EFFECTS OF INTER-JOINT COORDINATION DURING A HIGH-DEMAND ACTIVITY AFTER ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION

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The purpose of this study was to investigate the pattern and variability of inter-joint coordination during a high-demand activity after anterior cruciate ligament reconstruction (ACLR). All subjects needed performed a single-leg landing followed cutting as quickly as possible. Our findings indicated that the patients with ACLR had similar patterns of inter-joint coordination in performing a single leg landing and cutting comparing to the age, sex, body weight and sport-matched healthy subjects. Assessing the inter-joint coordination as well as facilitating the coordination in clinical treatments might improve the high-demand activities on ACLR subjects.

KEY WORDS: PHASE ANGLE, CONTINUOUS RELATIVE PHASE, LANDING AND CUTTING

INTRODUCTION: Anterior cruciate ligament (ACL) injury is a common sports-related knee injury. Most ACL injuries occur in a noncontact maneuver that involves a sudden deceleration before a change of direction, such as landing from a jump and cutting. ACL reconstruction (ACLR) is a surgical intervention to restore knee function and provide the chances of returning to sports activities. Unfortunately, abnormal landing movements still existed during high demand activities after ACLR. This might be attributed to the sensorimotor function is still not completely restored, and affected the neuromuscular control ability (Johansson, Sjolander, & Sojka, 1991).
Evaluation of the coordination and stability of the movement pattern is important after ACLR, owing to the integrity of sensorimotor function is essential for achieving a smooth, stable, accurate movement. Furthermore, inter-joint coordination might provide useful information on how the central nervous system (CNS) organizes the various joints to perform functional activities, which is the relationship between the movements of two joints, including angular positions and velocities (Burgess-Limerick, Abernethy, & Neal, 1993). An excessive variability may also reflect the presence of injuries, risks of injuries or diseases altering motor control patterns (Burgess-Limerick et al., 1993; Haddad, van Emmerik, Whittlesey, & Hamill, 2006). Hence, the purpose of this study was to investigate the pattern and variability of inter-joint coordination during a high-demand activity after anterior cruciate ligament reconstruction.

METHODS: Five subjects (4 men, 1 women) with a history of unilateral ACLR (Age: 22.6±1.1 years old; Height: 173.8±9.3 cm; Weight: 71.6±11.3 kg; Time since surgery: 30.8±19.4 months) five sex-, age- weight- and sport-matched subjects who served as the control group (Age: 22.0±2.1 years old; Height: 172.2±6.3 cm; Weight: 71.2±9.9 kg) were recruited for this study.
All subjects needed performed a single-leg landing followed cutting as quickly as possible (Misonoo, Kanamori, Ida, Miyakawa, & Ochiai, 2012); and three successful trials were collected. First, subjects stood on a 30 cm high platform on their testing leg, while raising their contralateral leg backwards. They were required to drop down and land on a clearly labelled a 40 cm by 20 cm square area in the center of the force plate, which were 30 cm (X) and 5 cm (Y) away from the platform. Subjects should land on their testing leg and push off to their contralateral leg making a 35°-55 ° angle cut. The ACLR group needed to complete above tasks on the reconstructed knee, and the control group only tested the same side. Totally 17 reflective markers were placed on bony landmarks of each subject, specifically on the sacrum and bilaterally on the shoulder, anterior superior iliac spine, medial and lateral femoral epicondyle, medial and lateral malleolus, calcaneus and second metatarsal head. In addition, triads of rigid reflective tracking markers were securely placed bilaterally on the

lateral surfaces of the subject's thigh, shank and dorsum of the foot. Marker trajectories were collected using a 10-camera motion analysis system (VICON, MX13+Oxford Metrics, UK) at a sampling rate of 200 Hz, and filtered using a low-pass, fourth order Butterworth filter with the cutoff frequency set at 12 Hz. Joint angles and angular velocities of the trunk and lower extremities were calculated using Visual3D^{TM} software (C-Motion, Rockville, MD, USA).

