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Dynamic Analysis of Upper- and Lower-Extremity Performance During Take-Offs and Landings in High-Wall Climbing: Effects of a Plyometric and Strength Training Intervention

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Abstract: This study used a 12-week plyometric and strength training program as an intervention to improve upper- and lower-extremity muscle strength for jumping and landing when climbing high walls. Sixty general non-athlete male college students were openly recruited and divided into an experimental group and a control group. The experimental group underwent a plyometric and strength training program twice a week for 12 weeks (24 sessions). The intervention was divided into three phases, each lasting four weeks, with the training intensity gradually increasing in each phase. A hand grip dynamometer was used to measure grip strength, and a PASCO double-track force plate was used to assess upper-extremity push-up force and lower-extremity take-off and landing strength. The results of the 12-week intervention showed that the experimental group experienced significant increases in grip strength (both hands), hand-ground reaction force, and upper-extremity hang time. Additionally, the time of upper-extremity action on the force plate decreased. Lower-extremity take-off strength improved, as reflected in increased ground reaction force, rate of force development, and passage time. Upon landing, ground reaction force decreased by 3.2%, and cushioning time shortened by 52.7%. This study concludes that plyometric and strength training have promising effects in enhancing upper- and lower-extremity strength, particularly in climbing and landing tasks.

Keywords: climbing high wall; plyometric and strength training; ground reaction force; ballistic push-ups; dynamic analysis

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1. Introduction

Numerous sports encompass climbing-related activities, including pole climbing, rope climbing, high-wall scaling, climbing on platforms, rock climbing, parkour, and modern pentathlon. These activities necessitate that participants exhibit substantial muscles, muscle strength, endurance, and physical coordination. Specific forms of climbing, such as sport climbing and modern pentathlon, have been integrated into the Olympic Games, underscoring the increasing popularity of this physical discipline. Among the various modalities, high-wall climbing is particularly significant in practical applications. In comparison to rock climbing, high-wall climbing is less technically demanding and often serves as a fundamental skill for all climbing-related activities.

Climbing a high wall requires the coordination of the upper and lower limbs in conjunction with the torso, as well as precise body control. Previous studies have highlighted the critical significance of upper-extremity strength in the climbing process, with the upper limbs primarily generating the pulling force while the lower limbs facilitate the initial jump [1–3]. Insufficient upper-extremity strength may impede the ability to ascend, even when lower-extremity strength is robust [4]. Consequently, the successful execution of a climb is contingent upon the combined strength of both arms, commonly referred to as left grip strength (LGS) and right grip strength (RGS) [5–7].

The existing literature suggests that an analysis of the take-off dynamics of the lower limbs during high-wall climbing provides valuable insights into the forces generated during vertical projection. Key mechanical indicators include ground reaction force (GRF), rate of force development (RFD), jump height, and the time taken to initiate take-off [8]. The vertical jump swing of the upper extremities is influenced by the integration of the vertical component of the lower extremities' reaction force over time [9]. The power output of the lower extremities is contingent upon the product of the vertical GRF and the extension velocity of the limbs [10]. RFD serves as a vital metric for assessing both upper- and lower-extremity strength, as it quantifies the rate at which force is exerted. A higher RFD is associated with expedited muscle contraction, which is critical for attaining optimal force output during dynamic activities. Therefore, a reduction in the duration of force application correlates with enhanced power and elevated force output [11–13]. In addition to take-off mechanics, the biomechanics of landing provide essential insights into the relationship between the forces generated by lower-extremity tissues and their subsequent impact on the ground. Numerous factors, including drop height, landing surface, technique, impact speed, footwear, and anthropometric parameters, affect the GRF experienced during landing [14]. Dynamic landing parameters, such as body weight, vertical force, and landing buffer time, are integral to understanding the impact forces experienced by the lower extremities [15,16]. Research has identified a significant positive correlation between the peak rate of centripetal force development and landing impact force, thereby illustrating Newton's third law of motion [17]. Specifically, the vertical impulse experienced during landing is congruent with the force exerted by the lower limbs upon ground contact [18].

