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Original Article

Gait modification strategies of trunk over left stance phase in patients with right anterior cruciate ligament deficiency

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Abstract: Purpose: To investigate the gait modification strategies of trunk over left stance phase in patients with right anterior cruciate ligament deficiency (ACL-D). Methods: Thirty-six patients with right ACL-D and thirty-six health subjects (control) were recruited to undergo a 3-dimensional (3D) gait analysis. Coordinate data from 26 reflective markers positioned on the body surface of participants were recorded with a 3D optical video motion capture system, as they walked on the ground, ascended and descended a custom-built staircase. Angle changes in the 3-planes under different walking conditions were analyzed. Results: There were statistically significant differences between the two groups in the trunk at the transverse plane angle in most measurements. With the walk pattern of stair descent, the trunk at all 3-plane angles, at the maximum value of the left knee sagittal/coronal/transverse plane moment, was significantly different between the two groups ($P \leq 0.03$). Conclusions: Our findings suggested that special gait modification of trunk is apparent over stance of left (healthy) side in patients with right ACL-D. The results of this study may supply more insight with respect to improving the diagnosis and rehabilitation of ACL-D. This information may also be helpful for a better use of walk and stair tasks as part of a rehabilitation program and provide a safe guideline for the patients.

Keywords: Anterior cruciate ligament injury, trunk, kinematics, gait modification strategy

Introduction

Anterior cruciate ligament (ACL) in the knee is a frequently injured ligament [1]. More than 70% of these injuries have been reported to be non-contact in nature [2].

Sports-related injuries lead to knee instability as a result of increased anterior tibial translation and anterolateral rotation. Such injury does not recover completely without surgical ACL reconstruction (ACL-R) and rehabilitation therapy [3-5]. ACL-R is a primary treatment for an ACL injury and allows the knee joint to return to a range of highly-energitic physical activities including sports. However, the surgical reconstruction is common to prone to further knee degeneration and early osteoarthritis (OA), and the progression to early articular cartilage degeneration and osteoarthritis is almost inevitable [6, 7], as reported that degeneration of the articular cartilage is also observed as early as 15 months after ACL-R surgery [8]. It has been reported that knee osteoarthritis occurs between 5 and 12 years after reconstruction [9].

Gait, like walking, running and jumping, includes a coordinative movement and equilibrium of muscles and joints. Any injury of muscle and joints leads to a discordant gait [10]. Therefore, gait analysis reflects the health and pathological features of muscles and joints. 3-D gait analysis technology records the walk movement on the basis of mechanics, anatomy and physiology [11] to reflect the coordination changes of injury on knees, hip joints, pelvises and trunk and to assess the rehabilitation and treatment effectiveness when disease or injury occurs.

Table 1. Basic characteristics of the participants in the two groups

	ACL-D group (*n* = 36)	Control group (*n* = 36)	*P*
Age (years)	28.0 ± 3.7	27.8 ± 3.7	0.78
Height (m)	1.74 ± 0.05	1.73 ± 0.04	0.58
Weight (kg)	68.7 ± 6.9	68.3 ± 6.6	0.84
Q Angle of left lower extremity (°)	11.8 ± 1.9	11.1 ± 1.4	0.27
Q Angle of right lower extremity (°)	11.8 ± 1.9	11.1 ± 1.4	0.27

Gait analysis includes time-distance, kinematics and dynamics parameters. Previous studies focused on changes of gait in the sagittal plane [12] and fully analyzed the kinematics and dynamics change of 6 degrees-of-freedom at the sagittal, coronal and transverse planes using 3-D gait analysis technology [13]. In the current study, kinematics and dynamics parameters of stance phase were observed as analyses of the biomechanical features of the lower extremities in five walk patterns (walking, from walking to stair ascent, stair ascent, stair descent and from stair descent to walking) at 3-planes between right ACL-D patients and healthy subjects. The purpose of the study was to investigate the gait modification of the trunk over the left stance phase after right ACL-D.

Materials and methods

Participant's selection and walking pattern

From Sept. 2009 to Dec. 2010, 36 right ACL-D patients (ACL-D group) were recruited from Departments of Sport Medicine and Rehabilitation Medicine of the East Hospital affiliated to Tongji University, Department of Orthopedics of Shanghai 6th People's Hospital affiliated to Shanghai Jiaotong University and Department of Orthopedics of Zhongshan Hospital affiliated to Fudan University. Meantime, 36 healthy individuals (Control group) were volunteers of postgraduate students from Tongji University and Shanghai Jiaotong University (Shanghai, China). The age, height, weight and Q angles of all participants in the two groups were matched as closely as possible (**Table 1**). The time that all the patients received gait analysis was 24.8 months averagely (from 22 months to 26 months) after they were diagnosed ACL-D.

General inclusion criteria were male gender [14], age (19-35 years old), right-handedness, 10° ≤ Q angle ≤ 15°. General exclusion criteria were metabolic bone diseases, inflammatory joint diseases, or other diseases contraindicating walking, climbing stairs and walking down stairs; other sensory, neuromuscular and skeletal diseases, injuries or impairments that could affect gait. Particular inclusion criteria for the ACL-D group were diagnosis of right knee ACL-D according to injury history, clinical features and MRI with or without arthroscopy or positive findings of ACL-R; posterior cruciate ligament injury or side ligament injury, meniscus injury, knee effusion, articular cartilage injury and fracture were excluded; the visual analogue scale (VAS) for knee pain had to be between 0-30 and the disease course from ACL-D to gait analysis ≥ 6 months.

Particular inclusion criteria for the control group were: no injury history; no abnormalities in clinical physical examination; no musculoskeletal disease and injury; and no other histories that could affect gait and stability of knees in clinical physical examination. All participants received a written notification and detailed descriptions of the experiments as well as acceptable answers to all questions. They submitted their written consent to participate in the study, which was approved by the Medicine and Life Science Ethic Committee of the Tongji University.

The two groups were those with ruptures of the right anterior cruciate ligament and the control group. The five walk patterns included walking on the ground, walking to stairs, stair ascent, stair descent, and stair descent to walking on ground, respectively.

Data collection instruments

This study was conducted at the gait analysis laboratory of Yueyang Hospital of Integrated Traditional Chinese and Western Medicine, Shanghai University of Traditional Chinese Medicine. (1) The infrared 3-D gait analysis system (Motion Analysis Corp., Santa Rosa, CA) consists of reflective marker balls (Diameter: 10 mm), 6 infrared digital cameras (Eagle Digital Camera, Sampling frequency: 60 Hz), an Eagle workstation and video processor, a high-performance computer host, an information conversion controller and the moving image collection software EvaRT4.2 (which recognizes the reflective markers). Cameras were located

Figure 1. Photograph of the force plates and stairs.

on 10 m × 6 m walls of the gait analysis laboratory at a mean height of 2.2 m from the floor. The direction of the cameras could be adjusted to the left, right, up and down, with a visual angle > 56° and a resolution > 1/60,000 (FOV). (2) Two force plates (AMTI®, Advanced Mechanical Technology Inc., Watertown, MA) were placed under an anti-skid carpet on the floor. The size of each force plate was 60 cm × 60 cm, with output data sampled at a frequency of 1,000 Hz and an output voltage of 10 mV. The distance from the start line to the first force plate was 3.3 m and the distance from the second force plate to the end line was 3 m. (**Figure 1**). (3) The wooden staircases without banister was composed of two parts: the first step (40 cm × 40 cm × 17 cm) being placed on the second force plate and the second step (100 cm × 90 cm × 34 cm) without a force plate below as previously reported [15, 16].

