Changes in interjoint coordination pattern in anterior cruciate ligament reconstructed knee during stair walking

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Abstract
Anterior cruciate ligament reconstruction (ACL-R) surgery can improve knee joint stability; however, altered sensory feedback after reconstruction surgery might affect the movement control which is required by proper multijoint coordination to compensate for the impaired sensorimotor function. The purpose of this study was to determine how interjoint coordination changed during stair walking in individuals with ACL-R compared with the control group and how interjoint coordination was affected by the stair height. Sixteen individuals with unilateral ACL-R and 16 healthy age- and sex-matched controls were recruited. Participants were instructed to ascend and descend a 4-step stairs with two different heights at their self-selected speed. Kinematic data were collected during stair walking using a motion analysis system. Interjoint coordination and muscle strength of the lower extremities were investigated. The root-mean-squared difference, cross-correlation coefficient, and deviation phase of the relative phase angles were used to quantify the interjoint coordination pattern. A mixed-model analysis of variance was used to compare the difference among variables. Muscle strength in the vastus femoris and biceps femoris of the affected side of the patient group was significantly decreased, compared with that of the healthy control. Higher variability of the knee-ankle interjoint coordination was observed in the affected side during stair walking in individuals with ACL-R than the healthy control. The findings suggested that the variation in interjoint coordination patterns between the patient group and control group was more distinct at a high stair height than a lower stair height. Inadequate muscle strength could affect the neuromuscular control and could not provide stability at the joints, which increases the variability of interjoint movement and changes the interjoint coordination.

Key words : Anterior cruciate ligament reconstruction, Interjoint coordination, Stair walking, Motor control
1. Introduction

The anterior cruciate ligament (ACL) is the primary ligament that stabilizes the knee joint (Beynnon et al. 2005; Trees et al. 2005; van Grinsven et al. 2010) and is also the most frequently disrupted ligament in the knee. After an ACL injury, a patient may receive an ACL reconstruction surgery (ACL-R) (Beynnon et al. 2005; Trees et al. 2005). Although surgery can help restore mechanical stability and function, (Chen et al. 2006) only static performance of the reconstructed knee can be improved, but not full performance. According to previous studies, the movement pattern and neuromuscular control among the joints of the lower extremity might still not fully recovery (Hooper et al. 2002; Tashman et al. 2004; Papannagari et al. 2006; Tashman et al. 2007; Bryant et al. 2008; Gao et al. 2011; Lustosa et al. 2011; Lyon et al. 2011; Roos et al. 2014). The poor neuromuscular control might be influenced by the altered sensory feedback after reconstruction surgery (Fremerey et al. 2000; Roberts et al. 2000; Bryant et al. 2008; Lustosa et al. 2011) and affect the movement control which is required by proper multijoint coordination to compensate for the impaired sensorimotor function (Hsu and Scholz 2012; Hsu et al. 2014). Thus, joint coordination ability should not be overlooked in post-surgery care for ACL-R patients.

Mounting evidence have shown that the knee joint kinematics are not fully restored when performing activities of daily living after ACL-R surgery (Hooper et al. 2002; Tashman et al. 2004; Papannagari et al. 2006; Tashman et al. 2007; Gao et al. 2011; Lyon et al. 2011). Stair walking is a common daily activity and requires an extensive motion range of the knee, compared with other activities, such as over ground walking (Laubenthal et al. 1972; Protopapadaki et al. 2007). The compressive loading and shear force at the knee joint during stair walking are relatively high (D'Lima et al. 2007; Mundermann et al. 2008), and the greater the stair height, the more interjoint control is required. Previous studies have indicated that abnormal neuromuscular control and asymmetric pattern during stair walking may accelerate knee joint degeneration (Hooper et al. 2002; Gao et al. 2011; Lyon et al. 2011). Therefore, the underlying mechanism such as abnormal interjoint coordination should be identified after reconstruction surgery for postsurgical intervention (Wang et al. 2015).

