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

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ABSTRACT

This study aimed to investigate the gait modification strategies of trunk over right stance phase in patients with right anterior cruciate ligament deficiency (ACL-D). Thirty-six patients with right chronic ACL-D were recruited, as well as 36 controls. A 3D optical video motion capture system was used during gait and stair ambulation. Kinematic variables of the trunk and kinematic and kinetic variables of the knee were calculated. Patients with chronic right ACL-D exhibited many significant abnormalities compared with controls. Trunk rotation with right shoulder trailing over the right stance phase was lower in all five motion patterns ($P < 0.05$). Compared with controls, trunk posterior lean was higher from descending stairs to walking when the knee sagittal plane moment ended ($P < 0.01$). Trunk lateral flexion to the left was higher when ascending stairs at the start of right knee coronal plane moment ($P = 0.01$), when descending stairs at the maximal knee coronal plane moment ($P < 0.01$), and when descending stairs at the end of the knee coronal plane moment ($P = 0.03$). Trunk rotation with right shoulder forward was higher at the minimal knee transverse plane moment ($P < 0.01$) and when the knee transverse plane moment ended ($P < 0.01$); during walking, trunk rotation with right shoulder trailing was lower at other knee moments during other walking patterns (all $P < 0.01$). In conclusion, gait modification strategies of the trunk were apparent in patients with ACL-D. These results provide new insights about diagnosis and rehabilitation of chronic ACL-D (better use of walking and stair tasks as part of a rehabilitation program).

1. Introduction

The anterior cruciate ligament (ACL) is one of the most commonly injured ligaments in the knee [1]. A previous study revealed that 4355 patients were registered with ACL deficiency (ACL-D) between 1993 and 2007 at a single Chinese center [2]. ACL-D is the chronic result of a passive ligament injury [3]. Indeed, the biomechanical properties of the knee rarely recover completely after an injury, despite appropriate treatments [4]. Significant articular cartilage degeneration is observed as early as 15 months after ACL reconstruction [5]. ACL-D leads to neuromuscular consequences of the knee biomechanics [6] because the ACL plays a major role in proprioception [7]. Indeed, in ACL-D, the ACL fails to respond to the corresponding mechanical stimuli during knee loading [8], leading to changes in muscle mobilization in the whole body [9]. ACL-D results in a detrimental increase in anterior translation of the tibia relative to the femur when the knee is non-weight bearing [10]. These changes often lead to falls in a large proportion of patients with ACL-D when they are descending stairs [11] or during unusual movements such as backward walking [12].

Nevertheless, the precise kinematic changes that occur in ACL-D are poorly defined. Therefore, the purpose of this study was to investigate the gait modification strategy of trunk over right stance in patients with chronic right ACL-D when walking, and when ascending and descending stairs.

2. Methods

2.1. Subjects

This was a prospective study carried out between January 2010 and January 2012. We recruited 36 male patients with right ACL-D from the Departments of Sports Medicine of the Shanghai East Hospital affiliated to Tongji University, from the Department of Orthopedics of the 6th People's Hospital affiliated to Shanghai

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Jiaotong University, and from the Department of Orthopedics of Zhongshan Hospital affiliated to Fudan University. Mean time between ACL-D diagnosis and study participation was 24.8 months (range: 22–26 months).

Thirty-six male healthy controls were recruited from postgraduate students at the Tongji and Jiaotong Universities. Controls and patients were matched 1:1 for age (24–32 years), height (1.69–1.79 m), weight (61.7–75.6 kg), and Q angle (9.7–13.7°).

Functional leg dominance was determined using three basic tests performed thrice: ball kicking, stepping up, and balance recovery. ACL-D diagnosis was based on injury history, magnetic resonance imaging (MRI), and/or arthroscopy [13]; the visual analogue scale (VAS) [14] for knee pain had to be 0–30 mm. Time from ACL injury had to be >6 months. Controls had to have no history of knee injury, no musculoskeletal disease, no injury at any site affecting gait, and normal knee stability.

Exclusion criteria were: (1) posterior cruciate ligament injury or collateral ligament injury, meniscus injury, knee effusion, articular cartilage injury or fracture; or (2) any condition affecting normal movement or gait. Female patients were excluded to lower variability.

The study was approved by the Ethics Committee of each participating university. All subjects provided a written informed consent.

2.2. Data collection

For visual details about the gait analysis system, please see the Supplemental figures and the Supplemental material. The infrared 3-D gait analysis system (Motion Analysis Corp., Santa Rosa, CA, USA) consists of 10-mm reflective markers, six infrared digital cameras (sampling frequency of 60 Hz), a workstation and video processor, a high-performance computer, an information conversion controller, and the image collection software EvaRT4.2. Cameras were located on 10 × 6 m walls at a mean height of 2.2 m from the floor; the direction of the cameras could be adjusted; they had a visual angle >56° and resolution >1/60,000.

