Research Paper

Corticomuscular Adaptations in the Single-Leg Jump Task in Response to Progressive Mechanical Perturbation Training in Individuals With Anterior Cruciate Ligament Deficiency

Sarah Jomhouri[1*], Saeed Talebian[2], Mohammad Vaez Mousavi[3], Bosra Hatef[4], Seyed Hamid Sadjadi-Hazaveh[5]

1. Department of Motor Behavior, Faculty of Physical Education and Sport Sciences, Central Branch, Islamic Azad University, Tehran, Iran.
2. Department of Physiotherapy, School of Rehabilitation, Tehran University of Medical Sciences, Tehran, Iran.
3. Department of Knowledge and Cognitive Intelligence, Imam Hossein University, Tehran, Iran.
4. Neuroscience Research Center, Baqiyatallah University of Medical Sciences, Tehran, Iran.
5. Department of Sport Management, Faculty of Physical Education and Sport Sciences, Central Branch, Islamic Azad University, Tehran, Iran.

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ABSTRACT

Introduction: Studies have repeatedly discussed the importance of training with sufficient cognitive and sensory-motor challenges in successfully transferring Anterior Cruciate Ligament Deficiencies (ACLDs) from rehabilitation centers to sports facilities. For this purpose, this study investigated the effect of mechanical perturbation training and standard training on the brain and muscle activity of these individuals while jumping on one leg.

Materials and Methods: A total of 30 athletes with unilateral Anterior Cruciate Ligament (ACL) rupture (in the coper classification) were randomly assigned to perturbation and standard training groups. To compare the effect of two types of intervention training methods, we examined the Similarity Index (SI) and Voluntary Response Index (VRI) in surface Electromyography (sEMG) tests of eight muscles in the lower extremities and relative power of alpha and beta spectra in Quantitative Electroencephalographic (QEEG) tests between two groups and between two limbs of each group members in the single-leg jump task.

Results: Both training groups showed improved neuromuscular control and increased SI on sEMG tests between the two limbs. However, this improvement in the perturbation training group showed an excellent increase in Effect Size (ES) (intra-group comparison values of SI for perturbation training group P=0.0001, ES=3.6; and P=0.008, ES=1.24 in the standard training group; and P=0.04, ES=0.87 in the inter-group comparison). Regarding the post-test of QEEG tests, no significant difference was found between the two groups (alpha P-value: 0.13, beta P-value: 0.07). However, in the intra-group comparison, the perturbation training group achieved excellent symmetry for the relative power spectrum of alpha and beta signals (the similarity values between the two limbs in the perturbation training group for alpha were P=0.92, ES=0.04 and for beta were P=0.92, ES=0.02; and these values for standard training group for alpha were P=0.07, ES=0.86 and for beta as P=0.08, ES=0.87).

Conclusion: The present study results showed that mechanical perturbation and standard training are suitable for transporting ACLDs to sports environments. Furthermore, in comparing these two training methods, mechanical perturbation training in the manner used in this study has higher adequacy to eliminate motor control and central nervous system defects.

*** Corresponding Author:**
Sarah Jomhouri, PhD.
Address: *Department of Motor Behavior, Faculty of Physical Education and Sport Sciences, Central Branch, Islamic Azad University, Tehran, Iran.*
Tel: *+98 (912) 1128110*
E-mail: *sa_physio@live.com; biophisical@gmail.com*

1. Introduction

Anterior Cruciate Ligament Deficiency (ACLD) is a common injury among young athletes, with approximately 70% of non-contact injuries occurring during landing or jumping and shear forces [1, 2], resulting in impaired sensory-motor function [3, 4]. Recent studies have shown that the main cause of abnormal neuromuscular disorders in the limbs, decrease in proprioception and balance [3, 5, 6], decrease in quadriceps muscle strength [1, 5, 7-9] and functional performance [3], motor asymmetry in both limbs, and altered motor patterns [1, 8], defective biomechanics [10], secondary knee injury and progression of joint osteoarthritis [1, 3, 5, 8, 10-12] due to repetitive dynamic instability [1, 8, 10, 13] is neuroplastic functional sensorimotor changes in the brain that occur following Anterior Cruciate Ligament (ACL) rupture [3, 6, 9, 14].

According to the Grooms framework in 2015, sensory-motor plasticity following ACL injury initially causes sensory neuroplasticity and altered somatosensory processing in the brain due to the lack of somatosensory signals from the ruptured ligament to the brain along with a pain and inflammation response. Then because of no proper somatosensory information, proprioception is reduced. As a result, because of no understanding of the position of the joint in relation to other joints and the environment, the efferent output also changes, and motor neuroplasticity occurs. These changes manifest in the form of motor excitability. Afterward, due to the dysfunction of gamma motor neurons and abnormal motor reflexes, the function of alpha motor neurons is not appropriately performed, and neuromuscular control is impaired. At this stage, the Central Nervous System (CNS) relies on other complementary mechanisms, such as visual feedback, to provide the sensory input needed for proper motor control, resulting in increased up-to-down cortical motor control strategies and impaired postural and motor control [15]. Thus, people with ACLD use motor control areas at higher levels to perform easier movements. Their activity in cortical regions increases, their focus and attention to visual data increases, and due to the inhibition of descending motor neurons, motor dysfunction, i.e., muscle weakness, aberrant biomechanical adaptations, and altered motor patterns occur. Finally, the nervous system's ability in feedforward control, i.e., responding to unexpected and sudden events and coping with joint loads, decreases [9, 14-19].

Surgical and conservative therapies are commonly used to resolve sensory-motor dysfunctions and successfully return people to sport and everyday life. Despite optimal treatment, there is a 25%-30% chance of ligament rupture in both knees [9, 15, 16]. A frequently mentioned issue in the literature is that neuromuscular dysfunction is not corrected by ACL reconstructive surgery and may even increase or become bilateral [6, 15].

