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Original article

Rehabilitation improves walking kinematics in children with a knee varus: Randomized controlled trial

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ABSTRACT

Background: Previous studies have demonstrated increased medial stresses in knee varus alignment. Selecting a suitable treatment strategy for individuals with knee malalignment should be a priority.
Objectives: We aimed to investigate the effects of a 16-week corrective exercise continuum (CEC) program on 3-D joint angles of the dominant and non-dominant lower limbs in children with genu varus during walking.
Methods: Overall, 28 male children with genu varus (age range 9–14 years) volunteered to participate in this study. They were randomly divided into 2 equal groups (experimental and control). The participants of the experimental group received CEC for 16 weeks. 3-D gait analysis involved using a Vicon Motion System. Paired and independent sample t-tests were used for within- and between-group comparisons, respectively.
Results: For the experimental group, comparison of pre- and post-test joint kinematics of the dominant lower limb revealed that CEC decreased the peak ankle dorsiflexion angle by 26% ($P = 0.020$), peak foot internal rotation angle by 53% ($P = 0.001$), peak knee internal rotation angle by 40% ($P = 0.011$), peak hip abduction by 47% ($P = 0.010$), and peak hip external rotation angle by 60% ($P = 0.001$). In contrast, peak knee external rotation angle of the dominant limb was increased after the training program by 46% ($P = 0.044$). For the non-dominant lower limb, CEC decreased the peak ankle inversion by 63% ($P < 0.01$), peak ankle eversion by 91% ($P < 0.01$), peak foot internal rotation by 50% ($P < 0.01$), peak knee internal rotation by 29%; $P = 0.042$), peak hip abduction angle by 38% ($P < 0.01$), and peak hip external rotation angle by 60% ($P < 0.01$).
Conclusions: CEC therapy reduced excessive foot and knee internal rotations as well as excessive hip external rotation during walking in children with genu varus.
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1. Introduction

Knee osteoarthritis (OA) is one of the most common and important diseases affecting about 10% of the adult population [1]. The distribution of tibiofemoral compressive forces between the medial and lateral compartments could be affected by frontal-plane joint position and affect degeneration of biological knee joint tissues [2]. Laboratory and cadaver studies have demonstrated increased medial stresses in knee varus alignment [3], which may result in accelerated articular cartilage degeneration. Therefore, selecting a suitable treatment strategy for individuals with knee malalignment should be a priority.

The treatment of varus malalignment of the knee is likely to benefit from an increased understanding of the biomechanical risk factors associated with knee injuries. In total, 13% of children with age 11 years showed knee varus deformity that needed treatment to prevent secondary deformity in adulthood [4]. Previous studies have investigated biomechanical changes during walking in children with genu varus (without knee OA) as compared with healthy controls [5,6]. Varus alignment of the knee in healthy children is associated with abnormally increased internal foot

Abbreviations: SMR, Self-myofascial release; MAA, mechanical axis angle; *d*, effect size; Q angle, quadriceps angle.

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placement and increased internal knee rotation during the stance phase of walking [5]. Bias of muscle activation to knee external rotators and lateral knee joint muscles may decrease knee joint internal rotation [7] and therefore reduce medial knee joint load. However, this was not evaluated from a scientific standpoint.

Kean et al. [3] argued that change in quadriceps strength (12-week quadriceps strengthening program) did not predict the change in peak vertical ground reaction force or average rate of loading (changes in quadriceps strength explained 3% of the variance in the change in maximum rate of loading) in individuals with medial knee OA and varus alignment. Another study reported that a quadriceps strengthening protocol had no significant effect on knee adduction moment, considered a main risk factor for OA [8]. However, we have a dearth of information regarding the impact of corrective exercise programs on joint kinematics of the lower extremities in children with genu varus. Further study is needed to assess the effects of different scientific training protocols on biomechanical variables of walking in these children.

Although childhood is the appropriate time to implement therapeutic interventions such as corrective protocols, unfortunately, most training programs do not feature the proper treatment guidelines for children [9]. Among various corrective exercise programs, the corrective exercise continuum (CEC) programming strategy is considered a popular and effective therapy modifying the anatomical alignment of the extremities [9]. The CEC includes 4 primary phases [9] with the aim of releasing tension of overactive neuromyofascial tissues (via self-myofascial release [SMR] techniques) [10–12], increasing the extensibility of neuromyofascial tissues [13,14], reeducating or increasing the activation of underactive tissues (by isolated strengthening exercises and positional isometric techniques) [9], and finally retraining the collective synergistic function of all muscles via progressive movements [9].

Previous studies demonstrated several positive effects of corrective exercise with suitable dosage for improving musculoskeletal disorders [15,16]. To the best of our knowledge, no study has investigated correcting gait kinematic alterations (3-D lower limb joint angles) in children with genu varus malalignment with a training protocol involving CEC.

The aim of this study was to assess the effectiveness of a 16-week CEC programming strategy on 3-D joint angles of the dominant and non-dominant lower limbs during walking in children with genu varus. We hypothesized that with improved strength of the knee external rotators and the lateral knee muscles resulting from using CEC, children with genu varus could have lower foot internal rotation as well as lower knee internal rotation in both limbs during walking.

2. Material and methods

2.1. Participants

This study was an open-label randomized controlled trial. We used G*Power 3.1 (for statistical power analysis) to calculate an *a priori* power analysis of the test family (*t*-tests) and the respective statistical test based on a related study that examined between-group differences in walking kinematics (i.e., hip external rotation) in individuals with and without genu varus [6,7]. With a statistical power of 0.8 at an effect size of 0.95 with an alpha level of 0.05 and allocation ratio of 1, we needed at least 14 participants for each group [17].

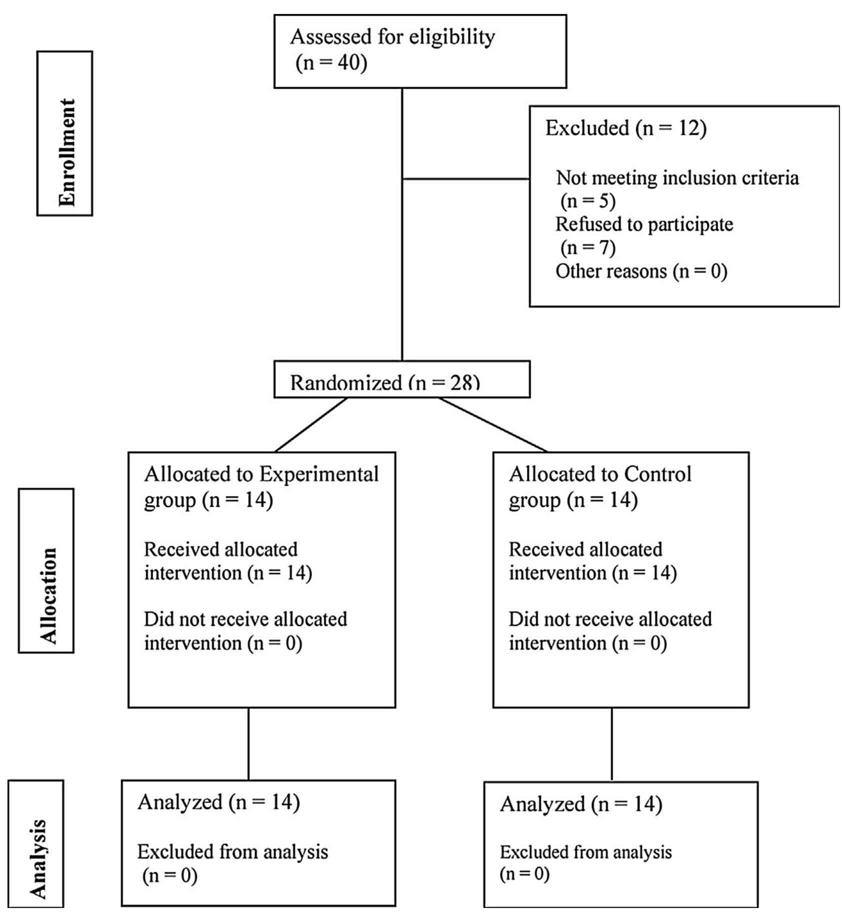

Fig. 1. Flow of the children in the study.

