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Liwen Zhang , Meizhen Zhang , Hui Liu *

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Effects of Coordination and Strength Training on the Lower Extremity Inter-Segmental Coordination of Instep Kicking

Liwen Zhang [1], Meizhen Zhang [1] and Hui Liu [2,*]

[1] Biomechanics Laboratory, School of Physical Education and Health Engineering, Taiyuan University of Technology, Taiyuan, China

[2] Biomechanics Laboratory, College of Human Movement Science, Beijing Sport University, Beijing 100084, China

* Correspondence: liuhuibupe@163.com

Abstract

The purpose of this study was to determine the effects of coordination training and strength training on the lower extremity inter-segmental coordination during instep kicking for novices. Thirty-two male college students with no soccer-specific training experience participated and were randomly assigned to either a coordination training group, a strength training group, or a kicking training group. Each participant executed exercise training three times a week for eight weeks. The instep kicking test was performed before and after the three training sessions. Two-way ANOVAs were conducted to determine the training effects on the kicking performance and the inter-segmental coordination. The maximum ball speed significantly increased after the three trainings, but the kicking accuracy significantly increased only after coordination training. The time spent percentage of knee-ankle shank-phase coordination pattern in the leg-cocking phase were significantly increased, but the time spent percentage of hip-knee thigh-phase in the back swing phase significantly decreased after the three trainings. The co-activation of the tibialis anterior and gastrocnemius muscles significantly decreased only after coordination training. The lower extremity inter-segmental coordination during instep kicking was significantly improved after training. Coordination training may improve the neuromuscular motor control functions during the instep kicking more effectively.

Keywords: motor control; dynamic system theory; coupling angle; training effect; kicking performance improvement

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1. Introduction

Inter-segmental coordination is one of the key factors influencing the techniques and performance in sports. Inter-segmental coordination has been defined as the mastering of redundant degrees of freedom of the musculoskeletal system employed during sport movements to produce a controllable system [1], and could be described using the vector coding method that calculates the angle of the vector between two adjacent data points in time on the angle-angle diagram relative to the right horizontal, named as coupling angle ranged from 0° to 360° [2]. In addition, the co-activation of the agonist and antagonist muscles, defined as the ratio of the two muscles, described the coordinated movement of the muscles during a specific sport movement [3]. It has been suggested that the athletes achieving better sports performance had more appropriate characteristics of the inter-segmental coordination in the sport of running [4], kicking [5–7], swimming [8,9], ice climbing [10], and ski jumping [11]. The variations in the inter-segmental coordination observed among skill levels indicated that such attributes can be improved through targeted training approaches.

Instep kicking is one of the most fundamental and frequently used skills in the sport of soccer. Improving the inter-segmental coordination of instep kicking is critical for achieving a high ball speed and improving the chances of scoring in soccer. Several previous studies have found that experienced soccer athletes had better control of the distal joints compared to novices [5,7,12,13]. Our recent study further revealed that compared to the novice, the experienced soccer athletes had more knee flexion dominant coordination patterns in the back swing and leg-cocking phase, and knee extension dominant patterns in the leg acceleration phase of the instep kicking movement, which contribute significantly to the increased ball speed. We also found that the experienced soccer athletes had lower co-activation of the tibialis anterior and gastrocnemius muscles, which increases the kicking accuracy. These results from previous literature specified the relationships between the inter-segmental coordination and instep kicking performance, and provided evidence for the evaluation of training effect in soccer.

The coordination training and strength training that are widely used in soccer practice may theoretically improve the inter-segmental coordination during instep kicking by improving the motor control ability of the central nervous system. The specific effect of the coordination training and strength training on the inter-segmental coordination in instep kicking, however, is unclear. Previous literature reported that although chronic soccer coordination training is beneficial to develop interlimb synchronization capabilities examined by the movement of the hand and foot under various directions and frequencies, the counter movement jump height proved to be a good predictor of the hand and foot coordinated movement in in-phase and anti-phase mode, explaining approximately 30% of the variance [14]. Another longitudinal study reported that the shuttle test with changes of direction and sprints time decreased significantly both after a short period of coordination training and strength training, but more so in the reference and coordination training groups compared to the strength training group [15]. The reasons for such multiple results from previous literatures may be related to the choice of indicators. Although the various shuttle tests with changes of direction and the hand and foot coordinated movement could provide several information about the motor control capability of the nervous system, the information about the dynamic coupling among lower extremity segments and muscles from a dynamical systems perspective of motor control in the kicking movement is still unclear.

The purpose of this study was to determine the effects of coordination training and strength training on the lower extremity inter-segmental coordination during instep kicking for novice. We hypothesized that 8 weeks of coordination training or strength training would significantly increase the time spent of knee flexion dominant coordination patterns in the back swing and leg-cocking phase, and knee extension dominant patterns in the leg acceleration phase of the instep kicking movement, and decrease the co-activation of the tibialis anterior and gastrocnemius muscles.

2. Materials and Methods

2.1. Participants

A total of 32 healthy male college students with no soccer-specific training experience and right foot dominance volunteered to participate in this study. Participants were randomly assigned to either a coordination training group, a strength training group or a kicking training group (Table 1). The use of human subjects was approved by the Institutional Review Board of Beijing Sport University. Written consent was obtained from each participant before any data collection.

Table 1. Descriptions of participants (mean ± SD).

Training group	Age (year)	Body mass (kg)	Standing height (cm)
Coordination training group (n = 12)	21.5 ± 1.7	74.0 ± 9.5	178.2 ± 7.0
Strength training group (n = 10)	21.0 ± 1.8	69.9 ± 9.5	175.3 ± 5.5
Kicking training group (n = 10)	21.7 ± 2.3	68.3 ± 9.1	177.0 ± 6.0

2.2. Procedures

Each participant had a pre-training test, eight-week coordination and kicking training, strength and kicking training, or single kicking training depending on experimental group assignment, and a post-training test to complete study. In each of the pre- and post-training tests, the participant completed an instep kicking test to collect lower extremity three-dimensional (3-D) kinematic and electromyographic (EMG) data for the dominant leg.

2.2.1. Kicking Test

A warm-up consisting of 10 minutes of running, stretching exercises for the lower limbs, and several practice kicks was conducted. A total of 19 passive reflective markers were placed bilaterally on each participant's lower extremity, including the anterior superior iliac spine (ASIS), mid-thigh, medial and lateral femoral condyles, tibial tuberosity, medial and lateral malleoli, posterior calcaneus, and first and fifth metatarsal heads. An additional marker was attached at the junction of the 4th and 5th lumbar spine vertebra (L4-5). A reflective marker was also attached to the soccer ball for estimating the time of foot-ball contact. Surface EMG electrodes were placed over the muscle belly of the rectus femoris, lateral femoris, medial femoris, semimembranosus, biceps femoris, tibialis anterior, and lateral gastrocnemius muscle of the dominant leg. A maximal voluntary contraction (MVC) was performed to collect MVC EMG data.

The markers on the medial femur condyles and malleoli were removed after a standing calibration. Each participant then performed ten successful trials for instep kicking tasks after an approach of two steps angled to 45º to the kicking direction. Kicking trials were performed against a goalpost (3 height ✕ 2 m width) located five meters from the ball. A standard sized and inflated ball was used for measurements. A one-minute rest interval between consecutive kicking trials was provided. Considering the speed and accuracy demand, the participant was instructed to kick the ball against the center of the goal as hard as possible.

The 3-D trajectories of the reflective markers were recorded using a Motion Analysis videographic data acquisition system (Raptor-4; Motion Analysis Inc., Santa Rosa, CA, USA) with 8 cameras at a sample rate of 200 frames/s. EMG data were recorded using a Delsys Trigno™ Wireless EMG acquisition system (Delsys Inc., Natick, Massachusetts, USA) at a sample rate of 2000 samples/channel/s. The videographic and EMG data collections were time synchronized using the Delsys Triger Synchronizer (Delsys Inc., Natick, Massachusetts, USA).

Two digital video cameras (GC-PX100, JVC, Tokyo, Japan) with a resolution of 1920 ✕ 1080 at a sampling frequency of 60 frames / s were used to record the 2-D coordinates of the ball trajectory and the position where the football enters the goal, respectively. One camera was set up five meters on the right side of the ball and perpendicular to the sagittal plane of the kicking movement. Another camera was set up behind the goal and parallel to the sagittal plane of the kicking movement.

2.2.2. Interventions

Participants in each experimental group had three intervention sessions per week for eight weeks, with at least 24 h between sessions. Participants in the kicking training group had 5 min of warm-up, 15 min of standardized instep kicking training drills, and 5 min of post-training cool down (Table 2). Participants in the coordination training group had 30 minutes of various forms of ladder, running, and jumping drills, while participants in the strength training group had 30 minutes of resistance training drills for the lower extremity (Table 2). Furthermore, the participants in the coordination and strength training group had the same instep kicking training drills as the kicking training group (Table 2).

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Table 2. Training exercises.

