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The effect of incorporating whole body vibration into exercise therapy on the corticomotor excitability of the quadriceps in athletes following anterior cruciate ligament reconstruction

Roya Khanmohammadi[1]✉, Sahar Zare[1], Ali Musavi[2] & Morteza Ahmadi[3]

Previous studies have shown that athletes recovering from anterior cruciate ligament (ACL) reconstruction experience a decline in motor cortex excitability and injury-related cortical reorganization, potentially leading to ongoing complications and a higher risk of subsequent injuries. Therefore, incorporating an intervention that consistently delivers sensory inputs to the central nervous system and enhances excitability at both spinal and supra-spinal levels, in addition to exercise therapy, may offer greater benefits. The purpose of this study was to explore whether combining whole body vibration (WBV) with exercise therapy enhances motor cortical excitability in athletes undergoing ACL reconstruction more effectively than exercise therapy alone. Additionally, it aimed to assess whether this combination improves quadriceps strength and reduces functional limitations in daily activities. This study is a randomized, single-blinded, controlled trial. Twenty-six participants were assigned to either the WBV plus exercise therapy group (intervention group) or the exercise therapy-only group (control group). Outcome measures, assessed before and after treatment, included motor cortex excitability [active motor threshold (AMT) and motor-evoked potential amplitude of the quadriceps], isometric peak torque of the quadriceps, and daily functional disabilities using the knee outcome survey activities of daily living scale (KOS-ADL scale). The treatment period consisted of 12 sessions (4 weeks, with 3 sessions per week). A two-way mixed ANOVA was conducted to examine the main effects of group, time and their interactions. The results showed that in the intervention group (WBV plus exercise therapy), AMT significantly decreased ($F(1, 12) = 11.35$, $P = 0.006$, $\eta^2 = 0.486$), while the control group (exercise therapy only) showed no significant change ($F(1, 12) = 0.252$, $P = 0.625$, $\eta^2 = 0.021$). In the intervention group, AMT decreased by 19.47% post-treatment. Both groups showed significant improvements in isometric peak torque and KOS-ADL scores ($P < 0.001$), with large effect sizes for these parameters. The study concluded that adding WBV to exercise therapy is more effective in increasing motor cortex excitability compared to exercise therapy alone. However, since both groups showed significant improvements in quadriceps peak torque and KOS-ADL scores, it suggests that the addition of WBV did not provide substantial added benefits in enhancing quadriceps strength and improving daily functional abilities. The observed improvements may primarily be attributed to exercise therapy. Nonetheless, it is important to consider the small sample size and low statistical power when interpreting these results.

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Keywords Anterior cruciate ligament, Excitability, Routine exercise, Whole body vibration

[1]Physical Therapy Department, Rehabilitation Faculty, Tehran University of Medical Sciences, P. O. Box 16535-188, Tehran, Iran. [2]Amir A'alam Hospital, Tehran University of Medical Sciences, Tehran, Iran. [3]The Rehabilitation Committee of the Sports Medicine Federation, Tehran, Iran. ✉email: rkhanmohammadi@sina.tums.ac.ir

The anterior cruciate ligament (ACL) is crucial for knee joint stability but is frequently injured in athletes. ACL reconstruction is a solution for athletes and young individuals with high physical activity levels who suffer from knee instability[1]. However, evidence shows that even after reconstruction, not all athletes can return to their pre-injury level of activity. Approximately two-thirds of athletes do not return to the same level of activity within a year post-reconstruction[2]. Only 65% of athletes return to their pre-injury level with an average follow-up of 3.5 years[2]. Additionally, 7 years after reconstruction, only 36% continue to participate in their main sport[3]. Furthermore, those who resume their previous activity level face up to a 29% risk of re-injury to the ligament of the same or opposite limb[4].

Quadriceps weakness contributes to the challenges athletes face when attempting to regain their pre-injury activity levels after ACL reconstruction[5]. This weakness develops rapidly following an ACL injury and subsequent reconstruction, and recovery of quadriceps strength is often incomplete, even years after reconstruction. Studies have reported strength deficits ranging from 2 to 20% in individuals over 2 years post-ACL reconstruction[5]. The quadriceps muscle is essential for dynamic knee joint stability, and evidence has shown that inadequate quadriceps function significantly contributes to the development of knee osteoarthritis[6]. Therefore, persistent quadriceps weakness is a common concern in the rehabilitation of these patients and should be a key consideration for determining readiness to return to activity[5].

Quadriceps weakness can result from alterations in the central nervous system (CNS) at both spinal and supra-spinal levels[7]. Brain regions continuously process proprioceptive information, but ACL injuries disrupt mechanoreceptor function, reducing sensory input to the brain. This decrease lowers motor cortex excitability and diminishes motor output to the quadriceps[7–9]. Quadriceps activity on the unaffected side is also diminished, highlighting the role of the CNS in quadriceps weakness[10].

Numerous studies have demonstrated the effects of ACL injury and reconstruction on motor cortex excitability. For instance, Lepley et al. observed that the active motor threshold (AMT) of the quadriceps increased 6 months after reconstruction, indicating a decrease in motor cortex excitability[9]. This implies that greater stimulation is required to activate the cortex. Pietrosimone's study supports this finding, showing that the AMT was higher in the injured limb of the ACL-reconstructed group, further suggesting corticomotor deficits following ACL reconstruction[11]. Both studies highlight alterations in corticomotor excitability post-surgery and suggest that changes in AMT may reflect a reduced ability of the motor cortex to activate the quadriceps effectively after ACL reconstruction. Grooms et al. compared brain activity between healthy individuals and those who underwent ACL reconstruction, finding that, post-surgery, brain activity shifted from a sensory-motor strategy to a visual-motor strategy during knee movements[12]. Additionally, a study of Héroux et al. on individuals with chronic ACL injury revealed increased resting motor threshold (RMT) of the quadriceps in both legs, indicating reduced bilateral motor cortex excitability[8]. Kapreli et al. used fMRI to examine brain activation patterns during knee flexion and extension in individuals with ACL injury. They found that ACL injury reorganizes multiple sensory-motor brain areas, showing decreased activity in key sensory-motor regions and increased activity in areas like the presupplementary motor area and posterior inferior temporal gyrus. This increased activity suggests greater effort and a compensatory reliance on visual processing due to reduced proprioception[13].

As indicated by previous research, an ACL injury is not solely a musculoskeletal problem; its underlying mechanisms are neurophysiological rather than just biomechanical and structural. The cortical reorganization caused by the injury may contribute to persistent complications, making patients more susceptible to further injuries[14]. Consequently, clinical interventions targeting CNS reorganization and increasing motor cortex excitability might be more effective than other treatments. Traditional post-surgical rehabilitation often includes exercise therapy. However, due to arthrogenic muscle inhibition, evidence indicates that exercise therapy alone is insufficient for effective muscle activation[15]. As previously mentioned, increasing motor cortex excitability and fully restoring quadriceps function is vital for neuromuscular recovery, especially for athletes striving to return to their pre-injury activity levels[7,16]. Therefore, combining exercise therapy with an additional treatment that repeatedly sends sensory inputs to the CNS and increases excitability at spinal and supra-spinal levels may be beneficial.

Whole body vibration (WBV) is an increasingly popular method in rehabilitation that activates muscle spindles, sending sensory signals to the spinal cord and brain, which in turn stimulates alpha motor neurons in the spinal cord and motor cortex[17]. Therefore, incorporating WBV into exercise therapy may provide additional benefits for athletes undergoing ACL reconstruction. In this regard, Pamukoff et al. found that WBV can immediately affect the CNS in individuals with ACL reconstruction, lowering the AMT and increasing motor cortex excitability[17]. Furthermore, two studies on healthy individuals have shown that WBV can immediately enhance motor cortex excitability[18,19]. Krause et al. found that one WBV session acutely enhanced cortico-spinal excitability while reducing spinal inhibition, suggesting greater neural modulation in the primary motor cortex and descending pathways[18]. Similarly, Mileva's study indicated that WBV affects cortical-spinal and intra-cortical processes, leading to increased corticospinal pathway excitability[19].