Therefore, we selected 28 male children (age range 9–14 years), with permission of their parents, to participate in the study. Children were recruited from physical therapy clinics in Hamedan City, Iran, and were randomly divided into experimental and control groups (Fig. 1). During the randomization process, a set of sealed, opaque envelopes was used to ensure allocation concealment. Each envelope contained a card indicating which group the participant was allocated to. Neither the participating child nor the parents were aware of the group children were allocated to. Participants included prepubertal children with genu varus selected during clinical visits (Table 1). We included only participants with a mechanical axis angle (MAA), defined as the angle formed by lines drawn from the center of the hip to the center of the knee and the center of the knee to the center of the ankle (Fig. 2A), >1.3° (participants with varus but not pathological) in both knees (determined on full-length standing anteroposterior radiograph) [5,18]. Furthermore, we selected males between age 9 and 14 years, with Q angle < 6° [19,20]; no history of musculoskeletal or neuromuscular dysfunction; no history of joint diseases, chronic joint infection, or bone diseases; and physically active in daily life. We excluded participants with signs of functional lower-limb instability, ligament injury, reconstruction of ligaments, neuromuscular dysfunction, obvious dysfunction of lower-limb muscles, discrepancy of leg length > 1 cm and history of major trauma or surgery of the lower extremity [5]. All participants were right-foot – dominant as determined by a kicking ball test [21].

Table 1
Demographic characteristics of participants in experimental and control groups.

Variable	Experimental group ($n = 14$)	Control group ($n = 14$)
Age (years)	11.71 ± 1.68	11.21 ± 1.80
Height (m)	1.40 ± 0.09	1.39 ± 0.08
Mass (kg)	35.14 ± 11.47	34.79 ± 12.41
BMI (kg/m^2)	17.49 ± 3.61	17.37 ± 4.22
Dominant MAA	9.12 ± 0.78	8.88 ± 1.31
Non-dominant MAA	9.09 ± 0.60	8.86 ± 1.19

Data are mean ± SD.
BMI, body mass index; MAA, mechanical axis angle; NA, not applicable.

Because participants were younger than 18 years, they gave verbal assent to their participation, and their parents gave written informed consent for them to participate in the study, as approved by the local ethics committee (IR-ARUMS-REC-1396-90B) and in accordance with the Helsinki Declaration.

2.2. Gait analysis

The gait analysis data were acquired in 2 stages. The first measurement (pre-test) was taken 2 days before the training protocols and the second (post-test) 6 days after the last

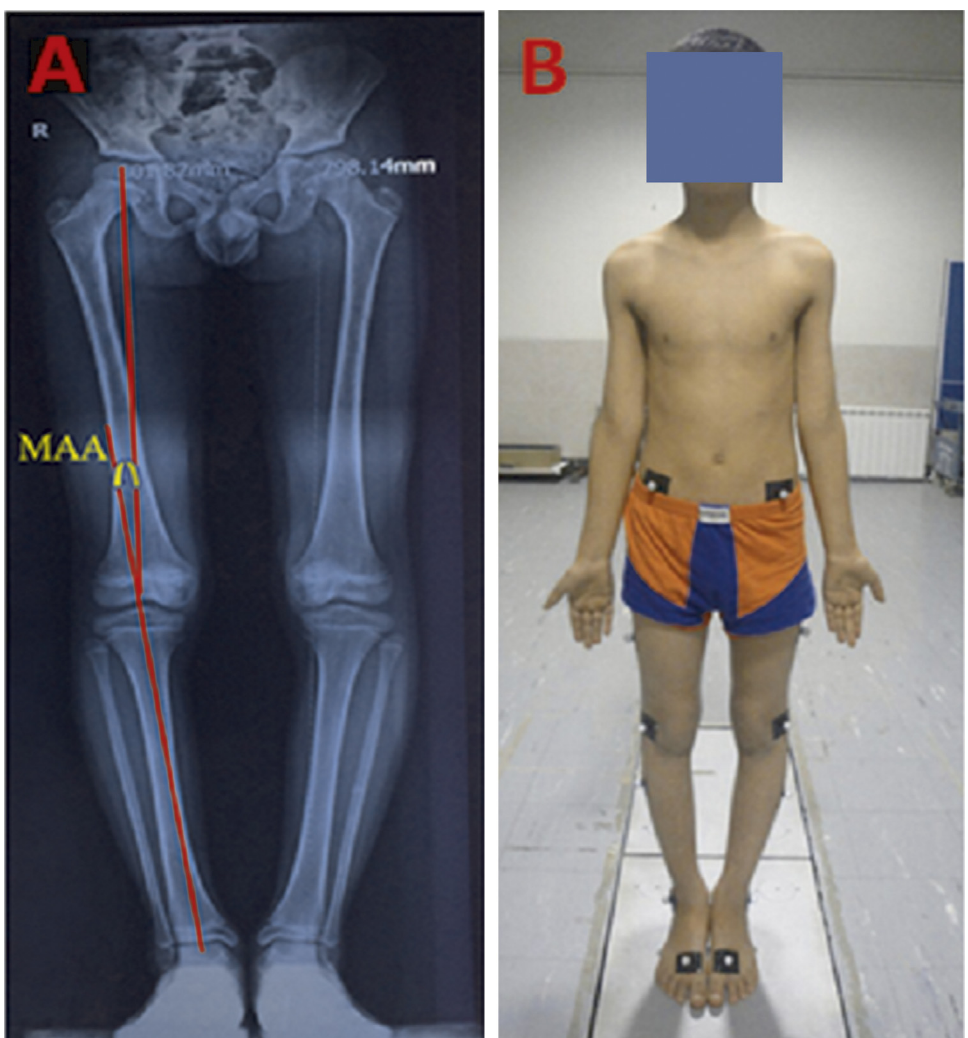

Fig. 2. (A) Full-length standing anteroposterior radiograph. (B) Static calibration in the standing position facing frontward.

intervention session to ensure that the acute physiological consequences of training did not interfere with the measures. Participants in the control group did no stretching or resistance training and were re-evaluated after 16 weeks.