Despite the extensive research on plyometric training aimed at enhancing jump height and power, there has been a lack of focus on strength training designed to improve jump landing mechanics or ground reaction forces. While studies on lower-extremity plyometric training are prevalent, investigations into upper-extremity plyometric training remain sparse. High-wall climbing necessitates a coordinated strength capacity from both the upper and lower extremities. In recent years, there has been a notable deficiency in dynamic analyses addressing the take-off strength of both the upper and lower extremities, as well as the landing forces of the lower extremities during high -all climbing. Consequently, this study employed a high wall measuring 2 m in height and 20 cm in width to evaluate the upper- and lower-extremity strength required for both climbing and the subsequent landing. Thereby, the effect of a plyometric and strength training program (PSTP) on enhancing upper- and lower-extremity muscle strength for both jumping and landing when scaling high walls was evaluated. It was hypothesized that a twelve-week PSTP would yield significant improvements in upper-extremity strength for climbing, enhance lower-extremity take-off strength, and increase strength and stability during landing. Engaging in high-wall climbing and landing subjects the body to considerable forces, necessitating substantial strength from both the upper and lower extremities. Thus, the primary focus of this research was to understand the dynamics of the upper and lower limbs during the ascent and descent phases.

2. Materials and Methods

2.1. Inclusions of Participants

Participants were exclusively non-athlete male college students. They reported not being on any medication, particularly pain medication, at the time of the experiment and had no prior history of spine, back, or any other physical activity injuries. A preliminary health assessment was conducted to collect basic information on their ages, heights, and weights for inclusion criteria.

2.2. Exclusions of Participants

Participants were excluded from this study if they exhibited current musculoskeletal injuries, chronic physical or mental health conditions, recent surgical interventions, physical or cognitive disabilities, cardiovascular or respiratory disorders, uncontrolled metabolic conditions, or a history of substance abuse. Furthermore, individuals categorized as competitive athletes or those possessing prior experience in plyometric training were deemed ineligible for participation. Additionally, participants who were sedentary, inactive, or had limb injuries, those on medications that could potentially influence physical performance, failure to provide informed consent, and inability to comply with the study schedule led to exclusion. These measures were instituted to safeguard participant welfare and uphold the integrity of the study outcomes.

2.3. Study Settings and Design

A total of 60 were recruited for this study. The potential risk to participants was deemed minimal and comparable to those not participating in the research, placing it within the lowest risk category. Consequently, there was no infringement upon the rights or interests of the participants. Participation was entirely voluntary, and informed consent was obtained prior to the commencement of this study, with participants required to sign and date the consent forms.

This study adhered to the sample size guidelines for experimental and control group comparisons as specified by Gay, which recommend a minimum of 30 participants per group [19]. Given that the total sample size was 60, a normal distribution was utilized to calculate the 95% confidence interval (CI), ensuring that the participants' ages, heights, and weights fell within the 95% CI range [20].

The 60 participants were randomly assigned to either an experimental group or a control group. Homogeneity tests were conducted on age, height, and weight to confirm the equivalence between the experiment and control groups, with the results presented in Table 1. The ages, heights, and weights of the participants were each subjected to normality tests. The results showed that the Q-Q plots for age, height, and weight were linear, indicating that the participants' data followed a normal distribution (see Figure 1). Although the participants were openly recruited, unaccounted-for variables or individual characteristics, such as varying levels of physical fitness or athletic ability, could potentially have influenced the outcomes.

Table 1. Participant homogeneity analysis.

Variable	EG (n = 30) M ± SD	CG (n = 30) M ± SD	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound	t-Value	p-Value
Age (years)	21.84 ± 1.78	21.81 ± 1.30	−0.55	0.62	0.117	0.908
Height (cm)	175.4 ± 5.81	175.3 ± 4.35	−1.54	1.78	0.148	0.883
Weight (kg)	73.8 ± 4.48	73.7 ± 7.98	−3.37	3.57	0.059	0.953

EG: experimental group; CG: control group; M ± SD: means ± standard deviations; t-test value: t-value (p-value).

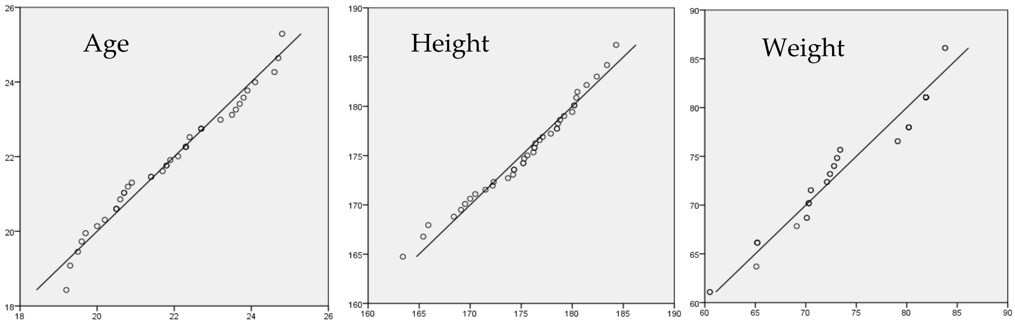

Figure 1. Q-Q plots of participants' age, height, and weight.

The 60 participants were randomly sampled to the experimental or control group by a computer-generated random number sequence to ensure unbiased group allocation. All participants engaged in a 4-mile run twice a week, while the experimental group additionally received the PSTP twice a week for a total of 12 weeks. The experimental setup was conducted in a controlled laboratory environment designed to simulate real-world conditions, thereby ensuring that the exercise routines closely resembled natural settings. In addition to participating in PSTP sessions twice per week, both the experimental and control groups engaged in 3000 m of aerobic exercise and 30 min of flywheel cycling twice per week. This study employed a quasi-experimental design featuring an experimental group and a control group. Both groups underwent pre-test and post-test evaluations to assess the outcomes of the intervention, allowing for comparative analysis [21].

Ethical approval for this study was granted by the Human Trials Review Committee at Tri-Service General Hospital, National Defense Medical College, under number C202305014.

2.4. Intervention

The intervention for this study was based on previous findings that highlighted the combination of plyometric drills to be more effective than single-drill approaches and showed that weighted pull-ups are an effective method for enhancing upper-arm strength [22,23]. These insights, along with a comprehensive review of the plyometric training literature [24–29], were utilized to develop the intervention protocol for the PSTP. The intervention lasted for 12 weeks, as this duration aligns with the timeline for significant strength training adaptations [30]. Training sessions were held twice per week for 90 min each session [31,32], with the exercises divided between upper- and lower-extremity strength training components, as detailed in Table 2.

Table 2. Participants PSTP intervention.

	Content	**Phase 1 (1–4 Weeks)**	**Phase 2 (5–8 Weeks)**	**Phase 3 (9–12 Weeks)**
Upper extremity	Dumbbell fly	One-handed dumbbell 6 kg, 15 reps (Set 1) One-handed dumbbell 8 kg, 10 reps (Set 2) One-handed dumbbell 10 kg, 1–5 rep (Set 3)		
	Dead lift	Barbell + weight plates 20 kg, 15 reps (Set 1) Barbell + weight plates 30 kg, 10 reps (Set 2) Barbell + weight plates 40 kg, 1–5 rep (Set 3)		
	Shoulder press	One-handed dumbbell 6 kg, 15 reps (Set 1) One-handed dumbbell 8 kg, 10 reps (Set 2) One-handed dumbbell 10 kg, 1–5 rep (Set 3)		
	Pull-up	4 reps (Set 1 to Set 3)	4 reps (Set 1 to Set 3)	4 reps (Set 1 to Set 3)
	Ballistic push-up	10 reps (Set 1 to Set 3)	10 reps (Set 1 to Set 3)	10 reps (Set 1 to Set 3)
	Bench press	Barbell + weight plates (20 kg) = 30 kg, 15 reps (Set 1) Barbell + weight plates (30 kg) = 40 kg, 10 reps (Set 2) Barbell + weight plates (40 kg) = 50 kg, 1–5 rep (Set 3)		
Lower extremity	Tuck jumps	10 reps (Set 1 to Set 3)	10 reps (Set 1 to Set 3)	10 reps (Set 1 to Set 3)
	Squat jump	10 reps (Set 1 to Set 3)	10 reps (Set 1 to Set 3)	10 reps (Set 1 to Set 3)

Table 2. *Cont.*

	Content	Phase 1 (1–4 Weeks)	Phase 2 (5–8 Weeks)	Phase 3 (9–12 Weeks)
Lower extremity	1—Stepper machine, Climbmill	20 steps/30 s (Set 1 to Set 3)	–	–
	2—Stepper machine, Climbmill	–	15 steps/30 s (Set 1 to Set 3)	–
	3—Stepper machine, Climbmill	–	–	12 steps/1 min (Set 1 to Set 3)
	2 steps jumping, Both feet	10 reps (Set 1 to Set 3)	12 reps (Set 1 to Set 3)	14 reps (Set 1 to Set 3)
	Smith-machine squats	30 kg, 15 reps (Set 1) 40 kg, 10 reps (Set 2) 50 kg, 1–5 rep (Set 3)		
	Squat jumps and twists	10 reps (Set 1 to Set 3)	12 reps (Set 1 to Set 3)	14 reps (Set 1 to Set 3)
	30 cm box jump, Both feet (total for left and right)	60 reps (Set 1 to Set 3)	72 reps (Set 1 to Set 3)	84 reps (Set 1 to Set 3)
	40 cm box jump, Both feet (total for left and right)	60 reps (Set 1 to Set 3)	–	–
	60 cm box jump, Both feet (total for left and right)	–	60 reps (Set 1 to Set 3)	72 reps (Set 1 to Set 3)

Note: "–" no exercise initiated; Barbell: 20 kg.