The basis of the treatment in these patients, both conservatively and surgically, is to restore the dynamic stability of the knee joint [20]. Recently, researchers have emphasized motor control, i.e., effective interactions between brain, body, and environment, and cognitive control training in these patients [15, 21]. One of the most widely-used therapies in recent years is the perturbation training or neuromuscular training based on the principle of feedforward and focus of external attention [1, 4, 7, 8, 10, 22-25]. These types of exercise can improve the quadriceps muscle's ability to stabilize the knee dynamically during functional activity in ACLD individuals by improving gamma-loop feedback and reducing antagonist muscle activity. The use of perturbation training strengthens the sensory-motor characteristics of the muscle more than strength exercises and creates better strength and motor symmetry [4, 7]. In the studied research, perturbation training has been used manually in different directions [7, 13, 22, 23, 26]. In the last few studies, mechanical perturbation training has been used in only a few limited directions, with only laboratory and research purposes. After comparing the results, mechanical perturbation training was preferable to manual perturbation training [1, 8, 10]. In treating ACLD individuals, environmental interactions that have many cognitive and sensory-motor processing requirements should be considered in the transition phase from the rehabilitation environment to sports fields. This issue requires including complex dynamic visual stimuli and highly variable levels, rapid movement and decision making, variable player positions, environmental interactions, and unforeseen disturbances. Also, to reduce the re-injury in ACLD individuals, they must achieve effective motor-cognitive control before entering the sports environment [15, 21]. Unfortunately, due to space constraints, therapists and medical equipment cannot work and operate well enough in rehabilitation centers.

According to the literature, few studies have been conducted on therapies that can alter cortical function (top-down control) and motor function (bottom-up) during sensory-motor tasks, and the effects of rehabilitation techniques, i.e., strength, balance, and perturbation training, have not been studied on neurological function after ligament injury [14]. Furthermore, researchers in questionnaire studies, functional tests, and electromyographic tests have reported major deficiencies in the use of neuromuscular training in terms of expert manpower, time, and characteristics of manual and instrumental training [1, 8, 10]. Treatment should also be designed to modulate the sensory-motor neuroplasticity secondary to ligament damage in the brain and create optimal and symmetrical movement control in the limbs to reduce the risk of re-injury [9, 15]. Unfortunately, similar research was not found in the review of ACLD studies except in our recent study [4], and most studies focused on the kinetic and kinematic aspects of biomechanics and Electromyography (EMG) activity.

Because of the training deficiencies and the lack of neurological studies and motor control following therapeutic exercises in ACLD individuals, we defined internal-external mechanical perturbation training with a new training approach. In this study, a device was used that generated perturbations in all directions and at relatively high speeds similar to unforeseen events of real events under controlled laboratory conditions. We hypothesized that internal-external perturbation training using cognitive instructions could effectively correct the movement pattern of ACLD individuals. We hypothesized that by performing similar neuromuscular training due to improved CNS control strategies (feedback and feedforward control patterns) as well as possible neuroplasticity changes due to the effective learning and reorganization process of the CNS, brain involvement in movement control would be reduced, improving lower limb muscle coordination while maintaining dynamic stability. To test the above hypothesis, we quantitatively assessed brain and muscle activity in the one-leg jump task during electroencephalographic and electromyographic tests, respectively.

2. Materials and Methods

Study participants

A total of 30 people (17 men and 13 women, aged between 18 and 40 years) with complete unilateral rupture of the Anterior Cruciate Ligament (ACL) of the left knee were selected from the athletes referred to the clinic of the Sports Medicine Federation of the Islamic Republic of Iran (SMFIRI). All participants were first diagnosed by an orthopedic surgeon through clinical tests and MRI images and then referred to a sports physiotherapist to evaluate the inclusion and exclusion criteria. All study participants were athletes with regular training for at least 3 sessions per week before their injuries. They suffered from a complete unilateral rupture of the ACL for at least the past 2 months and did not intend to have surgery for at least 6 months. Also, they have undergone at least 10 sessions of physiotherapy and achieved a full range of motion without pain and swelling. They must have adequate quadriceps strength and can jump on the injured limb without pain, discomfort, or fear. They would be excluded from the study if they had been injured for more than 6 months, had pain, swelling, and limited mobility in the knee and other lower limb joints, suffered from systemic diseases such as diabetes or any disease that requires the routine use of a specific drug that affects the musculoskeletal system, had an injury to other ligaments or meniscus of the same knee or opposite side, had a history of weakness, muscle atrophy, numbness, and tingling limbs as well as low back pain, or a history of ACL rupture on the opposite side, and finally had neurological disorders, mental problems, dizziness, fear and anxiety, and stress due to admission and lack of mental health. Then, they were randomly assigned to the perturbation training group (15 people) and the standard training group (15 people). This study was approved by the Ethics Committee of the Sports Sciences Research Institute (SSRI) (Approval ID: IR.SSRC.REC.1399.095), and all participants accepted and signed the consent form before entering the study.

Training interventions

Standard group

The training protocol of this group was cardiovascular, lower extremity muscle strength, balance, core stabilization, agility, and sport-specific exercises (according to Table 1). The training program of this group of participants was performed in 3 intermittent sessions per week for a month.

Perturbation group

In the perturbation group, a perturbation plate (conventionally named Exe-balance) was used that created movements on all motion plates of horizontal (anteroposterior, mediolateral, and a combination of both in a circular pattern front-rear-in-out), vertical (up-down), angular (in three directions: front-right, front-left, rear-down, with 120 degrees apart), and their simultaneous combination of all. This device was used in two ways: as a means of dynamic warming up of the muscles of the participants in the closed chain of motion in the front-right and front-left angular movement axes (as an internal-perturbation training), and as a stimulus to induce unpredictable postural neuromuscular reactions in participants (external-perturbation training or main training). In participants randomly assigned to the per-

Table 1. Guidelines for progression of training in the standard group

Type of Training	Activities	Timing	Difficulty Progression
Cardiovascular	- Stationary bike - Stepper - Outdoor running	- 10 min - 5 min - 30 min	- 60 to 80 rpm - up to 10 min - Flat ground to uphill
Lower extremity muscle strength	- NMES (Neuromuscular Electrical Stimulation) - Standing squat (0 to 80 degrees) - Sitting (90 to 35 degrees of knee extension) - SLR (Straight Leg Raise) (0 to 45 degrees of hip flexion) -Weight machines - Extension and flexion leg curls - Leg press - Elastic bands - Hip movements in four directions - Terminal knee extension - Lunges - Forward - Side	- 10 min (10 s contraction, 15 s rest) - 15 RM (Repetition Maximum), 5 sets, 10 reps - 3 sets, 10 reps - 3 sets, 10 reps	- Without weight cuffs - Two leg to one leg - Low to high strength - Without elastic bands
Balance	- Circular balance board - Straight knee - Semi squat knee	3 sets, 30 s	Eyes open to close eyes
Core stability	- Plank - Crunch - Side planks - Leg scissors crunch - Single leg bridge	- 3 sets, keep within tolerance for seconds - 3 sets, 10 reps	- Increase holding time
Agility	- Running fast in all directions with sudden starts and stops - 8-figure running - Side sliding to the right and left with sudden stops - Fast forward and backward shuttle run with sudden starts and stops - 45-degree cutting spinning drill	Tolerate speed training without pain or apprehension	Gradually to full speed
Sport-specific	- Routine sport form	Tolerate practice without pain or apprehension	Gradually to full sports specific skills

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turbation group, exercise therapy was performed alternately three sessions per week for one month as follows according to Table 2.

Warm-up stage (internal-perturbation training): In this stage, the participants first rode a stationary bicycle for five minutes, then they stood in the functional position on the pre-prepared Exe-balance and tried to apply push on the device in the adjustment directions (in two angles; front-right and front-left). They did this for 15 reps in each direction at the maximum speed and power they could create in their muscles. This internal-perturbation exercise was repeated immediately three times in both directions. Therefore, the participants first did 15 repetitions with maximum speed on the right and then 15 repetitions with maximum speed on the left and finally did the same thing alternately for the next two repetitions. The time interval between the exercises for each side was considered the rest time for the other side. Afterward, the participants got down from the device and rested for one minute, during which the physiotherapist adjusted the device to perform an external-perturbation exercise.

Main exercise stage (external-perturbation training): At this stage, the participants stood on the Exe-balance device, and the physiotherapist randomly and unpredictably disturbed the participants` balance. They were trying to maintain their postural stability in different directions of the device; front-right angle, front-left angle, rear-down angle, anteroposterior horizontal, mediolateral horizontal, up-down, and a combination of these six modes. The training program was defined in the same way for all participants in each training session, and the difficulty of each training session varied, such as the speed of the perturbations according to the ability of

Table 2. Guidelines for progression of training in the perturbation group

Type of Training	Activities	Timing	Difficulty Progression
Warm-up (internal-perturbation)	- Stationary bike - Internal perturbation - Front-right - Front-left	- 5 min - 3 sets, 15 reps alternately for each sides, maximum speed and power	-
Main exercise (external-perturbation)	- Therapist randomly and unpredictably disturb participant's balance in different directions: - Front-right angle - Front-left angle - Rear-down angle - Anteroposterior horizontal - Mediolateral horizontal - Up-down - Combination of six above modes	Suddenly and randomly, every 30 attempts, 1 min rest, low speed of change perturbation, focus with a look at the plate (internal attention), keep handles, eyes open, training without pain or apprehension	- Increase the speed of perturbation - look forward and straight the head (external attention) - Release handles - Close eyes
Cool-down	- Static stretching movements - Hamstrings - Quadriceps - Triceps surae Stationary bike - Ice pack for knees	- 3 sets, 15 s for every part - 5 min - 15 min	-

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each participant in each session. A total of 90 training attempts were considered for each participant at this stage, with a 1-min break between all 30 exercises. In the initial sessions of perturbation training, which were relatively difficult for the new participants to perform, the subjects paid more attention to the moving plate under their feet. They were allowed to look at it and focus on it. In the initial sessions, the change from one movement to the next was performed with an interval of 3 to 7 seconds of rest to achieve the essential stability of their trunk and limbs in the intervals between movements. After achieving progression stability, the participants were gradually asked to hold their heads as high as possible and not look at the plate. Also, the speed of transition from one movement to the next increased depending on each participant's ability. In addition, there were two handles in front of the participants that they could hold in the first stages of training to maintain their stability and balance, but gradually, as their balance mechanisms improved, they were asked to release the handles as much as possible and try to maintain their balance by relying on the trunk and lower limbs. Furthermore, as the balance improved, the participants were asked to close their eyes if possible and use protective mechanisms such as holding the handles or opening their eyes if they felt they were falling. According to this training protocol, the cognitive load of the training was gradually increased from internal attention to external attention.

Cool-down stage: After performing the internal-external perturbation exercises, all participants cooled down for 5 minutes by performing static stretching movements of the hamstrings, quadriceps, and triceps surae, and using stationary bicycles for 5 minutes, followed by cooling with an ice pack for 15 minutes. The total duration of participation in this group, including warm-up (20×3 seconds + 5 minutes), internal-external perturbation exercise (20×90 seconds + 3 minutes' rest), and cooling (10 minutes), would be 30 minutes taking into account the maximum lost time. Figure 1 shows an overview of the Exe-balance device and how to stand on it.

Characteristics of exe-balance instrument

To perform this study, a device that creates perturbations in all motion plates was designed, built, and nationally registered under the contract name Exe-balance. In engineering terms, the device's design consists of a rigid plate with six degrees of freedom of movement in space. Four pneumatic jacks in a special design were used to control and move the plates of the device. Each degree of freedom of movement was controlled separately by special joysticks. The diameter of the circular set was considered to be 65 cm. The degree of freedom of movement of the device was as follows: vertical displacement (up and down), 0-20 cm; angular displacement (sides), 0-20 degrees; translatory displacement (horizontal), 0-10 cm; and rotational displacement around itself, 20-25 degrees. These displacements could be adjusted at de-

Figure 1. The general panel of the exe-balance device, the perturbation plate, and two protective handles mounted on the wall to hold

The right picture shows a participant standing on the perturbation plate while flexing his knees to achieve more stability. The left image shows a standby participant standing with extended knees on the plate.

sired angles and in combination. The values of the given displacements were determined according to the range of normal values of stability in the human body according to Shumway-Cook et al. [27] so that the normal limit in front and rear balance was equal to 12.58 degrees and for lateral balance was set as 16.8 degrees. In this design, both values were set to about 5 degrees higher to apply slightly more pressure to strengthen the upper limbs, lower limbs, and trunk.

In this study, the Exe-balance device was used in two different modes when the person was standing on it: 1) active mode of the device, in which the device does not provide resistance to the person and the joystick of the device is in the hands of the therapist to create sudden perturbations in the desired directions (used in the practice phase as external-perturbation training); and 2) reinforcement mode or passive mode of the device, where the device resists at every 6 degrees of freedom of movement of the athlete (i.e., the device tends to return to its original position) (used in the warm-up phase as internal-perturbation training). In this study, only two front-right and front-left angular directions were used.