Reflective markers (a total of 26) were positioned on the 2nd sacrum spinous process, the 1st thoracic vertebra spinous process and bilateral to the acromion, humeral ectocondyle, styloid process of the ulna, anterior superior iliac spine, 1/3 juncture at middle and lower lateral side of the thigh, lateral condyle of the femur, medial condyle of the femur, 1/3 juncture at middle and lower lateral leg, prominence of the medial malleolus, prominence of the lateral malleolus, calcaneal tuberosity and the 2nd metatarsal head. To choose a comfortable walking speed, the subjects started walking from the start line 3.3 m away from the force plate and completed walking, stair ascent and descent at their own pace and this activity was repeated 16 times before formal test. When each subject was accustomed to the reflective markers and barefoot walking, their walking pattern was regarded as a random walk speed pattern [17] and the formal test was completed at this velocity (**Figure 2**).

Figure 2. Photograph of the distribution of the 26 reflective markers on the body surface of participants.

Movements and data collection

All studies were conducted by 2 researchers with 3 years' experience; one was responsible for calibrating the 3-D motion analysis system, positioning reflective markers and guiding the completion of the test on each participant; the other operated the computer and oversaw the collection of data. The participants were informed about the test process as well as the movement requirements. Three sequences of a gait cycle (**Table 2**) were tested in the gait analysis; they were a walking on floor (including number 1 only), a stair ascent (including number 2 and 3) and a stair descent (including number 4 and 5) [18-20]. It should be noted that each participant did the test in bare feet [21].

First, static images were collected when a participant stood still for 5 s and a standing erect position were determined. Then, 4 bilateral markers on the knees and medial ankle joints were removed. From the starting line, the participants completed the walking, stair ascent and stair descent at their own comfortable rate. The motion analysis system synchronously collected kinematics data and data from the force plate in real-time. Each type of gait cycle was repeated 3 times and averagely calculated.

Data analysis

Motion Analyser (ORTH TRAK. VA-OT624, Motion Analysis Corp., Santa Rosa, CA) was used for the data processing. In order to reduce background noise, a low pass filter was applied to the 3-D kinematics and dynamics data, with a cutoff frequency of 18 Hz [22, 23]. The joint center was defined by the static data. The joint angle was calculated using a multi-segment model [9]. The 3-D angle of the transverse plane, sagittal plane and the coronal plane that

Table 2. Sequences of movement force plate below

Number	Type of walking motion	1^{st} step	2^{nd} step
1	Walking	Left foot stepping on the first force plate	Right foot stepping on the second force plate
2	Stair ascent	Left foot stepping on the first force plate	Right foot stepping on the first stair, with the second force plate below
3	Stair ascent	Right foot stepping on the first force plate	Left foot stepping on the first stair, with the second force plate below
4	Stair descent	Right foot stepping on the first stair, with the second force plate below	Left foot stepping on the first force plate
5	Stair descent	Left foot stepping on the first stair with the second	Right foot stepping on the first force plate

Table 3. The correspondence of values of the different trunk plane angles to the trunk movement

	Positive	Negative
Value of trunk sagittal plane angle	anterior lean	posterior lean
Value of trunk coronal plane angle	laterior flexion to the left (the right shoulder up)	laterior flexion to the right rightleft (the right shoulder down)
Value of trunk transverse plane angle	anterior rotation (shoulder forward)	posterior rotation (shoulder trailing)

Table 4. The minimum and maximum value of the trunk at a sagittal plane angle over the left stance phase ($\overline{x}$ ± SD)