Training group		**Weeks**		
		1 - 2	**3 - 5**	**6 - 8**
Coordination training group	Exercise	(1) Forward and backward line hops (2) Lateral line hops (3) Scissors (4) Two-cone drills forward run (5) Ladder drills (One in the hole, lateral two in the hole, ickey shuffle, two in two out)	(1) Forward and backward line hops single-leg variation (2) Lateral line hops single-leg variation (3) Traveling scissors (4) Three-cone 180-degree drill (5) Ladder drills (cha-cha, carioca, Billy Sims crossover, Hopscotch)	(1) Forward and backward line hops single-leg variation across obstacles (2) Lateral line hops single-leg variation across obstacles (3) 180-degree Traveling line hop single- leg variation (4) Four-cone T drill (5) Ladder drills (Ali shuffle, Slaloms, cherry pickers, 180s)
			Instep kicking training	
	Reps and sets	(1) – (3):10 reps ✖ 2 sets, (4): 5 reps ✖ 2 sets, (5): 10 sec/drill ✖ 3 sets		
	Rest	30 s between sets, 2 min between exercise		
Strength training group	Exercise	Hip abduction, hip adduction, knee extension, knee flexion, ankle plantar flexion, ankle dorsiflexion		
			Instep kicking training	
	Reps and sets	10 reps ✖ 3 sets	10 reps ✖ 3 sets	6 → 5 → 4 → 3 → 2 reps ✖ 5 sets
	Load	50% of 1 RM	70% of 1 RM	70 → 75 → 80 → 85 → 90% of 1 RM
	Rest	60 s between sets, 3 min between exercise	60 s between sets, 3 min between exercise	90 s between sets, 3 min between exercise
Kicking training group	Exercise		Instep kicking training	

Abbreviations: reps = repetitions, RM = repetition maximum.

2.3. Data Reduction

A kicking movement cycle was defined as the duration from toe-off of the kicking leg to the contact of the kicking foot with the ball, and was divided into three phases. The back swing phase begins with the toe-off of the kicking leg and ends with maximum hip extension of the kicking leg. The leg-cocking phase begins with maximum hip extension of the kicking leg and ends with maximum knee flexion of the kicking leg. The leg acceleration phase begins with maximum knee flexion of the kicking leg and ends with contact of the kicking foot with the ball.

The raw 3-D trajectories of all but one reflective markers were filtered using a Butterworth low-pass filter at an estimated optimum frequency of 13 Hz [16]. The raw 3-D trajectories of the single marker on the ball were not filtered, as any filtering of this trajectory created ambiguity in the identification of the specific frame when ball impact occurred [17]. The pelvis, thigh, shank, and foot reference frame were defined as previously described [18]. The hip, knee, and ankle Cardan joint angles between adjacent segment reference frames were calculated in an order of flexion-extension, valgus-varus, and internal rotation [18], and were normalized and time-scaled to 100% of the kicking movement.

The vector coding method was used to quantify the hip-knee and knee-ankle coordination patterns of the kicking leg over the time course of kicking. The coupling angle (γ) for each time interval was derived as the angle from the horizontal of a vector connecting two consecutive data points on the angle-angle plot of the hip-knee and the knee-ankle motion of the kicking leg [2]:

$$\gamma_{j,i} = \tan^{-1}\left(\frac{y_{j,i+1} - y_{j,i}}{x_{j,i+1} - x_{j,i}}\right)$$

where $0^\circ \leq \gamma \leq 360^\circ$, and i is a data point of the j_{th} trial. Mean coupling angle ($\bar{\gamma}_i$) were calculated based on the average horizontal and vertical components at each instant using circular statistics due to the directional nature of coupling angle [19]. Within a subject and then across the group, $\bar{\gamma}_i$ was calculated from the mean horizontal ($\bar{x}_i$) and vertical ($\bar{y}_i$) components at each data point:

$$\bar{x}_i = \frac{1}{n}\sum_{j=1}^{n}(\cos y_{j,i})$$

$$\bar{y}_i = \frac{1}{n}\sum_{j=1}^{n}(\sin y_{j,i})$$

$$\bar{\gamma}_i = \begin{cases} \arctan(\bar{y}_i/\bar{x}_i), & if\ \bar{x}_i > 0 \\ 180 + \arctan(\bar{y}_i/\bar{x}_i), & if\ \bar{x}_i < 0 \end{cases}$$

Based on the mean coupling angle, four coordination patterns were defined (Table 3), including in-phase (rotating in the same direction), anti-phase (rotating in the opposite direction), proximal-phase (the hip is rotating dominantly in hip-knee coupling, and the knee is rotating dominantly in the knee-ankle coupling), and distal-phase (the knee is rotating dominantly in hip-knee coupling, and the ankle is rotating dominantly in the knee-ankle coupling). The time spent percentage of each coordination pattern in each kicking phase was calculated.