3-D gait analysis involved using a 6-infrared camera (sampling frequency of 100 Hz) VICON 512 motion analysis system (Oxford Metrics, Oxford, UK). For the motion capture, an area covering approximately 6 m (anterior-posterior) $\times$ 3.5 m (left-right) $\times$ 2 m (top-bottom) of a walkway was calibrated. The plug-in-gait marker set with 16 reflective markers (14 mm sphere) was used to measure the kinematics of the pelvis, thighs, legs, and feet. The markers were directly attached bilaterally to the skin on the following anatomical landmarks: anterior and posterior superior iliac spines, lateral femoral epicondyle, lateral side of the thigh and shank, lateral malleolus, calcaneus, and top of the feet at the base of the second metatarsal (Fig. 2B). Anthropometric characteristics, including height, weight, leg length, knee width, ankle width, and pelvic width, were measured and recorded by using Nexus v1.8.1. Anatomical landmarks were then defined relative to the global coordinate system in a static trial to reconstruct an anatomical coordinate system during a dynamic trial.

Afterwards, participants performed 5 practice walking trials, followed by 5 acceptable test walking trials. Acceptable test walking trials included 4 consecutive foot strikes with full marker visibility. Participants walked barefoot at their self-selected comfortable velocity. A trial was excluded if both feet did not land completely on the force plates, if there were any noticeable gait deviations, if the participant targeted the platforms, or with loss of reflective joint markers. Kinematics data were then filtered by using a fourth-order low-pass Butterworth filter with cutoff frequency of 20 Hz [21]. All joint kinematics data were extracted from the Nexus software during a complete walking stride [22].

The following outcomes were assessed for both dominant and non-dominant lower limbs: (1) 3-D joint kinematics data and (2) Q angle values.

2.3. Corrective training protocols

Among corrective training programs, CEC is one of the best and most complete treatments for structural abnormalities [9]. The CEC we used included 4 primary phases. The first phase was accomplished by the use of SMR techniques on the gluteus medius, medial part of the hamstring, and vastus medialis muscles of both limbs. The experimental group was taught SMR techniques by a physiotherapist who used a predetermined protocol [23]. The group was instructed to roll a foam roller, starting at the proximal portion of the muscles and continuing to the distal end of the muscle or vice versa for 120–300 s (Fig. 3) [11,12]. Participants were instructed to apply as much pressure as they could, pushing into discomfort but not pain, to have better benefits on flexibility [24]. The experimental group performed SMR (for 10 min on each region in each session) 5 times a week for a 2-week period [25].

The second phase was the lengthening phase using static and dynamic stretching techniques [13,14]. The static stretching protocol included 5 stretches. The stretching positions were described by Alter [26]. The muscle groups stretched were gluteus medius, medial part of hamstring, and vastus medialis muscles of lower extremities. Participants were instructed to hold a stretch just short of the point of discomfort for about 30 s [27]. For each muscle, the stretching was repeated 4 times with a rest interval of about 10 s [14]. During each session, this procedure was repeated 4 times, leading to a total stretch period of 120 s for each muscle group. Static stretching for 4$\times$ 30 s was reported to reduce muscle-tendon unit stiffness [28]. Moreover, each session involved 2 sets of the 3 dynamic movements (30 s for each set) [27]. The dynamic stretches included scissor gait, straight leg raise with scissor lower limb movements, and scissor running. The dynamic stretches were applied 5 times a week for a 2-week period (Fig. 4).

The third phase was characterized by the use of isolated strengthening exercises and positional isometric techniques [9]. The isolated strengthening exercises and positional isometric techniques included 3 exercises (Table 2). The muscle groups strengthened were vastus lateralis, biceps femoris, and hip adductors. Participants were accustomed to the training techniques before starting the training sessions. They performed resistance Thera-Band exercises 3 times per week for 10 weeks (30 strength training sessions). Each exercise session involved a 10-min warm-up (stationary bike), 40-min resistance training, and 5-min cool-down. All Thera-Band training was closely supervised by a physiotherapist and the participants received consistent verbal instructions. To prevent exercise-related injuries, resistance was gradually increased from a low resistance band (yellow TheraBand) to a high resistance band (red, blue and further to black) (based on the TheraBand® force-elongation table)[29]. As well, the exercise volume was enhanced by increasing the number of sets, whereas the rate of progression was based on individual improvements (band color was upgraded if participants were able to perform 2 more repetitions in the second set) [30].

Finally, the fourth stage was the integration phase (the last 2 weeks, 3 sessions per week). An example of an integrated dynamic movement may include a two-legged exercise with minimal challenge to stability (such as two-legged wall squat).

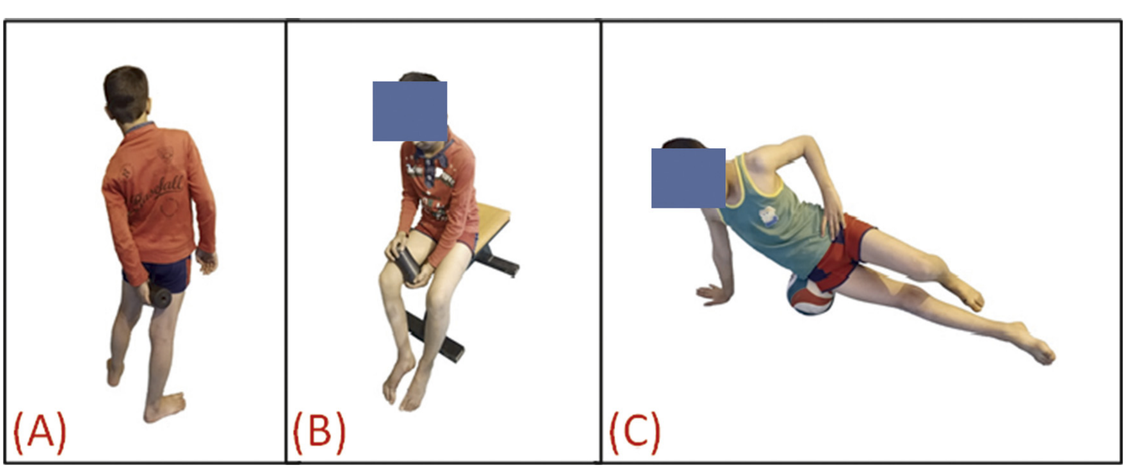

Fig. 3. The use of self-myofascial release (SMR) techniques on the (A) medial part of hamstring, (B) vastus medialis, and (C) gluteus medius muscles.