	Min			Max		
	ACL-D group (*n* = 36)	Control group (*n* = 36)	*P*	ACL-D group (*n* = 36)	Control group (*n* = 36)	*P*
Level walk	-3.68 ± 0.07	-3.42 ± 0.03	0.64	-0.84 ± 0.3	-0.86 ± 0.5	0.97
From level walk to stairs ascent	-2.73 ± 0.02	-1.40 ± 0.01	0.03	5.28 ± 0.5	4.76 ± 0.6	0.52
Stairs ascent	2.83 ± 0.03	2.78 ± 0.05	0.95	8.37 ± 0.7	7.46 ± 0.8	0.39
Stairs descent	-7.25 ± 0.08	-6.01 ± 0.04	0.08	-1.17 ± 0.6	-1.25 ± 0.4	0.92
From Stairs descent to Level Walk	-6.68 ± 0.09	-5.94 ± 0.07	0.29	-1.05 ± 0.5	-1.06 ± 0.5	0.98
F value for interaction			2.5			0.6
P value for interaction			0.08			0.51
F value for main effect			1.7			0.2
P value for main effect			0.2			0.63

Table 5. The minimum and maximum value of trunk at coronal plane angle over left stance phase ($\overline{x}$ ± SD)

	Minimum			Maximum		
	ACL-D group (*n* = 36)	Control group (*n* = 36)	*P*	ACL-D group (*n* = 36)	Control group (*n* = 36)	*P*
Level walk	-0.47 ± 0.2	-0.51 ± 0.2	0.90	1.52 ± 0.12	1.84 ± 0.08	0.25
From level walk to stairs ascent	0.02 ± 0.3	-0.25 ± 0.4	0.58	3.66 ± 0.13	3.24 ± 0.12	0.18
Stairs ascent	-2.14 ± 0.4	-1.96 ± 0.3	0.69	1.98 ± 0.12	1.12 ± 0.12	0.09
Stairs descent	-0.48 ± 0.3	0.03 ± 0.2	0.20	3.26 ± 0.12	3.07 ± 0.11	0.53
From stairs descent to level walk	-0.23 ± 0.3	-0.16 ± 0.3	0.86	4.19 ± 0.13	3.39 ± 0.11	0.01
F value for interaction			1.40			4.3
P value for interaction			0.23			0.01
F value for main effect			0.10			1.9
P value for main effect			0.79			0.17

support the trunk were studied via the relative position of the joints. Anatomically standing erect position was regarded as the benchmark for all angles (0°).

We defined the procedure of all kinematics and dynamics data in a single (100%) gait cycle. For walking on the floor, the left heel landing was defined as 0%, and the same foot landing again as 100%. For stair ascent, the start was defined from the foot made contact with the first force plate on the ground and ended when the contralateral foot lifted from the first stair with the second force plate below. For stair descent, measurements began when the foot stepped on the first stair with the second force plate below and ended with the contralateral foot lifting from the first force plate on the ground. In order to facilitate the comparison with walking, the cycle of ascending and descending stairs was divided into stance and swing phases. The ground reaction from the force plate was used as the marker for determining the node of gait cycle (foot landing and foot lifting). Because the stair had only two steps, it was difficult to collect the data of a complete gait cycle at one

Table 6. The minimum and maximum value of the trunk at a level plane angle over the left stance phase ($\bar{x}$ ± SD)

	Minimum			Maximum		
	ACL-D group (*n* = 36)	Control group (*n* = 36)	*P*	ACL-D group (*n* = 36)	Control group (*n* = 36)	*P*
Level walk	-2.08 ± 0.15	-5.40 ± 0.13	0.00	4.83 ± 0.16	1.36 ± 0.15	0.00
From level walk to stairs ascent	-32.81 ± 1.0	-38.77 ± 0.6	0.00	-25.85 ± 0.18	-33.77 ± 0.13	0.00
Stairs ascent	-36.21 ± 1.0	-41.71 ± 0.9	0.00	-26.42 ± 0.19	-34.46 ± 0.15	0.00
Stairs descent	-39.34 ± 0.9	-41.71 ± 1.3	0.14	-30.08 ± 1.0	-33.94 ± 0.12	0.01
From stairs descent to level walk	-40.57 ± 1.0	-45.12 ± 0.7	0.00	-32.56 ± 1.0	-39.05 ± 0.11	0.00
F value for interaction			3.8			8.1
P value for interaction			0.02			0.00
F value for main effect			17.3			37.4
P value for main effect			0.00			0.00