Table 3. Scheme used to categorize coordination patterns.

Coordination pattern	Coupling angle definitions
In-phase	22.5° ≤ γ < 67.5°，202.5° ≤ γ < 247.5°
Anti-phase	112.5° ≤ γ < 157.5°，292.5° ≤ γ < 337.5°
Proximal-phase	0° ≤ γ < 22.5°，157.5° ≤ γ < 202.5°，337.5° ≤ γ < 360°
Distal-phase	67.5° ≤ γ < 112.5°，247.5° ≤ γ < 292.5°

The raw EMG signals were filtered using a band-pass digital filter at a low-pass cutoff frequency of 800 Hz and a high-pass cutoff frequency of 10 Hz, and then rectified [20]. The band-pass filtered and rectified EMGs were filtered using a low-pass digital filter again at a cutoff frequency of 20 Hz to obtain the linear envelop EMGs [20]. The co-activation of the agonist and antagonist muscles was calculated by the ratio of the envelop EMGs of the quadriceps femoris and hamstrings, tibialis anterior and gastrocnemius muscles, respectively [3]. Average co-activation of the agonist and antagonist muscles was then calculated.

The 2-D coordinates of the ball center in the video were obtained using Fastmove 3D Motion (FastMove Inc., Dalian, China). The maximum ball speed was defined as the maximum value of the ratio of the displacement of the ball to the time between every two adjacent frames. The kicking accuracy was defined as the distance between the ball center and the goal center at the moment when the ball enters the goal, which was obtained by the video shooting.

2.4. Data Analysis

Two-way ANOVAs were performed to compare the maximal ball speed, the distance between the ball center and the goal center when the ball enters the goal, the time spent percentage of each of the hip-knee and knee-ankle coordination patterns, and the averaged co-activation of the agonist and antagonist muscles between the three groups and pre- and post-training period. Paired t-tests were performed as post-hoc tests to locate differences if no significant interaction of independent variables was detected, but significant main effects were detected. One-way ANOVAs were performed to determine the effects of each independent variable on a given dependent variable if a significant interaction effect of independent variables was detected. A Type I error rate greater than or equal to 0.050 was chosen as the indication of statistical significance.

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3. Results

No significant interaction effect of training group and time was detected on the maximum ball speed (p = 0.689). A significant main effect of training time on the maximum ball speed was detected. Paired t-tests revealed that the maximum ball speed in the three groups was significantly increased in the post-training test compared to the pre-training test. A significant interaction effect of group and time on the distance between ball center and goal center was detected (p =0.047). One-way ANOVAs revealed that the distance between ball center and goal center in the coordination training group was significantly decreased in the post-training test compared to the pre-training test.

Table 4. Comparison of maximum ball speed, and distance between the ball center and goal center between training groups and period.

Kicking performance	Time	Training group			P value
		Coordination training group (n = 12)	**Strength training group (n = 10)**	**Kicking training group (n = 10)**	
Maximum ball speed (m/s)	Pre-training	13.08 ± 2.54	13.71 ± 2.53	12.90 ± 2.19	0.873
	Post-training	15.49 ± 3.09	15.56 ± 2.00	14.37 ± 1.29	
	P value		< 0.001		
Distance between the ball center and goal center (m)	Pre-training	1.18 ± 0.29	1.02 ± 0.24	0.93 ± 0.23	0.053
	Post-training	0.83 ± 0.18	0.82 ± 0.27	0.89 ± 0.14	0.742
	P value	0.001	0.052	0.953	

No significant interaction effect of training group and time was detected on the time spent percentage of hip-knee in-phase (p = 0.106), thigh-phase (p = 0.337), and shank-phase (p = 0.309) coordination patterns in the back swing phase (Table 5). A significant main effect of training time on the time spent percentage of the hip-knee thigh-phase coordination pattern was detected. Paired t-tests revealed that the time spent percentage of hip-knee thigh-phase coordination patterns in the three groups was significantly decreased in the post-training test compared to the pre-training test. A significant main effect of group on the time spent percentage of hip-knee in-phase and shank-phase coordination patterns was detected. Paired t-tests revealed that the time spent percentage of the hip-knee in-phase coordination pattern (p = 0.013) and strength (p = 0.023) training group was significantly lower than that of the kicking training group, both in pre- and post-training tests. Paired t-tests also revealed that the time spent percentage of the hip-knee shank-phase coordination pattern of the coordination training group was significantly greater than that of the kicking training group, both in pre- and post-training tests (p = 0.013). A significant interaction effect of group and time on the time spent percentage of the hip-knee anti-phase coordination pattern in the back swing phase was detected (p = 0.008). One-way ANOVAs revealed that the time spent percentage of the hip-knee anti-phase coordination pattern in the coordination training group was significantly increased in the post-training test compared to the pre-training test.