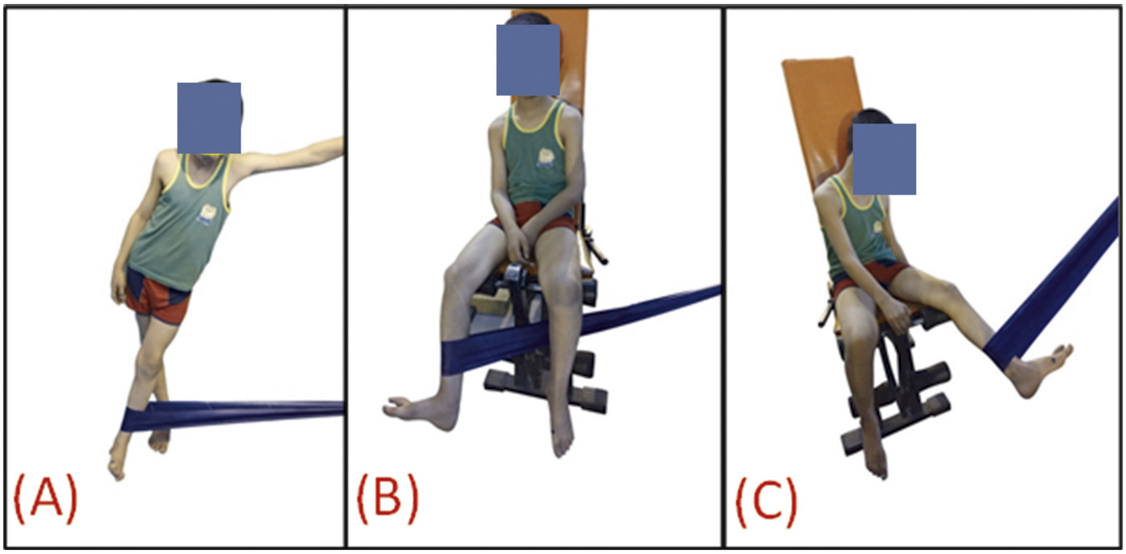

Fig. 4. Thera-band exercises for the (A) hip adductor, (B) vastus lateralis, and (C) biceps femoris muscles.

Table 2
The strength training exercises for the experimental group.

Movements	Description
Hip adductor strength training	The adductors were strengthened in the standing position while the participant tried to adduct against an elastic band in the distal region of the lower limb (Fig. 4A) (2-s isometric hold at end-range and 4-s eccentric [9]).
Vastus lateralis strength training	The exercise was performed with the participant seated on a massage table adjusted to position the hip at approximately 90° while extending the knee along with lateral rotation against resistance of elastic band (Fig. 4B) (2-s isometric hold at end-range and 4-s eccentric [9]).
Biceps femoris strength training	The exercise was performed with the participant seated on a bench adjusted to position the hip at approximately 90° while flexing the knee along with lateral rotation (Fig. 4C) (2-s isometric hold at end-range and 4-s eccentric [9]).

Progression from here would be to an alternating limb movement (e.g., single leg squat) and then progression to an intriguing and complicated exercise (e.g., combined squat) to more difficult dynamic movements on one leg (e.g., single leg multi-planar balance training) (Fig. 5). This progression can be performed first in the sagittal plane, then progress to the frontal (side to side) and eventually to transverse planes (rotation).

All participants were asked not to participate in any other sports activities throughout the investigation. To consider the response of both limbs to the training protocol, all exercises and measurements were performed on both the dominant and non-dominant lower limbs.

2.4. Statistical analysis

Data were found to be normally distributed by the Shapiro–Wilk test ($P > 0.05$) and met the criteria for normal distribution. Homogeneity of variance was examined by a Levene test and variance ratios. Descriptive data are expressed as mean (SD) for pre-, post- and change scores. Paired sample t-tests were used to compute the statistical significance of the differences between pre- and post-test joint angle measurements within each group. Independent sample t-tests were also used to compare the differences in change scores (post-test minus pre-test scores for each participant) between experimental and control groups. To calculate an effect size, Cohen's d was used: $d \leq 0.2$ was considered small, >0.8 large, and between these values moderate [31]. For all statistical tests, a two-tailed $P < 0.05$ was considered statistically significant. Data were analyzed by using SPSS v22.

3. Results

We found no within- and between-group differences in mean walking speed [experimental (pre-test: 1.24 ± 0.06; post-test: 1.25 ± 0.09 m/s); control (pre-test: 1.25 ± 0.13; post-test: 1.24 ± 0.05) ($P > 0.05$)] or Q angle values for the dominant limb [experimental (pre-test: -4.7 ± 1.9; post-test: -4.5 ± 1.9 m/s); control (pre-test: -4.8 ± 2.4; post-test: -4.8 ± 2.3) ($P > 0.05$)] or non-dominant limb [experimental (pre-test: -4.5 ± 1.8; post-test: -4.5 ± 1.9 m/s); control (pre-test: -4.5 ± 2.5; post-test: -4.6 ± 2.4) ($P > 0.05$)].

The maximum values of the lower extremity joint angles during a stride cycle for the dominant lower limb of the control and experimental groups are presented in Table 3. The peak values of the dominant lower limb joint angles did not significantly differ between the pre- and post-test for the control group ($P > 0.05$) (Table 3), but the peak ankle dorsiflexion angle, peak foot and knee internal rotation angles, peak hip abduction angle, and peak knee and hip external rotation angles significantly decreased between the pre- and post-test for the experimental group. The amount of decrease was 26% for peak ankle dorsiflexion angle ($P = 0.020$), 53% for peak foot internal rotation ($P = 0.001$), 40% for peak knee internal rotation ($P = 0.011$), 47% for peak hip abduction ($P = 0.010$), and 60% for peak hip external rotation ($P = 0.001$) (Table 3). However, after the CEC, the peak knee external rotation angle for the dominant lower limb was increased, by 46% ($P = 0.044$) (Table 3). Furthermore, for the dominant limb, the experimental group showed a large change ($d > 0.8$) in all these variables (peak ankle dorsiflexion angle, peak foot internal