Testing

The participants were objectively assessed using electrical activity tests of eight muscles in each lower limb and brain electrical activity tests in 21 active recording electrodes on two occasions of pre-test (one to two days before the start of the intervention training program) and post-test (one week after the end of the intervention training period). To perform the single-leg jump test, 50% of each participant's height was determined and marked on the ground [28-30]. Then, the participant stands on the marked line and, at the examiner's command, raises the untested leg and jumps forward (Figure 2). The tester recorded each jump and landing test 5 seconds before the verbal command and 5 seconds after the jump completion to avoid deleting erroneous data. The recording moment was determined by synchronous trigger recording on Electroencephalographic (EEG) and EMG software. Simultaneous recording of EEG and EMG jump and landing of each participant was stored in 3 series of replications for the analysis. The tests were repeated for the other limb.

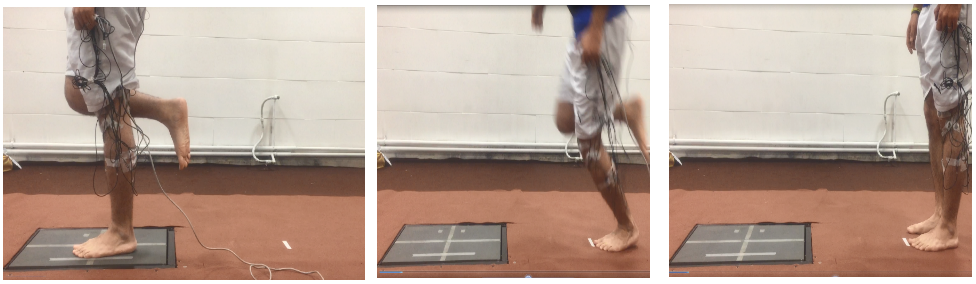

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Figure 2. (Left) The participant standing on the back of a line marked 50% of his or her height and waiting for the examiner's command to step on the test leg, (Middle) The participant hearing the command and jumping, (Right) The participant landing on one leg and holds this position for 5 seconds

Surface Electromyography (sEMG) tests

All surface Electromyography (sEMG) signals were recorded (DataLOG, Biometrics Ltd England). Pre-amplifier bipolar active electrodes (Type NOS.SX230, Biometrics Ltd) were located on the preferred wrist. The electrodes had a fixed center-to-center inter-electrode distance of 20 mm, recording diameter of 10 mm, with a gain of 1000, the input impedance of 1015 Ω, common-mode rejection ratio of 110 dB at 60 Hz, a bandwidth of 20–450 Hz, and ground electrodes. The participants were asked to shave their lower limbs the day before the test.

In this study, we used the Voluntary Response Index (VRI). Instead of measuring the activity of each muscle alone, the electromyographic activity of a group of muscles responsible for the task is studied as voluntary motor control in a work pattern [2, 4, 31]. This method has a high sensitivity in detecting altered patterns of muscle activity in individuals with movement disorders and has a high validity.

To attach the silver pre-gelled sEMG electrodes to the relevant muscles, the areas designated for the electrodes were chosen on the hairless skin and cleaned with non-sterile isopropyl alcohol impregnated gauze. Afterward, the sEMG electrodes were placed parallel to the gluteus maximus, gluteus medius, vastus medialis, vastus lateralis, medial hamstring, lateral hamstring, medial and lateral gastrocnemius fibers separately, once on the lower right limb and once again on the left, according to the SENIAM electrode protocol placement (surface electromyography for the non-invasive assessment of muscles [SENIAM], 1999). Data were taken at a 1000-Hz sampling rate for offline analysis.

To compare the motor control changes of the single-leg jump task by using sEMG data between the two study groups (intergroup) and also to compare between two limbs in each group (intragroup), the Root Mean Square (RMS) of each muscle was first calculated as the muscle response (R1, R2, R3, R4, R5, R6, R7, and R8). Then, the normalized response was measured by the ratio between each response (R1,….., R8) to the vector of baseline correction of each muscle to RMS of rest-activity Ri (Equation 1).

The sum of all muscle normalized responses (Rnorm) was named as Response Vector (RVi), and the average of them was Prototype Response Vector (PRVi). The above calculations were performed for all three groups (healthy, ACLD in two different treatments). Then the ratio between the multiplication of RVi and PRVi (ACLD groups) to RV and PRV of the healthy group, separately, indicated SI for each ACLD to healthy (Equation 2). The VRI was calculated by multiplying the magnitude to SI (RV * SI) for each group [30].

RVs of all eight muscles in the healthy and ACLD limbs of the participants in the two groups were separately inserted in Equation 1. The PRV values for both limbs in the single-leg jump task were calculated from the average of three attempts. The obtained value indicated the magnitude of all muscles used (eight muscles) in the single-leg jump task. The magnitude is the RV equal to the total amount of sEMG recorded from the single-leg jump task in microvolts and is equal to the denominator in Equation 2. The SI between two limbs in both groups was calculated by using Equation 2, and its value is a number between 0 and 1. One indicates the complete similarity between the two limbs.

In sEMG calculations, healthy limbs in both groups were considered as prototypes for comparisons. Baseline correction in the SI equation was calculated based on the average muscle activity at rest, exactly one second before the start of each single-leg jump maneuver. Then, the computed magnitude (in µV) and SI were plotted in both limbs and both groups as x and y pairs in a twodimensional coordinate (VRI) for the single-leg jump task [2, 4, 32, 33].

Equation 1. $R_{norm} = \frac{R_1 R_2 R_3 \ldots R_n}{\sqrt{\Sigma_i R_i^2}}$

Equation 2. $SI = \frac{\Sigma_i (RViPRV_i)}{|RV||PRV|}$

Equation 1 quantitatively shows the normalization of the RV of n muscles during motor tasks (Ri: RMS of each muscle, and the magnetite is equal to the denominator of the task in the same equation). Equation 2 shows the SI of the muscle group in a task. RVi: is the RMS equivalent of each muscle, and PRVi is the PRV of each muscle group in the task.

EEG tests

In this study, we used a Liv intelligent technology 32-channel wireless electroencephalogram device with input impedance specifications of 10 M, the bandwidth of 2 kHz, and 24-bit image resolution (made in Iran, ByaMed Company). After placing the device cap on each participant's head, the recording areas were cleaned and rubbed with alcohol. Then, by using a blunt needle, we inserted the gel into the series electrodes in contact with the scalp. Then in the laptop connected to the EEG device wirelessly, we checked each electrode so that its impedance reached less than 10 kΩ, and the corresponding light in the software was turned on. After turning on all recording electrodes, the subject was ready to be tested. In this study, 21 areas of the 32 brain regions of Fp1, Fp2, F7, F3, Fz, F4, F8, T7, C3, Cz, C4, T8, P7, P3, Pz, P4, P8, O1, O2, Fpz, and Oz were recorded for further analysis.

