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*Original Research*

# Acute Effects of a Hop-Stabilization Warm-Up Program on Dynamic Balance, Ground Reaction Force, and Muscle Activity During Cutting Movements in Collegiate Athletes with Chronic Ankle Instability

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ABSTRACT

***International Journal of Exercise Science 17(1): 343-358, 2024.*** First-time lateral ankle sprains often lead to chronic ankle instability (CAI), with 47% facing recurrent injuries, emphasizing the need for preventive measures. Side-cutting movements in sports pose a risk for CAI individuals due to potential biomechanical control alterations. While the hop-stabilization warm-up program has proven effective in preventing ankle sprains, its specific acute impact on CAI individuals lacks substantial evidence. This study employed a crossover design with eight CAI participants (23 ± 3.4 years, BMI 23 ± 1.5 kg/m$^2$) and eight healthy participants (25 ± 3.6 years, BMI 23 ± 1.7 kg/m$^2$) to investigate the acute effects of the hop-stabilization warm-up program on dynamic balance, ground reaction force (GRF), and muscle activity during 45- and 90-degree side-cutting movements. Each participant underwent hop-stabilization and control warm-up programs on two experimental days. Assessments, including the Y-balance test, GRF, and muscle activity pre- and post-warm-up, revealed significant improvements in dynamic balance, GRF, and muscle activity during 45-degree side-cutting movements in CAI participants. These findings suggest the potential benefits of incorporating the hop-stabilization warm-up program into the warm-up protocol for individuals with CAI.

KEY WORDS: Warm-up program, change of direction, chronic ankle sprain, recurrent ankle injury

## INTRODUCTION

Lateral ankle sprains are the most prevalent athletic injuries and result in direct and indirect financial burdens (11). They account for 65.67% of all ankle injuries in male collegiate soccer players (13). Over 40% of patients who sustain an acute ankle sprain report pain, reinjuries, and subjective instability for over a year after the injury, with chronic ankle instability (CAI) (34). Individuals with CAI have kinetic, neuromuscular, and functional deficits (23, 35). In the initial stance phase of a side-cutting movement, the CAI cohort demonstrated increased levels of ground reaction forces (GRF) in the posterior and vertical directions, as well as increased activity in the lower limb muscles. Furthermore, muscle activity declined during the mid-cutting phase compared to the healthy group (23, 35). The activation of trunk and abdominal muscles in individuals with CAI was significantly delayed during the testing of trunk muscle reflexes in a sudden unloading task (27). These deficits are caused by mechanical and functional ankle instability, contributing to impaired physical activity and suboptimal athletic performance in individuals with CAI (16). The side-cutting movement is an essential dynamic maneuver undertaken by athletes, especially in soccer and lacrosse, to quickly dodge opponents. Rapid direction changes during this movement require high levels of biomechanical and neuromuscular control to avoid unforeseen injuries (35). Thus, the impairments of biomechanical and neuromuscular control during side-cutting movements might increase the risk of repeated injuries in individuals with CAI.

The hop-stabilization exercise is a fundamental element of neuromuscular or dynamic warm-up techniques. It has demonstrated positive effects on enhancing neuromuscular control and the capacity to absorb force during landings in different directions (8, 32). Previous research has shown that incorporating hop-stabilization exercises into warm-up routines has yielded positive results in terms of improving landing biomechanics and reducing the risk of injuries among athletes (31). The utilization of these warm-up exercises has the potential to effectively stimulate dynamic balance and neuromuscular control in individuals who have CAI during side-cutting movements. Nevertheless, the hypothesis lacks substantial data to substantiate its claims. Hence, the objective of this study was to investigate the acute effects of the hop-stabilization warm-up program on dynamic balance, ground reaction force, and muscle activity during side-cutting movements in individuals with CAI.

## METHODS

*Participants*

This study adopted a crossover design and was approved by an institutional review board. This research was carried out fully in accordance with the ethical standards of the International Journal of Exercise Science (30). Before taking part in the study, participants signed an informed consent form. On a given day, we randomly assigned CAI participants (22.6 ± 4.3 years, BMI 23 ± 1.5 kg/m$^2$) and healthy participants (25.0 ± 3.6 years, BMI 23 ± 2.1 kg/m$^2$) (Table 1) to two distinct warm-up programs. We calculated the sample size using the two–sample crossover equality equation ($\sigma = 7.42$, $Z_{\alpha/2} = 1.96$, and $Z_{\beta} = 0.84$). Each group consisted of eight individuals.

All participants were competitive lacrosse or soccer players who practiced at least twice per week and had prior experience in jumping, landing, and side-cutting tasks. We selected eight participants with CAI using the following criteria from a controlled study (12): (a) A history of at least one significant ankle sprain with concurrent inflammatory symptoms (swelling, pain, and dysfunction); and (b) At least one day of planned physical activity interrupted by lingering symptoms (requiring no bearing weight, immobilization, and an abnormal gait). (c) The first sprain must have occurred at least a year before enrollment in the study, and the most recent injury must have occurred at least three months before enrollment. (d) The previously injured ankle joint has a history of "giving way" and recurrent sprains. The ankle also "felt unstable" in the six months preceding study enrollment, and participants must have experienced at least two instances of giving way. (e) Cumberland Ankle Instability Tool (CAIT) score < 24. (f) Functional ankle instability questionnaire (IdFAI) score of ≥11 points. Two physical therapists with over ten years of experience assessed ligamentous laxity and conducted clinically negative anterior drawer and talar tilt tests. (g) No rehabilitation during testing. The ankle with the lowest self-reported questionnaire score was designated the experiment limb (23).

