-intervention	post-intervention	F	*p*	after-test	η_p^2
Left knee flexion	30 Hz(A)	84.56 ± 6.81	91.16 ± 5.74	17.326	$<0.01^{**}$	$C<A^{**}$; $C<B^{**}$	0.32
	50 Hz(B)	84.44 ± 4.42	93.40 ± 3.99				
	Control group (C)	83.60 ± 4.98	85.68 ± 4.41				
Right knee flexion	30 Hz(A)	84.24 ± 7.87	93.80 ± 5.98	19.385	$<0.01^{**}$	$C<A^{**}$; $C<B^{**}$	0.35
	50 Hz(B)	85.20 ± 4.25	96.48 ± 4.58				
	Control group (C)	85.44 ± 3.00	87.80 ± 4.44				
Left knee extension	30 Hz(A)	136.20 ± 3.30	148.08 ± 6.08	41.723	$<0.01^{**}$	$C<A^{**}$; $C<B^{**}$	0.54
	50 Hz(B)	135.32 ± 2.87	149.20 ± 4.05				
	Control group (C)	135.64 ± 2.61	138.64 ± 2.66				
Right knee extension	30 Hz(A)	140.64 ± 9.57	151.64 ± 10.15	44.582	$<0.01^{**}$	$C<A<B^{**}$	0.55
	50 Hz(B)	136.52 ± 2.80	156.60 ± 3.92				
	Control group (C)	138.04 ± 3.30	139.60 ± 3.20				

Table 8. Between-Group comparison of knee joint total work at 180°/s Post-Intervention (unit: J; M ± SD). (Note: $p<0.05$, $p<0.01$ indicate significant and highly significant differences, respectively, in post-hoc between-group comparisons. A, B, C denote the 30 Hz, 50 Hz, and Control groups, respectively. Notation such as “C < A < B” indicates the direction of differences.).

period. These results indicate that both 30 Hz and 50 Hz WBVT were effective in enhancing peak torque compared to baseline levels. These findings indicate that 4 weeks of WBVT at 30–50 Hz (2 mm amplitude) can significantly enhance maximal knee joint strength in sub-elite short track speed skaters.This finding is consistent with the experimental results of whole-body vibration training for volleyball players by Wu C C et al.[14]. The observed strength gains may be partly explained by hypothetical neurophysiological mechanisms, such as the activation of α- and γ-motoneurons and enhanced reflex loops, which could increase motor unit recruitment[15]. However, these mechanisms were not directly measured in this study and remain speculative. The findings of the study conducted by Marinho and colleagues indicated that whole body vibration training did not result in a notable enhancement in muscular strength and quadriceps thickness in renal transplant recipients[16]. This outcome may be attributed to the discrepancies in the results arising from the varying intensities of the training loads and the diverse health profiles of the participants.

A comparison of the effects of WBVT at different frequencies on the participants revealed that the 50 Hz frequency had a more significant effect on the enhancement of the maximum strength of the knee flexor muscle group. Furthermore, Liu et al.[17] found that WBVT has a significant advantage on the activation level of the neuromuscular system, which improves the muscular strength of the lower limbs by increasing the number of motor units recruited. The findings of this study demonstrated that, in comparison to other frequencies, whole-body vibration training at 50 Hz resulted in a more pronounced enhancement in the peak torque of the bilateral knee flexor and right knee extensor muscle groups, thereby indicating a superior efficacy in increasing the maximum strength of the knee joint.

The effects of 4-Week WBVT at different frequencies on lower-limb power in sub-elite short-track speed skaters

Power, or rapid force capacity, is defined as the ability of a muscle to exert force quickly, quantified as the product of force and velocity. In this study, peak power at 180°/s was employed to assess alterations in rapid force of knee muscle groups following four weeks of WBVT at varying frequencies. It was observed that after four weeks of WBVT, the peak power of knee flexors and extensors of both legs exhibited a marked increase compared to the initial measurements. The impact of joint muscle group training was more pronounced in the 50 Hz group, whereas the peak power of the knee joints in the control group remained largely unchanged after four weeks of training. This suggests that the peak power of the knee joints in the control group did not undergo a significant alteration over the four-week period. The majority of participants exhibited no significant changes, indicating that WBVT with vibration frequencies of 30 Hz and 50 Hz and an amplitude of 2 mm has a notable impact on the rapid force development of the knee joints of sub-elite athletes in short track speed skating. This finding is consistent with the impact of whole body vibration (WBV) training on lower limb performance, which has been demonstrated to enhance lower limb performance indicators such as maximal isometric strength, deep squat jump, squat jump, floor jump and power endurance[5]. This conclusion was reached by Haleva[5], who conducted an intervention study to investigate the influence of WBV training on lower limb performance in a cohort of 24 healthy male physical education students.