Raw data were recorded in Excel software which first deleted the noises, and then the relative power spectrum of brain waves to jump on the right and left foot in all 21 electrodes were calculated as quantitative analysis of brain waves (Quantitative Electroencephalographic [QEEG]) in pre-test and post-test. The test was calculated for all participants. Because QEEG analyses showed the highest rate of thalamocortical rhythm disorder at alpha (8-12 Hz) and beta (12-30 Hz) frequencies in quantitative EEG data, electroencephalogram analyzes in this study were performed only on these two frequency bands.

Statistical analysis

To investigate the effect of therapeutic interventions (perturbation training or standard training) on muscle and brain variables in the jump-landing task on one leg, we used a Multivariate Analysis of Variance (MANOVA) test. Then, 1-way ANOVA and complementary tests were used to compare the effect of therapeutic interventions between groups in the post-test, within-group comparison, and the differences between the two limbs in terms of the studied variables.

Then, to evaluate the effectiveness of the therapeutic intervention for the tests that showed a significant difference in their comparison results, we used Effect Size (ES) Cohen's d test according to Equation 3 on the studied variables and interpreted the results at a significant level. For statistical analysis, a significance level of 0.05 was selected in all cases. For statistical analysis, we used IBM SPSS v. 22.

Equation 3. $d = \frac{\bar{x}_t - \bar{x}_c}{\sqrt{\frac{(n_t-1)\, S_t^2 + ((n_{c-1})\, S_c^2}{n_t + n_c}}}$

Equation 3 was used to calculate the effect size of Cohen's d. The mean and standard deviation (the numerators) between the two groups was reduced from the other group, and the result was divided by the standard deviation from the sampled population.

To interpret ES, d is considered as follows: negligible effect (≥ -0.15 and <0.15), small effect (≥0.15 and <0.40), medium effect (≥0.40 and <0.75), large effect (≥0.75 and <1.10), very large effect (≥1.10 and <1.45), huge effect (>1.45), huge decrease (<-75), very large decrease (≤-50 and >-75), large decrease (≤-30 and >-50), medium decrease (≤-15 and >-30), small decrease (≤-5 and >-15), and negligible change (≥ -5 and <5) [34].

3. Results

sEMG analysis of one-leg jump test

Pillai's trace values on intergroup comparison for SI and VRI variables were 0.01 and 0.000, respectively, indicating that the type of training intervention on muscle variables was significantly different between the two groups and the two limbs. By analogy, the two groups showed a significant difference in post-test SI with P = 0.04 and ES=0.87. These results mean that the muscle activity in the single-leg jump task in the post-test between ACLD and healthy limbs in the perturbation training group with a Mean±SD SI of 0.71±0.11 had a higher symmetry (with moderate increase) than the standard training group with a Mean±SD SI of 0.58±0.19 was achieved. This improvement was 0.4 of difference in the perturbation training group compared to 0.2 in the standard training group. The result of intragroup comparisons in the VRI variable of both limbs in both training

Table 3. Intragroup and intergroup comparison of sEMG variables in single-leg jump test

Groups			Mean±SD		
			SI	VRI-A	VRI-nA
Perturbation group	Pre-test		0.31±0.12	9.25±10.1	7.65±10.14
	Post-test		0.71±0.11	43.08±22.6	62.8±35.21
	P-value intragroup, ES		0.0001*, 3.6	0.001*, 2	0.001*, 2.2
Standard group	Pre-test		0.38±0.14	2.08±2.61	2.62±2.17
	Post-test		0.58±0.19	7.11±5.45	8.85±7.31
	P-value intragroup, ES		0.008*, 1.24	0.001*, 1.21	0.001*, 1.2
Intergroup differences	P-value, ES	Pre-test	0.17	0.01*	0.07
		Post-test	0.04*, 0.87	0.0001*, 2.27	0.0001*, 2.2
Pillai's trace			0.01	0.000	

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SI: Similarity Index; VRI-A: Voluntary Response Index Affected limb; VRI-nA: Voluntary Response Index non-Affected limb; *P<0.05.

groups showed a significant difference in the form of a considerable increase. This improvement was greater in the perturbation training group, which is shown in Figure 3 and is given in detail in Table 3.

The direction of the arrows shows the trend of changes from the beginning to the end of the sEMG tests. Continuous lines represent the perturbation group, and dotted lines represent the standard group. A solid arrow indicates a healthy limb, and a hollow arrow indicates an ACLD limb. In the plot, the ACLD limb in the perturbation group is pulled toward the healthy limb, and each limb shows an increase in similarity in the response vector. Also, the plot shows a positive increase in the magnitude of the ACLD limb response vector to the healthy limb in the standard group. As seen in the Figure, the similarity of the two limbs in the perturbation training group is greater.

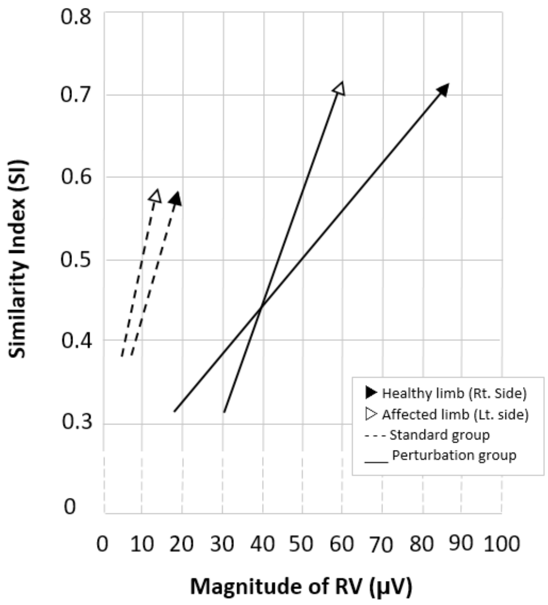

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Figure 3. Changes in the VRI in response to the jump-landing task in the perturbation and standard groups in ACLD and healthy limbs