Although numerous studies have highlighted the neuromodulatory effects of WBV, most of the existing evidence is based on research investigating its neurophysiological impact at the spinal level, primarily through H-reflex assessments. In contrast, research investigating the supra-spinal effects of WBV, particularly on the motor cortex, remains scarce and largely theoretical. To the best of my knowledge, only one study has examined this effect in individuals post-reconstruction[17], while two studies have focused on healthy participants[18,19], highlighting a gap in strong, conclusive evidence. Furthermore, these studies primarily assessed the immediate effects of a single WBV session, leaving the long-term impact largely unexplored.

In clinical and rehabilitation settings, WBV is rarely employed as a standalone intervention for athletes; rather, it is commonly integrated as a supplementary component alongside exercise therapy. In this study, we evaluated the effects of 12 sessions of WBV combined with exercise therapy compared to exercise therapy alone,

aligning more closely with real-world rehabilitation practices. Consequently, our findings may have greater generalizability than those derived from studies investigating only the short-term effects of a single WBV session.

Thus, an important question remains: Can multiple WBV sessions combined with exercise therapy lead to greater improvements in motor cortical excitability in athletes recovering from ACL reconstruction compared to exercise therapy alone? Moreover, can this combination further enhance quadriceps strength and reduce functional limitations in daily activities? Moreover, to explore whether potential changes in cortical excitability are associated with improvements in the assessed clinical outcomes, correlation analysis was conducted to evaluate the relationship between treatment-induced changes (post-test minus pre-test) in cortical excitability and clinical measures. We hypothesized that incorporating WBV into exercise therapy would result in a significant increase in cortical excitability, improved quadriceps strength, and reduced daily functional disabilities compared to exercise therapy alone. Additionally, we expected a relationship between treatment-induced changes in cortical excitability and clinical outcome measures.

Method

Study design

This study was a randomized, single-blinded, controlled trial. Participants were assigned to either a group receiving WBV combined with exercise therapy or a group performing exercise therapy alone. Outcome measures were assessed both before and after the treatment. Post-tests were performed within 24–48 h after completion of treatment. The outcome measures included assessing motor cortex excitability through the active motor threshold and motor-evoked potential (MEP) amplitude of the quadriceps. Muscle strength was evaluated using the isometric peak torque of the quadriceps, while daily functional disabilities were measured using the knee outcome survey activities of daily living scale (KOS-ADL Scale). Both groups received treatment in a laboratory setting. This study was registered as a clinical trial on the Iranian Registry of Clinical Trials (IRCT20220220054078N1) on April 11, 2022.

Participants

26 athletes who had undergone ACL reconstruction were included in the study (Table 1). A flow diagram based on the CONSORT statement illustrates the participants' progress from enrollment to analysis (Fig. 1). All protocols of this research adhered to the ethical principles outlined in the Declaration of Helsinki and received approval from the Tehran University of Medical Sciences Ethics Committee (IR.TUMS.FNM.REC.1400.206). Participants gave informed consent to participate in the study before taking part.

The inclusion criteria were as follows: (1) Participants aged between 18 and 40 years who have undergone ACL reconstruction using a hamstring graft at least 6 months prior[20]; (2) The reconstruction must have been performed on a unilateral, dominant limb (i.e., the limb typically used for kicking a ball); (3) Participants should engage in physical activity but not at the highest intensity levels. Consequently, individuals with a Tegner Activity Level Scale score of 8 or higher were not included in the study; (4) Participants must have returned to sports activities, possessing medical clearance, and have completed the prescribed rehabilitation program; (5) Absence of pain, inflammation, or limited range of motion in the knee; (6) No history of surgery or traumatic injuries to the contra-lateral limb; (7) No contraindications to WBV, including pregnancy, acute thrombosis, severe cardiovascular issues, pacemaker presence, discopathy, spondylosis, severe diabetes, epilepsy, acute infection, severe migraines, tumors, or kidney stones[21]; (8) Absence of contraindications for transcranial magnetic stimulation (TMS), such as a history of seizures or epilepsy, head or brain injuries, presence of metal in the head (e.g., surgical clips or cochlear implants), brain-related diseases (e.g., stroke, multiple sclerosis, tumors), fainting episodes, severe headaches, pregnancy or plans for pregnancy within the last 3 months, use of medications known to lower the seizure threshold (e.g., imipramine, amitriptyline), and recent drug or alcohol use[22]. Exclusion criteria included (1) inability to perform required maneuvers, (2) absence from two consecutive or three non-consecutive therapy sessions, and (3) unwillingness to continue participation. Participants were asked to avoid consuming caffeine and other medications from the day before the experiment.

Characteristics	Intervention (N = 13)		Control (N = 13)		*P* value
	Mean	SD	Mean	SD	
Age (years)	31.92	5.28	31.77	7.34	0.95
Height (cm)	179.77	7.79	178.62	5.84	0.67
Weight (kg)	78.85	10.81	85.00	9.55	0.14
Time since injury (months)	18.77	8.56	15.92	4.70	0.30
Time since operation (months)	12.08	5.41	9.69	1.84	0.15
Tegner activity level scale (0–10)	5.15	0.69	5.46	0.78	0.30
Physical activity (hours/week)	10.23	3.35	10.08	4.09	0.92
Gender (F/M)	4/9		3/10		0.66
Operated limb (L/R)	8/5		6/7		0.43

Table 1. The demographical and clinical characteristics of subjects at baseline. *F* female, *M* male, *L* left, *R* right.

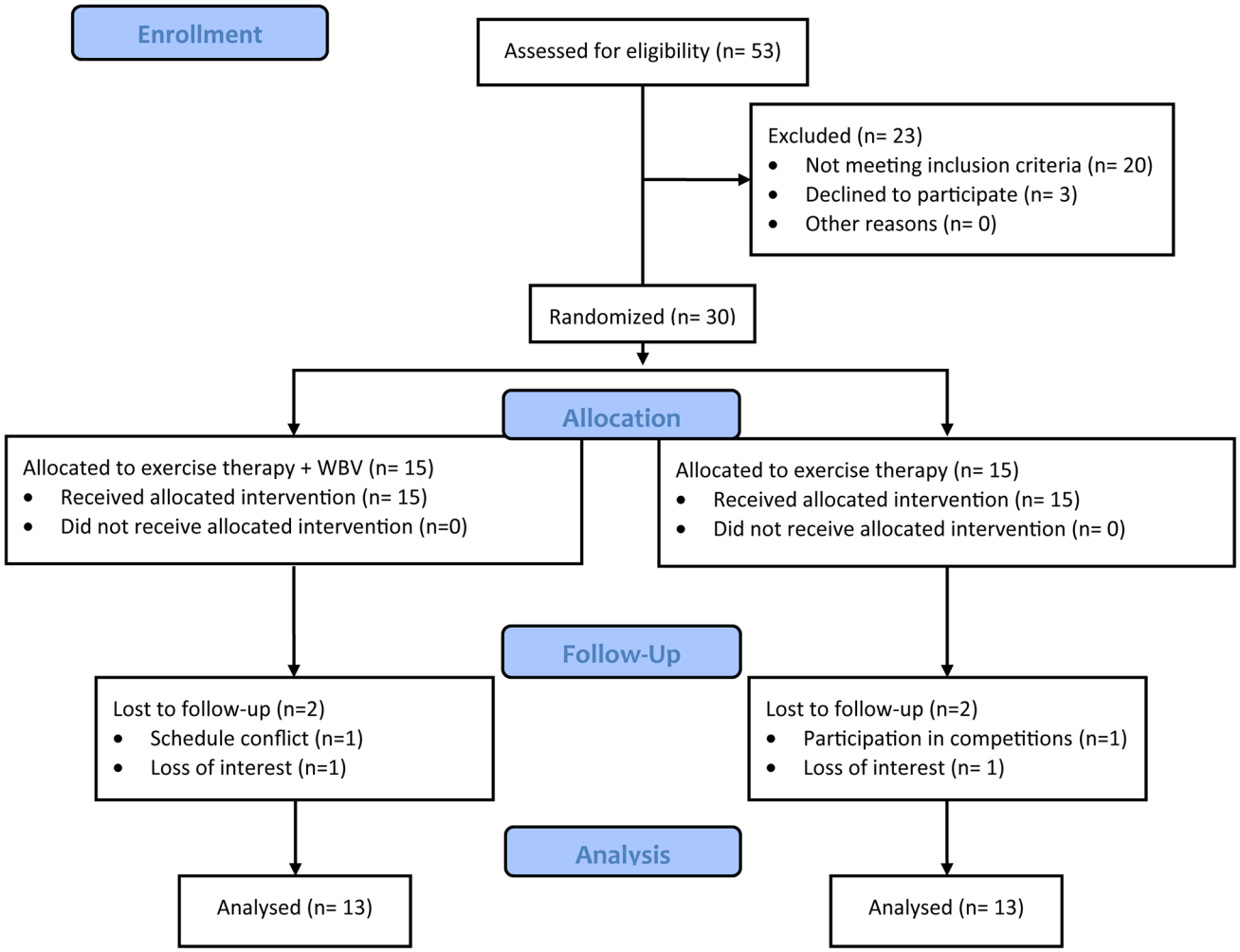

Fig. 1. The CONSORT flowchart.