The PSTP was structured into three distinct phases, each lasting four weeks, with rest periods between each phase, and weekly rest days were scheduled on Saturdays and Sundays. Participants in the experimental group completed the PSTP twice per week for the full 12-week duration. Circuit training was employed, with participants resting for 10–30 s between exercises within a circuit. Each complete circuit was considered one set, and participants rested for 3–5 min between sets, with three sets required per session. The load intensity for each round of the PSTP was based on the individual's maximum muscle strength (each participant in the experimental group was tested for their one-repetition maximum (1RM) for each exercise before starting the PSTP), as follows [33]:

First set (Set 1): High repetitions (H-rep) with light load (15 reps per set, using 60% to 70% of 1-rep maximum (1-RM)).

Second set (Set 2): Medium repetitions (M-rep) with medium load (10 reps per set, using 70% to 80% of 1-RM).

Third set (Set 3): Low repetitions (L-rep) with heavy load (1–5 rep per set, using 80% to 100% of 1-RM).

2.5. Research Variables and Tools

A force plate was positioned on the ground beneath a 2.2 m high horizontal ladder to replicate the conditions of ascending a high wall. Additionally, a hand grip dynamometer was utilized to assess participants' hand grip strength. The specific research variables and tools employed in this study are delineated below.

2.5.1. Research Variables

The research variables associated with take-off and landing on a high wall were categorized into measures pertaining to the upper and lower extremities. Upper Extremities: This category included hand grip strength and ballistic push-up (BPU) parameters, encompassing the rate of RFD, GRF, and airborne time. Lower Extremities: Variables measured during take-off encompassed RFD, RFD time, GRF area, duration of passage, and jump height. Those related to landing included GRF and landing buffer time at the moment of impact.

2.5.2. Research Tools

Kinetic data during exercise were captured using the PASCO PS-3230, a wireless two-axis force platform developed by PASCO (Roseville, CA, USA). This platform measures forces at each of its four corners with a range of ±1100 N and a total vertical force capacity of 4400 N. The system is equipped with overload protection of up to 1700 N per element and 6600 N for the total vertical load. The force plate's sampling rate was configured to 1000 Hz, yielding 1000 data points per second. This instrument is extensively employed for the mechanical analysis of various human movement behaviors [34].

Hand grip strength was quantified using a hand grip dynamometer (Camry (Shenzhen, China), model EH101), which operates within a range of 0–90 kg and possesses an accuracy of 0.1 kg.

2.5.3. Hand Grip Test

Pull-ups constituted a component of the Performance Strength Training Protocol, and prior research by Vigouroux et al., 2024 indicated that pull-up exercises can significantly enhance hand grip strength [23]. As such, measuring grip strength was a focal point of this study. Participants were instructed to stand with the arm being assessed in a neutral position, shoulder slightly abducted (~10°), and the elbow fully extended. The forearm maintained a neutral posture with the hand in a straight alignment. Grip strength was measured three times for each hand, and the average value was recorded.

2.5.4. Upper-Extremity Muscle Strength Test

The BPU parameters obtained via the force plate were utilized to evaluate upper-extremity muscle strength and explosive power. In accordance with Bartolomei et al., 2018, the following equation was employed to estimate upper-extremity strength: $11.0 \times (\text{body weight} + 2012.3) \times (\text{duration of passage} - 338.0)$ [35]. Both pre-test and post-test BPU performance were assessed, while parameters such as RFD, GRF, and duration of passage were recorded.

2.5.5. Lower-Extremity Take-Off Test

The lower-extremity take-off test involved a vertical jump, which was quantified using the PASCO force plate. Participants were instructed to stand upright on the force plate with their weight evenly distributed. Upon indicating readiness, they executed a rapid squat, swung their arms, and performed a vertical jump. Following the jump, participants landed with both feet simultaneously and then returned to a standing position. A total of five vertical jumps were completed, with a 10 s rest interval between each jump. The mean of the best three jumps was calculated to derive the final score. The force plate recorded several parameters, including RFD, GRF time, GRF, duration of passage, and jump height.

2.5.6. Lower-Extremity Landing Test

For the lower-extremity landing test, participants stood upright on the force plate, maintaining an even distribution of weight. A horizontal ladder was positioned at a height of 2.2 m to simulate a landing from an elevated surface. Participants executed a quick squat and swung their arms to grasp the horizontal pole, holding this position for 3 s prior to release and landing on the force plate. Measured parameters during the landing included GRF and buffer time, defined as the duration from initial ground contact to full stabilization.