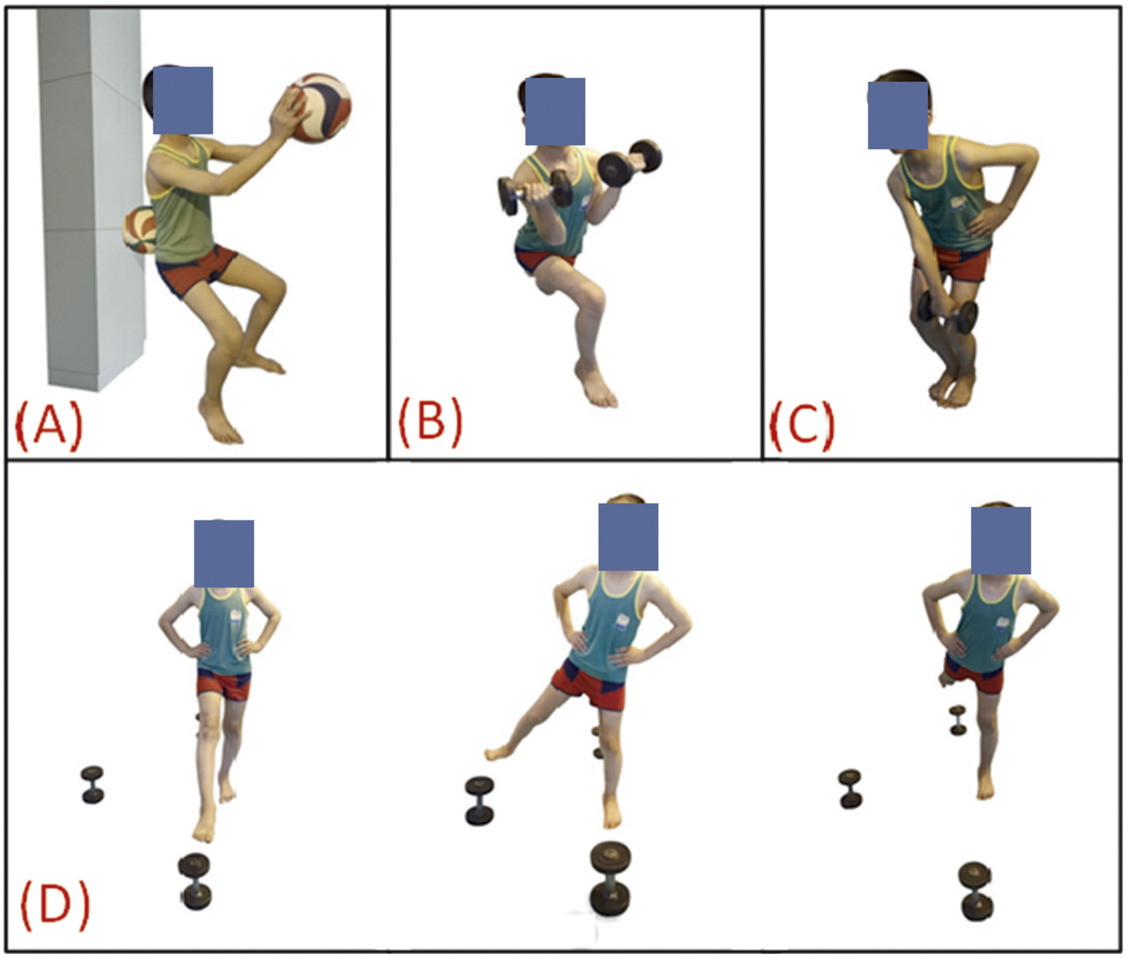

Fig. 5. Example of integrated dynamic movement progression, (A) two-leg, (B) alternating leg, (C) single leg, (D) single-leg multi-planar balance training.

Table 3
Comparison of dominant lower-limb joint angles (ankle, knee and hip) before and after 16 weeks (pre-test; post-test) in both groups.

Joint	Variable	Experimental group						Control group					
		Pre-test	Post-test	*P* value	Effect size	95% CI	Change	Pre-test	Post-test	*P* value	Effect size	95% CI	Change
Ankle	Dorsi flexion	16.5 ± 5.9	12.2 ± 2.3	0.02*	1.05	0.8–7.8	−4.3 ± 6.1	17.6 ± 3.6	17.3 ± 4.6	0.83	0.07	−2.4 to 2.9	−0.3 ± 4.6
	Plantar flexion	10.0 ± 4.7	10.1 ± 4.7	0.99	0.00	−3.8 to 3.9	0.1 ± 6.7	10.7 ± 2.7	10.1 ± 3.4	0.26	0.19	−1.6 to 0.5	−0.6 ± 1.8
	Inversion	1.6 ± 1.2	1.8 ± 1.9	0.80	0.11	−1.6 to 1.3	0.2 ± 2.5	1.6 ± 0.9	1.8 ± 0.9	0.41	0.22	−0.7 to 0.3	0.2 ± 0.9
	Eversion	0.9 ± 1.6	1.7 ± 1.8	0.18	0.42	−0.4 to 1.8	0.7 ± 1.9	0.9 ± 1.1	0.4 ± 1.9	0.15	0.33	−1.3 to 0.2	−0.5 ± 1.3
	Internal rotation	14.7 ± 1.6	6.9 ± 4.6	0.00*	2.50	5.1–10.3	−7.7 ± 4.5**	15.2 ± 1.9	14.7 ± 2.2	0.16	0.24	−0.2 to 1.0	−0.4 ± 1.1
	External rotation	8.5 ± 3.5	8.5 ± 3.7	0.93	0.03	−2.3 to 2.4	0.0 ± 4.1	9.0 ± 3.6	9.8 ± 1.9	0.25	0.29	−0.6 to 2.1	0.7 ± 2.3
Knee	Flexion	21.9 ± 7.9	25.1 ± 6.1	0.18	0.46	−8.1 to 1.6	3.2 ± 8.5	21.9 ± 4.2	21.1 ± 4.7	0.27	0.18	−0.7 to 2.4	−0.8 ± 2.8
	Extension	5.0 ± 7.2	5.7 ± 2.81	0.73	0.14	−5.0 to 3.6	0.7 ± 7.5	3.2 ± 4.7	5.3 ± 6.6	0.33	0.38	−6.6 to 2.4	2.1 ± 7.9
	Adduction	0.9 ± 1.8	1.2 ± 3.3	0.79	0.12	−2.7 to 2.1	0.3 ± 4.2	0.9 ± 2.1	0.8 ± 1.8	0.99	0.05	−0.8 to 0.8	−0.1 ± 1.4
	Abduction	8.3 ± 4.9	7.1 ± 3.3	0.27	0.27	−3.2 to 0.9	−1.1 ± 3.7	8.3 ± 5.0	8.0 ± 4.1	0.71	0.07	−2.0 to 1.4	−0.3 ± 3.0
	Internal rotation	10.9 ± 5.4	6.5 ± 2.1	0.01*	1.18	1.2–7.6	−4.4 ± 5.6**	11.6 ± 3.6	11.1 ± 2.9	0.66	0.15	−1.8 to 2.8	−0.5 ± 4.1
	External rotation	9.6 ± 5.2	14.1 ± 4.1	0.04*	0.96	0.1–8.8	4.5 ± 7.5**	10.2 ± 3.5	9.4 ± 2.8	0.21	0.25	−2.1 to 0.5	−0.7 ± 2.3
Hip	Flexion	30.7 ± 3.8	28.3 ± 5.3	0.16	0.52	−1.1 to 5.9	−2.4 ± 6.2	31.0 ± 3.8	29.1 ± 3.3	0.10	0.25	−0.4 to 4.1	−1.8 ± 3.9
	Extension	3.1 ± 4.6	6.2 ± 6.1	0.09	0.57	−0.7 to 6.7	3.0 ± 6.4	3.1 ± 4.9	2.9 ± 4.2	0.87	0.04	−1.7 to 1.5	−0.2 ± 2.9
	Adduction	5.9 ± 2.4	7.1 ± 1.3	0.13	0.63	−2.8 to 0.4	1.2 ± 2.8	6.0 ± 1.3	7.0 ± 6.0	0.51	0.28	−4.3 to 2.2	1.03 ± 5.7
	Abduction	8.6 ± 4.2	4.6 ± 2.5	0.01*	1.21	−7.0 to −1.1	−4.1 ± 5.1**	9.2 ± 2.9	10.3 ± 5.6	0.10	0.25	−6.2 to 8.7	1.1 ± 5.9
	Internal rotation	12.1 ± 18.6	7.7 ± 9.7	0.41	0.31	−15.6 to 6.8	−4.4 ± 19.3	10.4 ± 16.1	15.05 ± 5.9	0.18	0.42	−2.5 to 11.8	4.6 ± 12.4
	External rotation	23.4 ± 10.4	9.3 ± 3.2	0.00*	2.06	−19.6 to −8.4	−14.1 ± 9.6**	22.7 ± 9.1	21.4 ± 8.1	0.37	0.15	−4.4 to 1.7	−1.3 ± 5.3

Data are mean ± SD.
95% CI, 95% confidence interval.
* Significant within-group difference.
** Significant between-group difference.

rotation, peak knee internal rotation, peak hip abduction, peak hip external rotation, peak knee external rotation) when walking during the post-test (Fig. 6). Fig. 6 illustrates the patterns of the dominant lower-limb joint angles (i.e., hip, knee and ankle) during a walking cycle.