Sample size

The sample size was calculated using G*Power 3.1.3 software based on a pilot study (5 participants per group), focusing on the AMT and isometric peak torque of the quadriceps. The calculation used a within-between interaction effect size (partial η^2) of 0.115 and 0.081, a power of 0.8, $\alpha = 0.05$, non-sphericity correction (ε) = 1, and a correlation of 0.5 among repeated measures.

Effect sizes for AMT were calculated using the following mean (SD) values: for the intervention group, pre- and post-AMT values were 48.40 (5.37) and 40.20 (4.76), respectively, and for the control group, 46.20 (7.69) and 44.60 (14.91), respectively.

For isometric peak torque, the pre- and post-test means (SD) for the intervention group were 1.75 (0.30) and 2.32 (0.48), respectively, while for the control group, they were 1.90 (0.40) and 2.29 (0.44), respectively.

The analysis indicated that at least 26 participants were needed to detect a within-between interaction effect in a test design of 2 groups and 2 measurements with the specified parameters. Considering a 15% dropout rate, the study required a total of 30 participants.

Randomization and blinding

The participants were randomly assigned to either the intervention group (WBV plus exercise therapy) or the control group (exercise therapy) with a 1:1 allocation ratio. Randomization was conducted using a web-based randomization service (www.randomization.com) with block randomization (block size = 4) managed by an independent third party. Details of the allocated groups were written on cards and concealed using sequentially numbered, opaque, sealed envelopes. In this way, the allocation sequence was concealed from the main researchers. In this study, the assessor was blinded to group allocation.

Assessments

Outcome measures were assessed both before and after the treatment. Post-tests were performed within 24–48 h after completion of treatment.

Motor cortex excitability

Surface electromyography (EMG) For EMG recording, a pair of disposable, pre-gelled Ag/AgCl snap electrodes (Noraxon USA Inc, Arizona, USA) were positioned on the distal third of the thigh along the midline, with the electrode placed at the junction between the rectus femoris and vastus lateralis. This location has been shown in previous studies to effectively target the distal end of the rectus femoris and is optimal for capturing evoked potentials from the quadriceps muscles[8]. The ground electrode was placed on the iliac crest. The signals were recorded at a sampling rate of 2000 Hz, with EMG amplification set to a gain of 1000, filtered between 20 and 500 Hz, and stored for further analysis (Motion Lab Systems, MA400-22).

Participants were seated comfortably with their hips at 90° and knees at 60° of flexion, as this position helps maintain the length-tension relationship of the quadriceps muscle and optimize force production[23]. To achieve maximum voluntary isometric contractions, participants were instructed to extend their knee with maximal muscle effort against a belt secured to the distal part of the shank, just above the malleolus. This action was held for 5 s and repeated 3 times with 1-min rest intervals between each repetition[17]. The EMG signal was then recorded, and the raw signal was smoothed using a 20 ms sliding window root-mean-square (RMS). The peak EMG amplitude was determined as the highest 1-s moving average of the smoothed signal[17]. Subsequently, 10% of this RMS value was designated as the sub-maximal contraction level. This target was displayed on a monitor to ensure participants maintained the specified level throughout the recording.

Transcranial magnetic stimulation (TMS) A 95 mm outer diameter D-B80 Butterfly Coil (Tonica Elektronik A/S, Denmark) connected to a MagPro X100 stimulator with MagOption (MagVenture, Farum, Denmark) was used to measure motor cortex excitability. Stimulation was applied to the side opposite the operated limb. Using the international 10/20 system, the Cz (vertex) was identified, and the center of the coil was placed 1–2 cm posterior to the vertex and 1–2 cm laterally on the target hemisphere, with the coil oriented along the midline to produce a posterior-to-anterior (PA) current[19,23]. Lycra (Invista, Wilmington, DE) swim cap was placed on the participant's head, and the Cz and hotspot were marked to ensure consistent stimulation sites during pre- and post-treatment sessions.

The AMT was determined as the lowest TMS intensity that elicited a motor potential with minimum amplitude of 200 μV in at least 5 out of 10 repetitions[23]. The initial intensity was set at 25% of the stimulator output and adjusted in 1–3% increments until the required MEP amplitude (≥200 μV) was achieved. The stimulation intensity was then set to 120% of the AMT, and the peak-to-peak amplitude of the resulting biphasic waveform was recorded as the motor-evoked potential amplitude. For MEP amplitude, we administered 10 stimulations at 120% of AMT to the hotspot and then averaged the 10 responses.

Isometric peak torque of the quadriceps

To evaluate the isometric peak torque of the quadriceps, a Biodex System 3 Isokinetic Dynamometer (New York, USA) was utilized. The participant was positioned on the device with the hip at 90° and the knee at 60° of flexion. Stabilizing straps were used to secure the thigh, and upper body, and the lever arm was adjusted so that the ankle strap was positioned 2 finger widths above the malleolus. The participant was instructed to cross their arms over their chest and then extend the knee with maximal effort. This action was held for 5 s and repeated 3 times with 1-min rest intervals between each repetition and the average torque was recorded. The obtained values were normalized by dividing them by the participant's body weight.

Knee outcome survey activities of daily living scale (KOS-ADL scale)

To evaluate disability, the Persian version of the knee outcome survey activities of daily living scale was utilized. This version demonstrates strong reliability (ICC = 0.79) and internal consistency ($\alpha = 0.92$)[24]. The questionnaire is divided into two sections: symptoms (including pain, crepitus, stiffness, instability/slipping, locking, and weakness) and functional disabilities (such as difficulty walking on level surfaces, use of walking aids, limping, stair climbing and descending, standing, kneeling, squatting, sitting, and rising from a seated position). It consists of 14 items, with responses scored from zero to five for each item. The total score is calculated by summing the scores across all items, with a maximum score of 70 and a minimum of 0. The final score is converted into a percentage by dividing the obtained score by the maximum possible score (70) and multiplying by 100. A higher percentage indicates lower disability[24].

Groups

Control group

In this group, exercise therapy was performed, which included strength and perturbation-based balance training. The treatment period consisted of 12 sessions (4 weeks, with 3 sessions per week). The exercise therapy is detailed in Table 2[25,26].

Intervention group

In this group, WBV using the Power Plate® Next Generation (Power Plate North America, Northbrook, IL, USA) was incorporated alongside exercise therapy. Participants in each session first received WBV and then performed the exercises. The treatment period consisted of 12 sessions (4 weeks, with 3 sessions per week). The WBV protocol is detailed in Table 3 and illustrated in Fig. 2[25].