Two 60 × 60 cm force plates (Advanced Mechanical Technology Inc., Watertown, MA, USA) were embedded in the floor. The sampling frequency was 1000 Hz and output voltage was 10 mV. A custom wooden staircase without banister was used. The first step (40 × 40 × 17 cm) was on the second force plate, and the second step (100 × 90 × 34 cm) was without a force plate [15] (Supplemental Fig. 1).

Walking, and ascending and descending stairs were the three activities used for gait analysis [16]. All studies were performed by two skilled technicians with 3 years of experience, one for calibrating the system, positioning the reflective markers, and directing the subjects, and the other for collecting data.

Twenty-six reflective markers were positioned as previously described [17] (Supplemental Fig. 2).

Tests were performed barefoot. Static images were acquired after standing still for 5 s and the markers on the medial knees and ankle joints were removed. The subjects started walking from the start line, 3.3 m away from the first force plate, and completed all three activities at their own pace, repeated 16 times before formal testing. Motion data collection was completed over three trials. Kinematics and kinetics by force plate were recorded simultaneously. Upon each collection, the completeness of the data was assessed by the computer. Data collection was performed three times according to the sequence presented in Supplemental Table 1.

2.3. Data analysis

A motion analysis software (ORTH TRAK. VA-OT624, Motion Analysis Corp., Santa Rosa, CA, USA) was used. Low-pass filter techniques were applied to 3D kinematic and kinetic data (cutoff frequency of 18 Hz). The joint centers were defined as per the static data. A multi-segment model [18] was used to calculate the sagittal, coronal, and transverse plane angles of the trunk. Anatomically neutral positions were regarded as the reference for all angles (0°). The sagittal plane angles of the pelvis and lower extremity were calculated.

The time frame of all kinematic and kinetic data during level gait were standardized to a single complete (100%) gait cycle, in which initial contact was 0% and the following contact of the same foot was 100%. For ascending stairs, the cycle started when the foot made contact with the first force plate on the ground and ended when the ipsilateral foot made contact with the second step. For descending stairs, the gait cycle started when the foot landed on the first step mounted on the second force plate and ended when the ipsilateral foot made contact with the ground [19]. To facilitate the comparison with walking, the cycle of ascending and descending stairs was divided into stance and swing phases. The ground reaction force from the force plate was used as the marker for determining the gait cycle. Because the stair had only two steps, it was difficult to collect the data of a complete gait cycle during a single testing. In order to solve this problem, the subjects were required to start the test from the left and then to perform it again but starting from the right foot, resulting in a combined complete stance and swing phases of both lower extremities. Each complete sequence was performed three times. Data of three complete gait cycles were recorded for one subject and then the average values were calculated. When ascending and descending stairs, because the subjects might land with different parts of the feet (heel or toe), we used "foot landing" as the start of the gait cycle. For walking, the stance phase began when the vertical reactive force reached 5% of the body weight and ended when the vertical reactive force was reduced <5% of the body weight [19]. For ascending and descending stairs, the stance phase started when the vertical reactive force reached 20% of the bodyweight and ended when the vertical reactive force was reduced <20% of the bodyweight. Enhancing threshold values were used to avoid interferences due to the possible vibration during the stance phase [20].

Indicators for gait analysis included knee 3D moments [18,21], the maximal and minimal value of 3D angles of the trunk; the 3D angles of trunk at the start; and the minimal, maximal and end values of the knee moment. The maximal and minimal trunk angles during right side stance were analyzed in all three planes of motion for all conditions. The trunk angles in all three planes of motion were also assessed at the following time points: beginning and end of stance phase (presence of a knee moment), and at the point of maximal and minimal knee moment in each plane in all conditions. Finally, the maximal and minimal knee moments in the sagittal, coronal, and transverse planes were analyzed for all conditions

2.4. Statistical analysis

SPSS 17.0 (Chicago, IL, USA) was used for statistical analysis. Continuous data are presented as mean ± standard deviation. Variables were tested for spherical symmetry assumption; if absent, the Greenhouse–Geisser correction was used. Afterward, inter-group analyses were performed, as well as intra-group analyses. *P*-values <0.05 were considered statistically significant.

3. Results

3.1. Patient characteristics

Patients and controls were well matched for age (ACLD: 28.0 ± 3.7 vs. controls: 27.8 ± 3.7 years, $P = 0.78$), height (ACLD: