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ORIGINAL RESEARCH

Unstable surface training as a rehabilitation exercise modality improves strength, range of motion, and postural control in young adults with grade 1 ankle sprain

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Abstract

Background: Ankle sprains are one of the most common musculoskeletal injuries in young adults, often leading to chronic ankle instability if inadequately rehabilitated. Restoring range of motion (ROM), strength, and postural balance are critical to prevent recurrence. This study investigated the comparative effects of stable surface training (SST) and unstable surface training (UST) on ankle joint function and balance in individuals with Grade 1 ankle sprains. **Methods**: Twenty healthy adult males diagnosed with Grade 1 ankle sprains were randomly assigned to SST (n = 10) or UST (n = 10) groups. Participants underwent a 4-week balance training program, three times per week. Pre- and post-intervention assessments included ankle joint ROM (dorsiflexion, plantarflexion, inversion, eversion), isokinetic muscle function, and static and dynamic balance tests (eyes-closed single-leg stance test (ECSLT) and Y-balance test). **Results**: Both groups showed significant improvements over time in ankle strength and balance ($p < 0.05$). However, only the UST demonstrated significant increases in dorsiflexion, plantarflexion, and inversion ROM ($p < 0.05$), as well as in total and average ROM ($p < 0.05$). While both SST and UST enhanced balance, UST showed a greater tendency for improvement, particularly in dynamic postural control. UST was more effective than SST in improving multidirectional ankle ROM and enhancing postural balance. **Conclusions**: These findings suggest that proprioceptively challenging rehabilitation protocols should be prioritized in early-stage rehabilitation for Grade 1 ankle sprains to support comprehensive functional recovery. **Clinical Trial Registration**: This study was registered in the Clinical Research Information Service (CRiS), Republic of Korea, under the registration number KCT0010569 (https://cris.nih.go.kr/cris/search/detailSearch.do?seq=30039&search_page=L).

Keywords

Ankle sprain; Rehabilitation exercise; Proprioception; Functional recovery; Balance training

1. Introduction

Ankle sprains are among the most common musculoskeletal injuries, particularly in physically active young individuals. Of these, grade 1 lateral ankle sprains, characterized by mild ligamentous stretching and minimal functional impairment, are frequently underestimated in clinical settings despite their high recurrence rate. Epidemiological studies have shown that lateral ankle sprains account for approximately 15–20% of all sports-related injuries, with recurrence rates ranging from 30% to 70% in individuals who do not receive appropriate rehabilitation [1–3].

This highlights the critical need for early and effective intervention strategies to prevent the development of chronic ankle instability (CAI), which can substantially impair athletic performance and quality of life [4, 5]. Moreover, ankle injuries often have biomechanical consequences that extend beyond the joint itself. Compensatory movement patterns adopted after injury can place undue stress on the knee, hip, and lumbar spine, increasing the risk of secondary injuries [6, 7]. These findings indicate that the ankle is not an isolated joint but a key contributor to postural control and dynamic balance, underscoring the need for comprehensive rehabilitation [5, 8]. In the rehabilitation of ankle sprains, several clinical metrics are used to assess recovery progress and functional restoration. Static and dynamic balance are key to preventing re-injury, as deficits in proprioceptive feedback can compromise neuromuscular control during both rest and activity [5, 9, 10].

Specifically, restoration of ankle joint ROM is essential for full functional recovery and reducing the risk of recurrent sprains or compensatory movement patterns [4, 11]. Similarly, muscle strength around the ankle not only contributes directly to joint stabilization but also facilitates shock absorption and reduces excessive mechanical demands on the proximal joints in the kinetic chain [12, 13].

Exercise therapy is an essential component in the rehabilitation of ankle sprains [8, 14], and stimulation of ankle proprioceptive information through exercise enables integration for posture and balance control [5, 9]. In addition, it has been reported to be effective in reducing the prevalence of recurrent injuries [11, 15], improving ankle function, and reducing the time to return to the sports field after ankle sprain [12, 16]. In particular, exercise therapy has been reported to be the most effective when performed early in Grade 1 injury management [14, 17]. Regarding exercises to improve ankle injuries such as sprains, balance exercises are most widely used in sports due to their effectiveness in improving neuromuscular coordination, enhancing joint muscle activity, and reducing the incidence of joint injuries [5, 15, 18]. Balance training can be largely divided into SST and UST. Both SST and UST are effective in improving joint stiffness and function [16, 19]. However, UST is reported to have greater physiological and functional utility than SST because it utilizes an unstable surface [18, 20, 21]. UST has been shown to provide a more effective training environment by activating more tendon, ligament, and joint receptors [19, 22] and by providing higher-intensity muscle contractions to the muscles [18].

While numerous studies have explored rehabilitation strategies for ankle sprains, several limitations reduce their clinical applicability. Many previous studies grouped together different injury severities, including chronic and acute cases, obscuring outcomes specific to Grade 1 injuries [2, 3]. Moreover, a large proportion of research neglects to compare UST with SST under consistent, clearly defined protocols [20, 23]. Studies also often rely on single-outcome measures and fail to address muscle strength, pain, ROM, and balance collectively. Notably, few include eversion strength, despite its critical role in lateral ankle stability [6, 13, 21].