No significant interaction effect of training group and time was detected on the time spent percentage of each knee-ankle coordination pattern in the back swing phase (p > 0.113, Table 5). A significant main effect of training time on the time spent percentage of knee-ankle in-phase coordination pattern was detected. Paired t-tests revealed that the time spent percentage of the knee-ankle in-phase coordination pattern in all groups was significantly increased in the post-training test compared to the pre-training test.

Table 5. Comparison of the time spent percentage of each coordination patterns in the back swing phase between training groups and time.

Segment	Patterns	Time	Training group			P value
			Coordination training group (n = 12)	Strength training group (n = 10)	Kicking training group (n = 10)	
Hip-knee	In-phase	Pre-training	38.0 ± 17.2^B	30.0 ± 15.0^B	44.0 ± 18.2^A	0.025
		Post-training	29.7 ±18.6^B	39.2 ± 21.8^B	54.0 ± 12.7^A	
		P value		0.368		
	Anti-phase	Pre-training	4.4 ± 2.6	7.9 ± 5.3	7.3 ± 5.8	0.186
		Post-training	10.9 ± 5.2	8.2 ± 7.4	8.4 ± 4.8	0.501
		P value	< 0.001	0.883	0.443	
	Thigh-phase	Pre-training	8.5 ± 6.1	13.6 ± 9.0	9.8 ± 5.8	0.323
		Post-training	6.7 ± 4.9	7.2 ± 2.5	8.1 ± 5.1	
		P value		0.031		
	Shank-phase	Pre-training	49.1 ± 21.5^B	48.6 ± 16.8	38.9 ± 17.9	0.041
		Post-training	52.7 ± 19.5^B	41.1 ± 20.1	29.4 ± 10.7	
		P value		0.252		
Knee-ankle	In-phase	Pre-training	24.9 ± 17.9	22.7 ± 15.9	37.3 ± 20.2	0.079
		Post-training	28.9 ± 16.7	40.0 ± 15.8	46.3 ± 23.1	
		P value		0.012		
	Anti-phase	Pre-training	3.9 ± 4.2	8.2 ± 9.0	6.7 ± 6.7	0.419
		Post-training	6.6 ± 4.4	7.6 ± 10.1	4.9 ± 3.9	
		P value		0.091		
	Shank-phase	Pre-training	57.8 ± 21.9	40.4 ± 26.0	39.1 ± 21.7	0.099
		Post-training	46.0 ± 24.0	32.7 ± 11.7	36.2 ± 22.6	
		P value		0.097		
	Foot-phase	Pre-training	13.4 ± 10.4	28.6 ± 23.5	17.0 ± 12.7	0.189
		Post-training	18.5 ± 21.0	19.8 ± 8.6	12.6 ± 7.3	
		P value		0.405		

[A] Indicates statistical significance compared to the strength training group. [B] Indicates statistical significance compared to the kicking training group.

No significant interaction effect of training group and time was detected on the time spent percentage of each hip-knee coordination pattern in the leg-cocking phase ($p > 0.327$, Table 6). A significant main effect of training time on the time spent percentage of the hip-knee in-phase coordination pattern was detected. Paired t-tests revealed that the time spent percentage of the hip-knee in-phase coordination pattern in the three groups was significantly decreased in the post-training test compared to the pre-training test.

No significant interaction effect of training group and time was detected on the time spent percentage of each knee-ankle coordination pattern in the leg-cocking phase ($p > 0.197$, Table 6). A significant main effect of training time on the time spent percentage of the knee-ankle anti-phase and shank-phase coordination pattern was detected. Paired t-tests revealed that the time spent percentage of knee-ankle anti-phase coordination pattern in the three groups was significantly decreased in the post-training test compared to the pre-training test, while the time spent percentage of knee-ankle shank-phase coordination pattern in the three groups was significantly increased in the post-training test compared to the pre-training test.

Table 6. Comparison of the time spent percentage of each coordination pattern in the leg-cocking phase between training groups and time.