The decision to begin therapy no earlier than 6 months post-surgery was made with careful consideration of both clinical and safety factors. It was essential to ensure sufficient recovery had occurred before introducing an additional intervention like WBV. The early phases of ACL recovery involve substantial healing and repair, and introducing WBV too early could potentially disrupt these processes. Clinically, the 6-month timing for

Session	Strength training					Perturbation-based balance training (each exercise consists of 2 sets of 2 repetitions, with a 30-s rest time between sets)	
	Muscle groups	Intensity	Sets	Repetitions	Rest time between sets (s)		
1	Hip abductors and adductors	10RM	3	8	60	Bilateral stance on a rocker board Perturbation in the AP direction	The injured limb on a roller board and the healthy limb on a platform Perturbation in the AP direction Exchanging the injured limb with the healthy one
2	Hip abductors and adductors + external rotators	10RM	3	8	60	Bilateral stance on a rocker board Perturbation in the ML direction	The injured limb on a roller board and the healthy limb on a platform Perturbation in the ML direction Exchanging the injured limb with the healthy one
3	Hip abductors and adductors and external rotators + extensors	10RM	3	8	60	Unilateral stance on a rocker board Perturbation in the AP direction Perturbation in the ML direction	The injured limb on a roller board and the healthy limb on a platform Perturbation in the AP direction Perturbation in the ML direction Exchanging the injured limb with the healthy one
4	Hip abductors and adductors and external rotators and extensors + leg press	10RM	4* 3**	8	50	Unilateral stance on a rocker board Perturbation in the AP direction Perturbation in the ML direction Perturbation in diagonal direction	The injured limb on a roller board and the healthy limb on a platform Perturbation in the AP direction Perturbation in the ML direction Perturbation in the rotation Exchanging the injured limb with the healthy one
5	Hip abductors and adductors and external rotators and extensors and leg press + leg curl	10RM	4* 3**	10	50	Unilateral stance on a rocker board Perturbation in the AP direction Perturbation in the ML direction Perturbation in diagonal direction	The injured limb on a roller board and the healthy limb on a platform Perturbation in the AP direction Perturbation in the ML direction Perturbation in the rotation Exchanging the injured limb with the healthy one
6	Hip abductors and adductors and external rotators and extensors and leg press and leg curl + quadriceps	10RM	4* 3**	10	40	Unilateral stance on a rocker board Perturbation in the AP direction Perturbation in the ML direction Perturbation in diagonal direction	The injured limb on a roller board and the healthy limb on a platform Perturbation in the AP direction Perturbation in the ML direction Perturbation in the rotation Exchanging the injured limb with the healthy one
7	Hip abductors and adductors and external rotators and extensors and leg press and leg curl + quadriceps	10RM	4	10	40	Unilateral stance on a rocker board Perturbation in the AP direction Perturbation in the ML direction Perturbation in diagonal direction Throwing ball against wall	The injured limb on a roller board and the healthy limb on a platform Perturbation in the AP direction Perturbation in the ML direction Perturbation in the rotation Throwing ball against wall Exchanging the injured limb with the healthy one
8	Hip abductors and adductors and external rotators and extensors and leg press and leg curl and quadriceps + mini squat	10RM 1/10 BW	4* 3**	10	40	Unilateral stance on a rocker board Perturbation in the AP direction Perturbation in the ML direction Perturbation in diagonal direction Throwing ball against wall /floor	The injured limb on a roller board and the healthy limb on a platform Perturbation in the AP direction Perturbation in the ML direction Perturbation in the rotation Throwing ball against wall/floor Exchanging the injured limb with the healthy one
9	Hip abductors and adductors and external rotators and extensors and leg press and leg curl and quadriceps + mini squat	10RM 1/10 BW	4	10	40	Unilateral stance on a rocker board Perturbation in the AP direction Perturbation in the ML direction Perturbation in diagonal direction Throwing ball against wall /floor Thrown by other	The injured limb on a roller board and the healthy limb on a platform Perturbation in the AP direction Perturbation in the ML direction Perturbation in the rotation Throwing ball against wall/floor Thrown by other Exchanging the injured limb with the healthy one
10	Hip abductors and adductors and external rotators and extensors and leg press and leg curl and quadriceps + squat	10RM 1/8 BW	4* 3**	10	30	Unilateral stance on a rocker board Perturbation in the AP direction Perturbation in the ML direction Perturbation in diagonal direction Throwing ball against wall /floor Thrown by other Other individually adjusted relevant sport-specific activities	The injured limb on a roller board and the healthy limb on a platform Perturbation in the AP direction Perturbation in the ML direction Perturbation in the rotation Throwing ball against wall/floor Thrown by other Other individually adjusted relevant sport-specific activities Exchanging the injured limb with the healthy one

Continued

Session	Strength training					Perturbation-based balance training (each exercise consists of 2 sets of 2 repetitions, with a 30-s rest time between sets)	
	Muscle groups	Intensity	Sets	Repetitions	Rest time between sets (s)		
11	Hip abductors and adductors and external rotators and extensors and leg press and leg curl and quadriceps + squat	10RM 1/8 BW	4	10	30	Unilateral stance on a rocker board Perturbation in the AP direction Perturbation in the ML direction Perturbation in diagonal direction Throwing ball against wall /floor Thrown by other Other individually adjusted relevant sport-specific activities	The injured limb on a roller board and the healthy limb on a platform Perturbation in the AP direction Perturbation in the ML direction Perturbation in the rotation Throwing ball against wall/floor Thrown by other Other individually adjusted relevant sport-specific activities Exchanging the injured limb with the healthy one
12	Hip abductors and adductors and external rotators and extensors and leg press and leg curl and quadriceps + squat	10RM 1/6 BW	4	10	30	Unilateral stance on a rocker board Perturbation in the AP direction Perturbation in the ML direction Perturbation in diagonal direction Throwing ball against wall /floor Thrown by other Other individually adjusted relevant sport-specific activities	The injured limb on a roller board and the healthy limb on a platform Perturbation in the AP direction Perturbation in the ML direction Perturbation in the rotation Throwing ball against wall/floor Thrown by other Other individually adjusted relevant sport-specific activities Exchanging the injured limb with the healthy one

Table 2. The protocol of exercise therapy. 10RM: 10 repetition maximum. 10RM is the maximum weight a person can lift for exactly 10 repetitions of a specific exercise. 10RM was changed every week. *BW* body weight. *Number of sets for muscle groups already trained. **Number of sets for muscle groups that are newly added.

Session	Frequency (Hz)	Amplitude	Number of sets	Duration of each set (s)	Rest time between sets (s)	Duration of vibration application (min)	Different positions of standing on the plate and number of sets for each								
							P1	P2	P3	P4	P5	P6	P7	P8	P9
1	30	Low	8	30	60	4	2	2	1	–	1	–	–	1	1
2	30	Low	11	30	60	5.5	3	3	2	–	1	–	–	1	1
3	30	Low	13	30	60	6.5	3	3	3	–	1	–	–	1	2
4	35	Low	16	30	60	8	3	3	3	1	2	–	1	1	2
5	35	Low	16	45	60	12	2	2	3	2	2	–	1	2	2
6	35	Low	16	45	60	12	2	2	3	2	2	–	1	2	2
7	40	High	18	45	60	13.5	2	2	3	2	2	1	2	2	2
8	40	High	20	45	60	15	2	2	3	2	3	1	2	2	3
9	40	High	20	45	60	15	2	2	3	2	3	1	2	2	3
10	50	High	16	60	60	16	1	1	2	2	2	2	2	2	2
11	50	High	16	60	60	16	1	1	2	2	2	2	2	2	2
12	50	High	16	60	60	16	1	1	2	2	2	2	2	2	2

Table 3. The protocol of whole body vibration. P1: Limbs positioned in the middle of the plate, slightly apart, knees slightly bent and back straight. P2: Standing on one limb with the foot in the middle of the plate, knee slightly bent and back straight. P3: Mini squat. P4: Mini squat on one limb. P5: Squat. P6: Squat on one limb. P7: Squat with limbs apart. P8: One limb in the middle of the plate and the other limb outside the plate, knees bent at 90 degrees, and back straight. P9: Standing on the toes.

WBV initiation was also recommended by the surgical team, who stressed the importance of allowing the initial recovery phase to stabilize before implementing further treatments like WBV.

Furthermore, a recent meta-analysis of 46 ACL studies, which combined ACL-deficient and ACL-reconstructed groups due to their comparable outcomes and minimal heterogeneity, revealed that although deficits in strength and voluntary activation were evident early in recovery, cortical excitability did not exhibit significant changes before 6 months post-surgery or injury. Studies conducted between 6 and 12 months post-surgery reported a large effect size, while those beyond 24 months showed a moderate effect size[20]. This indicates that the neurophysiological effects of WBV may be better assessed in the later stages of recovery when neural adaptations are more pronounced and responsive to intervention. Therefore, implementing WBV at least 6 months post-surgery offers a more suitable timeframe for evaluating its impact on cortical excitability.