QEEG analysis of one-leg jump test

The relative power spectrum of alpha and beta waves of training groups in the jump-landing task in ACLD and healthy limbs were examined according to the MANOVA test using Pillai's trace. The findings show that the relative power spectrum of the alpha wave is not significant (P=0.27) in the intergroup comparison of two limbs, but the relative power spectrum of the beta wave is significantly different (P=0.004). According to Table 4, this difference was observed only in the intergroup comparison of the relative power spectrum of the beta wave in the pre-test, so that the relative power spectrum of the beta wave in the perturbation training group was significantly higher in the pre-test than the standard training group. Regarding the intragroup comparison, the relative power spectrum of the alpha wave in the perturbation training group in the post-test of both limbs shows a

Table 4. Intragroup and intergroup comparison of QEEG variables in single-leg jump test

Relative Power Spectrum of EEG Signals			Mean±SD			
			Alpha		Beta	
			nAL	AL	nAL	AL
Perturbation group	Pre-test		21.69±8.36	25.82±11.62	26.8±10.62	38.21±13.73
	Post-test		20.98±7.96	20.68±8.47	38.21±19.43	38.55±13.34
	P-value intragroup, ES		0.46, 0.09	0.19, 0.52	0.03*, 0.75	0.95, 0.03
	P-value interlimb (post-test), ES		0.92, 0.04		0.92, 0.02	
Standard group	Pre-test		17.39±6.02	25.21±8.25	29.26±18.32	24.78±7.9
	Post-test		19.2±6.8	25.39±7.84	42.31±17.16	30.21±10.95
	P-value intragroup, ES		0.37, 0.3	0.95, 0.02	0.14, 0.76	0.18, 0.59
	P-value inter-limb (post-test), ES		0.07, 0.86		0.08, 0.87	
Intergroup differences	P-value, ES	Pre-test	0.12	0.87	0.65	0.003*
		Post-test	0.62, 0.24	0.13, 0.6	0.54, 0.23	0.07, 0.71
	Pillai's trace		0.27		0.004*	

nAL: non-Affected Limb; AL: Affected Limb; *P<0.05.

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small decrease that is not observed in the standard group, and the relative power spectrum of the beta wave in both groups shows an increase. This increase is significant only in healthy limbs of the perturbation training group (P=0.03, ES=0.75).

Comparing the intragroup post-test of jump-landing on ACLD and healthy limbs, we found no significant difference between any groups in terms of symmetry of relative power spectrum of alpha and beta waves, and brain waves were relatively symmetrical in the jump-landing task on each limb. However, the symmetry between the jump-landing on the ACLD and healthy limbs in the perturbation training group was significant for the relative power spectrum of the alpha wave (P=0.92, ES=0.04) and the beta wave (P=0.92, ES=0.02), and in the standard training group for the relative power spectrum of the alpha wave (P=0.07, ES=0.86) and beta wave (P=0.08, ES=0.87) was very low. The examined differences are shown in Figure 4.

4. Discussion

This study aimed to compare the altered voluntary motor control in the lower limbs and quantify brain activity following one month of mechanical perturbation training with standard training in coper ACLD individuals through electromyographic and electroencephalographic tests in the single-leg jump-landing task. To our knowledge, this is the first study to examine voluntary motor control and quantitatively measure brain activity after training interventions in the single-leg jump-landing test in ACLD individuals.

Suitable people to participate in this study were copers selected according to the protocols of previous studies [4, 23, 26, 35]. The results showed that perturbation and standard training programs improved neuromuscular control in the measured sEMG parameters. The ACLD limb in both groups was extended to the PRV of the healthy limb, and this improvement had a significantly higher SI in the perturbation training group. Also, the pattern of muscle activity after training interventions in both groups showed movement symmetry in both limbs in the jump-landing task, and this symmetry was higher in the perturbation training group. Despite the symmetry in the movement pattern of the two limbs, the amount of muscle activity in the two limbs was slightly different from each other. In both groups, the ACLD limb had less muscle activity than the healthy limb.

Regarding the intragroup comparison of QEEG analyses on the relative power spectrum of the alpha wave in the jump-landing task on both limbs, the perturbation training group showed a significant decrease, and the standard training group showed a non-significant increase. However, the relative power spectrum of the beta wave in the jump-landing task on a healthy limb

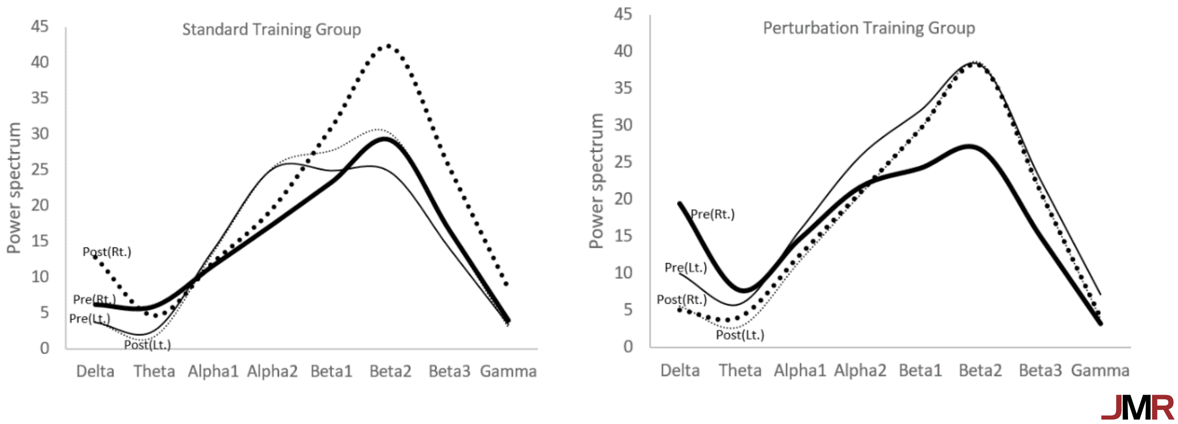

Figure 4. No significant difference between the two groups regarding the relative power of alpha and beta signals in the single-leg jump task on the healthy and ACLD limbs in the post-test; but in the intragroup post-test comparison, the perturbation training group achieving excellent symmetry for the relative power of the alpha and beta signals compared to the standard training group

was significantly increased in the perturbation training group and did not change in the ACLD limb, and the standard training group showed a non-significant increase in both jump-landing tasks. In conclusion, in two jump-landing tasks on two limbs, the perturbation training group showed excellent symmetry in the relative power spectrum of the alpha and beta frequency bands compared to the standard training group that achieved low symmetry. The present study's findings can be used in exercise programs to prevent primary and secondary ACL injury and after surgery.