Segment	Patterns	Time	Training group			P value
			Coordination training group (n = 12)	Strength training group (n = 10)	Kicking training group (n = 10)	
Hip-knee	In-phase	Pre-training	0.5 ± 1.4	1.3 ± 1.3	1.1 ± 2.4	0.584
		Post-training	0.1 ± 0.5	0.1 ± 0.3	0.0 ± 0.1	
		P value		0.009		
	Anti-phase	Pre-training	48.0 ± 12.2	45.9 ± 10.4	47.1 ± 10.0	0.450
		Post-training	51.3 ± 12.9	46.4 ± 15.4	41.7 ± 9.4	
		P value		0.822		
	Thigh-phase	Pre-training	18.1 ± 4.4	15.9 ± 8.0	14.3 ± 3.7	0.118
		Post-training	17.5 ± 3.0	15.6 ± 3.7	15.5 ± 3.1	
		P value		0.934		
	Shank-phase	Pre-training	33.4 ± 12.9	36.9 ± 14.1	37.5 ± 10.2	0.255
		Post-training	31.1 ± 14.1	35.6 ± 16.9	42.8 ± 7.2	
		P value		0.822		
Knee-ankle	In-phase	Pre-training	6.7 ± 4.6	7.0 ± 5.8	7.5 ± 8.0	0.930
		Post-training	4.4 ± 7.7	4.9 ± 6.0	3.1 ± 2.0	
		P value		0.071		
	Anti-phase	Pre-training	33.0 ± 21.3	41.1 ± 17.7	32.7 ± 18.6	0.485
		Post-training	32.7 ± 24.0	29.1±12.6	20.9 ± 15.6	
		P value		0.039		
	Shank-phase	Pre-training	51.4 ± 24.0	42.2 ± 19.1	53.1 ± 19.8	0.371
		Post-training	54.0 ± 27.1	58.1 ± 15.3	69.9 ± 18.1	
		P value		0.003		
	Foot-phase	Pre-training	8.9 ± 4.0	9.6 ± 5.3	6.6 ± 2.8	0.235
		Post-training	8.9 ± 4.8	7.9 ± 3.9	6.1 ± 4.0	
		P value		0.277		

No significant interaction effect of training group and time was detected on the time spent percentage of each hip-knee and knee-ankle coordination patterns in the leg acceleration phase ($p > 0.138$, Table 7). No significant main effects of group and time were detected on the time spent percentage of each hip-knee and knee-ankle coordination pattern (Table 7).

Table 7. Comparison of the time spent percentage of each coordination pattern in the leg acceleration phase between training groups and time.

Segment	Patterns	Time	Training group			P value
			Coordination training group (n = 12)	Strength training group (n = 10)	Kicking training group (n = 10)	
Hip-knee	In-phase	Pre-training	39.5 ± 13.0	38.7 ± 10.2	37.9 ± 14.3	0.813
		Post-training	39.2 ± 8.7	36.7 ± 17.1	35.0 ± 11.2	
		P value		0.491		
	Anti-phase	Pre-training	0.0 ± 0.0	0.1 ± 0.4	0.5 ± 1.2	0.463
		Post-training	0.0 ± 0.0	1.0 ± 3.2	0.0 ± 0.0	
		P value		0.690		
	Thigh-phase	Pre-training	8.4 ± 7.4	6.2 ± 4.5	4.3 ± 3.1	0.113
		Post-training	6.9 ± 3.1	4.6 ± 3.3	5.3 ± 2.4	
		P value		0.526		
	Shank-phase	Pre-training	52.2 ± 16.9	55.1 ± 13.4	57.3 ± 17.0	0.570
		Post-training	53.9 ± 10.3	57.7 ± 18.1	59.7 ± 12.4	
		P value		0.465		
Knee-ankle	In-phase	Pre-training	17.4 ± 11.5	16.6 ± 12.2	20.6 ± 13.2	0.701
		Post-training	22.8 ± 12.5	19.4 ± 11.0	23.0 ± 12.6	
		P value		0.164		
	Anti-phase	Pre-training	6.3 ± 5.7	7.1 ± 12.5	11.9 ± 7.6	0.202
		Post-training	9.0 ± 11.6	18.8 ± 12.7	13.3 ± 11.8	

	P value		0.051		
Shank-phase	Pre-training	69.1 ± 21.9	74.6 ± 20.1	67.2 ± 13.2	0.850
	Post-training	67.4 ± 16.2	61.4 ± 13.7	63.6 ± 16.8	
	P value		0.162		
Foot-phase	Pre-training	1.2 ± 3.3	1.7 ± 3.4	0.3 ± 0.4	0.335
	Post-training	0.8 ± 1.5	0.4 ± 1.3	0.2 ± 0.3	
	P value		0.291		