Statistical analysis

The Shapiro–Wilk test was used to evaluate the normality of the data distribution, revealing that all parameters followed a normal distribution except for two cases: AMT after the control condition and peak torque after the intervention. A Box-Cox transformation was applied to adjust the non-normal data to a normal distribution. The independent t-test and chi-square test were performed for quantitative and qualitative data, respectively, to

Fig. 2. The protocol of whole body vibration. P1: Limbs positioned in the middle of the plate, slightly apart, knees slightly bent and back straight; P2: Standing on one limb with the foot in the middle of the plate, knee slightly bent and back straight; P3: Mini squat; P4: Mini squat on one limb; P5: Squat; P6: Squat on one limb; P7: Squat with limbs apart; P8: One limb in the middle of the plate and the other limb outside the plate, knees bent at 90°, and back straight; P9: Standing on the toes.

compare the two groups at baseline. The results indicated no significant differences between the groups, showing they were comparable at baseline. A two-way mixed ANOVA with one within-subjects factor and one between-groups factor was conducted to examine the main effects of group (exercise therapy and exercise therapy plus WBV), time (before and after) and their interactions. When interactions were significant, separate one-way repeated measures ANOVAs were conducted for each group to further explore these interactions. In contrast, the non-significant interaction effect indicates that the behavior of both groups was similar over time. As a result, the time effect can be applied to both groups collectively, eliminating the need for separate within-group analyses. Descriptive statistics for changes in parameters over time, where the interaction effect is not significant but the time effect is, are reported for the combined groups rather than individually. However, when both the interaction and time effects are significant, descriptive statistics are provided separately for each group. Additionally, partial eta squared (η^2) was reported as a measure of effect size, with small (0.01–0.06), moderate (0.06–0.14), and large (≥ 0.14) categories. Furthermore, to investigate the relationship between treatment-induced changes (post-test minus pre-test) in cortical excitability and clinical outcomes, Pearson's correlation coefficient was used for normally distributed change values, while Spearman's correlation was applied for non-normally distributed change values (KOS-ADL Scale).

These correlations were conducted across all participants, regardless of group assignment, to explore whether potential changes in cortical excitability are associated with additional benefits in the assessed clinical outcomes.

Parameters	Pre-test				Post-test			
	Intervention		Control		Intervention		Control	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
MEP amplitude (μV)	696.31	271.50	652.92	266.54	777.37	224.80	717.04	225.66
AMT (%MSO)	42.62	9.88	41.15	9.07	35.69	5.53	40.46	9.64
Isometric peak torque (Nm/kg)	1.71	0.23	1.74	0.46	2.18	0.37	2.03	0.44
KOS-ADL scale (%)	79.08	8.08	77.54	10.41	85.77	6.72	84.77	7.52

Table 4. The mean and standard deviation of parameters. *MEP* motor-evoked potential, *AMT* active motor threshold, *MSO* maximum stimulator output, *KOS-ADL Scale* knee outcome survey activities of daily living scale, *SD* standard deviation.

Parameters	Time effect			Group effect			Time* group effect		
	F	*P*	η^2	F	*P*	η^2	F	*P*	η^2
MEP Amplitude	2.070	0.163	0.079	0.388	0.539	0.016	0.028	0.868	0.001
AMT	9.467	**0.005***	0.283	0.270	0.608	0.011	6.337	**0.019***	0.209
Isometric Peak Torque	47.217	**< 0.001***	0.663	0.209	0.651	0.009	2.700	0.113	0.101
KOS-ADL Scale	19.007	**< 0.001***	0.442	0.200	0.658	0.008	0.028	0.868	0.001

Table 5. The ANOVA results. η^2 is effect size (small = 0.01–0.06, medium = 0.06–0.14 and large ≥ 0.14). Significant values are in [bold]. *MEP* motor-evoked potential, *AMT* active motor threshold, *MSO* maximum stimulator output, *KOS-ADL Scale* knee outcome survey activities of daily living scale. *Significant differences ($P < 0.05$).

The strength of correlation was assessed using the correlation coefficient r, with values between 0.80 and 1.0 indicating a very strong correlation; 0.60–0.79 a strong correlation; 0.40–0.59 a moderate correlation; 0.20–0.39 a weak correlation; and values less than 0.20 indicating a negligible correlation[27].

Results

Participants

A total of 26 participants were enrolled in the study, comprising 13 individuals in the intervention group and 13 in the control group. The demographic characteristics of the participants are presented in Table 1.

The mean age of participants was 31.85 years (SD = 6.27), with ages ranging from 18 to 40 years. Gender distribution was relatively balanced, with 7 females and 19 males across both groups. Regarding the operated limb, 14 participants had surgery on their left leg, while 12 had surgery on their right leg.

Time since injury varied among participants, with an average of 17.35 months (SD = 6.92), ranging from 9 to 39 months. Time since surgery averaged 10.88 months (SD = 4.14), with a range of 7–22 months. Both groups reported similar activity levels, with a mean Tegner Activity Level Scale score of approximately 5.31 (SD = 0.74), with a range of 4–7, indicating moderate physical activity. On average, participants engaged in 10.15 h of physical activity per week (SD = 3.66).

No significant differences were observed between the intervention and control groups concerning demographic characteristics, indicating comparability at baseline.

Outcome measures

The descriptive data and the results of ANOVA are presented in Tables 4 and 5, respectively.

Motor cortex excitability

For the MEP amplitude of the quadriceps, neither the effects of time, group, nor their interaction were statistically significant ($P \geq 0.163$, $\eta^2 = 0.001–0.079$).

For the AMT of the quadriceps, the two-way mixed ANOVA revealed a significant interaction effect between group and time, indicating that the groups' behaviors differed over time, $F(1, 24) = 6.337$, $P = 0.019$, $\eta^2 = 0.209$. Therefore, separate one-way repeated measures ANOVAs were conducted for each group. In the intervention group (WBV + exercise therapy), the effect of time was significant ($F(1, 12) = 11.35$, $P = 0.006$, $\eta^2 = 0.486$). However, in the control group, the effect of time was not significant ($F(1, 12) = 0.252$, $P = 0.625$, $\eta^2 = 0.021$).

In the intervention group, AMT decreased from 42.62% of Maximum Stimulator Output (MSO) (SD = 9.88) before treatment to 35.69% MSO (SD = 5.53) after treatment, reflecting a 19.40% improvement. The mean difference was − 6.92% MSO, with a 95% confidence interval (CI) of (− 11.40, − 2.45) (Tables 4 and 5).

Isometric peak torque of the quadriceps

The two-way mixed ANOVA revealed that neither the main effect of group, $F(1, 24) = 0.209$, $P = 0.651$, $\eta^2 = 0.009$, nor the interaction effect between time and group, $F(1, 24) = 2.700$, $P = 0.113$, $\eta^2 = 0.101$, were statistically significant. This indicates that both groups showed comparable patterns of change in peak torque over time.

However, there was a significant main effect of time, $F(1, 24) = 47.217$, $P < 0.001$, $\eta^2 = 0.663$, indicating that participants, regardless of group assignment, exhibited a significant increase in peak torque post-treatment.

Overall, peak torque increased from 1.72 Nm/kg (SD = 0.35) before treatment to 2.11 Nm/kg (SD = 0.41) after treatment, representing a 22.17% improvement. The mean difference was 0.39 Nm/kg, with a 95% CI of (0.26, 0.50). Effect size analysis confirmed that the magnitude of change from pre-treatment to post-treatment was large ($\eta^2 = 0.663$) (Tables 4 and 5).

Knee outcome survey activities of daily living scale (KOS-ADL scale)

For the KOS-ADL Scale, the two-way mixed ANOVA indicated no significant interaction effect between time and group, $F(1, 24) = 0.028$, $P = 0.868$, $\eta^2 = 0.001$, suggesting that the pattern of change over time did not differ between the intervention and control groups. There was a significant main effect of time, $F(1, 24) = 19.007$, $P < 0.001$, $\eta^2 = 0.442$, demonstrating significant improvement in daily functional abilities from pre- to post-treatment across both groups. The main effect of group was not significant, $F(1, 24) = 0.200$, $P = 0.658$, $\eta^2 = 0.008$, indicating no difference in overall KOS-ADL scores between the groups.