For the dominant lower limb, the changes significantly differed between the groups in peak internal rotation ankle angle ($P < 0.01$), peak internal ($P = 0.043$) and external rotation ($P = 0.024$) knee angles, peak abduction ($P = 0.020$) and external rotation hip angles ($P < 0.01$) (Table 3).

For the non-dominant lower limb joint angles, the peak values did not significantly differ between the pre- and post-test for the control group ($P > 0.05$) (Table 4). Nevertheless, the experimental group showed significant differences in peak ankle inversion, peak ankle eversion, peak ankle internal rotation, peak knee internal rotation, peak hip abduction, and peak hip external rotation before and after training (Fig. 7). Fig. 7 depicts the patterns of the non-dominant lower limb joint angles (i.e., hip, knee and ankle) during a walking cycle. The CEC decreased peak angle values of the 6 variables for the non-dominant side. The amount of decrease was 63% for the ankle inversion angle ($P < 0.01$), 91% for ankle eversion ($P < 0.01$), 50% for foot internal rotation ($P < 0.01$), 29% for knee internal rotation ($P = 0.042$), 38% for hip abduction, and 60% for hip external rotation ($P < 0.01$) (Table 4). Moreover, for the non-dominant limb, the experimental group showed a large change ($d > 0.8$) in all these variables (peak ankle inversion, peak ankle eversion, peak ankle internal rotation, peak knee internal rotation, peak hip abduction and peak hip external rotation) when walking during the post-test.

For the non-dominant limb, the changes significantly differed between the groups in peak ankle inversion angle ($P = 0.040$), peak ankle eversion ($P < 0.01$), peak ankle internal rotation ($P < 0.01$), and peak hip external rotation ($P < 0.01$) (Table 4).

4. Discussion

The bias of knee muscle strength to knee external rotators and knee lateral muscles after a training protocol were hypothesized to be associated with lower-foot internal rotation and lower tibial internal rotation in both limbs. This study is the first to identify the effect of a corrective training program on those kinematics variables that may lead to progression of OA in genu varus patients over a long period. After the CEC, in common with the dominant limb, the peak foot internal rotation, peak knee internal rotation, peak hip abduction, and peak hip external rotation angles decreased in the non-dominant limb. Also, after the CEC, peak ankle dorsiflexion of the dominant limb as well as peak ankle inversion and eversion angles of the non-dominant limb were decreased. This proves our hypothesis and reveals that the CEC could reduce the risk factors that possibly lead to OA in individuals with genu varus, which is further reinforced by a high effect size.

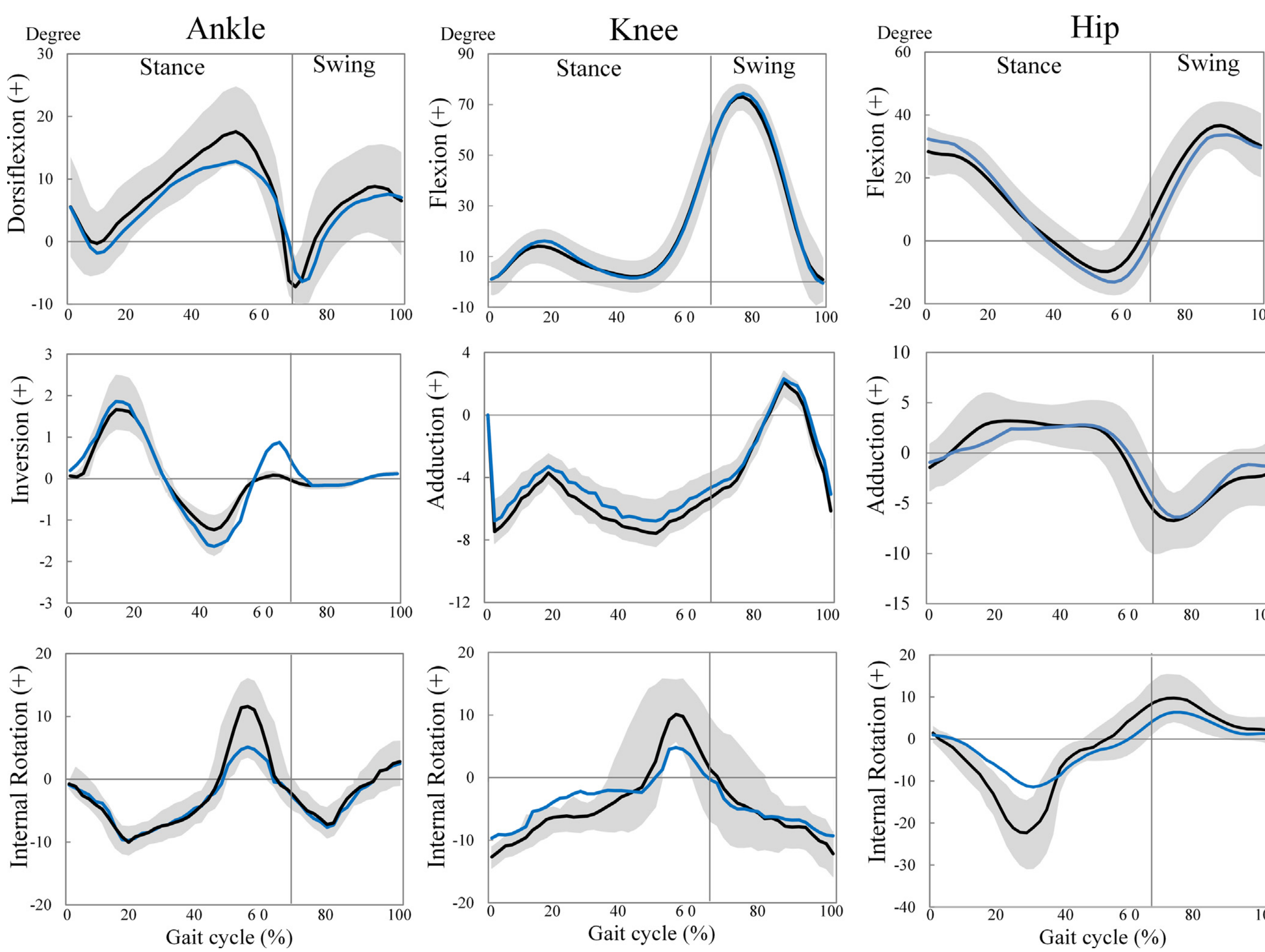

Fig. 6. Ensemble average kinematics for the dominant limb for all 14 participants in the experimental group. The black and blue curves represent the values pre-test (before corrective exercise continuum [CEC]) and post-test (after CEC), respectively. Gray shading illustrates the 95% confidence interval for the pre-test condition. For clarity, errors are not shown for the post-test condition.

Table 4
Comparison of non-dominant lower limb joint angles (ankle, knee and hip) before and after 16 weeks (pre-test; post-test) in experimental and control groups.

Joint	Variable	Experimental group						Control group					
		Pre-test	Post-test	*P* value	Effect size	95% CI	Change	Pre-test	Post-test	*P* value	Effect size	95% CI	Change
Ankle	Dorsi flexion	15.5 ± 6.7	16.1 ± 3.4	0.76	0.12	−5.0 to 3.8	0.6 ± 7.7	15.5 ± 4.5	16.0 ± 4.6	0.30	0.11	−1.6 to 0.5	0.54 ± 1.86
	Plantar flexion	7.4 ± 4.3	6.8 ± 5.6	0.75	0.12	−4.6 to 3.4	−0.6 ± 6.9	7.7 ± 3.4	7.6 ± 3.5	0.78	0.03	−1.1 to 0.8	−0.1 ± 1.7
	Inversion	3.1 ± 2.5	1.2 ± 1.1	0.01*	1.11	0.5–3.4	−1.9 ± 2.5**	3.1 ± 2.2	2.8 ± 2.1	0.31	0.14	−0.3 to 1.0	−0.3 ± 1.2
	Eversion	2.8 ± 1.5	0.2 ± 1.6	0.00*	2.94	−3.6 to −1.5	−2.6 ± 1.8**	2.7 ± 1.3	2.6 ± 1.1	0.22	0.08	−0.4 to 0.1	−0.2 ± 0.5
	Internal rotation	12.7 ± 4.6	6.3 ± 3.4	0.00*	1.60	4.0–8.8	−6.4 ± 4.2**	12.8 ± 2.9	12.8 ± 1.9	0.95	0.00	−1.5 to 1.5	−0.0 ± 2.7
	External rotation	10.3 ± 4.2	8.29 ± 4.6	0.27	0.45	−5.7 to 1.7	−1.9 ± 6.5	10.3 ± 4.1	10.5 ± 4.7	0.73	0.05	−0.8 to 1.2	0.2 ± 1.8
Knee	Flexion	26.0 ± 6.2	26.9 ± 4.6	0.71	0.15	−5.5 to 3.8	0.8 ± 8.1	26.7 ± 6.1	24.1 ± 5.3	0.15	0.46	−1.1 to 6.3	−2.6 ± 6.5
	Extension	2.3 ± 2.6	1.64 ± 0.8	0.38	0.38	−0.9 to 2.2	−0.6 ± 2.7	1.7 ± 3.3	2.04 ± 2.9	0.64	0.11	−1.7 to 1.1	0.31 ± 2.5
	Adduction	4.6 ± 2.1	3.0 ± 4.1	0.24	0.50	−1.2 to 4.3	−1.6 ± 4.8	5.2 ± 3.0	4.9 ± 2.5	0.47	0.11	−0.5 to 1.0	−0.3 ± 1.3
	Abduction	6.8 ± 3.5	8.55 ± 3.5	0.33	0.50	−2.0 to 5.5	1.7 ± 6.6	7.1 ± 1.9	6.9 ± 3.5	0.80	0.07	−1.6 to 1.3	−0.2 ± 2.6
	Internal rotation	7.9 ± 3.1	5.6 ± 1.8	0.04*	0.91	0.1–4.4	−2.2 ± 3.7	8.0 ± 3.0	8.2 ± 2.4	0.78	0.07	−1.6 to 1.2	0.2 ± 2.6
	External rotation	10.9 ± 3.9	9.6 ± 3.5	0.38	0.38	−4.8 to 1.9	−1.4 ± 5.9	12.1 ± 4.7	10.3 ± 4.1	0.11	0.41	−4.1 to 0.5	1.8 ± 4.0
Hip	Flexion	30.1 ± 4.7	28.3 ± 2.9	0.20	0.47	−1.1 to 4.6	−1.8 ± 4.9	28.8 ± 2.9	29.1 ± 5.1	0.80	0.08	−3.0 to 2.4	0.3 ± 4.8
	Extension	1.6 ± 7.0	5.7 ± 3.3	0.08	0.78	−0.5 to 8.5	4.0 ± 7.9	1.2 ± 6.4	1.8 ± 7.0	0.30	0.09	−0.6 to 1.8	0.6 ± 2.1
	Adduction	7.4 ± 3.9	6.1 ± 2.4	0.35	0.40	−1.6 to 4.2	−1.3 ± 5.0	7.9 ± 2.7	8.4 ± 3.8	0.50	0.13	−1.8 to 0.9	0.4 ± 2.4
	Abduction	6.2 ± 2.8	3.8 ± 2.0	0.01*	0.99	−3.8 to −0.9	−2.4 ± 2.5	7.5 ± 2.4	6.6 ± 0.8	0.12	0.56	−1.9 to 0.3	0.8 ± 1.9
	Internal rotation	4.7 ± 4.4	8.6 ± 5.5	0.122	1.60	−1.1 to 8.9	3.9 ± 8.8	5.8 ± 2.3	4.8 ± 3.5	0.28	0.31	−2.8 to 0.9	−0.9 ± 3.2
	External rotation	17.5 ± 7.5	7.0 ± 4.0	0.00*	1.82	−16.1 to −4.7	−10.5 ± 9.8**	16.9 ± 5.1	17.2 ± 5.7	0.74	0.06	−1.7 to 2.4	0.3 ± 3.7

Data are mean ± SD.
95% CI, 95% confidence interval.
* Significant within-group difference.
** Significant between-group difference.