The continuous relative phase (CRP) can be used to quantify the interjoint coordination pattern because it combines joint position and angular velocity information (Burgess-Limerick et al. 1993; Haddad et al. 2006; Lu et al. 2008; Chiu et al. 2010; Busquets et al. 2013; Rinaldi and Monaco 2013). Afferent fiber of the mechanoreceptor of joints and muscles primarily senses the joint position and velocity and may affect interjoint coordination. Therefore, the interjoint coordination of two adjacent joints can be evaluated by CRP approach. Compared to conventional kinematic studies which consider the joint position and velocity separately, CRP approach includes more dynamic information by combining these two biomechanical variables and provides insight into changes in joint coordination that may be caused by mechanical or sensory changes in the ACL-R knee.

Kurz et al used the CRP approach to investigate interjoint coordination in individuals with ACL-R during walking and running (Kurz et al. 2005). They observed that the thigh-shank and shank-foot coordination were altered during walking whereas only the shank-foot coordination was altered during running (Kurz et al. 2005). Therefore, the coordination in individuals with unilateral ACL-R differed from that of the participants without ACL injuries in gait. These changes are associated to a loss of sensory information that is typically provided by the ACL. Whether interjoint coordination in other daily activities, such as stair walking, also differs after ACL-R surgery needs to be investigated.

Although passive component injuries such as a ligament tear can be restored after ACL-R surgery, the active component such as muscle control might still not fully recover and may affect the interjoint coordination pattern (Mortaza et al. 2013). Therefore, this study investigates how interjoint coordination changed during stair walking in individual with ACL-R compared with the healthy control group and how interjoint coordination was affected by the stair height. We hypothesized that (1) the interjoint coordination of individuals with ACL-R would demonstrate a less coordinative pattern during stair walking compared with...
that of healthy control participants, and (2) individuals with ACL-R would demonstrate a less coordinative pattern during stair walking at a higher stair height compared with that at a shorter stair height.

2. Methods

2.1 Ethics Statement

This study adhered to the principles of the Declaration of Helsinki for human research. The Research Ethics Committee of National Taiwan University Hospital approved this study. Written informed consent was acquired from each participant.

2.2 Participants

Participants were volunteers who responded to advertisements in the Taipei City area, Physical Therapy Center, and Department of Orthopaedic Surgery of National Taiwan University Hospital. Participants were divided into 2 groups: the patient group (participants who had received unilateral ACL-R) and the control group (healthy age- and sex-matched participants). Sixteen individuals with unilateral ACL-R and 16 healthy age- and sex-matched controls were recruited.

The inclusion criteria for the patient group with unilateral ACL-R were: (1) at least three months after receiving unilateral ACL-R surgery, (2) able to ascend and descend stairs independently by using a step-over-step pattern, and (3) aged between 20 and 45 years. The exclusion criteria for the patient group were: (1) multiple ligament injury, (2) meniscus injury, (3) lower limb fracture that affects movement, (4) systematic disorder that affects balance and ambulation, and (5) body mass index higher than 30 or lower than 18.

The inclusion criteria for the control group were: (1) able to ascend and descend stair independently by using a step-over-step pattern and (2) aged between 20 and 45 years. The exclusion criteria were: (1) lower limbs injury or surgical history, (2) any systematic disorder that would affect the balance and ambulation, and (3) body mass index higher than 30 or lower than 18.

2.3 Data collection

Movement data were recorded using a motion analysis system (VICON Bonita, Oxford metrics, UK). This motion analysis system consists of 8 infrared-sensitive cameras that were used to track the trajectory of 15 mm spherical reflective markers attached to the participants’ bony landmarks. The sampling rate of the motion system was set at 120 Hz. The full body Plug-in-Gait marker set was attached to the participants’ anatomical bony landmarks and secured using Micropore tape (3M, Maplewood, USA).

The following data of the participants were collected before the experiment: height, weight, anthropometric measurements, dominant side, injured side, date of injury, and type of reconstruction surgery. The participant's muscle strength in gluteus maximus, rectus femoris, vastus femoris, biceps femoris, and tibialis anterior were measured bilaterally using a handheld dynamometer in a standard manual muscle testing position. (Perotto and Delagi 1994) The knee function of individuals with ACL-R was evaluated using the Lysholm-Tegner Score, which displayed excellent reliability and validity for individuals with ACL-R (Briggs et al. 2009).