In total, KOS-ADL scores improved from 78.31 (SD = 9.16) before treatment to 85.27 (SD = 7.01) after treatment, reflecting an 8.89% increase. The mean difference was 6.96, with a 95% CI of (3.74, 10.19). Effect size analysis also revealed that the changes in this parameter post-treatment compared to pre-treatment were substantial ($\eta^2 = 0.442$) (Tables 4 and 5).

Relationships

The findings showed no significant association between treatment-induced changes in cortical excitability and variations in quadriceps isometric peak torque ($P \geq 0.764$) or the KOS-ADL Scale ($P \geq 0.241$), with correlation strengths ranging from negligible to weak. The correlations, along with their corresponding r and *P* values, are presented in Figs. 3, 4, 5 and 6.

Discussion

The study hypothesized that incorporating WBV into exercise therapy would provide additional benefits compared to exercise therapy alone. The results showed that AMT of the quadriceps significantly decreased post-treatment in the intervention group (exercise therapy + WBV), whereas no notable change was observed in

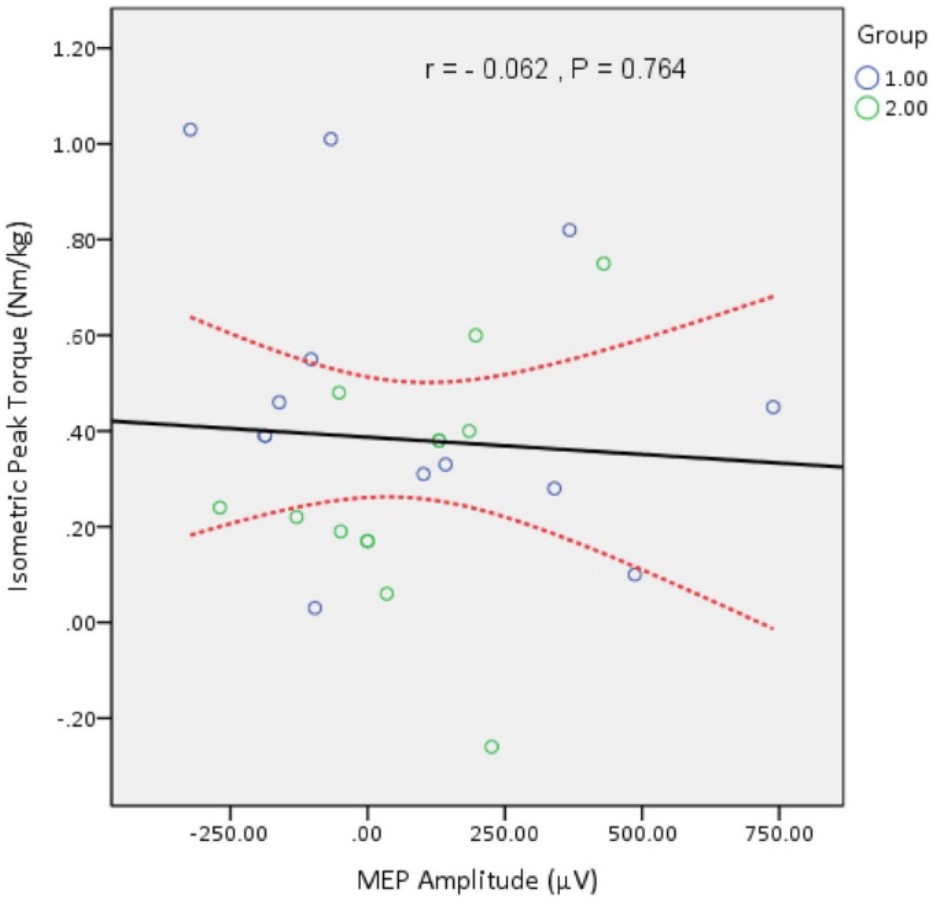

Fig. 3. Relationship between treatment-induced changes (post-test minus pre-test) in MEP amplitude (μV) and isometric peak torque (Nm/kg).

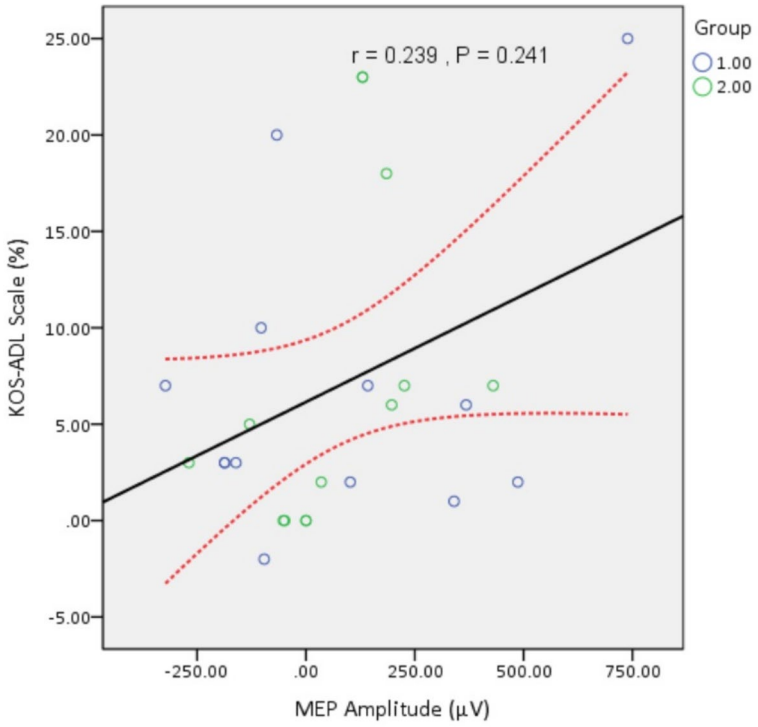

Fig. 4. Relationship between treatment-induced changes (post-test minus pre-test) in MEP amplitude (µV) and KOS-ADL score (%).

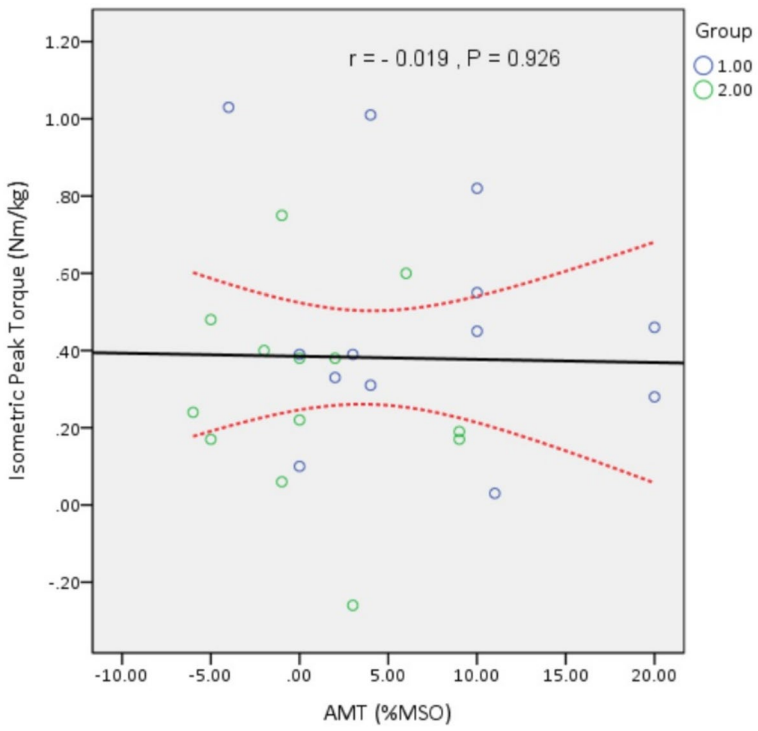

Fig. 5. Relationship between treatment-induced changes (post-test minus pre-test) in AMT (%MSO) and isometric peak torque (Nm/kg).