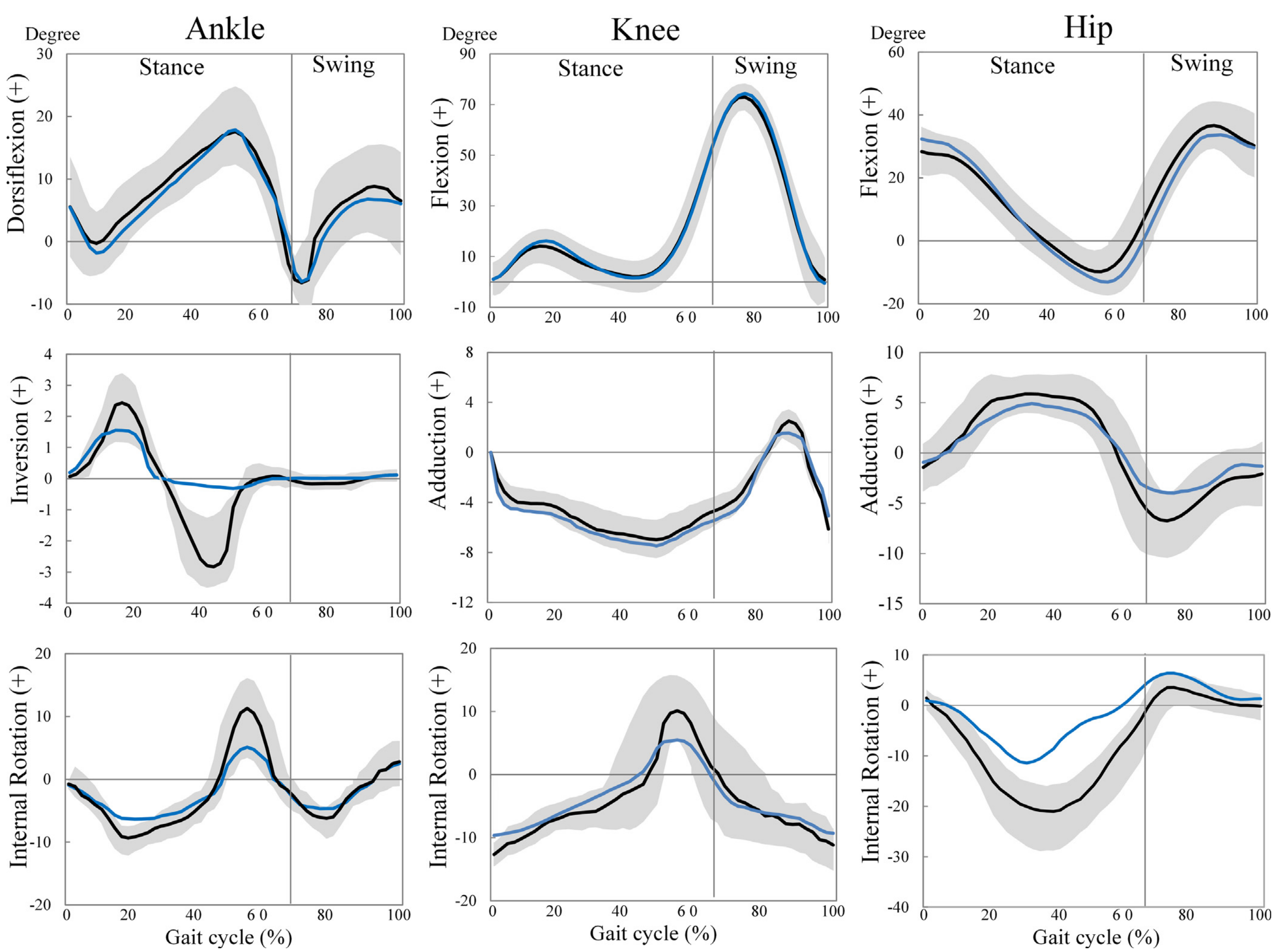

Fig. 7. Ensemble average kinematics for the non-dominant limb for all 14 participants in the experimental group. The black and blue curves represent the values pre-test (before CEC) and post-test (after CEC), respectively. Gray shading illustrates the 95% confidence interval for the pre-test condition. For clarity, errors are not shown for the post-test condition.

The experimental group in the present study walked at similar speeds during the pre- and post-test. Thus, differences in gait patterns could not be attributed to differences in walking speed. Our findings demonstrate that the effects of CEC on 3-D lower-limb joint angles differ in dominant and non-dominant lower limbs. Results of previous investigations demonstrated significant bilateral differences in the cartilage volume [32], bone density [33], and strength and coordination abilities [34,35]. These asymmetries in lower-extremity anatomy may result in different joint angle production in response to the same training in dominant and non-dominant lower limbs. Newton et al. argued that responses to eccentric exercise were not necessarily the same between dominant and non-dominant limbs [36]. Our findings justify the continued use of the dominant limb in clinical settings.

The reduced peak foot internal rotation, knee internal rotation, hip abduction and hip external rotation of both limbs as well as reduced peak ankle inversion of the non-dominant limb in the experimental group can be explained in part by the altered medial and lateral knee joint muscle length–tension relationship due to CEC. The increased strength of lateral knee external rotator muscles (biceps femoris and vastus lateralis) may aid in controlling knee internal rotation with genu varus and provide greater knee joint stability against the external knee adduction moment [37]. Genu varus in healthy children is associated with increased peak foot internal rotation angle, peak knee internal rotation angle, and increased external hip rotation moments during the stance phase of walking [5,6]. The most important function of the subtalar joint is to absorb the rotation of the lower limb during the support phase of walking [37]. With the foot fixed on the surface and the femur and tibia rotating internally at the beginning of stance and externally at the end of stance, the subtalar joint absorbs the rotation through the opposite actions of pronation and supination [37]. The increased knee internal rotation in terminal stance results in higher external knee adduction moment in children with genu varus [5], which is a contributing factor to articular cartilage degeneration and disease progression in the medial compartment of the knee [38,39]. Therefore, lower knee internal rotation of both limbs due to CEC could possibly reduce compressive loads applied to the knee's medial compartment during the terminal stance of walking. Furthermore, cohort studies evaluating adolescents or children until adulthood to confirm the reduction in risk of developing knee OA with the CEC program are warranted.

In addition, our results indicated lower ankle eversion in the non-dominant limb after CEC, which could result in a decreased risk of injury. Excessive tibial internal rotation coupled with rearfoot eversion during the first half of the stance phase of walking is associated with different injuries such as patellafemoral pain syndrome, shin splints, and achilles tendon pain [37,40,41]. Pronation can be present in as much as 55–85% of stance, creating problems when the lower limb moves into external rotation and extension as the subtalar joint is still pronating [37]. Excessive pronation has been speculated to be a major risk factor for injury, but it is not necessarily the maximum degree of pronation.

We did not investigate coupling between the leg and foot kinematics. Perhaps it would be an interesting idea for future studies to assess the effects of a corrective exercise program on coordination between movements of tibia and foot during gait in genu varus patients.

Stief et al. [6] reported higher maximum hip abduction moment during the stance phase of walking in genu varus patients. In the present study, we observed a reduction in peak hip abduction angles of both limbs after CEC. In addition, the study showed that these patients exerted greater hip adductor muscle forces (due to strengthening of these muscles by CEC) to move their trunks laterally [42]. This change in loading pattern was a compensatory mechanism, which possibly resulted from the CEC, used by children with genu varus to reduce the mediolateral distance between the center of mass and the knee joint center.

In the present study, in both dominant and non-dominant limbs, the Q angle values in the experimental group did not significantly differ between the post-test and pre-test. Also, the CEC had no significant effects on peak knee extension and flexion angles of both dominant and non-dominant limbs. In line with our results, Wang et al. demonstrated that kinematic and kinetic gait parameters did not improve significantly after whole-body vibration training with a quadriceps strengthening exercise in patients with medial compartment knee OA [43]. Genu varus is associated with reduction of the maximum knee extension moment in terminal stance [6]. Although the CEC had no effect on knee joint angles in the sagittal plane, further study is warranted to evaluate the effects of this training protocol on lower-limb joint moment variables for children with genu varus during walking.

Several methodological limitations are acknowledged with our approach. Our analysis was restricted to the joint angles of both lower extremities. However, 3-D lower-limb kinetics and electromyographical activity of lower extremity muscles are considered by many to be a critical factor in walking-induced injuries. Furthermore, the training period was short. Males were exclusively used for this study; however, further investigation, with females and different ages, are warranted.

5. Conclusion

Overall, CEC could decrease the possibility of injuries by a reduction in foot internal rotation, knee internal rotation, hip external rotation, and hip abduction of both lower limbs and an increase in dominant peak knee external rotation angle for children with genu varus during walking. Furthermore, the dominant and non-dominant lower limbs do not show similar responses to the same training protocol.

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Disclosure of interest

The authors declare that they have no competing interest.

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