Within group comparison was only analyzed in the patient group between the affected side and the sound side. Between groups comparisons were analyzed between the affected side of the patient group and the dominant leg of the control group, as well as between the sound side of the patient group to the dominant leg of the control group.
2.4 Experiment setup

For the stair walking task, participants were asked to ascend and descend a 4-step wooden stair (width: 90 cm, tread: 30 cm). The stair was set into two heights: 16 cm and 21 cm. Participants were instructed to ascend and descend the stair by using a step-over-step pattern at their self-selected speed (Fig. 1). Participants performed 6 complete stair ascent trials and 6 descent trials for each stair height and initiated with their right or left foot randomly. Before data collection, participants were also asked to practice the stair walking task 3 times before to become familiar with the task. Participants were allowed to rest as much as they required between trials to prevent fatigue.

Fig. 1 Experiment setup for (A) stair ascend and (B) stair descend.

Data analysis

The Vicon Nexus Plug-in-Gait biomechanical modeling software was used for processing and computing the joint angle data. A custom written program in MATLAB (version R2008b, Mathworks, USA) was used to define the gait events. During stair walking, a gait cycle was defined beginning with foot contact on a step and ending at the next foot contact of the same foot on the next step (Zachazewski et al. 1993). Foot-contact time was determined by identifying a contact-induced vertical acceleration of the heel marker (McClinton et al. 2007) and the minimal vertical distance between the toe marker and supporting surface. This study focused on the stance phase of the gait cycle because of its importance to weight acceptance in ACL-R individuals.

Interjoint coordination

After establishing the foot-contact times, the joint angular data in the sagittal plane during a gait cycle were obtained. The angular velocity was calculated by differentiating the joint angular data. The amplitude of the joint angle and angular velocity was normalized. The normalization procedure is described as follows. The maximal and minimal values of joint angle during a gait cycle were normalized to 1 and -1, respectively. The zero point in the normalized joint angular position corresponds to the midpoint range of the joint angle. The maximal and minimal values of angular velocity were also normalized to 1 and -1, respectively. After normalization, the phase plot for each joint throughout a gait cycle was generated by plotting the normalized angular positions ($\theta$) along the x-axis and normalized angular velocities ($\omega$) along the y-axis (Fig. 2). (Burgess-Limerick et al. 1993; Chiu et al. 2010) Next, the phase angle ($\phi$) was calculated as $\phi = \arctan (\omega/\theta)$ for each data point of the time series of gait cycles.
Fig. 2 Phase plane of the (A) control knee and (B) affected knee.

Continuous relative phase (CRP)

The graphical configuration of the continuous relative phase (CRP) curve was evaluated for the various locomotive strategies between the patient group and control group (Kurz et al. 2005; Lu et al. 2008). Because the CRP is defined as the coordination of two adjacent joints, the CRP was obtained by subtracting the phase angle of the distal joint from that of the proximal joint (Lu et al. 2008). CRP represents the phasing relationships or coupling between the movements of the two segments that surround the joint. CRP values closer to 0 degree indicate that the two segments are moving in a similar manner, or they are closer to being in phase. CRP values closer to 180 degree indicate that the two segments are moving in the opposed direction or they are closer to being out of phase. In this study, the CRPs of the hip-knee and knee-ankle were calculated. Next, the CRPs were interpolated to 100% of a single complete gait cycle. CRPs were also separately evaluated in the stance and swing phases. This study focused on the stance phase of the gait cycle because of its importance to weight acceptance in individuals with ACL-R (Kurz et al. 2005).

Performance index for inter-joint coordination

To quantify the similarity of the interjoint coordination pattern between affected and sound legs (surgical side vs. non-surgical side) and between group conditions (patient group vs. control group), the root-mean-squared difference (RMS) and cross-correlations were calculated to quantify the variations of magnitude and temporal evolution, respectively (Haddad et al. 2006; Chiu et al. 2010). The RMS values of each interjoint CRP pattern for the stance phase in a gait cycle were first calculated. The difference of RMS values was calculated by subtracting the RMS value between conditions. A greater difference of RMS values implies a substantial dissimilarity of CRP patterns between conditions. The cross-correlation coefficient can assess the possible variations of temporal evolution (phase shift) between the patterns of the experimental and baseline conditions. The cross-correlation coefficient also can yield information specific to changes in the spatiotemporal evolution of CRP patterns (Haddad et al. 2006; Chiu et al. 2010). In this study, the cross-correlation coefficient was assessed by calculating the correlation coefficient between the CRP pattern of the affected side and sound side in the patient group. A high cross-correlation coefficient suggests a similar CRP pattern in the temporal domain between the affected side and the sound side. Therefore, a high cross-correlation coefficient with a low difference of RMS value indicates that the two CRP patterns between affected side and sound side are similar. The deviation phase (DP) represents the cycle to cycle variability of each interjoint CRP pattern. The DP can be assessed with the average value of all standard deviations calculated for each data point over a gait cycle from all CRP curves (Chiu et al. 2010). A high DP indicates a
high variable coordination between two adjacent joints. For each interjoint coordination measure, CRP curves of all participants were averaged for each group.

- **Statistical analysis**

  The sample size was estimated using the power analysis with the pilot data results. To determine the anticipated differences between groups for an \( \alpha \) level of 0.05, each group required 13 participants for approximately 80% power. Sixteen participants were recruited into each group to ensure sufficient power to detect differences.

  The normality was tested using the skewness, kurtosis and Shapiro-Wilk tests. An independent \( t \) test was used to detect the participant characteristics variations between groups (ACL-R group vs. control group). A \( 2 \times 2 \) mixed-model analysis of variance (ANOVA) was used for within group comparison (affected side vs. sound side), as well as the effect of stair height on the difference of RMS values and cross-correlation coefficient (higher stair height vs. shorter stair height). A \( 2 \times 3 \) mixed-model ANOVA was used for within group comparison (affected side vs. sound side), between group comparisons (ACL-R group vs. control group), as well as the effect of stair height (higher stair height vs. shorter stair height) on other variables. The significance level was set at 0.05. All analyses were performed using SPSS (version 18.0, SPSS Inc., Chicago, IL, USA).

3. **Results**

**Participants characteristics**

Sixteen ACL reconstructed individuals (11 men, 5 women; age: 19-39 years) and 16 controls (11 men, 5 women; age: 21-39 years) participated in this study. No significant variations were observed between the patient group and control group in age (\( t(30) = -0.324, P = .748 \)), height (\( t(30) = 1.103, P = .279 \)), weight (\( t(30) = 1.246, P = .222 \)), and body mass index (BMI) (\( t(30) = 0.885, P = .383 \)). The average time after surgery for the patient group was 5.93 ± 3.18 months. The modified Lysholm score for the patient group was 73–99. The demographic data of the participants are presented in Table 1.

|                           | Patient (n = 16) | Control (n = 16) | \( P \) value |
|---------------------------|-----------------|-----------------|--------------|
| **Age (years)**           | 27.4 ± 7.0      | 28.1 ± 4.8      | .748         |
| **Sex**                   | 11 Male, 5 Female | 11 Male, 5 Female | ----        |
| **Body height (m)**       | 1.72 ± 0.09     | 1.69 ± 0.08     | .279         |
| **Body weight (kg)**      | 70.6 ± 12.1     | 65.3 ± 12.3     | .222         |
| **BMI (kg/m\(^2\))**      | 23.7 ± 2.7      | 22.7 ± 3.3      | .383         |
| **Affected / Dominant Side** | 12 Left, 4 Right | 15 Right, 1 Left | ----        |
| **Post-surgery duration (month)** | 5.93 ± 3.18 | ---- | ---- |
| (Range 3.2 – 14.3)        |                 |                 |              |
| **Surgical type**         | 14 hamstring graft | ---- | ---- |
|                           | 2 patellar tendon graft | ---- | ---- |
| **Lysholm-Tegner Score (0-100)** | 90.3 ± 5.59 | ---- | ---- |