The effect of perturbation training on neuromuscular control

We believe that ACLDs, due to altered motor patterns and cortical activity, are suitable for a therapeutic exercise program and a successful return to sports and competition settings. The settings require concentration of external attention, coping with high variables, complex motor planning, and rapid decisions in certain situations, environmental interactions, and fast prediction of perturbations [26, 36]. According to studies, the documented treatment algorithm for ACLD individuals in both conservative and surgical treatments has been reported for perturbation enhanced rehabilitation [1], with long-term effectiveness in returning patients to irregularly high levels of recreational or sporting activities that require jumping, changing direction, and rotation [1, 7, 8, 10, 13, 23, 26]. According to studies, the use of perturbation training in rehabilitation centers has major shortcomings, including that they are entered manually at non-functional speeds. In addition, the presence of a therapist and spending a lot of time on treatment is mandatory in performing this type of training, so they are not used in clinics or are rarely used. Also, because manual perturbation training can only be conducted on limited motor axes and cannot simulate normal functional movements, such as jumping and changing directions, researchers have always mechanically substituted manual types for more appropriate perturbation training. In recent studies, mechanical perturbation training has been used in limited directions and laboratory conditions. By comparison, mechanical perturbation training was preferable to manual types [1, 8, 10].

Instruments that create environmental perturbations are composed of specific neuromuscular training. This training can improve the quadriceps muscle's ability to stabilize knee dynamics during functional activity in ACLD individuals by improving gamma loop feedback and reducing antagonist muscle activity [7]. The researchers showed that by performing mechanical perturbation training, they could achieve an increase in large muscle contraction, knee stability, and production of larger muscle forces and motor symmetry during functional movements [8, 10]. Therefore, in this study, we designed and built a device to simulate real-world events at real acceleration and velocities. The results of our study showed the higher symmetry of the activity pattern of using muscles between the two limbs in the mechanical perturbation training group in the jump-landing task on one leg. We also expected to achieve greater stability in the knee joint and other lower limb joints due to increased muscle activity in both limbs, possibly due to greater contraction. The results of this study, similar to previous studies [10], suggest that perturbation training on mechanical plates with the production of greater muscle force during functional activities can be effective in transferring to other more complex motor activities.

Comparing the present study with previous studies in the field of perturbation training, we can conclude that none of the devices that created mechanical perturbation training have included all the motor axes and were often limited to one or two motor axes. In contrast, our device produced unpredictable perturbations in all axes of motion that were not similar to previous studies. In this study, the perturbation training device had novel capabilities that could be used to perform functional training in the chain of movement and on all joints of the trunk and lower limbs, as well as to maintain rapid compensatory motor reactions that provide the center of mass at the base of support to maintain balance. One of the drawbacks of using perturbation training is the phenomenon of habit that appears after the first and second attempts for the individual and reduces muscle strength [37]. In perturbation training, both feedback control (postural setting is compensation that begins with the feedback of sensory signals after perturbation) and feedforward control (postural setting is a predictor that enters the body before perturbations are applied) occur [24]. Studies have also shown that when perturbations are not visually predictable, stronger predictive activity is formed, and latencies are shortened in the tested muscles. This finding suggests that when postural perturbations are unexpected, the cognitive load increases the recovery of post-disturbance body stability [38] and induces patterns of effective neuromuscular compensatory muscle activity in ACLD individuals [26]. Also, Bittencourt identified risk factors from various biomechanical, physiological, psychological, and training characteristics and their relationships with an ACL injury, among which unpredictable events were the priority of ACL injury. Therefore, it is suggested that unpredictable perturbation training be included in rehabilitation programs [25]. The device used in this study may not conduct the subject into normal processes due to the rapid and sudden perturbations it causes in all axes of movement. Thus, the subject uses strong feedback and control mechanisms and constant external attention focus. So the device needs more studies. Based on the present study results, we suggest that researchers design and study devices similar to real-world and sports events to treat injuries with defective neuromuscular control and achieve a more effective treatment outcome.

Effect of the type of training intervention on the motor control of the jump-landing task on one leg

In the literature review, we found no research that studied SI and VRI in the jump-landing task in preoperative ACLD individuals. Therefore our knowledge in this regard is little. Early studies on respiratory muscle movement control [38] and movement control pattern in patients with shoulder disorders [39] reported that SI and VRI were lower in patients than in healthy individuals. These results were similar to the results of our study, especially before entering the training programs, so that the similarity of the movement control pattern of the two limbs was low. After the application of training interventions, this similarity increased significantly. Gustavsson and Neeter reported that for an ACLD to enter the sport without developing knee instability, the ACLD limb must be tested in isokinetic power dynamometry tests, and its functional evaluation reaches 85% to 90% of the healthy limbs [40, 41]. The results of these two studies were similar to our research in terms of obtaining symmetry in muscle strength and movement pattern.

Letafatkar et al. reported a decrease in muscle contraction (quadriceps/hamstrings) after using perturbation training in the tuck-jump task, which increases the functional stability of the knee joint dynamics. The researchers reported that the neuromuscular control of knee stiffness that results from altered gamma neuronal function and reflex perturbation following ACL injury allows the ACLD individuals [22]. In our study, muscle contraction and motor kinematics were not studied and should be investigated in future studies. In a systematic review by Theisen et al. to examine the onset of muscle activity in reducing landing acceleration, they reported no difference between ACLD limb muscles and a healthy control group. However, the studies were very unreliable [42]. Although in our study, the pattern of muscle activity in the whole jump-landing time in the two limbs was compared, in the pre-test, there was little similarity in the pattern of muscle utilization between the two limbs, which was contrary to the above research. After training intervention, motor symmetry was observed between the two limbs. According to Nawasresh et al., unpredictable mechanical disturbance perturbation training improved knee function and limb-to-limb symmetry in functional activities (hop tests). When symmetry increases, the injured limb can withstand high-risk physical activity and, consequently, the risk of osteoarthritis decreases [1]. Hartigan et al. reported that the use of perturbation training compared to power training further strengthens the sensorimotor characteristics of the muscle and creates better strength and motor symmetry. Also, the perturbation training group gained more symmetrical strength and knee movements than the strength training group [7]. The results of the above studies were in line with our research in that participants in the perturbation training group achieved a more similar movement control pattern in both limbs and higher strength compared to standard training. Thus, coordination and muscle strength in the perturbation training group in both limbs show a symmetrical and large increase compared to the standard training group. In other words, motor defects in the neuromuscular system are eliminated and corrected by performing this perturbation training.