2.6. Statistical Analysis

Statistical analysis was conducted utilizing SPSS version 28.0 (IBM, Armonk, NY, USA). Initially, an independent *t*-test was performed to evaluate the homogeneity of the experimental and control groups concerning age, height, and weight. The pre-test and post-test data were presented as means and standard deviations (SDs). Differences between the pre-test and post-test results of the two groups were analyzed using a two-way mixed ANOVA. The significance level for the analysis was established at $p < 0.01$. Partial Eta Squared is used to measure the contribution of the independent variable to the dependent variable. The value of Partial Eta Squared ranges between 0 and 1 in sports sciences, which can vary, with values closer to 1 indicating a greater contribution of the independent variable to the dependent variable. In other words, the independent variable has a large effect on the dependent variable when $\eta^2 > 0.14$ [36].

3. Results

3.1. Analysis of Muscle Strength of Upper Body

The effect size for each parameter was initially analyzed using the Eta Squared (η^2), which quantifies the proportion of variance attributable to the experimental effect. The statistical results for LGS, RGS, GRF time spent, GRF max, RFD, and duration of passage all showed effect sizes ranging from 0.378 to 0.831, indicating large effects. Among them, 'GRF time spent' had the largest effect size, with 83.1% of the variance, which can also be interpreted as an 83.1% reduction in experimental error [37]. Similarly, 'LGS' had 37.8% of the variance, representing the smallest effect size for the upper extremities, but still achieved a large effect size of over 0.14, as shown in Table 3.

Table 3. Analysis of upper-extremity strength for climbing high walls.

Parameters		**EG (*n* = 30) M ± SD**	**CG (*n* = 30) M ± SD**	***F*-Value**	***p*-Value**	η^2
LGS $_{(\text{kg})}$	Pre	42.9 ± 1.7	43.2 ± 1.3	35.32 *	<0.01	0.378
	Post	46.0 ± 2.2	43.0 ± 1.8			
RGS $_{(\text{kg})}$	Pre	43.4 ± 1.5	43.4 ± 1.1	62.13 *	<0.01	0.517
	Post	46.6 ± 2.2	43.1 ± 1.6			
GRF time spent $_{(\text{s})}$	Pre	1.04 ± 0.11	1.05 ± 0.11	285.28 *	<0.01	0.831
	Post	0.82 ± 0.09	1.05 ± 0.09			
GRF max $_{(\text{N})}$	Pre	617 ± 61.8	621 ± 73.5	209.0 *	<0.01	0.783
	Post	663 ± 57.8	620 ± 66.9			
RFD $_{(\text{r})}$	Pre	5210 ± 492.8	5264 ± 670.1	142.1 *	<0.01	0.710
	Post	5488 ± 468.7	5268 ± 665.2			
Duration of passage $_{(\text{s})}$	Pre	0.13 ± 0.01	0.14 ± 0.01	426.5 *	<0.01	0.880
	Post	0.21 ± 0.02	0.13 ± 0.01			

EG: experimental group; CG: control group; LGS: left grip strength; RGS: right grip strength; GRF max $_{(\text{N})}$: ground reaction force maximum (Newton); r: rate of force development; *s*: duration of passage; M ± SD: mean ± standard deviation; *p*-value: F-test values presented as *F*-value; * $p < 0.01$.

The analysis of upper-extremity strength in this study encompassed critical parameters such as hand grip strength, upper-extremity performance on the force plate, BPU metrics, RFD, GRF, time spent, and duration of passage. After 12 weeks of PSTP intervention, the experimental group's left-hand grip strength increased by 7.23% (an average of 3.1 kg), and the right-hand grip strength increased by 7.37% (an average of 3.2 kg), both showing significant improvement. In the post-test of upper-extremity operation BPU for the experimental group, the time of upper-extremity action on the force plate was reduced by an average of 0.82 s, the reaction force between the palm and the ground increased by an average of 663 newtons, and the duration of passage significantly increased by an average of 0.21 s. As for the control group, they did not demonstrate any significant improvements, as shown in Table 3. These findings substantiate the study's hypothesis that a 12-week PSTP can markedly enhance upper-extremity strength, particularly in the context of climbing high walls.

3.2. Analysis of Lower-Body Muscle Strength

3.2.1. Analysis of Take-Off Dynamics

The effect size of each parameter related to lower-body take-off dynamics was initially assessed. The statistical results for RFD, GRF, GRF time spent, jump height, and duration of passage all showed effect sizes ranging from 0.149 to 0.427, indicating large effects across all measures. Among these measures, "GRF time spent" had the largest effect size, accounting for 42.7% of the variance. This can also be interpreted as a 42.7% reduction in experimental error. Similarly, "GRF" accounted for 14.9% of the variance, which is the smallest effect size during the take-off phase. However, it still achieved a large effect size of over 0.14, as shown in Table 4.