We excluded participants if the following criteria were met (14, 23): (a) A history of lower limb fractures or surgery or significant musculoskeletal injuries (other than a history of lateral ankle sprain in the CAI group); (b) Ankle inflammation and swelling, as well as any muscular pain that could impair the side-cutting movement during testing; (c) A history of acute injuries to back and other lower limb joints within three months; and (d) Any diagnosed neurologic dysfunction or balance disorders, such as multiple sclerosis, Parkinson's disease, head injury, neuropathies, diabetes, or other conditions that affect balance.

*Protocol*

We used three measurement tools in this experiment. Initially, we used the FMS Professional Y-Balance Test Kit™ to determine the dynamic balance (25). Participants stood on a central Y-Balance Test Kit, one foot pushing the reach-indicator block in the anterior, posteromedial, and posterolateral directions. To eliminate the balance and stability provided by shoes, all testing and practice were performed barefoot on the tested limbs. Each participant was given six practice trials in each direction, followed by three test trials in each direction. The respondent kept a single-leg stance with hands on the pelvis and moved the reach indicator block as far as possible along the three directions with the contralateral leg. The distance was measured in half-millimeters. We measured the participants' lower-limb lengths bilaterally in supine from the anterior superior iliac spine to the center of the ipsilateral medial malleolus for standardization. We utilize the limb length to normalize the reach distance in each direction for data analysis by calculating the maximum reach distance (%MAXD) using the formula: (excursion distance/limb length) 100 = %MAXD. For the data analysis, the mean distance in each direction on the right and left sides was employed. Second, we used a force plate (Kistler, Winterthur, Switzerland) to monitor the GRF during the side-cutting movement at a frequency of 1000 Hz (24). Third, we used a wireless surface EMG system (DL-590; S&ME, Tokyo, Japan) to record muscle activity of nine muscles, including the gluteus medius (GMed), rectus femoris (RF), medial hamstring (MH), medial gastrocnemius (MG), tibialis anterior (TA), peroneus longus (PL), tested side internal abdominal oblique (tested IAO), non-tested side internal abdominal oblique (non-tested IAO), and elector spinae (longissimus) (ES), at 1000 Hz (22). We prepared the skin of the participant by shaving the area where the electrodes were placed and cleaning it with alcohol-soaked cotton. We used surface EMG for noninvasive muscle assessment criteria as an electrode placement guideline (15). We placed 10-mm disposable Ag/AgCl electrodes over each muscle with a 25-mm center-to-center spacing (6) and simultaneously monitored the ground reaction force and muscle activity using the TRIAS synchronization software (DKH Co. Ltd., Tokyo, Japan)..

There were at least six days (9 + 2 days) separating each session. On each testing day, we randomly allocated each participant to the hop-stabilization or control warm-up programs. The pre-testing comprised Y-balance tests as well as 45- and 90-degree side-cutting movement tests. Each participant then underwent a warm-up program. We examined the immediate post-warm-up outcomes using the same tests.

During the side-cutting movement test, the participants wore prepared sports shoes and chose a starting position five meters from the center of the force plate. Subsequently, we instructed the participants to begin running, land on the force plate with the testing foot, turn 45-degree to the contralateral side of the testing foot, and sprint as rapidly as possible for at least 2.5 meters. We provided instructions and practices to the participants until they felt confident. We recorded three successful side-cutting movement tests (1 minute of rest between trials) and performed 90-degree side-cutting tests using the same procedure.

The hop-stabilization warm-up consisted of six hopping exercises for 7 minutes. Before commencing, the certified physical therapist described the warm-up exercises and allowed the participants to practice until they could accurately perform them. During the hop-stabilization warm-up session, the physical therapist provided verbal feedback to the participants to control the quality of the program. The criteria for adjudication were maintaining balance, finishing the motion smoothly, and avoiding excessive trunk or pelvic movement. The program featured: (a) hopping in a four-square shape on tested legs (5 rounds × 2 sets); (b) hopping in a zigzag shape on tested legs (5 steps × 2 sets); (c) hopping in a figure-8 shape on tested legs (5 rounds × 1 set); (d) forward and backward hopping on the tested leg (10 reps × 1 set); (e) forward hopping on the tested leg (5 reps × 1 set); and (f) hopping side to side with the tested leg (10 reps × 1 set) (Figure 1). Furthermore, the control warm-up program was 7 minutes of free running at an easy pace.

We filtered the raw GRF signals using a 15 Hz low-pass filter and defined the stance phase as the interval between when the vertical GRF surpassed 10 N after initial foot contact (IC) and when it dropped below 10 N (i.e., toe-off) (1). We standardized the stance phase of each participant at 100% from initial foot contact (0%) until toe-off (100%). Subsequently, we recorded the peak GRF and the time to peak GRF.

Finally, we collected 5 seconds of EMG data twice for each muscle for normalization. Participants performed simultaneous maximal voluntary isometric contractions (MVIC) against manual resistance (21). We filtered raw MVIC measurements using a passband of 20–450 Hz and an RMS of 20 Hz, identified EMG data during the middle 2 seconds of the 5 seconds of significant activity (17), and calculated the peaks of each muscle.