Therefore, this study aims to address these gaps by comparing the effects of unstable and stable surface training in young adults recovering from Grade 1 ankle sprains. By incorporating multidimensional outcome measures, including joint ROM, muscle strength, and static and dynamic balance, this study aims to provide more focused and clinically applicable rehabilitation strategies.

2. Materials and methods

2.1 Participants

Using G*Power 3.1.9.2 (Franz Faul, University of Kiel, Kiel, SH, Germany), a power analysis was conducted with a power of 0.80, an effect size of 0.3, and a significance level of 0.05 [24]. This analysis determined that a sample size of 16 participants was optimal. To enhance the robustness of the findings and account for potential dropouts, 20 participants (age: 24.15 ± 3.82 years) were recruited following Institutional Review Board approval in August 2023, all of whom completed the intervention and assessments without any attrition. The participants of this study were 20 adult males aged 18–35 years who were diagnosed with grade 1 ankle sprains by an orthopedic specialist within the past month. Participants were excluded if they had a history of previous lower extremity injuries (*e.g.*, ankle fracture, chronic knee instability), neurological disorders, vestibular deficits, or other musculoskeletal conditions that could affect balance or movement. These exclusion criteria were added to ensure homogeneity and reduce confounding influences. The participants were randomly assigned to SST group (SSTG, n = 10) and UST group (USTG, n = 10). The physical characteristics of the subjects are shown in (Table 1). Before conducting this study, the purpose, procedure, and instructions of the study were explained through an informational guide, and the study was conducted after obtaining consent for participation. In addition, this study was reviewed and approved by the Institutional Review Board of Konkuk University (7001355-202308-HR-680) before implementation and was conducted in accordance with the Declaration of Helsinki. Participants were recruited between September 2023 and August 2024.

2.2 Rehabilitation program

The balance exercise program performed by SSTG and USTG is shown in (Table 2). The balance exercise program was performed for approximately 40 minutes, three times a week, for 4 weeks, and the exercise intensity was level 4–6 on the OMNI-resistance exercise scale (OMNI scale). The program consisted of 5 stages: Stage 1—bending the knee joint, Stage 2—bending the knee and hip joints, Stage 3—walking in place while maintaining a constant speed, Stage 4—maintaining a squat position, Stage 5—bending and straightening only the hip joint. Each stage of exercise was performed for 5 minutes, and a 180-second rest period was provided between each stage of the movement. In addition, the USTG performed the same 5 stages of exercise as the SSTG with the floor (a hard flat surface) of the both sides utilized (BOSU) balance trainer facing downward.

2.3 Static and dynamic balance test

All subjects were tested for static and dynamic balance before and after 4 weeks of treatment. Static balance was measured using ECSLT. All participants were instructed to remove their footwear and stand on their one leg, with the contralateral knee flexed so that the foot did not touch the ground. The arms were positioned akimbo (hands on hips), and participants were asked to close their eyes and maintain balance for as long as possible. The test was conducted on a level, firm surface in a quiet environment. Each participant completed three trials, with a 30-second rest period between trials [22]. This test has shown good reliability with Intraclass Correlation Coefficient (ICC) values ranging from 0.83 to 0.99. Dynamic balance test was measured using Y-balance test (Y-Balance Test Kit, Functional Movement Systems Inc, Danville, VA, USA). Participants were instructed to stand barefoot on their dominant leg at the center footplate and reach with the non-stance leg in three directions: anterior, posteromedial, and posterolateral, as far

TABLE 1. Participants' characteristics.

Variables	SSTG (n = 10)	USTG (n = 10)	*p*-value
Injured side	R(5), L(5)	R(3), L(7)	
Age	23.90 ± 3.38	24.40 ± 4.37	0.778
Height (cm)	176.70 ± 7.41	178.80 ± 5.47	0.480
Body weight (kg)	79.74 ± 15.70	78.16 ± 10.12	0.792
BMI (kg/m^2)	25.47 ± 3.30	24.29 ± 3.32	0.436

Note. Values are expressed as mean ± standard deviation. SSTG: stable surface training group; USTG: unstable surface training group; R: right; L: left; BMI: body mass index.

TABLE 2. Rehabilitation exercise program.

Exercise program	Volume	Intensity	Frequency
1. Knee joint flexion 2. Knee joint Flexion and Hip joint flexion 3. Walking 4. Squat position 5. Hip joint flexion	All participants performed exercise freely with certain movements in each program for 5 min	OMNI scale 4–6	40 min, 3 d/wk, 4 wk

OMNI scale: OMNI-resistance exercise scale.

as possible while maintaining single-leg stance. Hands were placed on the hips to prevent compensation through upper body movement. Reach distances were measured to the nearest 0.1 cm. The maximum reach distance in each direction was normalized to leg length (measured from the anterior superior iliac spine to the distal tip of the medial malleolus) using the formula: normalized: reach distance (%) = (reach distance (cm)/leg length) × 100. Each participant completed three trials, recording the best of which.