Differences in muscle strength between the two groups are presented in Table 2. The affected side of the patient group exhibited lower muscle strength in vastus lateralis (\( F(2,45) = 4.190, P = .021 \)) and biceps femoris (\( F(2,45) = 5.372, P = .008 \)) compared with that of the control group. However, the muscle strength of the gluteus maximus, rectus femoris, and tibialis anterior exhibited no significant difference between the two groups.
Table 2  Mean and standard error of the mean (SEM) of muscle strength of the lower extremities (unit: percentage of the body weight). + Statistical significance between affected side and control within the patient group (P < 0.05). * Statistical significance in between groups effects (P < 0.05).

| Muscle            | Patient group | Control group | Group Effect | P value |
|-------------------|---------------|---------------|--------------|---------|
|                   | Affected side | Sound side    |              |         |
| Gluteus Maximius  | 0.29 ± 0.03   | 0.31 ± 0.02   | 0.34 ± 0.01  | 1.264   | .292   |
| Rectus Femoris    | 0.31 ± 0.02   | 0.33 ± 0.02   | 0.37 ± 0.02  | 2.509   | .093   |
| Vastus Femoris    | 0.32 ± 0.02*  | 0.39 ± 0.02   | 0.42 ± 0.03  | 4.190   | .021*  |
| Biceps Femoris    | 0.19 ± 0.03*  | 0.25 ± 0.02   | 0.31 ± 0.03  | 5.372   | .008*  |
| Tibialis Anterior | 0.35 ± 0.03   | 0.37 ± 0.03   | 0.40 ± 0.02  | 0.677   | .513   |

STAIR ASCENT

Difference of RMS values and cross-correlation coefficient

The differences of the CRP curve pattern between the patient and the control groups were evaluated using the difference of RMS values (Fig.3A) and cross-correlation (Fig.4A). The differences of RMS values of the hip-knee ($F_{(2,45)} = 5.576, P = .025$) and knee-ankle ($F_{(2,45)} = 6.311, P = .018$) coordination were increased when the stair height was increased. A significant variation between the two groups was observed in the distal joints only with a high stair height. For the variable of temporal difference of CRP curves, the affected side and sound side exhibited similar hip-knee and knee-ankle cross-correlation values for all heights.

![Fig. 3](image)

Fig. 3 Root-mean-squared difference of hip-knee and knee-ankle CRP curves of the patient group and the control group in stance phase during stair ascent (A) and stair descent (B). Values are means±SEM. + Statistical significance in height effects (P < .05). * Statistical significance in group effects (P < .05).
Fig. 4 Cross-correlation coefficient of hip-knee and knee-ankle CRP curves of the patient and the control groups in the stance phase during stair accent (A) and stair descent (B). Values are means±SEM. + Statistical significance in height effects (P < .05).

Deviation phase values
The deviation phase in the stance phase during stair accent is presented in Fig. 5A. The deviation phase values in the stance phase during stair ascent differed significantly among the affected side, sound side, and the control. The affected side exhibited greater hip-knee ($F_{(2,45)} = 17.402, P < .001$) and knee-ankle ($F_{(2,45)} = 15.711, P < .001$) deviation phase values for all heights. However, the values were similar between the 2 stair heights.

Fig. 5 Deviation phase of hip-knee and knee-ankle CRP curves of the patient and control groups in stance phase during stair accent (A) and stair descent (B). Values are means±SEM. + Statistical significance in height effects (P < .05). * Statistical significance in group effects (P < .05).

STAIR DESCENT

Difference of RMS values and cross-correlation coefficient
The differences of RMS values of the hip-knee or knee-ankle did not differ significantly between the affected side and sound side (Fig. 3B). However, the stair height effect was observed in the proximal joints ($F_{(2,45)} = 4.678, P = .039$). In the variable of the temporal difference of CRP curves, the cross-correlation value of the hip-knee and knee-ankle coordination was similar between the two groups during stair descent (Fig. 4B). The cross-correlation coefficient of the knee-ankle coordination was decreased when the stair height was increased ($F_{(2,45)} = 5.030, P = .032$).
Deviation phase values
The deviation phase values in the stance phase during stair descent are presented in Fig. 5B. The affected side exhibited significantly higher hip-knee deviation phase values \( (F_{(2,45)} = 4.800, P = .013) \) and knee-ankle deviation phase values \( (F_{(2,45)} = 7.236, P = .002) \) than the control group did, but the between legs effect in the patient group was not observed in the hip-knee deviation phase value. The stair height effect was observed in the hip-knee deviation phase value \( (F_{(2,45)} = 6.789, P = .012) \).