A custom written Matlab program (version 7.4; The Mathworks Inc.) was used to calculate the continuous relative phase (CRP). First, sagittal plane joint angle and angular velocity data were interpolated to 100% of a landing phase (between initial contact and takeoff). Phase plots of each joint were then generated by plotting the normalized angular positions (θ) along the x-axis and normalized angular velocities (ω) along the y-axis (Fig. 1). Angular positions and velocities were normalized to a range of between -1 and 1 along both dimensions of phase plane, as suggested previously to minimize the influence of different movement amplitudes and frequencies (Stergiou, Jensen, Bates, Scholten, & Tzetzis, 2001). Phase angles (φ) were calculated as $\varphi = \tan^{-1}(\omega/\theta)$ for each data point of a landing phase (Fig. 2). The CRP, which recognizes as the coordination between two adjacent joints, were then calculated by subtracting the phase angle of distal from that of the proximal joint ($\varphi_{trunk\text{-}hip}$, $\varphi_{hip\text{-}knee}$, $\varphi_{knee\text{-}ankle}$)(Burgess-Limerick et al., 1993).

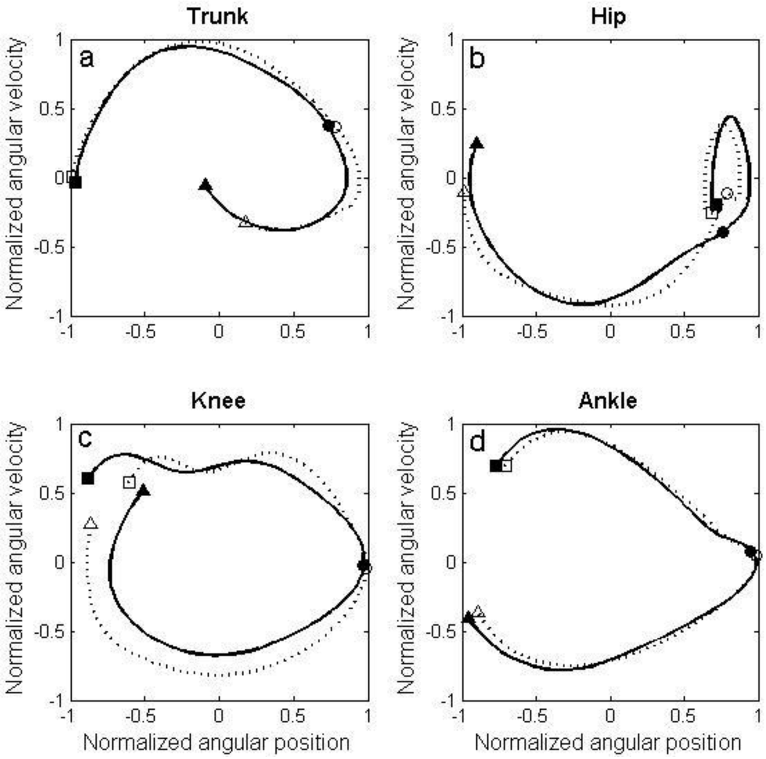

Figure 1: The ensemble-averaged phase plots of the trunk, hip, knee and ankle. Each pattern represents ACLR group (solid lines, black markers) and control group (dotted lines, white markers), respectively. Square markers indicate initial foot contact, circular markers indicate maximum knee flexion and triangular markers indicate end of landing phase.

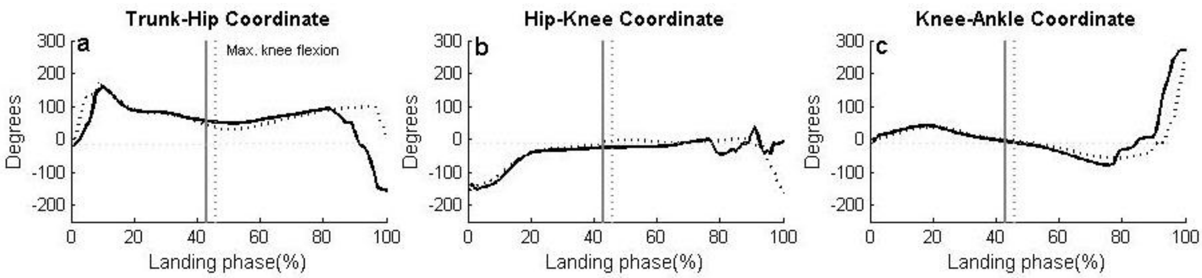

Figure 2: The ensemble-averaged CRP of the trunk-hip, hip-knee and knee-ankle coordination. Each pattern represents ACLR group (solid lines) and control group (dotted lines), respectively.

Cross-correlation measures and root-mean-square (RMS) differences were both used to quantify the similarity of the CRP patterns and joint angles across the entire landing phase, which examined the differences between the ensemble mean curves of the ACLR group and the control group. The cross-correlation measures quantified spatio-temporal differences in the CRP patterns, and the RMS measures quantified the magnitude differences in the CRP patterns. A high cross-correlation coefficient with a low RMS difference would indicate that the two curves are similar (Haddad et al., 2006). Furthermore, deviations phase (DP) was use to quantify the stability of the inter-joint coordination, which calculated by averaging the standard deviations of the ensemble CRP pattern points for the entire landing phase. A low DP value indicates a more stable relationship between the two joints (Stergiou et al., 2001). Nonparametric test (Wilcoxon signed ranks) was used to compare ACLR group and control group (α = .05).

RESULTS: The ensemble-averaged phase plots of the trunk, hip, knee and ankle joints shown in Fig. 1. These trajectories were almost the same for each joint, although small differences existed in knee joint for the reconstructed limb of ACLR (Fig. 1-c). The ensemble-averaged trunk-hip, hip-knee and knee-ankle CRP are shown in Fig. 2. The greater differences between each curve were observed after 80% of landing phase.
The similarities of CRPs and joint angles were demonstrated with RMS differences (Fig. 3). When compared to control group, RMS values were greater in trunk-hip (58.1°) and hip–knee (42.2°) CRP (Fig. 3a) than in knee-ankle (3.1°) CRP and in individual joint angles (range: 1.1°-3.8°) (Fig. 3b).

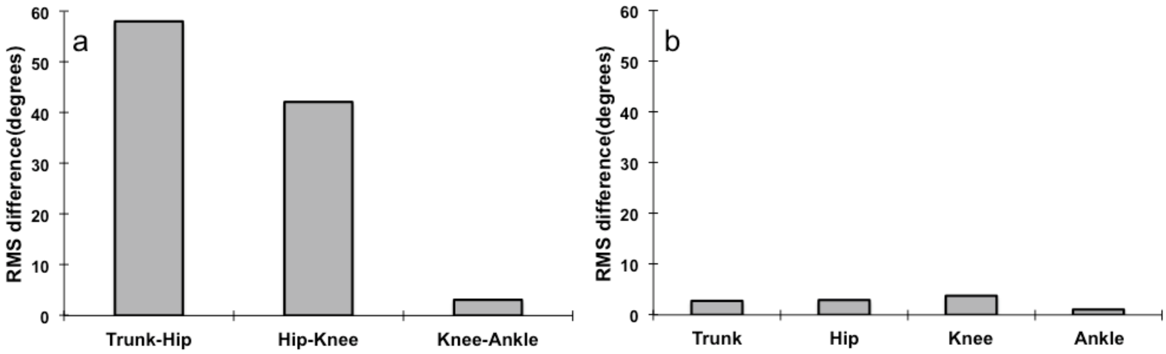

Figure 3: Between-group RMS differences (°) in (a) trunk-hip, hip-knee and knee-ankle CRP patterns and (b) trunk, hip, knee, ankle joint angles over a landing phase.

Cross-correlation measures between ACLR and control group were strong for knee-ankle CRP patterns and joint angles (r^2 > 0.96), but not in trunk-hip (0.39) and hip-knee (0.86) CRP patterns (Fig. 4).