No significant interaction effect of training group and time was detected on the co-activation of the quadriceps femoris and hamstrings in the kicking movement (p = 0.545, Table 8). No significant main effects of group and time were detected on the co-activation of the quadriceps femoris and hamstrings (Table 8). A significant interaction effect of group and time on the co-activation of the tibialis anterior and gastrocnemius in the kicking movement was detected (p = 0.047, Table 8). One-way ANOVAs revealed that the co-activation of the tibialis anterior and gastrocnemius in the coordination training group was significantly decreased in the post-training test compared to the pre-training test. Paired t-tests revealed that there was no significant difference of the co-activation of the tibialis anterior and gastrocnemius between the three groups in the pre-training test, but the co-activation of the tibialis anterior and gastrocnemius of the coordination training group (p = 0.006) and strength training group (p = 0.021) was significantly lower than that of the kicking training group in the post-training test (Table 8).

Table 8. Comparison of the average co-activation of the agonist and antagonist muscles in the kicking movement between training groups and time.

Muscles	Time	Training group			P value
		Coordination training group (n = 12)	Strength training group (n = 10)	Kicking training group (n = 10)	
Quadriceps femoris - hamstrings	Pre-training	4.63 ± 3.65	7.71 ± 6.45	5.81 ± 6.20	0.743
	Post-training	4.17 ± 3.04	3.52 ± 4.59	4.39 ± 3.36	
	P value		0.142		
Tibialis anterior - gastrocnemius	Pre-training	2.75 ± 1.49	1.81 ± 1.44	2.72 ± 1.25	0.333
	Post-training	2.00 ± 0.98[B]	2.15 ± 0.92[B]	4.36 ± 2.83[A]	0.013
	P value	0.024	0.747	0.207	

[A] Indicates statistical significance compared to the strength training group. [B] Indicates statistical significance compared to the kicking training group.

4. Discussion

The results of this study partially support our hypothesis that 8 weeks of coordination training or strength training would significantly increase the time spent of knee flexion dominant coordination patterns in the back swing and leg-cocking phase, and knee extension dominant patterns in the leg acceleration phase of the instep kicking movement, and decrease the co-activation of the tibialis anterior and gastrocnemius muscles. The results showed that in the back swing phase of the kicking movement, the time spent percentages of hip-knee thigh-phase coordination pattern were significantly decreased. While in the leg-cocking phase of the kicking movement, the time spent percentages of the hip-knee in-phase coordination pattern and knee-ankle anti-phase were significantly decreased, but the time spent percentage of the knee-ankle shank-phase was significantly increased after the eight weeks of single kicking training, or kicking training combined with coordination training or strength training. Further, the time spent percentages of each of the hip-knee and knee-ankle coordination patterns in the leg acceleration phase were not significantly changed after the eight weeks of training. Our recent study demonstrated that compared with the novice, the experienced athletes achieved a higher maximum ball speed and had less hip-knee thigh-phase coordination patterns in the back swing phase, as well as less hip-knee in-phase, knee-ankle anti-phase, and more knee-ankle shank-phase coordination patterns in the leg-cocking phase during the kicking movement. Our recent study also demonstrated that the maximum ball speed was

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significantly negatively correlated with the time spent percentage of hip-knee thigh-phase coordination patterns in the back swing and knee-ankle anti-phase coordination patterns in the leg-cocking phase of the kicking movement. These results taken together indicated that the lower extremity inter-segmental coordination of the kicking leg was significantly improved after eight weeks of single kicking training, or kicking training combined with coordination training or strength training. Specifically, these results indicated that regardless of the training programs used, more knee flexion dominant coordination patterns in the back swing and leg-cocking phase were involved, but no more knee extension dominant coordination patterns in the leg acceleration phase were involved after training.

The results of the present study were consistent with the literature. Previous study had shown that there was an increasement in the knee flexion prior to the hip flexion after 10 weeks of instep kicking practice for novice, and this flexion continued to occur as the hip was flexed forward [5], suggesting a reduced dynamic involvement of the proximal segment (hip) but with increased involvement of the distal segments (knee) after instep kicking practice [5,7]. These findings lend some support to Bernstein's ideas on the acquisition of skilled behaviour [1]. Bernstein originally argued that the acquisition of skill progresses from a reorganization of motor system degrees of freedom and suggested that a learner initially demonstrates rigid and awkward coordination modes, subsequently known as freezing joint motions, to cope with the abundance of motor system degrees of freedom [1]. As control over degrees of freedom is gained, joint motion is gradually released or freed [1]. The results of this study, combined with the results of previous studies, indicated that the knee joint was given greater freedom of movement as the freezing constraints were lifted after a period of training, and a coordinative structure that enabled the knee joint to take greater advantage of the flexion movement in the back swing and leg-cocking phase of the kicking movement developed. The greater freedom of movement for the knee flexion further contributed to increasing the knee extension torque before foot-ball contact and the final ball speed by stretching the knee extensor muscles at the beginning of the kicking movement [6,21].

Although the lower extremity inter-segmental coordination was improved after the eight weeks of single kicking training, or kicking training combined with coordination training or strength training, the results of the present study indicated that the coordination training had more positive effects on the improvement of inter-segmental coordination during instep kicking. On the one hand, the results showed that only after the coordination training did the distance between the ball center and the goal center when the ball enters the goal decrease, which means that the kicking accuracy improved. The results also showed that only after the coordination training did the co-activation of the tibialis anterior and gastrocnemius muscles decrease. Our recent study demonstrated that the co-activation of the tibialis anterior and gastrocnemius muscles of experienced athletes was significantly lower than that of novices during the instep kicking movement. We also found that the lower co-activation of the tibialis anterior and gastrocnemius muscles, the better the kicking accuracy. The coordination training programs used in this study primarily incorporated the ladder drills, complemented by the directional running and jumping exercise. The ladder drills could enhance the dynamic coupling among lower extremity muscles by alerting the foot speed and direction rapidly across multiple planes, which was one of the most important aspects for faster and more accurate shooting during the instep kicking movement [22]. These results taken together indicated that the coordination training used in the present study increased the kicking accuracy by improving the coordinated activation of lower extremity muscles.

On the other hand, the results showed that only after the coordination training did the time spent percentage of the hip-knee anti-phase coordination pattern in the back swing phase increase. This was supported by the results of our recent study that demonstrated a greater time spent percentage of hip-knee anti-phase coordination pattern in the back swing phase for the experienced soccer athletes compared to the novices. Similar to the theory of Bernstein, studies of inter-limb coordination during oscillating on a ski simulator [23], volley ball serve [24], or swimming [9] showed that beginners freeze the degrees of freedom while experts release the degrees of freedom not useful to

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the task. Freezing the degrees of freedom is mostly related to a basic coordination mode, like in-phase [25], while releasing the degrees of freedom corresponds to the anti-phase coordination mode [9,23,24]. Another previous study indicated that the in-phase coordination pattern in the human movement emerges spontaneously without requiring additional neural input from the brain, whereas the anti-phase coordination pattern necessitates more direct and deliberate neural control [26]. Therefore, the findings of this study suggested that coordinated training may improve the neuromuscular and motor control functions of the nervous system during the instep kicking movement more effectively.

The strength training did not have an additional effect on the improvement of inter-segmental coordination compared with the single kicking training or kicking training combined with coordination training in the present study. One possible explanation for the lack of effect is that our strength intervention was not long enough in duration to induce the altered co-activation pattern of the lower extremity muscles. It has been suggested that kicking performance was achieved through an altered co-activation pattern after strength training [27]. The participants in the strength training group might still have been in an early stage of training, and their increase in the maximum ball speed might be mainly due to increased muscle strength without significantly altered muscle co-activation. Another likely explanation is that the type of strength training programs used in this study was resistance training consisting of low-intensity and multiple repetitions exercises, which may be less effective in altering the muscle co-activation compared to the explosive muscle strength training programs. Further studies are needed to determine the effect of the explosive muscle strength training on the inter-segmental coordination of instep kicking.

Although the current study evaluated the immediate effects of eight weeks of coordination training and strength training on the lower extremity inter-segmental coordination of instep kicking, further investigations are needed to confirm the effects of different training periods on the inter-segmental coordination to understand the learning and development of motor skills from the perspective of motor control. Also, the coordination training program selected in this study mainly focuses on the common ladder training, supplemented by a mixed training program of various directional running and jumping movements. Additional studies are needed to evaluate the effect of separate ladder training, directional running training, jumping training, and other various coordination training programs, such as soccer game training, etc, on the inter-segmental coordination of instep kicking.

5. Conclusions

Maximum ball speed and lower extremity inter-segmental coordination were significantly improved after the eight weeks of single kicking training, or kicking training combined with coordination training or strength training. Specifically, more knee flexion dominant coordination patterns in the back swing and leg-cocking phase were involved, but no more knee extension dominant coordination patterns in the leg acceleration phase were involved after training. Coordination training programs in this study resulted in significant increases in kicking accuracy, and a decrease in the co-activation of the tibialis anterior and gastrocnemius muscles. Strength training programs did not have an additional effect on the improvement of inter-segmental coordination compared with the single kicking training or kicking training combined with coordination training in this study. The coordination training may improve the neuromuscular and motor control functions of the nervous system during the instep kicking movement more effectively.

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