2.4 Measurement of ankle range of motion

Ankle joint ROM was assessed using a universal goniometer. Four primary directions were evaluated: dorsiflexion, plantarflexion, inversion, and eversion. For dorsiflexion, participants were positioned in a seated posture with their knee flexed at 90° to reduce tension from the gastrocnemius. The fulcrum of the goniometer was aligned with the lateral malleolus, the stationary arm aligned with the fibular shaft, and the movable arm aligned parallel to the fifth metatarsal. Participants actively dorsiflexed the ankle to their maximum pain-free range. For plantarflexion, the same anatomical landmarks were used, and participants were instructed to plantarflex the foot maximally. To assess inversion and eversion, participants remained seated with the foot and ankle in a neutral position. The fulcrum of the goniometer was placed over the anterior aspect of the ankle between the malleoli, with the stationary arm aligned with the tibial shaft and the movable arm aligned with the second metatarsal. For inversion, participants turned the sole of the foot medially as far as possible. For eversion, participants turned the sole of the foot laterally. All measurements were performed three times by a trained examiner, and the mean value (in degrees) was recorded for each direction. The goniometric measurements have demonstrated high inter-rater reliability (ICC >0.90) in previous studies [25]. Active ROM was measured to reflect functional voluntary control, and care was taken to prevent compensatory movements at the hip or knee.

2.5 Isokinetic muscle function test

Ankle muscle strength was evaluated using an isokinetic dynamometer (Biodex System 3 Pro; Biodex Medical Systems, Shirley, NY, USA). Participants were seated in the testing chair with the hip flexed to approximately 85°, the knee in slight flexion, and the ankle positioned in neutral alignment. The dominant limb was secured to the footplate using straps, and proper alignment of the lateral malleolus with the axis of rotation of the dynamometer was ensured. Stabilization straps were applied across the trunk, pelvis, and thigh to minimize compensatory movements. Each motion was assessed concentrically at angular velocities of 30 °/s and 120 °/s, reflecting both muscle strength and muscle power, respectively. After a standardized warm-up and familiarization session, participants completed five maximal voluntary repetitions at each velocity. A rest period of at least 60 seconds was provided between test conditions. All measurements were conducted by the same experienced examiner to ensure consistency. Biodex isokinetic dynamometers have established test-retest reliability (ICC: 0.86–0.98) in previous validation studies [26].

2.6 Statistical analysis

Statistical analysis was performed using IBM SPSS Statistics version 25.0 (IBM Corp., Armonk, NY, USA), and the mean and standard deviation for all dependent variables before and after the treatment were calculated. To evaluate the group-by-time interaction effect or main effect, repeated two-way repeated measures analysis of variance (ANOVA) was performed. When significant interaction or main effects are detected, independent *t*-test or paired *t*-test and were used to analyze the differences within or between groups, respectively. All statistical significance levels in this study were set to less than 5%. A flow diagram summarizing participant enrollment, randomization, intervention, and follow-up is presented in Fig. 1.

3. Results

3.1 Ankle joint range of motion

There was no group-by-time interaction effect of the 4-week rehabilitation exercise program on the ankle joint ROM of the injured side. However, significant time effect was observed for dorsiflexion ($p = 0.010$, $\eta_p^2 = 0.313$), plantarflexion ($p = 0.026$, $\eta_p^2 = 0.246$), inversion ($p = 0.009$, $\eta_p^2 = 0.320$), and eversion ($p = 0.006$, $\eta_p^2 = 0.346$) in both groups (Table 3). The paired *t*-test results showed that only USTG have significant improvement in the ROM of dorsiflexion ($p = 0.026$), plantarflexion ($p = 0.003$), and inversion ($p = 0.012$). In addition, changes of total ($p = 0.021$) and average ($p = 0.020$) ROM were significantly higher in USTG (Fig. 2A,B).

3.2 Ankle joint isokinetic muscle function

The ankle joint isokinetic muscle functions are presented Table 4. There was no group-by-time interaction effect on isokinetic muscle function at 30 °/s and 120 °/s in either group. However significant time effects were found in dorsiflexion ($p < 0.010$, $\eta_p^2 = 0.603$), plantarflexion ($p < 0.010$, $\eta_p^2 = 0.674$), inversion ($p < 0.010$, $\eta_p^2 = 0.759$), and eversion ($p < 0.010$, $\eta_p^2 = 0.711$) at 30 °/s to evaluate muscle strength, and in dorsiflexion ($p < 0.010$, $\eta_p^2 = 0.540$), plantarflexion ($p < 0.010$, $\eta_p^2 = 0.766$), inversion ($p < 0.010$, $\eta_p^2 = 0.625$), and