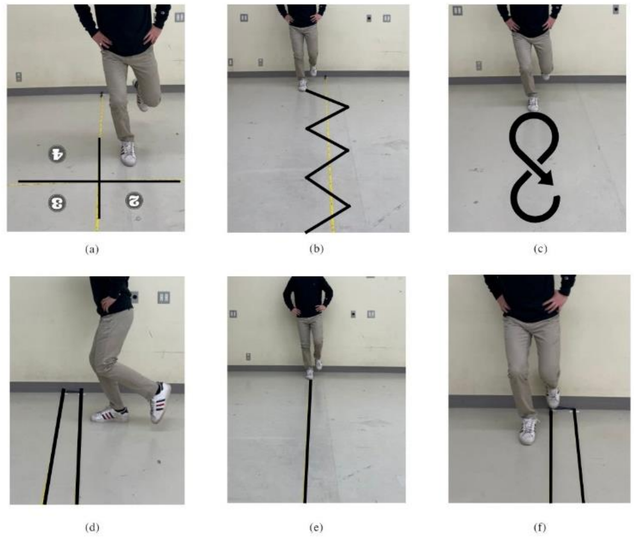

**Figure 1.** The hop-stabilization warm-up program consists of (a) hopping in a four-square shape on tested legs; (b) hopping in a zigzag shape on tested legs; (c) hopping in a figure-8 shape on tested legs; (d) forward and backward hopping on the tested leg; (e) forward hopping on the tested leg; and (f) hopping side to side with the tested leg.

We performed subsequent procedures on muscle activity during the side-cutting movement. Initially, we processed the raw EMG data using a fourth-order Butterworth bandpass filter with cutoff frequencies ranging from 20–450 Hz, full-wave rectification, and a 20 Hz calculation of the root mean square. Subsequently, we normalized the processed EMG data to the filtered MVIC of each muscle. We used standardized stance phase muscular activity time scales from initial ground contact (0%) to toe-off (100%) and detected the EMG peak for each muscle. Finally, we calculated the onset time of muscular activity (time of muscle activation) by continuously integrating each data point.

The integrated EMG trace was compared with that of the reference line, with a slope of 1. We defined the onset time of the EMG activity of each muscle as the instance when the distance d between the integrated normalized EMG signal inclination and the reference line was the largest relative to the initial ground contact (38). We then estimated the time to peak EMG from the time between the onset and peak amplitude. Finally, we calculated the average RMS values for the 200 milliseconds preceding ground contact and normalized them by the MVIC to determine pre-onset muscle activity (3).

*Statistical Analysis*
We compared general characteristics and self-reported function questionnaire results between CAI and healthy participants using an independent sample t-test. We also compared the mean difference between GRF and muscle activities, one between group factors (warm-up protocols in each group) and one within group factors (45- and 90-degree side-cutting movements), using a two-way mixed-design ANOVA. We classified the partial $\eta^2$ based on the following effect size criteria: trivial, < 0.02; small, 0.02–0.129; medium, 0.13–0.259; and large, > 0.26 (5). We also set

the significance level ($p$) at 0.05 and performed the statistical analyses using SPSS version 28 (IBM Corp., Armonk, NY, USA).

**RESULTS**

The demographic characteristics of the CAI and healthy participants were identical (Table 1). The CAI participants scored significantly lower on the CAIT ($p$ = 0.001) and significantly higher on the IdFAI ($p$ = 0.001) than the healthy participants. To identify confounding variables, we evaluated the stance time and velocity of the side-cutting movement. The 45-degree (F (3, 28) = 1.125, $p$ = 0.356, partial $\eta^2$ = 0.108) and 90-degree ($F$ (3, 28) = 0.05, $p$ = 0.985, partial $\eta^2$ = 0.005) side-cutting stance times did not significantly differ between the groups. There was minimal variation in the side-cutting speed observed between groups during the 45-degree and 90-degree side-cutting movements ($F$ (3, 28) = 2.216, $p$ = 0.108, partial $\eta^2$ = 0.192, and $F$ (3, 28) = 3.93, $p$ = 0.109, partial $\eta^2$ = 0.196, respectively).

**Table 1.** General characteristic and self-reported function questionnaire.

| General characteristic and questionnaires | Participants, Mean ± SD | | Independent sample test | |
|---|---|---|---|---|
| | CAI[c] athletes ($n$ = 8) | Healthy athletes ($n$ = 8) | $t$ (14) | Significant |
| Age, years | 23 ± 3.42 | 25 ± 3.62 | −1.348 | 0.199 |
| BMI, kg/m$^2$ | 23 ± 1.51 | 23 ± 1.66 | 3.14 | 0.758 |
| CAIT, Score[a] | 17.87 ± 5.35 | 28.12 ± 3.35 | −4.586 | < 0.001[d] |
| IdFAI, Score[b] | 22.25 ± 4.36 | 7.37 ± 4.30 | 6.859 | < 0.001[d] |

[a]The Cumberland Ankle Instability Tool, [b]The Identification of Functional Ankle Instability, [c]Chronic ankle instability, [d]Independent sample test, Significant ($p$ < 0.05)

The hop-stabilization and control warm-up programs immediately improved dynamic balance (relative reach distance, %) in participants with CAI and healthy people ($p$ = 0.017) (Figure 2). Nevertheless, the hop-stabilization warm-up program were more likely to enhance the dynamic balance of CAI participants than the control programs.

According to the data presented in Table 2, it was observed that individuals with and without CAI who participated in the hop-stabilization warm-up program experienced a significant decrease in peak medial GRF during both the 45-degree and 90-degree side-cutting movements, as compared to those who performed the control warm-up program ($p$ = 0.009). During 45-degree side-cutting movements, the hop-stabilization warm-up program could lower the peak posterior GRF in CAI participants than in healthy individuals ($p$ = 0.021). Furthermore, the hop-stabilization program significantly reduced the time to peak medial and anterior GRF in CAI individuals compared with that in healthy participants during 45-degree side-cutting movements ($p$ = 0.014). During 90-degree side-cutting movements, the hop-stabilization warm-up program significantly increased the time to peak posterior GRF ($p$ = 0.02). However, it significantly decreased the time to peak anterior GRF ($p$ = 0.024) compared with that in healthy individuals.

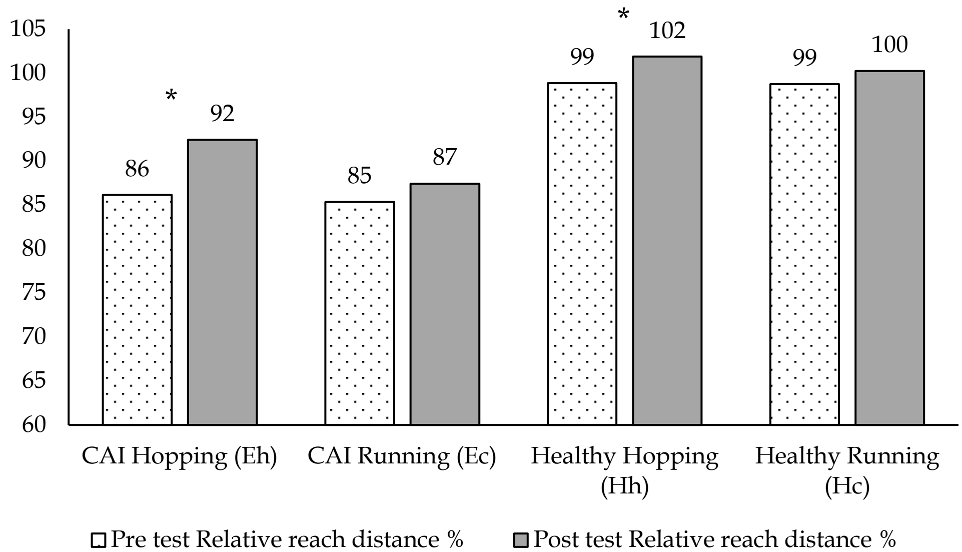


**Figure 2.** The relative reach distance (%) between pre and post the hop-stabilization warm-up programs in each group.

We evaluated the muscle activity of CAI and healthy individuals prior to executing the warm-up programs to confirm that CAI participants had muscular impairment during side-cutting movements. The CAI individuals demonstrated higher peak MH ($p$ = 0.039) and TA ($p$ = 0.046) activities than the healthy participants. The pre-activity of the PL was lower in the CAI group than in the healthy individuals ($p$ = 0.032). The onsets of GMed ($p$ = 0.023), MH ($p$ = 0.043), tested IAO ($p$ = 0.024), ES ($p$ = 0.037), TA ($p$ = 0.038), and MG ($p$ = 0.011) were slower in patients with CAI than in healthy individuals. In addition, the time to peak for the RF ($p$ = 0.048), tested IAO ($p$ = 0.018), and PL ($p$ = 0.016) was shorter in individuals with CAI than in healthy individuals.

The results shown in Table 3 indicate that individuals with CAI who participated in the hop-stabilization warm-up program demonstrated significantly reduced preparatory muscular activation of the TA ($p$ = 0.046) and MG ($p$ = 0.029) during 45-degree side-cutting movements compared to those who were assigned to the control warm-up program. On the contrary, PL preparatory muscle activation was found to be substantially increased in CAI individuals through the hop-stabilization warm-up program as compared to the control warm-up program (p = 0.02). Nevertheless, the hop-stabilization warm-up program did not acutely affect peak muscular activation during 45-degree and 90-degree side-cutting movements in the CAI or healthy participants (Table 4).

As shown in Table 5, individuals with CAI who participated in the hop-stabilization warm-up program had a more significant increase in the time to peak muscular activation of the TA ($p$ = 0.007) and PL ($p$ = 0.036) during 45-degree side-cutting movements than those who participated in the control warm-up program.

As shown in Table 6, individuals with CAI who participated in the hop-stabilization warm-up program demonstrated a significant reduction in the onset muscle activation of the MH ($p$ = 0.043) and tested IAO ($p$ = 0.024) during 45-degree side-cutting movements compared to those who participated in the control warm-up program. Furthermore, during the 90-degree side-cutting movement, the hop-stabilization warm-up program significantly reduced the onset of muscle activation in the tested IAO ($p$ = 0.01).

**Table 2.** Mean difference (Posttest-Pretest) of the peak GRF (Peak (%Body Weight)) and time to peak GRF (TTP (%Cutting phase)) during 45-degree and 90-degree side-cutting movements between group.