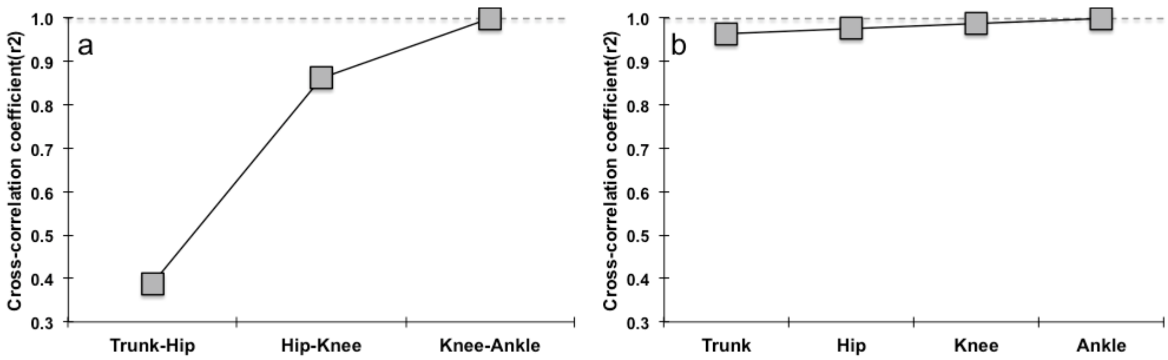

Figure 4: Between-group cross-correction coefficient (r^2) in (a) trunk-hip, hip-knee and knee-ankle CRP patterns and (b) trunk, hip, knee, ankle joint angles over a landing phase.

The DP values of the CRP curves (trunk-hip, hip-knee and knee–ankle) during landing phase are shown in Fig. 5. The ACLR demonstrated higher DP values of the trunk-hip and knee-ankle CRP curves when compared to controls ($p < .05$).

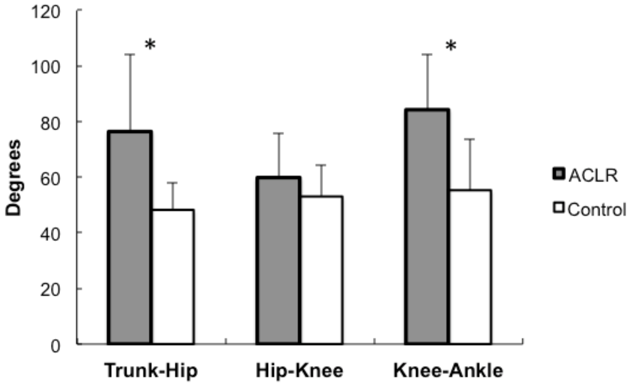

Figure 5: DP values for CRP curves of ACLR and controls

DISCUSSION: Our findings suggested that abnormal landing movements still existed during high-demand activities after ACLR surgery. These results were mainly accomplished by changing the relative phase angles between the two adjacent joints, especially in trunk-hip and hip-knee CRP (high RMS differences and low cross-correlation coefficient)(Fig. 2 and Fig. 3). Although there were also differences in cross-correlation measures and RMS differences of individual trunk, hip, knee and ankle joint angles, these differences were relatively small when compared to CRP. This suggests that only accessing individual's joint motion along might be insufficient to monitor recovery on ACLR subjects. Hence, the use of inter-joint coordination might provide more insights on the neuromuscular control during a high-demand activity.

The variability of inter-joint coordination was significantly affected by ACLR, resulted in higher variability of trunk-hip and knee-ankle coordination on the reconstructed limb. This might be attributed to a compensatory strategy or an adaptation of a new movement pattern.

CONCLUSION: Our finding indicated that ACLR had similar patterns of inter-joint coordination, but with different levels of stability, which may be associated with the insufficient sensorimotor function. Assessing the inter-joint coordination as well as facilitating the coordination in clinical treatments might improve the high-demand activities on ACLR subjects.

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Acknowledgement

This work is particularly supported by "Aim for the Top University Plan" of the National Taiwan Normal University and the Ministry of Education, Taiwan, R.O.C and NSC 102-2410-H-003 -135