Table 4. Dynamic analysis of lower-extremity take-off pre- and post-tests.

Parameters		**EG (n = 30)** **M ± SD**	**CG (n = 30)** **M ± SD**	***F*-Value**	***p*-Value**	η^2
RFD $_{(r)}$	Pre	4344 ± 779.2	4184 ± 1379	18.88 *	<0.01	0.246
	Post	5231 ± 1687	4181 ± 1368			
GRF $_{(N)}$	Pre	1725 ± 97.2	1733 ± 73.9	10.15 *	<0.01	0.149
	Post	1761 ± 85.2	1734 ± 77.6			
GRF time spent $_{(s)}$	Pre	0.66 ± 0.09	0.65 ± 0.09	43.26 *	<0.01	0.427
	Post	0.50 ± 0.07	0.64 ± 0.08			
Jump height $_{(m)}$	Pre	0.49 ± 0.04	0.50 ± 0.03	24.21 *	<0.01	0.294
	Post	0.53 ± 0.05	0.49 ± 0.03			
Duration of passage $_{(s)}$	Pre	0.45 ± 0.08	0.44 ± 0.07	12.48 *	<0.01	0.177
	Post	0.48 ± 0.03	0.43 ± 0.07			

EG: experimental group; CG: control group; RFD (r): rate of force development; GRF (N): ground reaction force maximum (Newton); Unit (s): duration of passage; M ± SD: mean ± standard deviation; *p*-value: F-test values presented as *F*-value; * $p < 0.01$.

The analysis of the pre- and post-test results for lower-extremity take-off strength encompassed the following parameters: RFD, GRF time, GRF area, duration of passage, and jump height. Following the 12-week plyometric and PSTP intervention, the experimental group's lower-limb jump dynamics parameters were all superior to those of the control group. A two-factor mixed ANOVA revealed significant differences in the F-values of each parameter ($p < 0.01$), as summarized in Table 4. The experimental group showed a 20.4% increase in RFD, a 2.1% increase in GRF, a 24.2% reduction in GRF time spent during take-off, an 8.2% increase in jump height, and a 6.7% increase in duration of passage. Based on the above results, the PSTP intervention increased the lower-extremity muscle strength of the experimental group. Additionally, the increase in upper-extremity muscle strength enhanced the arm swing force, which contributed to greater upward muscle pull. This allowed the lower extremities to execute a more powerful concentric contraction during the jump, instantly creating a larger RFD.

These findings substantiate the acceptance of the research hypothesis, demonstrating that 12 weeks of PSTP significantly improved lower-extremity take-off strength for climbing high walls.

3.2.2. Analysis of Landing Dynamics

First, the effect sizes for various parameters of lower body landing kinetics were analyzed. The statistical results showed that the effect size for "GRF when landing instantly" was 0.563, and the effect size for "landing buffer time" was 0.388, both indicating large effects. After 12 weeks of PSTP intervention, the experimental group's landing force decreased by 3.2% (an average of 51 newtons), indicating that the experimental group landed more lightly. The experimental group's landing buffer time was reduced by 54.5% (an average of 0.30 s), indicating that the experimental group landed more stably. The two-factor mixed ANOVA conducted between the experimental and control groups showed that the F-values for "GRF when landing instantly" and "landing buffer time" both reached significant differences ($p < 0.01$), as shown in Table 5 and Figure 2. These results substantiate the research hypothesis, indicating that 12 weeks of PSTP significantly enhance both the strength and stability of lower-extremity landing.

Table 5. Dynamic analysis of lower-extremity landing.

Parameters	**EG (*n* = 30) M ± SD**	**CG (*n* = 30) M ± SD**	***F*-Value**	***p*-Value**	**η^2**
GRF when landing instantly (N)					
Pre	1571 ± 34.6	1575 ± 42.0	74.7 *	<0.01	0.563
Post	1520 ± 40.3	1573 ± 31.3			
Landing buffer time (s)					
Pre	0.55 ± 0.29	0.65 ± 0.35	36.8 *	<0.01	0.388
Post	0.25 ± 0.99	0.59 ± 0.28			

EG: experimental group; CG: control group; M ± SD: mean ± standard deviation; *p*-value: F-test values presented as F-value; * $p < 0.01$.