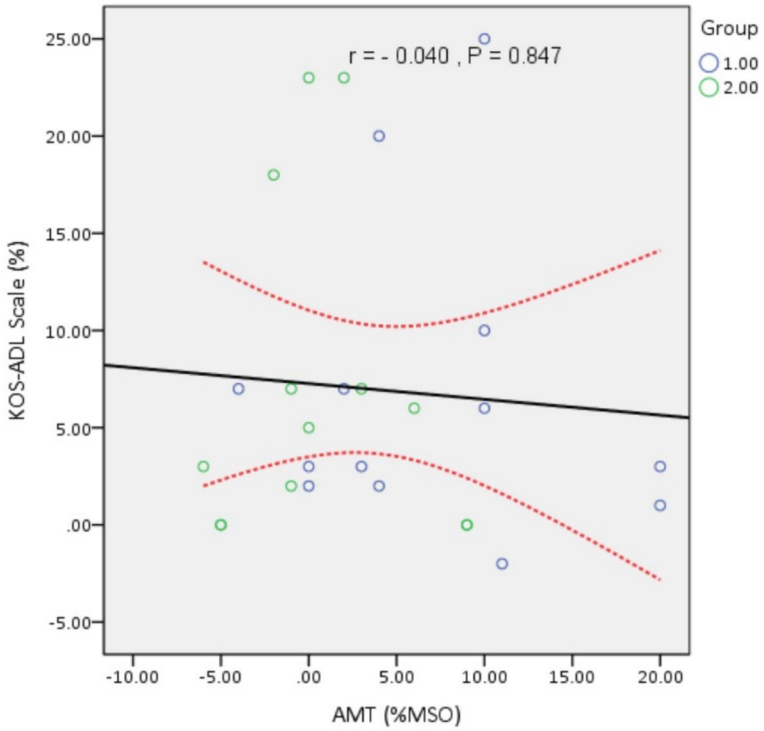

Fig. 6. Relationship between treatment-induced changes (post-test minus pre-test) in AMT (%MSO) and KOS-ADL score (%).

the control group. Furthermore, both groups experienced significant improvements in quadriceps peak torque and daily functional ability, with no clear advantage of one group over the other.

These results indicate that adding WBV to exercise therapy may enhance motor cortex excitability. However, for quadriceps isometric peak torque and KOS-ADL scores, the absence of significant differences between the groups, along with similar patterns of changes observed over time in both groups, suggests that the addition of WBV did not offer substantial added benefits. The observed improvements may primarily be attributed to the common factor between both groups—exercise therapy. In other words, exercise therapy seems sufficient for enhancing muscle strength and functional performance. Furthermore, the absence of a significant correlation between treatment-induced changes in cortical excitability and improvements in quadriceps isometric peak torque or KOS-ADL scores—where correlation strengths ranged from negligible to weak—indicates that improvements in cortical excitability do not necessarily translate into additional clinical benefits. In other words, changes in corticospinal excitability may not be a determining factor for enhancing quadriceps strength and functional abilities. Overall, WBV did not appear to have a significant positive effect on the evaluated parameters in this study. However, it is important to note that the small sample size may have contributed to low statistical power and an increased risk of a Type II error (false negative). For instance, although the mean values for MEP amplitude and quadriceps isometric peak torque slightly favored the WBV + exercise intervention, the time effect for MEP amplitudes and the interaction effect for quadriceps isometric peak torque yielded *P* values of 0.163 and 0.113, respectively, with medium effect sizes. Additionally, power analysis indicated low statistical power values of 0.282 and 0.351, respectively. Therefore, it is possible that with a larger sample size, these parameters could reach statistical significance. As a result, this study should be considered preliminary, and further research with a larger sample would be helpful to confirm these findings.

As previously mentioned, evidence suggests that individuals with ACL injuries or those who undergo ligament reconstruction exhibit altered brain activity compared to healthy individuals. In these patients, motor cortex excitability decreases, necessitating higher intensity stimulation to evoke a response[8,9,13,28]. The 1996 study by Valeriani was the first to show cortical plasticity in individuals with ACL injuries. The researchers suggested that ligament injuries damage proprioceptive receptors and sensory afferents, resulting in reduced sensory input to brain regions. This reduction leads to decreased motor cortex excitability and diminished motor output to the quadriceps[8,9]. Even post-surgery, these patients tend to rely more on visuomotor strategies rather than sensorimotor strategies for knee movements[12].

Therefore, it was hypothesized that WBV, through mechanical stimulation, could activate muscle spindles and potentially increase sensory input to spinal and supra-spinal centers. This increased input might enhance motor cortex excitability and alter excitability of corticospinal pathways. The study results supported this hypothesis, demonstrating that adding WBV to exercise therapy significantly increased motor cortex excitability compared to exercise therapy alone.

Pamukoff et al. similarly found that applying WBV or local vibration to the quadriceps could have an immediate effect on the CNS in patients who underwent ACL reconstruction, reducing AMT and increasing motor cortex excitability. However, MEP amplitude did not show significant changes[17]. They proposed that the interval between the end of vibration application and testing might have been longer than the duration of the vibration effects, since these effects are known to last about 5 min, whereas AMT tests, conducted before MEP measurements, averaged 8.3 min. They thus suggested that future studies should measure MEP amplitude shortly after stopping treatment or during the vibration application[17]. While the study by Pamukoff et al. concentrated on the immediate effects of a single WBV session, the current study utilized a 12-session treatment period with post-testing conducted 24–48 h after completion of treatment. Additionally, the study designs differed: Pamukoff et al. compared WBV to a control group that did not receive WBV, whereas the present study compared an intervention group that received WBV along with exercise therapy to a control group that received only exercise therapy. Despite these differences, both studies demonstrated that vibration effectively increased cortical excitability. One reason for the noticeable change in AMT but not in MEP amplitude in both studies could be that MEP amplitude is calculated as 120% of the AMT, meaning it is directly dependent on the threshold itself. After treatment, the AMT was, on average, lower than before treatment, which means the MEP amplitude was calculated based on a threshold that had changed due to the treatment. Consequently, the changes in MEP amplitude might not be as apparent. However, if post-treatment MEP amplitudes were calculated using the same threshold as before treatment, the changes in corticospinal excitability would likely be more apparent.

In this regard, Rodriguez et al. conducted a meta-analysis and observed a significant increase in the motor threshold for both the reconstructed and non-reconstructed legs when compared to the healthy control leg, whereas no significant changes were found in MEPs[10]. They pointed out that MEPs in the studies included were measured at a fixed percentage of the motor threshold (typically 120% of AMT). This approach meant that the stimulator intensity was adjusted to elicit a similar MEP response across legs and groups, potentially leading to a lack of significant differences[10]. Therefore, future studies are recommended to maintain a consistent motor threshold across time points and directly use MEP amplitudes as a measure of corticospinal excitability.

Mileva et al. assessed MEP amplitude and the muscle map area for the soleus and tibialis anterior muscles before, during, and after vibration in healthy individuals. They observed that vibration led to increased MEP amplitude and muscle map area which suggested enhanced excitability of the motor pathways[19]. Similarly, Krause et al. found that MEP amplitude increased immediately after WBV and remained elevated for 10 min, suggesting WBV has immediate effects on corticospinal excitability[18]. These studies were conducted with healthy individuals, yet their results, like those of the present study, support the effectiveness of WBV.

Furthermore, the results revealed significant improvements in peak torque of quadriceps and daily functional abilities, as assessed by the KOS-ADL questionnaire, in both groups after treatment. There were no significant differences between the groups, indicating that adding WBV to exercise therapy did not notably affect these parameters. Exercise therapy was effective in boosting muscle strength and enhancing daily functional capabilities. However, as previously noted, the small sample size and statistical power limitations should be taken into account when interpreting the findings.

This study incorporated both strengthening exercises and perturbation-based balance training as part of the exercise therapy. Perturbation-based balance exercises, a type of neuromuscular training, challenge balance through both predictable and unpredictable forces. This is achieved using devices like rocker boards, roller boards, and through ball throws. These advanced exercises are designed to improve postural adjustments, which can be either predictive or reactive. Predictive adjustments involve anticipating and controlling balance based on previous experiences to minimize the impact of disturbances and reduce the need for corrective actions. Reactive adjustments involve immediate motor responses to unexpected disturbances, guided by sensory feedback[29]. Reinforcing these strategies enables individuals to handle dynamic environmental challenges more efficiently, potentially leading to improved daily functional abilities and higher scores on the KOS-ADL questionnaire.