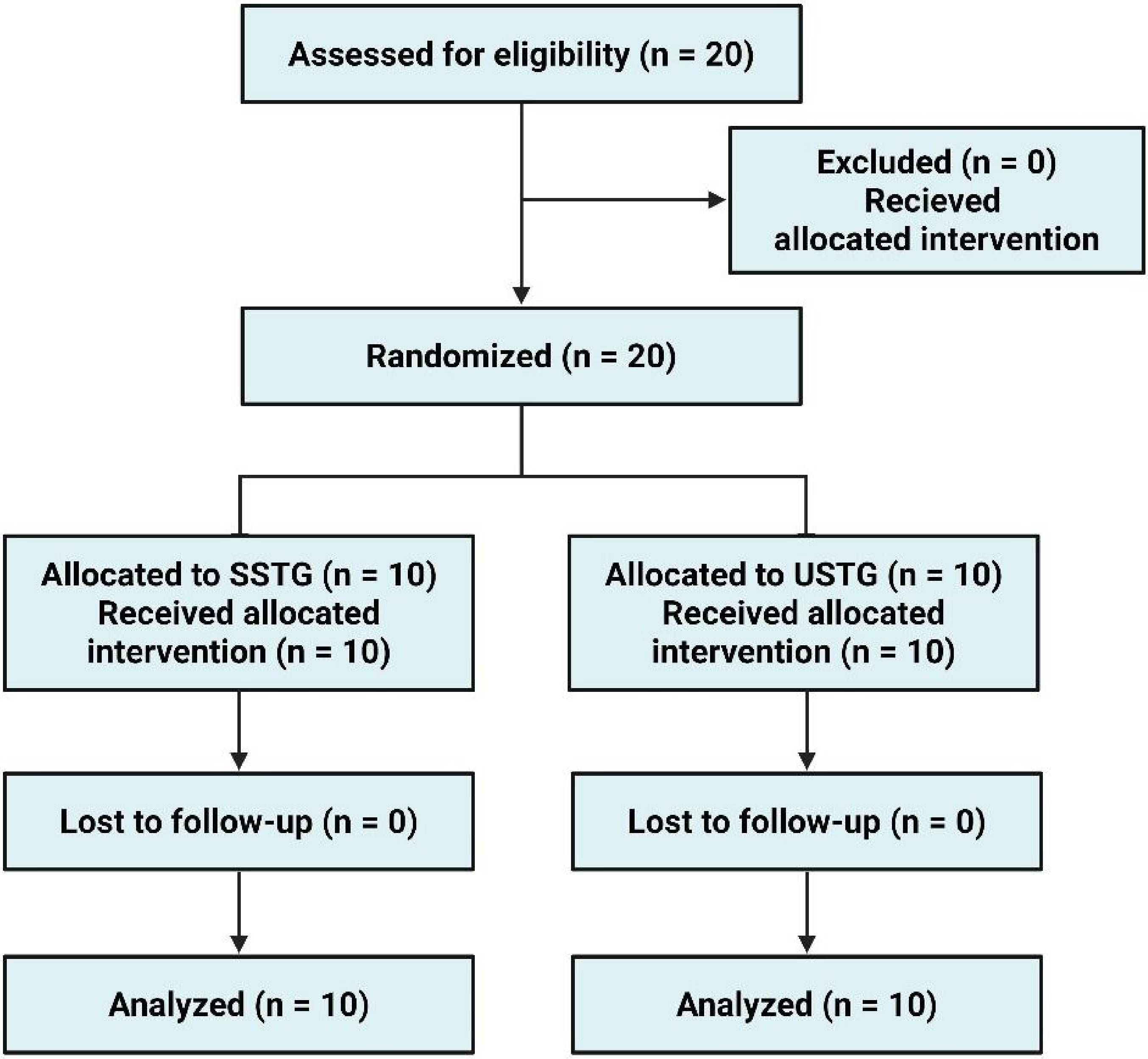

FIGURE 1. Flowchart of participant recruitment, randomization, intervention, and outcome analysis. SSTG: stable surface training group; USTG: unstable surface training group.

TABLE 3. Pre- and post-intervention data for range of motion in sprain ankle with main analysis of variance results.

Variables	SSTG (n = 10)			USTG (n = 10)			p (η_p^2) value		
	Pre	Post	p-value	Pre	Post	p-value	Time	Group	Inter
Dorsiflexion (degree)	13.90 ± 2.60	16.00 ± 3.83	0.209	14.90 ± 3.69	19.30 ± 3.97	0.026*	0.010† (0.313)	0.071 (0.170)	0.324 (0.054)
Plantarflexion (degree)	42.70 ± 11.08	44.30 ± 7.51	0.653	39.50 ± 8.32	47.50 ± 8.07	0.003*	0.026† (0.246)	1.000 (0.000)	0.123 (0.127)
Inversion (degree)	14.30 ± 4.45	15.50 ± 4.84	0.350	16.70 ± 5.03	20.50 ± 3.69	0.012*	0.009† (0.320)	0.059 (0.184)	0.147 (0.113)
Eversion (degree)	12.20 ± 3.90	14.50 ± 2.91	0.051	12.70 ± 3.90	15.10 ± 3.90	0.062	0.006† (0.346)	0.708 (0.008)	0.948 (0.000)

*Note. Values are expressed as mean ± standard deviation. SSTG: stable surface training group; USTG: unstable surface training group; Inter: interaction. †Significant interaction or main effect, *p < 0.05 vs. before intervention.*