A comparison of the peak power of the knee joints of the three groups after four weeks of WBVT intervention revealed that a vibration frequency of 50 Hz was more effective than 30 Hz in enhancing the rapid force of the bilateral knee flexor muscle groups and the left knee extensor muscle group. Enhancement of motor neurons can increase the mobility of the muscles during exercise, which is beneficial for rapid muscular strength enhancement. A motor unit is defined as an alpha motor neuron and the muscle fibres it innervates, which collectively constitute the fundamental unit of muscle contraction. The excitability of motor neurons enables the recruitment of slow motor units from smaller cell bodies and fast motor units from larger cell bodies during muscle contraction, in accordance with the principle of recruitment size. The observed strength enhancement may be attributed to the kinetic change of the muscle fibres or muscle bundles during contraction[18]. It is hypothesized that vibratory stimuli may prompt the rapid recruitment of fast motor units with high excitation thresholds. Conversely, when examined through a biomechanical lens, the acceleration generated by vibratory stimulation markedly amplifies the degree of stimulation received by proprioceptors. This alteration could potentially increase the number of synaptic nerve conduction pathways engaged in the vibration-contraction reflex, resulting in the activation of motor units at varying excitatory thresholds and the recruitment of a larger pool of motor units for participation in the work.

These adaptive responses may lead to improved neuromuscular efficiency and potentially structural adaptations over longer training periods, though changes in muscle cross-sectional area were not assessed here[19]. Whole-body vibration training may enhance explosive power by potentially augmenting tendon complex stiffness and optimising the storage of elastic potential energy, though these mechanisms were not directly assessed. This, in turn, facilitates improved neuromuscular conduction and elongates the cycle.

Effects of 4-week WBVT at different frequencies on lower-limb muscular endurance in sub-elite short-track speed skaters

The term “strength endurance” is used to describe the ability of a muscle to function in a sustained manner against an external load. This is evidenced by the length of time a muscle can continuously perform a contraction within a specified timeframe until it is completely fatigued or maintains a specific 1RM percentage of weight[20]. The term “total work” is used to describe the work done by muscle contraction. This can be used to assess the muscle endurance of muscles during exercise, with the numerical value increasing in line with the number of repetitions and load weight.

The findings of this experimental study demonstrated that the total work of both the knee flexor and extensor muscle groups of the participants in the experimental group exhibited a notable enhancement, indicating that WBVT exerts a contributory influence on the improvement of knee strength endurance in sub-elite athletes engaged in short track speed skating. This outcome aligns with the results reported by Cai C M[21] et al.A comparison of the total work values between the three groups before and after the intervention revealed that WBVT affects the improvement of knee muscle endurance. The lack of significant differences between 30 Hz and 50 Hz for muscular endurance outcomes may be attributed to the short intervention period, which might not be sufficient to elicit differential adaptations in fatigue resistance, or the possibility that endurance is less sensitive to vibration frequency compared to maximal and power[22].

The research of Carlucci et al.[23] is worthy of note. The research demonstrated that at the resonant frequency, due to the existence of the maximum displacement between the organs and skeletal structures of the human body, the repeated accumulation of resonance can produce kinetic energy accumulation, which can be released at a specific period of time to enhance the ability of muscle contraction to do work. This process might lead to biodynamic strain in relevant tissues and could involve vibration-induced energy metabolism in muscle tendons. This improves the maximum exercise capacity of the body and is conducive to the improvement of athletic performance. For coaches and athletes, incorporating 50 Hz WBVT into the preparatory phase of training may enhance maximal and power, while both frequencies could be used for maintaining strength endurance. It is recommended to integrate WBVT 2–3 times per week for at least 4–6 weeks to observe significant adaptations[24].

This study has several limitations. Firstly, the 4-week intervention duration was relatively short. Muscular endurance adaptations typically require > 6 weeks of consistent training, which may explain the non-significant difference in endurance outcomes between 30 Hz and 50 Hz groups. Longer-term interventions (8–12 weeks) are needed to explore frequency-specific adaptations in muscular endurance and potential cumulative effects on maximal strength and power. Secondly, the study included only male sub-elite skaters. The exclusion of female athletes, while simplifying the control for potential confounders such as hormonal fluctuations during the menstrual cycle, limits the generalizability of our findings to female athletes and represents a significant limitation of the current research[12]. Thirdly, the assessors, although blinded, could not be completely blinded due to the nature of the WBVT intervention. Finally, while muscular strength parameters improved, functional on-ice performance measures were not included, which would be valuable for assessing translational benefits for speed skaters. Future studies should investigate the effects of WBVT in female athletes, explore different amplitudes and durations, and include functional on-ice performance metrics to better translate laboratory findings to competitive settings.

Conclusions

A four-week WBVT program at different frequencies significantly improved knee muscular strength in sub-elite short-track speed skaters. The vibration frequency of 50 Hz demonstrated superior outcomes in terms of maximal and power when the amplitude was 2 mm, compared to the 30 Hz frequency.

Data availability

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Received: 18 March 2025; Accepted: 16 January 2026

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Author contributions

Q.Q. Designed and performed the experiments, writied the thesis, Y.F. Proposed a thesis topic and designed the thesis framework, Y. G. Presented the thesis topic and guided the revision of the thesis.

Funding

the Applied Basic Research Project of Liaoning Province, (grant number 2022JH2/101300133); Liaoning Province General Higher Education Undergraduate Teaching Reform Research Project, (grant number 20230003).

Declarations

Competing interests

The authors declare no competing interests.

Ethics approval and consent to participate

This research has obtained the approval of the Ethics Committee of Shenyang Sport University and adheres to the Declaration of Helsinki. All participants were novices in WBVT and provided informed consent prior to participation.

This study complies with the CONSORT guidelines

This study was conducted in accordance with the CONSORT guidelines. The CONSORT checklist is available as supplementary material upon request.

Additional information

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