Table 7. Trunk at the sagittal plane angle at a minimum and maximun value of the left knee sagittal plane moment over the left stance phase ($\bar{x}$ ± SD)

	Minimum			Maximum		
	ACL-D group (*n* = 36)	Control group (*n* = 36)	*P*	ACL-D group *(n = 36)*	Control group *(n = 36)*	*P*
Level Walk	-1.49 ± 0.3	-1.49 ± 0.4	1.00	-2.58 ± 0.27	-2.27 ± 0.25	0.51
From Level Walk to Stairs Ascent	2.95 ± 0.5	2.01 ± 0.6	0.24	1.73 ± 0.18	1.76 ± 0.17	0.92
Stairs Ascent	6.76 ± 0.5	5.91 ± 0.6	0.31	5.66 ± 0.37	5.98 ± 0.28	0.71
Stairs Descent	-3.46 ± 0.7	-3.69 ± 0.5	0.79	-5.60 ± 0.36	-3.74 ± 0.25	0.03
From Stairs descent to Level Walk	-4.78 ± 0.7	-4.95 ± 0.5	0.85	-4.48 ± 0.15	-4.09 ± 0.13	0.52
F Value for Interaction			0.6			1.5
P Value for Interaction			0.60			0.21
F Value for Main Effect			0.5			1.0
P Value for Main Effect			0.48			0.31

time. In order to solve this problem, the participants were required to start the test with the left and the right foot respectively, to obtain the complete stance and swing phase of both lower extremities.

Indicators for gait analysis were: the maximum and minimum value of the 3-D angles of the trunk; the 3-D angles of the trunk at the start time; the minimum value time; the maximum value time and the end time of the knee moment.

Statistical analysis

The average value of 3 repeated tests was used to calculate the mean ± SD. SPSS Version 17.0 (SPSS Inc., Chicago, IL) was used to look for patterns in repeated measurements using analysis of variance. T test was used for comparison between two groups, and one-way ANOVA for comparison among multiple groups. $P < 0.05$ was considered to be statistically significant ($\alpha = 0.05$). First of all, the interaction between the observation group factor and walk pattern factor was investigated. If a spherical symmetry assumption was accepted at $P > 0.05$, an assumed sphericity result was used. If the spherical symmetry assumption was refused ($P < 0.05$), the calibration result of Greenhouse-Geisser was used. Afterwards, the main effect differences of gait characteristics of walking pattern between two groups were observed to determine whether they were significantly different statistically. If there was no interaction ($P > 0.05$), the indicator was significant; if there was interaction ($P < 0.05$), the indicator was insignificant. Finally, the differences of gait characteristics of normal walk in the two groups were observed.

Results

The definition of values of the different trunk plane angles to the corresponding trunk movement was manifested in **Table 3**.

Table 8. Trunk at a coronal plane angle at minimum and maximum values of the left knee coronal plane moment over the left stance phase ($\bar{x}$ ± SD)

	Minimum			Maximum		
	ACL-D group (*n* = 36)	Control group (*n* = 36)	*P*	ACL-D group (*n* = 36)	Control group (*n* = 36)	*P*
Level walk	0.82 ± 0.05	1.24 ± 0.09	0.14	0.26 ± 0.05	0.38 ± 0.06	0.66
From level walk to stairs ascent	2.44 ± 0.05	2.07 ± 0.07	0.45	1.69 ± 0.03	1.46 ± 0.01	0.42
Stairs ascent	0.70 ± 0.03	0.11 ± 0.01	0.18	-1.11 ± 0.04	-0.66 ± 0.05	0.34
Stairs descent	0.68 ± 0.03	1.24 ± 0.06	0.19	-0.50 ± 0.06	-2.77 ± 0.04	0.00
From stairs descent to level walk	1.28 ± 0.09	0.87 ± 0.02	0.26	3.07 ± 0.08	2.38 ± 0.03	0.07
F value for interaction			2.8			7.8
P value for interaction			0.04			0.00
F value for main effect			0.1			3.2
P value for main effect			0.79			0.08