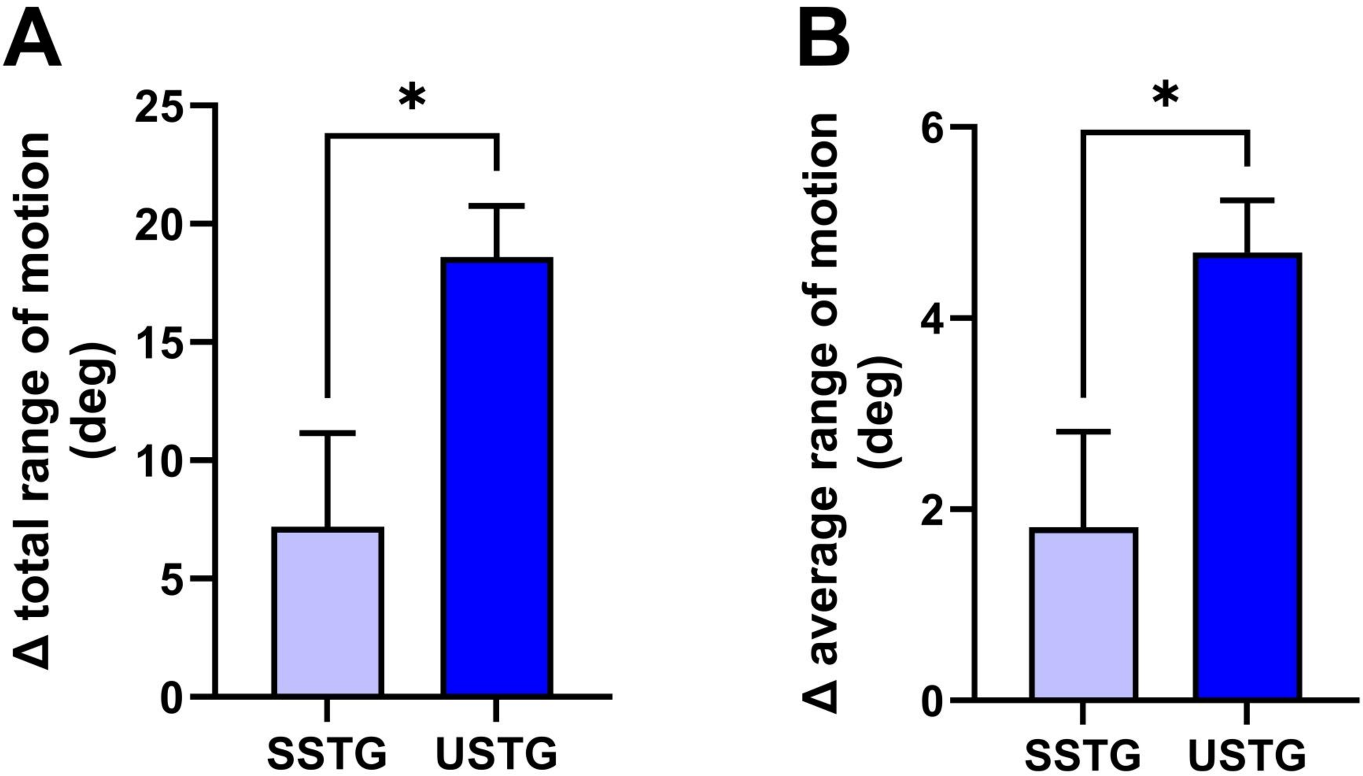

FIGURE 2. Changes of total and average range of motion after 4 wk of intervention. (A) Changes of total range of motion. (B) Changes of average range of motion. Data are presented as mean ± S.E. *Significant difference between labelled groups ($p < 0.05$). SSTG: stable surface training group; USTG: unstable surface training group; deg: degrees.

eversion ($p < 0.010$, $\eta_p^2 = 0.666$) at 120 °/s to evaluate muscle power. The paired t-test showed significant improvement in dorsiflexion (SSTG: $p = 0.009$, USTG: $p = 0.003$), plantarflexion (SSTG: $p = 0.002$, USTG: $p = 0.002$), inversion (SSTG: $p < 0.001$, USTG: $p < 0.001$), eversion (SSTG: $p < 0.001$, USTG: $p = 0.002$) at 30 °/s for all groups, and dorsiflexion (SSTG: $p = 0.012$, USTG: $p = 0.008$), plantarflexion (SSTG: $p < 0.001$, USTG: $p < 0.001$), inversion (SSTG: $p = 0.007$, USTG: $p = 0.002$), eversion (SSTG: $p = 0.010$, USTG: $p < 0.001$) at 120 °/s for all groups.

3.3 Static and dynamic balance

There was no group-by-time interaction effect for the 4-week rehabilitation exercise program on static (ECSLT) and dynamic (Y-balance) balance abilities. However significant time effect was observed in the static balance ($p = 0.001$, $\eta_p^2 = 0.722$) and the dynamic balance ($p < 0.001$, $\eta_p^2 = 0.878$) (Table 5). As a result of the paired t-test, both the SSTG and USTG showed significant improvements in ECSLT (SSTG: $p < 0.001$, USTG: $p = 0.001$) and Y-balance (SSTG: $p < 0.001$, USTG: $p < 0.001$). In addition, the changes ECSLT ($p = 0.083$), and the average percentage changes of ECSLT and Y-balance showed a higher tendency in the USTG than in the SSTG ($p = 0.098$) (Fig. 3A,B).

TABLE 4. Pre- and post-intervention data for isokinetic muscle function with main analysis of variance results.

Variables	SSTG (n = 10)			USTG (n = 10)			p (η_p^2) value		
	Pre	Post	p-value	Pre	Post	p-value	Time	Group	Inter
Peak torque (30 °/s)									
Dorsiflexion (Nm)	24.39 ± 4.27	26.95 ± 4.10	0.009*	25.80 ± 5.85	29.87 ± 4.92	0.003*	<0.001† (0.603)	0.309 (0.057)	0.249 (0.073)
Plantarflexion (Nm)	88.01 ± 20.15	116.91 ± 25.88	0.002*	107.46 ± 32.50	139.37 ± 26.73	0.002*	<0.001† (0.674)	0.069 (0.172)	0.766 (0.005)
Inversion (Nm)	23.42 ± 6.21	36.13 ± 10.06	<0.001*	25.62 ± 7.73	41.16 ± 7.28	<0.001*	<0.001† (0.759)	0.247 (0.074)	0.461 (0.031)
Eversion (Nm)	27.72 ± 9.33	33.82 ± 9.78	<0.001*	27.56 ± 7.96	36.23 ± 9.12	0.002*	<0.001† (0.711)	0.777 (0.005)	0.262 (0.069)
Peak torque (120 °/s)									
Dorsiflexion (Nm)	11.66 ± 3.03	13.64 ± 2.09	0.012*	13.57 ± 4.80	15.94 ± 5.26	0.008*	<0.001† (0.540)	0.240 (0.076)	0.685 (0.009)
Plantarflexion (Nm)	50.37 ± 10.49	64.61 ± 11.33	<0.001*	58.83 ± 18.91	80.63 ± 17.82	<0.001*	<0.001† (0.766)	0.069 (0.172)	0.125 (0.126)
Inversion (Nm)	18.80 ± 4.56	24.98 ± 5.75	0.007*	19.85 ± 4.76	27.91 ± 4.06	0.002*	<0.001† (0.625)	0.263 (0.069)	0.479 (0.028)
Eversion (Nm)	19.65 ± 4.11	24.88 ± 5.81	0.010*	19.76 ± 4.69	27.51 ± 4.30	<0.001*	<0.001† (0.666)	0.467 (0.030)	0.260 (0.070)

*Note. Values are expressed as mean ± standard deviation. SSTG: stable surface training group; USTG: unstable surface training group; Inter: interaction. †Significant interaction or main effect, *p < 0.05 vs. before intervention.*

TABLE 5. Pre- and post-intervention data for static and dynamic balance with main analysis of variance results.

Variables	SSTG (n = 10)			USTG (n = 10)			p (η_p^2) value		
	Pre	Post	p-value	Pre	Post	p-value	Time	Group	Inter
ECSLT (s)	28.20 ± 13.12	39.97 ± 15.97	<0.001*	29.20 ± 18.85	48.31 ± 12.15	<0.001*	<0.001† (0.722)	0.477 (0.028)	0.121 (0.128)
Y-balance (%)	78.75 ± 5.17	88.44 ± 4.99	<0.001*	85.39 ± 7.28	95.32 ± 8.87	<0.001*	<0.001† (0.878)	0.015 (0.288)	0.367 (0.045)

*Note. Values are expressed as mean ± standard deviation. ECSLT: eyes closed single leg test; SSTG: stable surface training group; USTG: unstable surface training group; Inter: interaction. †Significant interaction or main effect, *p < 0.05 vs. before intervention.*

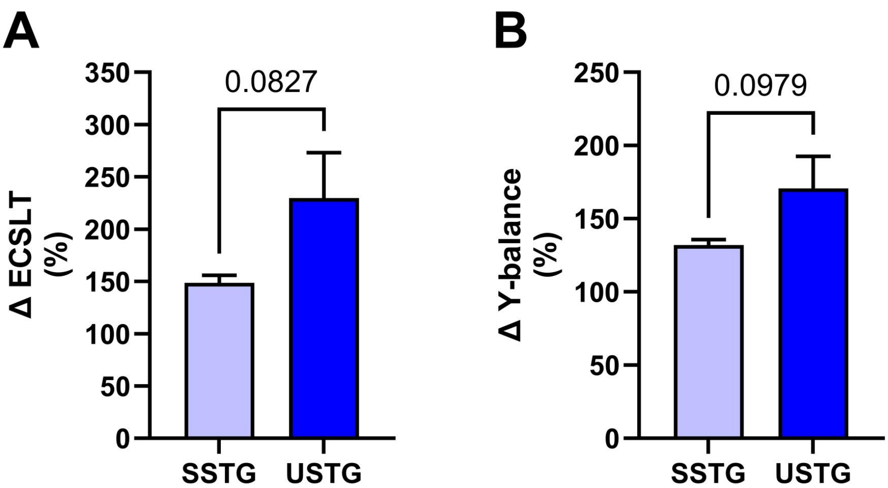

FIGURE 3. Changes of average ECSLT and Y-balance after 4 wk of intervention. (A) Changes of average ECSLT. (B) Changes of average Y-balance. Data are presented as mean ± S.E. SSTG: stable surface training group; USTG: unstable surface training group; ECSLT: eyes closed single leg balance test.