4. Discussion
In this study, we examined the changes of interjoint coordination during stair walking in ACL reconstructed (ACL-R) individuals and the effect of stair height on interjoint coordination. The results support the hypotheses that individuals with ACL-R demonstrate altered coordinative pattern, compared with healthy control participants and that coordination pattern would be influenced by stair height. Our findings indicate that interjoint coordination was altered in the individuals with ACL-R, particularly in the increased variability of interjoint movement. The varied interjoint coordination pattern might be caused by reduced muscle strength in individuals with ACL-R.

Movement variability was increased in individuals with ACL-R
During stair ascent, significantly increased hip-knee and knee-ankle deviation phase values were observed in the affected side than in the sound side and control. The results of stair descent were similar to those of stair ascent. The affected side exhibited significantly greater knee-ankle deviation phase values than the control did, but the hip-knee deviation phase values of the affected side were similar to those of the control during stair descent. These results corresponded with the previous study that the thigh-shank and shank-foot relative phase dynamics altered by ACL-R when walking and running (Kurz et al. 2005). Our results indicated that interjoint coordination of the affected side was more varied than that of the sound side and that of the control participants, particularly in the distal joints of the lower extremity. The varied interjoint coordination of the affected side might be caused by improper neuromuscular control and insufficient muscle strength (Yang et al. 2015). Increased joint variability could be associated with stabilizing the perturbed postural balance (Hsu et al. 2013). As mentioned previously, inadequate muscle strength can affect the neuromuscular control and cannot provide stability at the joints, which increases the variability of interjoint movement.

Altered interjoint coordination pattern in individuals with ACL-R
For the CRP curve pattern, during stair ascent, increased differences of RMS values of the hip-knee and knee-ankle coordination were observed when the stair height was increased. The variation in interjoint coordination patterns between the patient group and control group was more distinct at a high stair height than a lower stair height. This might be caused by the larger hip and knee joint movement range for the high stair during stair ascent (Riener et al. 2002). Similar cross-correlation values imply that the temporal pattern of interjoint coordination in the patient group may resemble that in the control group.

Altered interjoint coordination pattern may result in degeneration of the knee
According to previous studies (Lohmander et al. 2007; Holm et al. 2010), the residual abnormalities after ACL-R accelerated the cartilage degeneration and development of knee osteoarthritis. Based on our findings, we determined a possible mechanism which might accelerate the process of degeneration of the knee joint. Although the laxity and functional status of the patient group was already restored through ACL-R, the muscle strength was still not fully recovered. Inadequate muscle strength might reduce the muscle coactivation and alter neuromuscular control. Thus, movement variability could be increased during stair walking.

The varied movement pattern might result in abnormal positioning of the loads during motion. Previous studies have shown that the peak compression load and peak shear force at the knee joint during stair walking were 3-3.5 times and 0.26 times of the body weight, respectively, which is greater than those of other activities.
These relatively high loads might affect the cartilage that is not commonly loaded in a healthy knee. Over time, this may accelerate the process of knee osteoarthritis.

**Clinical importance and application**

The findings of this research provide information on muscle strength and interjoint coordination during stair walking. This information can help us understand the mechanism of changes in neuromuscular control and interjoint coordination after ACL-R and develop a rehabilitation training program. Clinicians must provide adequate muscle strengthening exercises and highlight the importance of neuromuscular control training.

**5. Conclusion**

This study investigated the interjoint coordination during stair walking in individuals with ACL-R. Significant changes of interjoint coordination in individuals with ACL-R during stair walking were observed using continuous relative phase method. The varied interjoint coordination patterns might be caused by reduced muscle strength in individuals with ACL-R. The dynamic knee stability in the stance phase during stair descent also changed after ACL-R. Clinicians should provide adequate muscle strengthening exercises for individuals with ACL-R and focus on the importance of neuromuscular training for preventing inappropriate neuromuscular control and interjoint coordination during stair walking.

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