Table 9. Trunk at a level plane angle at the minimum and maximum values of the left knee level plane moment over the left stance phase ($\bar{x}$ ± SD)

	Minimum			Maximum		
	ACL-D group (*n* = 36)	Control group (*n* = 36)	*P*	ACL-D group (*n* = 36)	Control group (*n* = 36)	*P*
Level walk	2.89 ± 0.52	-0.51 ± 0.08	0.00	-0.58 ± 0.02	-3.92 ± 0.7	0.00
From level walk to stairs ascent	-30.90 ± 1.0	-36.64 ± 0.7	0.00	-25.28 ± 0.9	-35.31 ± 0.7	0.00
Stairs ascent	-28.52 ± 1.1	-36.48 ± 1.0	0.00	-32.15 ± 1.0	-38.01 ± 0.9	0.00
Stairs descent	-35.64 ± 0.9	-41.33 ± 0.8	0.00	-34.96 ± 0.9	-38.95 ± 0.9	0.00
From stairs descent to level walk	-36.59 ± 1.1	-42.01 ± 0.6	0.00	-34.13 ± 0.9	-41.15 ± 0.8	0.00
F value for interaction			4.8			7.5
P value for interaction			0.00			0.00
F value for main effect			28.8			34.3
P value for main effect			0.00			0.00

The minimum and maximum value of the trunk 3-plane angles over the left stance phase

The only difference on the minimum value of the trunk at the sagittal plane angle over the left stance phase between two groups was statistically significant from walking on floor to stair ascent ($P < 0.05$, **Table 4**). However, there were no detectable differences between any of the other measurements between two groups (**Table 3**).

The maximum value of the trunk at the coronal plane angle over the left stance phase from stair descent to walking on floor in the ACL-D group significantly increased ($P < 0.05$, **Table 4**). The interaction between the group and walk pattern factors was significantly different between two groups at the maximum value of the angle of trunk coronal plane angle over the left stance phase (**Table 5**).

Except the results from the stair descents between two groups at a minimum value, significant differences were found between two groups at the minimum and maximum value of the trunk at a transverse plane angle over the left stance phase (**Table 6**). This important finding indicates that the gait change of the trunk at a transverse plane angle were significant between two groups.

Trunk 3-plane angles at minimum and maximum value time of left knee moment over left stance phase

Table 7 shows that the only significant difference ($P = 0.03$) of stair descent between two groups on the angle of the trunk occurred at a maximum value of the sagittal plane angle of the left knee sagittal plane moment over the left stance phase. Similar to the results presented in **Table 6**, all the results except the stair descent measurements revealed no dif-

Table 10. Trunk sagittal plane angle when the left knee sagittal plane moment over the left stance phase started and ended ($\bar{x}$ ± SD)

	Start			End		
	ACL-D group (*n* = 36)	Control group (*n* = 36)	*P*	ACL-D group (*n* = 36)	Control group (*n* = 36)	*P*
Level walk	-1.42 ± 0.3	-1.66 ± 0.5	0.67	-2.41 ± 0.02	-1.92 ± 0.5	0.39
From level walk to stairs ascent	-1.19 ± 0.3	-0.18 ± 0.5	0.08	5.19 ± 0.05	4.59 ± 0.06	0.46
Stairs ascent	2.88 ± 0.4	3.41 ± 0.6	0.45	7.65 ± 0.05	5.16 ± 0.07	0.01
Stairs descent	-2.41 ± 0.6	-3.11 ± 0.5	0.39	-6.55 ± 0.05	-5.53 ± 0.04	0.13
From stairs descent to level walk	-4.71 ± 0.6	-4.83 ± 0.4	0.88	-2.39 ± 0.04	-2.81 ± 0.05	0.52
F value for interaction			2.5			6.5
P value for interaction			0.08			0.00
F value for main effect			0.00			0.5
P value for main effect			0.87			0.49

Table 11. Trunk coronal plane angle when the left knee coronal plane moment over the left stance phase started and ended ($\bar{x}$ ± SD)

	Start			End		
	ACL-D group (*n* = 36)	Control group (*n* = 36)	*P*	ACL-D group (*n* = 36)	Control group (*n* = 36)	*P*
Level walk	0.65 ± 0.01	1.20 ± 0.02	0.07	-0.20 ± 0.2	-0.39 ± 0.2	0.50
From level walk to stairs ascent	1.86 ± 0.08	2.12 ± 0.05	0.34	0.23 ± 0.3	-0.24 ± 0.4	0.37
Stairs ascent	-1.42 ± 0.03	-1.08 ± 0.03	0.39	-1.02 ± 0.4	-0.97 ± 0.4	0.93
Stairs descent	2.07 ± 0.03	2.31 ± 0.04	0.51	0.49 ± 0.3	0.86 ± 0.3	0.40
From stairs descent to level walk	3.31 ± 0.01	2.83 ± 0.01	0.11	0.21 ± 0.3	0.26 ± 0.3	0.91
F value for interaction			3.0			1.20
P value for interaction			0.03			0.31
F value for main effect			0.5			0.00
P value for main effect			0.48			0.92

ferences of the trunk at the coronal plane angle at the minimum and maximum time of the left knee coronal plane moment of the left stance phase between two groups (**Table 8**).

Surprisingly, there were significantly different measurements of the trunk at a transverse plane angle at the minimum and maximum value time of the left knee transverse plane transverse plane moment over the left stance phase between two groups (all $P < 0.001$; **Table 9**), indicating that gait changes of the trunk at the transverse plane angles are significant between two groups.

Trunk 3-plane angles when left knee 3-plane moment over left stance phase started and ended

The results in **Tables 10** and **11** showed that there were no significant differences between most measurements of the trunk at a sagittal/coronal plane angle when the left knee sagittal/coronal plane moment over the left stance phase started and ended. However, almost all measurements in the trunk angle at the transverse plane when left knee transverse plane moment of left stance phase started and ended between two groups were significantly different ($P < 0.01$; **Table 12**). The results demonstrated that transverse plane of the gait modification between two groups are significantly different.

Discussion

The most interesting finding in the present study is that almost all measured parameters at the transverse plane were significantly different between two groups, compared with those at sagittal/coronal plane measurements. The results suggest that the parameters at the transverse plane are more important measurements to reflect ACL-D. The five walking patterns in the study were similar to those investigated by Desloovere et al. [18], who reported

Table 12. Trunk at the level plane angle when the left knee level plane moment over the left stance phase started and ended ($\overline{x}$ ± SD)

	Start			End		
	ACL-D group (*n* = 36)	Control group (*n* = 36)	*P*	ACL-D group (*n* = 36)	Control group (*n* = 36)	*P*
Level walk	4.53 ± 0.28	1.19 ± 0.13	0.00	-1.12 ± 0.06	-3.91 ± 0.17	0.00
From level walk to stairs ascent	-26.20 ± 0.9	-34.55 ± 0.7	0.00	-31.23 ± 1.1	-36.47 ± 0.8	0.00
Stairs ascent	-27.41 ± 0.9	-34.81 ± 0.7	0.00	-34.39 ± 1.1	-39.24 ± 1.0	0.00
Stairs descent	-36.10 ± 0.8	-41.07 ± 1.0	0.00	-32.17 ± 1.1	-35.99 ± 0.8	0.01
From stairs descent to level walk	-33.39 ± 0.9	-40.84 ± 0.9	0.00	-36.33 ± 1.2	-41.21 ± 0.7	0.00
F value for interaction			9.90			1.70
P value for interaction			0.00			0.15
F value for main effect			42.30			14.40
P value for main effect			0.00			0.00

that the repeatability of knee kinematics parameters at walking and stair descent was better.

Sheehan et al. reported that there was a significant change of sagittal plane control between ACL-injury patients and healthy subjects. However, the measurement method in this report was different to the methods used in the current study. With our measurements, we did not observe significant differences in most measurements of sagittal/coronal plane angles.

A series of gait modification strategies of core stability system were conducted over the left stance phase in normal walk after right ACL injury, and the modification strategies are specific to walk patterns. It might be an important reference for diagnosis, rehabilitation assessment, treatment of ACL injury, and the prevention and treatment of osteoarthritis. Specialized core stability training programs are needed to improve rehabilitation after ACL injury.

Under physiological conditions, there is a three-dimensional biomechanical regulation relationship between the trunk, knees and ACL. In the sagittal plane, the angle of the trunk lean is remarkably related to the arm and force in the knees, and the angle of the trunk lean increases in the single-leg landing test [24]. The greater the distance between the median point and the back supporting plane the higher the risk of ACL [25]. An increase in trunk flexion protects the ACL through strengthening shock absorption, flexion of knees and reducing anterior shear and mobilization of the quadriceps femoris. On the contrary, an increase in posterior lean trunk may raise anterior shear and tension in the ACL and add risk of ACL-D by strengthening mobilization of the quadriceps femoris and reducing the flexion angle of the knees [26-28]. At the coronal plane, the trunk lateral flexion develops valgus loading on the knees, therefore the trunk lateral flexion angle is biomechanically connected with the valgus loading of the knees [29]. If the median point shifts inside, the valgus moment of the knees will decrease [30]. Trunk lateral flexion [31] is closely related to the valgus loading of the knees (correlation coefficient 0.62~0.77) [32, 33]; as ACL is the main structure that restricts the valgus of knees [34]. Excessive valgus loading of the knees will cause ACL injury; therefore, the excessive lateral flexion of trunk over stance phase and valgus loading of knees are closely biomechanical connected with ACL injury. At the transverse plane, the trunk anterior lean and the lateral flexion are biomechanically connected with tibial internal rotation [35]. The mechanical relationship between the central stabilization system and the knees can be used in a gait retraining program to improve the biomechanical properties of the knees. For example, trunk lateral flexion training with real-time visual feedback can decrease the adduction moment of the hip joints and the various moment of the knees [36].

Gait analysis has become a rehabilitation assessment method in the field of rehabilitation medicine. However, an intensive and long-term study is required to develop a scientific, efficacious, practical and specific rehabilitation program for ACL injury.

The gait-retraining program has effects not only on the injured side but also on the healthy side, because of central nervous system plasticity. Our study has revealed trunk modification strategies over the stance phase of the healthy side (left lower extremity) after right ACL injury: the trunk posterior rotation angle decreases during a normal walk. The five walk patterns have their own features: trunk anterior rotation angle increases during a walking; trunk posterior lean angle increases during a walking to stair ascent; the trunk anterior rotation angle increases during stair ascent; the angle of trunk lateral flexion to the left decreases and the posterior lean angle increases during stair descent; the angle of trunk lateral flexion to the right increases during stair descent to a walking.

Conclusions

Our results might be an important reference for diagnosis, rehabilitation assessment, treatment of ACL injury and prevention and treatment of osteoarthritis. A specialized core stability training programs are needed to improve rehabilitation after ACL injury.

Gait analysis has become a rehabilitation assessment method in the field of rehabilitation medicine. However, an intensive and long-term study is required for developing a scientific, efficacious, practical and specific rehabilitation programmed for ACL injury.

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Disclosure of conflict of interest

None.

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