| | | Group, Mean (SE) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 45-degree side-cutting movements | | | | 90-degree side-cutting movements | | | | |
| **Direction** | **Kinetics Variables** | **CAI Hopping** | **CAI Running** | **Healthy Hopping** | **Healthy Running** | **CAI Hopping** | **CAI Running** | **Healthy Hopping** | **Healthy Running** | **Effect size** |
| Medial (Fx−) | Peak* ** | −0.47 (0.04) | −0.21 (0.04) | −0.35 (0.04) | 0.07 (0.04) | −0.34 (0.05) | 0.07 (0.05) | −0.50 (0.05) | 0.08 (0.05) | 0.829 |
| | TTP* | −2.38 (0.40) | 1.00 (0.40) | −2.75 (0.40) | 1.13 (0.40) | −3.88 (0.62) | −3.87 (0.62) | −2.13 (0.62) | −2.50 (0.62) | 0.773 |
| Anterior (Fy+) | Peak | 0.14 (0.03) | 0.11 (0.03) | 0.09 (0.03) | 0.11 (0.03) | 0.13 (0.03) | 0.14 (0.03) | 0.12 (0.03) | 0.15 (0.03) | 0.821 |
| | TTP* | −0.63 (0.32) | −0.50 (0.32) | −0.75 (0.32) | 0.88 (0.32) | 1.38 (0.37) | 1.50 (0.37) | −0.88 (0.37) | −0.75 (0.37) | 0.533 |
| Posterior (Fy−) | Peak* | −0.10 (0.01) | −0.05 (0.01) | 0.09 (0.01) | 0.08 (0.01) | −0.02 (0.01) | −0.04 (0.01) | −0.003 (0.01) | 0.002 (0.01) | 0.856 |
| | TTP* ** | 1.00 (0.44) | 1.12 (0.44) | 3.00 (0.43) | 2.63 (0.44) | 2.25 (0.76) | 2.25 (0.76) | −2.25 (0.76) | −2.00 (0.76) | 0.531 |
| Vertical (Fz) | Peak | −0.21 (0.07) | −0.23 (0.07) | −0.24 (0.07) | −0.22 (0.07) | −0.30 (0.06) | −0.28 (0.06) | −0.27 (0.06) | −0.28 (0.06) | 0.790 |
| | TTP | 1.00 (0.26) | 1.38 (0.26) | 1.13 (0.26) | 1.38 (0.26) | 1.38 (0.33) | 1.25 (0.33) | 1.00 (0.33) | 0.88 (0.33) | 0.820 |

*Significant change between experiment group ($p$ < .05) during 45-degree side-cutting movements. **Significant change between experiment group ($p$ < .05) during 90-degree side-cutting movements.

**Table 3.** Mean difference (Posttest-Pretest) of preparatory muscle activation (%MVIC) during 45-degree and 90-degree side-cutting movements between group.

| | Group, mean (SE) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 45-degree side-cutting movements | | | | 90-degree side-cutting movements | | | | |
| **Muscle** | **CAI Hopping** | **CAI Running** | **Healthy Hopping** | **Healthy Running** | **CAI Hopping** | **CAI Running** | **Healthy Hopping** | **Healthy Running** | **Effect size (95%CI)** |
| GMed | 3.67 (0.86) | 3.38 (0.86) | 5.09 (0.86) | 3.54 (0.86) | −1.73 (1.51) | −1.73 (1.54) | 2.91 (1.51) | 2.31 (1.51) | 0.437 |
| RF | 3.56 (1.22) | 2.06 (1.22) | 9.93 (1.22) | 4.74 (1.22) | −4.77 (0.88) | −8.62 (0.88) | −2.77 (0.88) | −4.12 (0.88) | 0.827 |
| MH | −2.25 (0.67) | −2.73 (0.67) | −1.68 (0.67) | −5.10 (0.67) | −7.56 (1.47) | −5.10 (1.47) | −5.81 (1.47) | −5.79 (1.47) | 0.348 |
| MG* | −1.91 (1.40) | −3.22 (1.40) | 10.15 (1.40) | 6.76 (1.40) | −1.87 (2.54) | −2.21 (2.54) | −15.32 (2.54) | −13.90 (2.54) | 0.732 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Tested IAO | 0.97 (3.89) | 1.18 (3.89) | 3.69 (3.87) | 5.19 (3.89) | −4.34 (5.53) | −8.79 (5.53) | −6.73 (5.53) | −6.60 (5.53) | 0.018 |
| Non-tested IAO | −2.78 (3.99) | −2.23 (3.99) | −4.15 (3.99) | −8.39 (3.99) | −5.39 (4.35) | −2.82 (4.34) | −3.44 (4.35) | −6.14 (4.35) | 0.079 |
| TA* | −8.03 (1.56) | −0.49 (1.56) | −1.39 (1.56) | −4.30 (1.56) | −6.55 (1.74) | −3.387 (1.74) | −2.19 (1.74) | −2.47 (1.74) | 0.599 |
| PL* | 4.03 (1.25) | 0.69 (1.25) | 3.13 (1.25) | 0.16 (1.25) | −4.04 (3.36) | −2.40 (3.36) | −1.91 (3.36) | −0.93 (3.36) | 0.533 |
| ES | −0.22 (1.52) | −0.34 (1.52) | −1.83 (1.52) | −0.51 (1.52) | −4.01 (2.32) | −2.19 (2.32) | −8.37 (2.32) | −2.685 (2.32) | 0.347 |

Abbreviations: GMed, gluteus medius; RF, rectus femoris; MH, medial hamstring; MG, medial gastrocnemius; Tested IAO, tested side internal abdominal oblique; Non-tested IAO, non-tested side internal abdominal oblique; TA, tibialis anterior; PL, peroneus longus; ES, elector spinae. *Significant change between experiment group ($p < .05$) during 45-degree side-cutting movements. **Significant change between experiment group ($p < .05$) during 90-degree side-cutting movements.

**Table 4.** Mean difference (Posttest-Pretest) of peak muscle activation (%MVIC) during 45-degree and 90-degree side-cutting movements between group.

| | **Group, mean (SE)** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **45-degree side-cutting movements** | | | | **90-degree side-cutting movements** | | | | |
| **Muscles** | **CAI Hopping** | **CAI Running** | **Healthy Hopping** | **Healthy Running** | **CAI Hopping** | **CAI Running** | **Healthy Hopping** | **Healthy Running** | **Effect size (95%CI)** |
| GMed | −18.50 (4.30) | −22.77 (4.30) | −28.83 (4.30) | −27.49 (4.30) | 0.57 (3.25) | 4.58 (3.25) | 7.65 (3.25) | 3.63 (3.25) | 0.318 |
| RF | 18.01 (2.91) | 19.87 (2.91) | 19.12 (2.91) | 18.28 (2.91) | −11.05 (2.32) | −9.42 (2.32) | −8.42 (2.32) | −6.79 (2.32) | 0.831 |
| MH | 3.49 (1.04) | 9.92 (1.04) | 5.94 (1.04) | 2.72 (1.04) | −0.37 (1.41) | −7.53 (1.41) | −3.80 (1.41) | −4.84 (1.41) | 0.834 |
| MG | −23.40 (6.68) | −22.76 (6.68) | −20.16 (6.68) | −25.54 (6.68) | 7.75 (1.45) | 1.25 (1.45) | 4.63 (1.45) | 0.25 (1.45) | 0.629 |
| Tested IAO | −6.80 (6.11) | −10.93 (6.11) | −2.59 (6.11) | −8.14 (6.11) | −1.56 (7.01) | −2.85 (7.01) | −8.65 (7.01) | −11.78 (7.01) | 0.230 |
| Non-tested IAO | −17.90 (10.67) | −15.45 (10.67) | −8.49 (10.67) | −2.27 (10.67) | −2.88 (8.01) | −10.53 (8.01) | −11.22 (8.01) | −3.45 (8.01) | 0.205 |
| TA | 4.03 (1.98) | 3.61 (1.98) | 3.95 (1.98) | 2.53 (1.98) | 8.83 (4.15) | 3.53 (4.15) | 3.88 (4.15) | 2.59 (4.15) | 0.029 |
| PL | 2.60 (3.42) | 7.55 (3.42) | 4.45 (3.42) | 2.93 (3.42) | 0.34 (1.41) | 0.99 (1.41) | 2.75 (1.41) | 2.20 (1.41) | 0.480 |
| ES | 7.63 (3.66) | 7.80 (3.66) | 9.83 (3.66) | 6.89 (3.66) | 4.57 (3.91) | 9.46 (3.91) | 0.64 (3.91) | 2.64 (3.91) | 0.290 |

Abbreviations: GMed, gluteus medius; RF, rectus femoris; MH, medial hamstring; MG, medial gastrocnemius; Tested IAO, tested side internal abdominal oblique; Non-tested IAO, non-tested side internal abdominal oblique; TA, tibialis anterior; PL, peroneus longus; ES, elector spinae. *Significant change between experiment group ($p < .05$) during 45-degree side-cutting movements. **Significant change between experiment group ($p < .05$) during 90-degree side-cutting movements.

**Table 5.** Mean difference (Posttest-Pretest) of time to peak muscle activation (%Cutting phase) during 45-degree and 90-degree side-cutting movements between group.

| Muscle | Group, mean (SE) | | | | | | | | Effect size (95%CI) |
|---|---|---|---|---|---|---|---|---|---|
| | 45-degree side-cutting movements | | | | 90-degree side-cutting movements | | | | |
| | CAI Hopping | CAI Running | Healthy Hopping | Healthy Running | CAI Hopping | CAI Running | Healthy Hopping | Healthy Running | |
| GMed | −4.36 (1.34) | −3.13 (1.34) | −6.63 (1.34) | −7.75 (1.34) | −19.50 (2.45) | −21.25 (2.45) | −13.50 (2.45) | −15.75 (2.45) | 0.537 |
| RF | 10.75 (2.42) | 7.38 (2.42) | 10.38 (2.42) | 8.38 (2.42) | −9.88 (2.86) | −9.63 (2.86) | −8.50 (2.86) | −9.88 (2.86) | 0.319 |
| MH | 9.75 (2.75) | 6.00 (2.75) | 3.38 (2.75) | 7.75 (2.75) | 16.88 (2.39) | 11.50 (2.39) | 6.38 (2.39) | 13.75 (2.39) | 0.416 |
| MG | 7.00 (2.44) | 1.63 (2.44) | 8.50 (2.44) | 7.25 (2.44) | 5.50 (2.88) | 3.25 (2.88) | 3.88 (2.88) | 7.38 (2.88) | 0.081 |
| Tested IAO | 11.50 (3.47) | 10.13 (3.47) | 14.50 (3.47) | 15.13 (3.47) | 10.00 (6.39) | 2.88 (6.39) | 3.63 (6.39) | 7.63 (6.39) | 0.330 |
| Non-tested IAO | 5.75 (5.63) | 5.50 (5.63) | 4.00 (5.63) | 2.88 (5.63) | 14.00 (9.50) | 1.63 (9.50) | 0.13 (9.50) | 7.25 (9.50) | 0.043 |
| TA* | 21.13 (5.05) | 12.25 (5.05) | 0.75 (5.05) | 4.50 (5.05) | 13.375 (3.48) | 13.50 (3.48) | 14.50 (3.48) | 21.00 (3.48) | 0.307 |
| PL* | 46.00 (3.00) | 43.63 (3.00) | 32.50 (3.00) | 33.38 (3.00) | −9.00 (7.51) | −8.75 (7.51) | −0.25 (7.51) | −6.75 (7.51) | 0.187 |
| ES | 3.38 (5.36) | 6.75 (5.36) | 11.50 (5.36) | 12.88 (5.36) | −14.38 (5.40) | −15.75 (5.40) | −9.75 (5.40) | −9.25 (5.40) | 0.330 |

Abbreviations: GMed, gluteus medius; RF, rectus femoris; MH, medial hamstring; MG, medial gastrocnemius; Tested IAO, tested side internal abdominal oblique; Non-tested IAO, non-tested side internal abdominal oblique; TA, tibialis anterior; PL, peroneus longus; ES, elector spinae. *Significant change between experiment group ($p < .05$) during 45-degree side-cutting movements. **Significant change between experiment group ($p < .05$) during 90-degree side-cutting movements.

**Table 6.** Mean difference (Posttest-Pretest) of onset (%Cutting phase) during 45-degree and 90-degree side-cutting movements between group.

| Muscle | Group, mean (SE) | | | | | | | | Effect size (95%CI) |
|---|---|---|---|---|---|---|---|---|---|
| | 45-degree side-cutting movement | | | | 90-degree side-cutting movement | | | | |
| | CAI Hopping | CAI Running | Healthy Hopping | Healthy Running | CAI Hopping | CAI Running | Healthy Hopping | Healthy Running | |
| GMed | −2.25 (1.06) | −0.75 (1.06) | −2.50 (1.06) | −0.63 (1.06) | 5.63 (1.44) | 7.75 (1.44) | −8.50 (1.44) | −9.50 (1.44) | 0.753 |
| RF | 6.38 (1.49) | 4.50 (1.49) | 5.00 (1.49) | 4.50 (1.49) | 9.50 (1.30) | 6.75 (1.30) | 4.88 (1.30) | 1.88 (1.30) | 0.767 |
| MH* | −32.50 (1.26) | −18.88 (1.26) | −8.13 (1.26) | −8.25 (1.26) | 2.38 (0.82) | 0.25 (0.82) | −0.13 (0.82) | −1.38 (0.82) | 0.943 |
| MG | 34.75 (9.15) | 50.18 (9.15) | 27.47 (9.15) | 24.29 (9.15) | −8.62 (1.79) | −8.50 (1.79) | −8.75 (1.79) | −8.13 (1.79) | 0.442 |
| Tested IAO* ** | −2.75 (2.99) | −7.75 (2.99) | 26.75 (2.99) | 18.38 (2.99) | 7.63 (1.75) | 6.88 (1.75) | 4.75 (1.75) | 2.13 (1.75) | 0.763 |
| Non-tested IAO | 0.75 (3.49) | 0.88 (3.49) | 0.88 (3.49) | 1.38 (3.49) | −0.63 (4.36) | 6.88 (4.36) | 5.63 (4.36) | 0.63 (4.36) | 0.176 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| TA | −12.88 (4.32) | −14.25 (4.32) | −10.35 (4.32) | −12.63 (4.32) | −5.63 (1.82) | −6.50 (1.82) | −2.88 (1.82) | −0.75 (1.82) | 0.331 |
| PL | −15.13 (2.56) | −14.63 (2.56) | −12.75 (2.56) | −17.00 (2.56) | −6.25 (3.67) | −12.38 (3.67) | −7.75 (3.67) | −12.00 (3.67) | 0.297 |
| ES | −16.63 (2.02) | −16.88 (2.02) | −21.75 (2.02) | −19.88 (2.02) | 19.13 (4.98) | 25.63 (4.98) | 18.75 (4.98) | 11.25 (4.98) | 0.285 |

Abbreviations: GMed, gluteus medius; RF, rectus femoris; MH, medial hamstring; MG, medial gastrocnemius; Tested IAO, tested side internal abdominal oblique; Non-tested IAO, non-tested side internal abdominal oblique; TA, tibialis anterior; PL, peroneus longus; ES, elector spinae. *Significant change between experiment group ($p < .05$) during 45-degree side-cutting movements. **Significant change between experiment group ($p < .05$) during 90-degree side-cutting movements.

## DISCUSSION

We investigated the immediate effects of the hop-stabilization warm-up program on dynamic balance, GRF, and muscle activity during side-cutting movements in individuals with CAI. Our findings demonstrated that the hop-stabilization warm-up program promptly enhanced dynamic balance, modified medial and posterior GRF, and improved muscular activity in participants with CAI, with notable effects observed during 45-degree side-cutting movements.

The efficacy of hop-stabilization warm-up program in improving dynamic balance, akin to control warm-up programs (running), can be attributed to their targeted activation of neuromuscular systems and facilitation of joint stability (1, 9, 28). Executing hop-stabilization exercises demands precise coordination and activation of muscles crucial for maintaining balance, fostering the development of neuromuscular control vital for dynamic activities (1, 28). Furthermore, these exercises stimulate proprioception, heightening the body's spatial orientation perception and refining the ability to execute precise movements (33). Hop-stabilization warm-up program, designed to replicate real-world circumstances through functional movement patterns, play a crucial role in preparing individuals for the multi-directional demands of dynamic balance tests (9). Additionally, the emphasis on joint stability throughout these exercises enhances lower extremity stability, vital for activities involving side-cutting, jumping, or pivoting movements (4). The effect of control warm-up programs (running) refers to physiological changes occurring in the body before engaging in physical activity. These changes, including increased blood flow, joint lubrication, and elevation in body temperature, collectively contribute to optimizing neuromuscular function, ultimately resulting in improved dynamic balance (10, 20).