4. Discussion

The findings of this study demonstrate that a 4-week rehabilitation program significantly improved ankle joint function and postural control in young adults with Grade 1 lateral ankle sprains. Notably, only the USTG exhibited significant improvements across multiple directions of ankle joint ROM, including dorsiflexion, plantarflexion, and inversion.

This distinction is critical, as restoration of joint ROM is not merely an indicator of flexibility but a prerequisite for normal biomechanical function, neuromuscular integration, and injury prevention [4, 27]. Importantly, the total and average ROM reflecting the composite mobility across dorsiflexion, plantarflexion, inversion, and eversion showed statistically significant increases only in the USTG. This suggests that unstable surface training provides a more potent stimulus for restoring full multidirectional mobility of the ankle joint compared to stable surface interventions [18, 19, 28]. These findings are reinforced by a recent meta-analysis indicating that exercise programs incorporating unstable surface training significantly enhance joint ROM and proprioceptive function in patients with chronic ankle instability [29].

Such global improvements in joint mobility may stem from the greater engagement of proprioceptive and mechanoreceptive pathways that are continuously challenged under unstable conditions [19]. Furthermore, recent evidence highlights that unstable surface training not only improves peripheral sensorimotor pathways but also induces neuroplastic changes within the central nervous system. These adaptations enhance cortical motor planning and sensorimotor integration, which are critical for sustaining long-term functional recovery and reducing recurrent injury risk [30, 31]. Such neuromuscular training facilitates motor learning by reinforcing efficient movement patterns and optimizing reflex pathways. The repetitive perturbations characteristic of unstable surface exercises promote synaptic plasticity and sensorimotor recalibration, supporting improved postural control in dynamic environments [32]. Furthermore, these sensorimotor improvements align with reports indicating that altered neuromuscular control and ankle joint kinematics during gait characterize individuals with functional ankle instability. These deficits underscore the importance of proprioceptive and neuromuscular retraining strategies, such as unstable surface training, to restore normal motor patterns and improve joint stability during dynamic activities [33]. These adaptations likely enhance not only voluntary movement control but also reflexive stabilization mechanisms critical for dynamic posture and reactive balance [5, 9, 34]. Such training may facilitate neuromuscular retraining by intensively engaging mechanoreceptors and restoring sensorimotor integration, which are critical for preventing recurrent ankle sprains [35]. Clinically, an increase in total and average ROM implies a more complete and symmetrical restoration of functional ankle movement, which is essential for activities that require multidirectional foot placement, such as cutting, pivoting, and landing [27, 33]. Limited ROM in any one direction especially in dorsiflexion or eversion can impair shock absorption and redistribute mechanical stress to adjacent joints, increasing the risk of reinjury and overuse syndromes [4, 6]. Ankle sprains are among the most common musculoskeletal injuries. A substantial proportion progresses to chronic ankle instability, characterized by recurrent sprains and persistent joint dysfunction. The high incidence and clinical burden of ankle sprains emphasize the need for effective early rehabilitation to prevent progression to chronic instability [36]. In elite adolescent dancesport athletes, both acute ankle sprains and chronic instability show notable prevalence, underscoring the importance of targeted preventive and rehabilitative strategies in high-risk groups [37]. Therefore, interventions that yield consistent ROM gains across all planes, as seen with UST, are especially valuable for achieving long-term recovery and preventing CAI.

Regarding isokinetic muscle function, both SSTG and USTG groups demonstrated within-group improvements across all measured parameters, including dorsiflexion, plantarflexion, inversion, and eversion at both 30°/s and 120°/s. Although no group-by-time interaction was observed, these findings indicate that both interventions were effective in strengthening the ankle joint musculature.

Additionally, the observed improvements in static and dynamic balance in both groups underscore the effectiveness of proprioceptive training for neuromuscular control. However, limitations should be acknowledged. Physical activity level was not assessed or controlled for, which may have influenced baseline neuromuscular function. Nevertheless, the USTG showed a tendency toward superior gains, particularly in the ECSLT and Y-Balance Test. These enhancements are clinically meaningful, as balance control is essential for functional recovery and re-injury prevention, particularly in sports or dynamic environments where postural adjustments are frequently required [5, 34, 38]. The Y-Balance Test used in this study is a validated tool for assessing dynamic postural control deficits, supported by evidence of its reliability and sensitivity in detecting functional impairments related to ankle instability. Incorporating such validated outcome measures strengthens the interpretability and clinical relevance of balance improvements observed post-intervention [39]. The improvement in static balance reflects enhanced integration of proprioceptive input and neuromuscular control during conditions with limited sensory feedback [22, 40]. Ankle strengthening exercises performed on unstable surfaces have been shown to significantly improve static balance in adults with functional ankle instability [41].