Effect of the training interventions on the cortical activity of the jump-landing task on one leg

Studies have shown that after an ACL injury, functional sensorimotor neuroplasticity and a sustained change in morphological or functional characteristics of brain activity occurs. This change is often associated with cortical maladaptation [3, 6, 14, 15]. Because of neuroplasticity, disrupted neuromuscular control occurs in the form of numerous clinical defects, such as proprioception change, impaired postural control, poor and asymmetric strength, and motor control, and in summary, reduced ability of the nervous system to react to unexpected and sudden events and inability to control loads on the joint. This outcome can be associated with the risk of secondary injury that is not limited to the ACLD limb, and the healthy side might be injured, too [14-16, 43]. When sensory and proprioceptive feedback is lost due to rupture of the ACL ligament, the brain's involvement in motor control increases, and the pattern of motor neuron discharge changes from normal to that of motor neurons at lower frequencies compared to the normal conditions. This status is followed by a decrease in co-contraction and strength, as well as muscle coordination in maintaining dynamic stability.

In conclusion, if the drive of proprioception origin decreases, the drive of cortical origin increases as a functional reorganization of the cortex, resulting in the imposition of sensory areas of the secondary motor to maintain normal movement patterns [15, 44]. The findings of our pre-test study confirm the above studies. In the present study, we used healthy limbs as a reference and lacked a separate healthy control group. The study results in the pre-test of the single-leg jump-landing task on each limb showed low coordination and motor asymmetry in both training groups, and there was asymmetric brain activity in the frequency spectrum of alpha and beta waves.

In the literature review, the main studies on the treatment of impaired motor control due to neuroplasticity in ACLD individuals were neuromuscular training in neurocognitive domains [21, 25, 45], and no study similar to the present study was found. Studies have shown that despite treatments for correcting biomechanical disorders associated with an ACL injury and gaining muscle strength in corrective and strength training, neuroplastic changes remain unresolved. In this case, performance and return to the sports field will be limited, and dysfunction and defective motor control will remain for years [46]. Perturbation training strengthens the feedforward and feedback control mechanisms necessary to prevent future injuries. In addition, they create better strength and movement symmetry than strength training alone [7, 14].

In the present study, because the perturbations occurred at all angles of motion and relatively high speeds, the individuals were exposed to the challenges of sudden surface changes that should be avoided due to the outcome of the movement, motor planning, and swift postural control decision for prevention of falls. So, we expected the external attention focus mechanisms to be strengthened in this training group. But in the standard training group, because the person's focus was more on his body, the internal focus mechanisms were mainly reinforced. In this way, with external attention, intracranial inhibition increases, which results in improved automated control processes and improved dynamic stability [25, 46].

A study by Baumeister et al. showed that after ACL rupture and then reconstructive surgery, there was an increase in frontal theta strength and a decrease in parietal alpha-2 strength. Frontal theta is associated with working memory and increases in cases where attention is needed, and parietal alpha-2 is more active in processing sensory information in the somatosensory cortex [46].

In a study conducted by Miao et al. on ACLDs to examine changes in the power characteristics of the EEG spectrum in functional tasks, they reported that the strength of all delta, theta, alpha, and beta frequency bands in three recording regions (frontal, central, and parietal) were significantly higher than the healthy group. Because of these deficiencies in afferent information, these patients needed more knowledge and attention to reduce irrelevant information. The researchers also reported that the strength of EEG signals in the ACLD group in both hemispheres is asymmetric. The healthy group in this study did not show any hemispherical differences in any frequency band [43]. Our research results of the QEEG characteristics in the pre-test in the jump-landing task were asymmetric between the right and left limbs, confirmed by the Miao study. Still, since we did not have a healthy group for comparison, we could not comment on frequency band strength. Also, in the post-test of the perturbation training group, excellent symmetry between the two hemispheres and the alpha and beta frequency bands was obtained. In the standard training group, there was a non-significant asymmetry in jump-landing on two limbs.

The result obtained from the strength of the alpha and beta frequency bands in the perturbation training group confirms that the decreasing symmetry of the alpha band in both hemispheres indicates the activation of the cortex (release from inhibition) to perform the jump-landing task. According to Gola, higher beta-band activity in the parieto-occipital region in a visually conscious task acts as a stimulus carrier in humans, is associated with a decrease in alpha-band oscillation in the occipital region [47]. In our study, a significant increase in beta-band strength in jump-landing on the right limb may indicate the activation of attention processes, which is similar to the Gola study and also with a decrease in alpha-band strength. But in the standard training group, an apparent non-significant asymmetry between the alpha and beta frequency bands was seen as increasing. These results indicate that in the jump-landing task, in the perturbation training group, the inhibitory activity of the alpha band is reduced and possibly in the form of symmetry of beta waves as a carrier of attention stimulation to increase the coordination of sensorimotor performance in the relevant task which is determined by visual alertness. By reducing the oscillation strength of the alpha band, the activity of the motor part of the cortex is improved by visual awareness of the relay through the beta band, which can be traced symmetrically in the sEMG findings.

5. Conclusion

A review of previous studies showed that current rehabilitation programs for ACLD patients and after reconstructive surgery are insufficient to correct motor control and CNS deficits, and patients after appropriate neuromuscular rehabilitation and surgery still suffer from motor control deficiencies [25, 48]. In the present study, we compared the two types of training interventions regarding the changes in muscle activity in ACLD and healthy limbs and the brain's electrical activity in the jump-landing task on one leg. The results of the present study showed that the perturbation training group had a significantly higher SI in the patterns of using muscle activity in sEMG tests and also achieved excellent symmetry in the relative power spectrum of alpha and beta frequency bands in the single-leg jump-landing task on each limb compared to the standard training group. The results of this study can be used in the rehabilitative treatment of ACLD subjects with outcomes of a faster return to sports and competitive settings, less cost, lower complications, and less required manpower without invasive interventions. These outcomes are generally desired in modern treatment methods.

Ethical Considerations

Compliance with ethical guidelines

This study was approved by the Ethics Committee of the Sports Sciences Research Institute (SSRI), (Code: IR.SSRC.REC.1399.095).

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Authors contributions

All authors equally contributed to preparing this article.

Conflict of interest

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