In this study, a variety of sensory-motor components were included in the exercise therapy. The program featured both strengthening exercises and balance activities performed on both legs and one leg, along with exercises on unstable surfaces. These activities consistently stimulate sensory receptors, especially proprioceptors, which relay information about muscle length, tension, and joint position to both spinal and supra-spinal centers[30]. This stimulation aids in developing optimal motor strategies. Since motor outputs depend on sensory inputs, and sensory information is essential for selecting suitable motor strategies and maintaining stability, improved proprioceptive input leads to more effective motor responses[30]. This could result in increased muscle strength. Additionally, this improvement enables individuals to better handle environmental challenges in dynamic situations, leading to enhanced performance and functional abilities.

A 2023 systematic review confirms that incorporating perturbation-based balance exercises alongside other types of exercise, such as strengthening, can enhance muscle strength, maximum torque, performance and daily functional abilities[31]. Additionally, research shows that perturbation-based exercises enhance range of motion, reduce muscle co-contraction during activities like walking and jumping, and improve coordination among the quadriceps, hamstrings, and soleus muscles, resulting in better dynamic knee stability[31]. Thus, the observed gains in muscle strength and daily functional abilities are likely due to improved neuromuscular control from these exercises.

Following a ligament injury, the loss of sensory feedback from mechanical receptors disrupts the gamma loop, resulting in quadriceps muscle weakness. Engaging in these exercises helps individuals concentrate on their weight distribution on the support surface, while receiving tactile, verbal, and proprioceptive feedback. This approach may aid in restoring gamma loop function, potentially improving feedback, reducing muscle inhibition, and enhancing the quadriceps' capacity for dynamic knee stability[32]. Such improvements could manifest as increased muscle strength and better daily functional abilities.

It was expected that WBV would decrease muscle inhibition and, consequently, increase peak torque, based on research suggesting that WBV can reduce muscle inhibition. For instance, Pumakuff et al. investigated the immediate effects of a single WBV session and local vibration on muscle inhibition and found an increase in muscle activation right after vibration[17]. Similarly, Blackburn et al. studied the impact of WBV and local vibration on quadriceps function following experimental knee effusion, which induced arthrogenic muscle inhibition via saline injection. They observed that both WBV and local vibration reduced muscle inhibition and increased peak voluntary torque immediately after the intervention, with no significant differences between the groups[33]. The current study's finding of no significant WBV effects on muscle strength and daily functional abilities might be due to a ceiling effect, where the exercises were already highly effective, and WBV provided minimal additional benefit despite enhancing cortical excitability. The results revealed that the average peak torque after treatment was 2.18 Nm/kg for the intervention group and 2.03 Nm/kg for the control group. Additionally, the KOS-ADL questionnaire scores were 85.77 for the intervention group and 84.77 for the control group, indicating relatively high values for both groups. Therefore, if the participants had been in a weaker condition, the additional benefits of the WBV might have been more noticeable, which should be taken into account in future research. Moreover, previous studies mainly used WBV alone and concentrated on its immediate effects, whereas this study examined a longer treatment period with WBV combined with exercise. This difference in methodology could influence the outcomes of WBV, making it difficult to directly compare with previous research. Further research is required to investigate this in greater detail. Future studies should involve three groups: one receiving only WBV, one receiving only exercise, and one receiving both treatments, to better understand the effects.

The decision to apply WBV before exercise therapy was based on its potential neuromodulatory effects, which may enhance motor cortex excitability and optimize neuromuscular performance. WBV is known to repeatedly deliver sensory inputs to the CNS, activating muscle spindles and sending afferent signals to the spinal cord and brain. This process could stimulate neurons at both spinal and supra-spinal levels, potentially increasing cortico-spinal excitability and facilitating greater motor output during subsequent exercise.

Some prior research supports this sequencing. Pamukoff et al. reported that WBV can immediately reduce the AMT and enhance motor cortex excitability in individuals with ACL reconstruction[17]. Likewise, studies by Krause et al. and Mileva et al. on healthy individuals have shown that WBV may acutely increase cortico-spinal excitability while reducing spinal inhibition, suggesting a potential role in modulating neural activity within the primary motor cortex and descending pathways[18,19]. These findings indicate that applying WBV before exercise could prime the neuromuscular system, leading to more effective engagement during training.

If WBV were applied after exercise, its immediate neuromodulatory effects might not contribute to motor performance enhancement during training, potentially influencing the observed outcomes. However, since the effects of WBV sequencing on long-term neuromuscular adaptations remain uncertain, future studies should investigate whether the order of WBV and exercise training modulates post-treatment effects. To ensure transparency, we have explicitly described the sequence in the methods section, allowing researchers to interpret the results within this specific protocol.

Limitations

A key limitation of this study was the issue of low statistical power, which was attributed to the small sample size. This limitation was particularly relevant when interpreting the results related to the time effect for MEP amplitudes and the interaction effect for quadriceps isometric peak torque, as these analyses yielded *P* values ranging from 0.11 to 0.16. Although the mean values slightly favored the WBV + exercise intervention and the effect size of changes was medium, the statistical power for these effects was low (0.282 and 0.351, respectively). This suggests that the lack of significant findings may have been attributed to insufficient statistical power. As such, these results should be interpreted with caution, and the need for further studies with larger sample sizes was emphasized to confirm these findings. Another the limitation of this study was the absence of a group that received only WBV, which would have made it easier to interpret the results and attribute the observed changes to either the combined treatments or the individual effects of each treatment. Additionally, the study did not consider the durability of the treatment effects. It is possible that adding WBV could increase the longevity of the effects. Furthermore, if the study had been conducted longitudinally with consecutive evaluations at the end of each week, we could have better interpreted the progression of improvement and determined whether incorporating WBV shortened the time needed to achieve desirable results. Another limitation of this study was the absence of a dynamic strength parameter alongside isometric strength, which could have provided a more comprehensive assessment of quadriceps function. Additionally, we did not evaluate stability and neuromuscular performance, which are crucial for understanding the broader functional implications of WBV. Despite these limitations, our study contributed to the literature by examining the effects of WBV on corticomotor excitability and functional outcomes in ACL-reconstructed athletes, providing insights into its potential role as an adjunct to rehabilitation. The results of this study are taken from the athletes, who have been at least 6 months after their ACL reconstruction, and they had an average of 10 h of sports activity per week, and their average activity level was 5 according to Tegner Activity Level Scale, so one should be careful in generalizing the results to other people.

Conclusion

Adding WBV to exercise therapy appears to enhance motor cortex excitability compared to exercise therapy alone. However, for quadriceps isometric peak torque and KOS-ADL scores, the absence of significant differences between the groups, along with similar patterns of changes observed over time in both groups, suggests that the addition of WBV did not offer substantial added benefits. The observed improvements may primarily be attributed to the common factor between both groups—exercise therapy. Additionally, the lack of a significant

correlation between treatment-induced changes in cortical excitability and improvements in quadriceps isometric peak torque or KOS-ADL scores—where the correlation strengths were negligible to weak—implies that changes in cortical excitability may not directly contribute to further clinical benefits. Nonetheless, it is important to consider the small sample size and low statistical power in this study, particularly regarding the interaction effect on quadriceps isometric peak torque, when interpreting these results. Therefore, additional research with larger sample sizes is required to confirm these findings.

Data availability

Data are available upon reasonable request to the corresponding author via Email address.

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Author contributions
R.KH. contributed to conceptualization, formal analysis, resources, supervision, and writing—review and editing. S.Z. and A.M. contributed to data curation, and writing—original draft preparation. M.A. contributed to methodology, investigation, and writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Declarations

Competing interests
The authors declare no competing interests.

Ethics approval
This study involves human participants. All protocols of this research adhered to the ethical principles outlined in the Declaration of Helsinki and received approval from the Tehran University of Medical Sciences Ethics Committee (IR.TUMS.FNM.REC.1400.206). Participants gave informed consent to participate in the study before taking part.

Patient consent for publication
The individual depicted in Fig. 2 has provided written informed consent for the publication of their images in this online open-access publication.

Patient and public involvement
Patients and/or the public were not involved in the design, or conduct, or reporting, or dissemination plans of this research.

Additional information
Correspondence and requests for materials should be addressed to R.K.

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