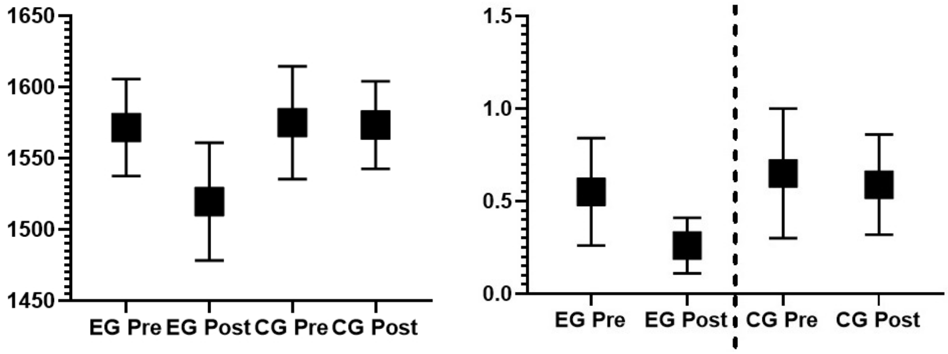

Figure 2. Pre- and post-test of GRF when landing instantly and landing buffer time. Note: The left side was the average GRF of each group at the moment of landing, and the right side was the buffer time of each group when landing.

4. Discussion

4.1. Plyometric Training Benefits

This study investigated the upper and lower extremities during obstacle course climbing and landings from elevated surfaces. Following a 12-week regimen of plyometric training, post-test data regarding muscle strength in the upper and lower extremities of the experimental group exhibited significant enhancements. Plyometric training improves muscle contraction, resulting in increased strength and explosive power, as it necessitates the exertion of the maximum force within a brief time frame, predominantly targeting fast-twitch muscle fibers. A plethora of studies has corroborated the efficacy of plyometric training as an effective methodology for augmenting muscle performance [24–26]. Plyometric training entails a rapid transition from eccentric muscle contraction to concentric contraction. In this investigation, explosive BPUs were employed to exemplify the three phases of plyometric training: eccentric pre-stretch, amortization (rebound), and concentric shortening. The eccentric pre-stretch phase generates force through ground reaction, serving as the predominant source of explosive power [38]. Seiberl et al., 2021 confirmed that plyometric training enhances the rapid stretching of muscles [39], by leveraging the stretch-shortening cycle to optimize power output [40]. Additionally, plyometric training facilitates high-intensity eccentric contractions immediately following concentric contractions [41]. This training technique has been demonstrated to improve the rapid contraction and stretching of muscles, particularly in vertical jumping exercises [42]. Substantial evidence supports the assertion that plyometric training enhances vertical jump height [26–29]. In the present study, the plyometric and strength training program included exercises such as upper-extremity BPUs, pull-ups, and lower-extremity jumping and weighted squats, culminating in increased muscle strength in both the upper and lower extremities among the experimental group.

4.2. Upper-Extremity Muscle Strength for Climbing High Walls

The post-test results for the experimental group revealed a reduction in the time spent on ballistic push-ups, indicating that participants exerted force on the surface for a shorter duration while generating greater GRF and RFD values. The increased duration of passage is consistent with the findings of previous studies [2,43–45]. This study validated that BPUs serve as an effective assessment tool for predicting upper-extremity muscle strength and explosive power. However, for individuals exhibiting low upper-extremity strength, alternative measurement techniques may be warranted. Although BPUs possess certain limitations, they provide a more convenient evaluative method compared to previous approaches. Climbing high walls necessitates substantial hand grip and centripetal arm strength [5,46,47]. The Physical Strength Training Program effectively augmented upper extremity strength in the experimental group through a range of exercises, including standing dumbbell flies, ballistic push-ups, dumbbell shoulder presses, barbell deadlifts, bench presses, and pull-ups. This regimen enhanced the rate of force development during concentric contractions of the upper extremities, aligning with the findings of Maffiuletti et al., 2016 [48]. Pull-ups, notwithstanding their apparent simplicity, constitute a multi-joint, closed-chain upper-body resistance exercise that necessitates dynamic concentric strength from the arm and shoulder musculature to execute the elbow flexion and shoulder extension required for wall climbing [49,50]. Consequently, the experimental group demonstrated significant improvements in upper-extremity strength relevant to wall climbing, corroborated by prior research [23,50–52].

4.3. Lower-Extremity Muscle Strength for High Wall Take-Off

The PSTP intervention significantly enhanced lower-extremity muscle strength for wall climbing and take-off in the experimental group. Post-test results indicated improvements in GRF, RFD, jump height, and the duration of passage. The augmented RFD reflects effective development of explosive power [53]. The existing literature suggests that plyometric training potentiates increases in muscle thickness, fascicle length, and tendon stiffness, subsequently enhancing jump performance and lower body strength [40]. Furthermore, plyometric training activates muscle fibers, thereby improving overall muscular system performance [1]. Macaluso et al., 2012 demonstrated that plyometric training facilitates adaptations in slow-twitch muscle fibers, enabling them to exhibit characteristics more akin to fast-twitch fibers [54]. Research has identified that enhanced body coordination and muscle strength contribute to improved lower-extremity strength during high-wall climbing and take-off [23]. The results of the current study indicated that the experimental group experienced an increase in take-off height due to the reaction force generated by the legs and the elevation of arm segments during take-off, in line with the findings of Lees et al. 2004 [55]. The rapid contraction of muscles during climbing enables energy storage within muscle cells, facilitating explosive movements [56]. However, certain studies have reported no changes following plyometric training, potentially attributed to variables such as participant age, gender, training volume, and fatigue [57].

4.4. Lower-Extremity Muscle Strength for High-Wall Landing

The GRF generated by the lower extremities during landing varies according to individual height and landing surface characteristics. Individuals with stronger lower-extremity muscles exhibit a greater ability to withstand the impacts of GRF on the knee and ankle joints, particularly during heel strikes [58]. The study results showed that the experimental group's landing force decreased by 3.2%, while the landing buffer time was reduced by 52.7%. This indicates that following the intervention, greater lower-extremity muscle strength led to shorter landing buffer times, as the ankle more efficiently absorbed the GRF during landing, resulting in improved landing stability. For instance, in the present study, the height of the climbing wall was 2.2 m, and participants of approximately 170 cm in height typically maintained a 20 cm distance between their feet and the ground upon landing. Some participants executed immediate jumps after scaling the wall, resulting in variable impact forces on the lower extremities contingent upon jumping speed and angle [59]. Plyometric training was found to enhance the landing stability of the lower extremities in the experimental group, as it prioritizes body control and GRF modulation [60]. An appropriate landing technique, characterized by gentle cushioning of the knees, facilitates the generation of centripetal force and joint support [61]. Milosevic et al., 2019 observed that the rapid reflexive response of spinal nerves during landing triggers muscle contractions that provide support extending from the knee to the ankle [62]. Myer et al., 2006 further corroborated that plyometric training mitigates ankle eversion during landing and improves ground control by enhancing the hamstring-to-quadriceps ratio, thereby potentially reducing the risk of injury [63]. Consequently, plyometric training resulted in significant improvements in the stability of the landing posture within the experimental group.

4.5. Limitations

This study had few limitations in its experimental environment, designed to simulate high-wall climbing, though it may have differed from natural high-wall settings, which may have introduced measurement inaccuracies. The lack of control over participants' baseline activity levels meant general physical activity outside the experimental setting may have influenced the results, potentially affecting the generalizability of the findings to more sedentary or highly active populations. Additionally, some participants struggled to complete the required number of pull-ups during the PSTP sessions due to their individual fitness levels. The experimental group underwent the PSTP, and prior to the training, each participant's 1 RM for the PSTP exercises was tested to determine their maximum number of repetitions. As the training period progressed, participants' 1 RM values improved. However, trainers had to frequently remind participants to adjust the load, which presented a limitation of this study. Although BPUs were employed as an effective training tool, this exercise may have limitations in fully capturing all aspects of upper-extremity strength. Finally, because the participants lacked experience in climbing-related sports or competitions, their improvement threshold was higher, potentially influencing the overall results.

4.6. Recommendations for Future Studies

While this study demonstrated significant improvements in upper- and lower-extremity strength through plyometric training, future research should consider including female participants to explore the effectiveness of this training across genders. Moreover, expanding the range of plyometric exercises and adjusting the training volume and intensity could provide additional insights into optimizing performance. Researchers should continue utilizing force plates for precise evaluations of muscle strength and seek to develop more targeted interventions for obstacle course training. Furthermore, plyometric training could be applied to other obstacle-related activities, such as high jumps, pole climbing, and sand pit jumps, as it enhances agility, muscle strength, and coordination. Future studies should also investigate the neuromuscular and biomechanical adaptations resulting from such interventions, particularly for athletes and individuals participating in obstacle courses.

5. Conclusions

This study found that plyometric and strength training effectively improved upper- and lower-extremity muscle strength in the experimental group. Following the completion of the 12-week PSTP, participants demonstrated notable improvements in hand grip strength, arm flexion strength, and GRF in the lower extremities, as well as an increased RFD during both jumping and landing, which contributed to enhanced landing stability. Compared to the control group, which relied on instinctive techniques, the experimental group exhibited substantial progress in climbing, jumping, and landing performance. The PSTP incorporates pull-up exercises as a key component to train the upper body, effectively strengthening all muscle groups above the waist. Athletes in sports such as Olympic climbing and modern pentathlon can benefit from these exercises to enhance upper limb endurance and explosive power, with pull-ups serving as highly effective training models.

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