Individuals with CAI often exhibit elevated peak GRF and a shorter time to peak GRF during side-cutting movements. This phenomenon can be attributed to neuromuscular and biomechanical deficits associated with CAI, including altered muscle activation patterns and impaired proprioception (22). Our study demonstrated that the hop-stabilization warm-up program significantly reduced peak medial GRF more than the control program during both 45- and 90-degree side-cutting movements in participants with and without CAI. This reduction can be attributed to the program's targeted impact on enhancing neuromuscular control and biomechanical patterns (18). Specifically, these warm-up program likely facilitated improved muscle activation and joint stability, effectively mitigating the excessive medial GRF observed in individuals with CAI. Moreover, the program's ability to reduce peak posterior GRF and the time to peak medial and anterior GRF more in participants with CAI than in healthy individuals, especially during 45-degree side-cutting movements, suggests its specific efficacy in addressing the deficits associated with CAI. This differential impact emphasizes the program's potential to address CAI-related impairments and enhance dynamic stability.

However, the immediate lack of reduction in vertical GRF during the side-cutting movements in CAI participants following the hop-stabilization warm-up program may be attributed to the complex and nuanced nature of biomechanical adaptations. Variables such as muscle activation patterns, joint rigidity, and neuromuscular control impact vertical GRF (2). Although the hop-stabilization warm-up program aims to improve dynamic stability and alleviate CAI-related impairments, such as enhanced muscle activation, the direct impact of these alterations on vertical GRF may not be immediately apparent (2). The delayed impact on vertical GRF may result from the intricate structure of the side-cutting movement, which involves sudden direction changes and varied muscle recruitment. Understanding the temporal dimensions of biomechanical adaptations is crucial, and future studies could explore the hop-stabilization warm-up program's longitudinal impact on vertical GRF to determine its effectiveness in alleviating CAI-related deficits.

Our findings align with previous research indicating that individuals with CAI exhibit lower limb muscle activity deficits (22, 23). CAI participants demonstrated increased peak MH and TA activity, decreased preparatory muscular activation of the PL, delayed onset of GMed, MH, tested IAO, ES, TA, and MG, and increased time to peak of the RF, tested IAO, and PL during a 45-degree cutting movement compared to healthy individuals. Notably, our study revealed significant changes in muscle preparation activities and time to peak muscular activation when applying hop-stabilization warm-up program to CAI participants. Specifically, there was a substantial decrease in muscle preparation activities for MG and TA, coupled with an increase in PL muscle preparation. This suggests that the hop-stabilization warm-up program influenced the pre-activity patterns of these muscles in CAI individuals. Furthermore, during 45-degree side-cutting movements, the hop-stabilization warm-up program exhibited a more pronounced increase in the time to peak muscular activation for the TA and PL muscles compared to the control program. This indicates that the program introduced alterations in the timing of muscle activation during the specific movement, potentially contributing to improved neuromuscular control. However, there were no significant changes in muscle preparation activities or the time to peak muscular activation when applying hop-stabilization warm-up program to CAI participants during 90-degree side-cutting movements. The warm-up programs may not have sufficiently addressed the intricacy of the 90-degree side-cutting movements, which encompasses unique difficulties in muscle recruitment and coordination. The effectiveness of the program could be increased by modifying the intensity and duration or incorporating specific exercises that target the demands of 90-degree side-cutting movements.

The improvement in muscle activation observed in CAI participants during side-cutting movements following hop-stabilization warm-up program can be attributed to a combination of plyometric or stretch-shortening cycle theory and the stimulation of afferent pathways (26, 29, 36). Plyometric exercises involving rapid lengthening (eccentric) and shortening (concentric) muscle actions optimize the stretch-shortening cycle within muscles and tendons, enhancing neuromuscular coordination and efficiency (7, 26). Additionally, incorporating stimulating afferent pathways, such as proprioceptive exercises challenging balance and joint position sense, enhances sensory input (19, 29, 36). Improved proprioception contributes to a more precise and coordinated muscle response during dynamic tasks. The synergistic effect of plyometric activities and enhanced sensory input likely facilitates a more efficient stretch-shortening cycle, leading to improved muscle activation in CAI participants (26, 29, 36). This integrated approach aligns with a comprehensive strategy addressing both biomechanical and sensory aspects, optimizing neuromuscular control during complex movements like side-cutting.

However, the hop-stabilization warm-up program did not immediately affect peak muscle activation during 45- and 90-degree side-cutting movements in individuals with CAI or healthy participants. The intensity of the program may not have been sufficient to increase peak muscle activation. Previous research has reported that a more intensive and complex warm-up resulted in a significant increase in MVIC torque and enhanced muscle activation (37). Additionally, neuromuscular adaptations may require a certain amount of time to manifest, and immediate changes might not be apparent. Future studies could explore the optimal intensity and duration of the hop-stabilization warm-up program to maximize its impact on peak muscle activation in individuals with CAI and healthy individuals.

This study is subject to certain limitations that warrant consideration. Despite efforts to minimize muscle crosstalk by carefully selecting electrode size, interelectrode distance, and electrode placement locations, it may have influenced surface EMG measurements. The absence of follow-up evaluations limits our understanding of the duration of the benefits observed. Additionally, the participants performed side-cutting movements in a controlled environment, where factors like the pressure of an opposing player or the slickness of the court surface did not affect the technique's success. This controlled setting may limit the generalizability of the findings to real-world scenarios. Further research is essential to ascertain the persistence of these benefits and could incorporate the monitoring of kinematic variables to analyze the program's efficiency in promoting joint motion.

In conclusion, the hop-stabilization warm-up program demonstrated prompt improvements in dynamic balance, as well as in medial and posterior GRF, accompanied by enhanced muscle activity during side-cutting movements in individuals with CAI. These findings suggest that the hop-stabilization warm-up program has the potential to immediately enhance neuromuscular control during side-cutting movements in individuals with CAI. Consequently, incorporating this warm-up regimen into the routine for individuals with CAI could offer significant advantages.

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