Since the ECSLT removes visual cues, it emphasizes the role of somatosensory systems in balance maintenance. Training on an unstable surface stimulates this system more robustly than stable platforms, promoting greater motor adaptability and core stability [9, 42]. On the other hand, dynamic balance assessed through the Y-balance test requires coordinated multi-joint control, precise force distribution, and rapid sensory feedback processing. This study's results indicate that improvements in dynamic balance may be associated with both increased ROM and improved muscular coordination around the ankle joint, particularly in USTG. Proprioceptive training using intelligent rehabilitation systems that incorporate dynamic stimuli has been found to enhance joint position awareness and postural control in individuals with functional ankle instability [43]. The outcome measures used in this study, including goniometric ROM, isokinetic strength, ECSLT, and the Y-Balance Test, are known to have high reliability, with ICC values ranging from 0.85 to 0.98. In addition, the observed improvements generally exceeded the established minimum detectable change (MDC) thresholds, such as 3 to 4% for the Y-Balance Test and 8 to 15% for isokinetic strength. Notably, the improvements in the Y-Balance Test also surpassed the minimal clinically important difference (MCID) of 4 to 6% reported in previous research, suggesting potential clinical relevance.

Although formal MCID values for ECSLT and ankle ROM are not well established, the pattern and magnitude of change in the UST group indicate meaningful functional improvement, particularly in early rehabilitation settings.

The multidirectional perturbations encountered during UST may enhance the functional stability of the ankle by training the neuromuscular system to respond to a wide variety of stimuli, ultimately leading to better control during sport-specific and daily movements [5, 17]. Further research with longer follow-up is needed to clarify whether the observed changes represent a full recovery or continued adaptation. Future longitudinal studies are warranted to evaluate the sustainability of neuromuscular adaptations induced by unstable surface training and their impact on patients' quality of life and return-to-activity rates. Such research could inform evidence-based guidelines for chronic ankle instability management and comprehensive rehabilitation planning [29, 44]. While some degree of spontaneous healing may have occurred, the structured and progressive nature of the intervention, which included gradually increased intensity and individualized progression, likely contributed meaningfully to the observed functional gains. Importantly, both groups received active exercise-based rehabilitation protocols under identical conditions; thus, any natural recovery effects are likely to have been distributed equally across groups. The between-group differences can therefore be more confidently attributed to the specific effects of unstable surface training. Moreover, previous clinical studies have reported significant functional gains after 3–4 weeks of balance or proprioceptive training in individuals with ankle instability, supporting the validity of our intervention duration [41]. While the current findings support the functional benefits of unstable surface training, certain methodological considerations should be acknowledged. Specifically, the absence of a no-intervention control group limits the ability to completely disentangle the effects of natural recovery from the observed improvements. Nevertheless, as both groups underwent active rehabilitation under identical conditions, any spontaneous healing effects were likely distributed evenly. Furthermore, the relatively short duration of the intervention and the inclusion of only healthy young males may limit the generalizability of the results to other populations or longer-term rehabilitation contexts.

5. Conclusions

Collectively, the findings suggest that unstable surface training not only facilitates joint-specific improvements such as ROM but also fosters systemic functional adaptations, including postural control and dynamic balance. These combined effects are essential for preventing recurrence of injury and achieving full functional return to activity. These findings suggest that proprioceptively challenging rehabilitation exercises may offer additional benefits in early-stage recovery and could be considered as part of a comprehensive rehabilitation program.

ABBREVIATIONS

SST, stable surface training; UST, unstable surface training; SSTG, stable surface training group; USTG, unstable surface training group; ROM, range of motion; ECSLT, eyes-closed single-leg stance test; CAI, chronic ankle instability; CRiS, clinical research information service; ANOVA, analysis of variance; MDC, minimum detectable change; MCID, minimal clinically important difference; BOSU, both sides utilized; OMNI scale, OMNI-resistance exercise scale; ICC, intraclass correlation coefficient.

AVAILABILITY OF DATA AND MATERIALS

Data are available from the corresponding author upon reasonable request.

AUTHOR CONTRIBUTIONS

GC, JJ and HYP—wrote the original draft and performed data collection and formal analysis. JJ and HYP—wrote and reviewed the manuscript. GC and JJ—performed data interpretation, visualization, and statistical analysis. HYP—conceptualized and supervised the manuscript. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Ethical approval was obtained from the Institutional Review Board (IRB) of Konkuk University (7001355-202308-HR-680). All participants provided informed consent before participating in the study. This study was registered in the Clinical Research Information Service (CRiS), Republic of Korea, under the registration number KCT0010569.

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CONFLICT OF INTEREST

The authors have no direct or indirect interests that are in direct conflict with the conduction of this study.

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