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Inter-segmental Postural Coordination Measures Differentiate Athletes with ACL Reconstruction from Uninjured Athletes

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Abstract

Athletes who sustain non-contact anterior cruciate ligament (ACL) injuries and undergo surgical reconstruction exhibit deficits in sensorimotor control, which often impairs lower-limb movement coordination. The purpose of this experiment was to measure the influence of sensorimotor deficits on the ankle-hip coordination of a postural coordination task in athletes following ACL reconstruction. Twenty-two female athletes who were cleared to return to sports participation following ACL reconstruction and 22 uninjured female athletes performed a unilateral dynamic postural rhythmic coordination task at two movement frequencies (0.2 and 0.7 Hz). Athletes with

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Conflict of interest statement

No financial or personal relationships exist between any of the authors and other people or organizations that could inappropriately influence this work.

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ACL-reconstruction exhibited greater ankle-hip relative phase variability and reduced regularity of coupling than uninjured athletes, especially during the 0.2 Hz condition. The results of this study show altered lower extremity coordination patterns in athletes following ACL reconstruction and return to sports participation. The results also indicate that dynamical coordination measures may provide objective measures of sensorimotor deficits following ACL reconstruction and can potentially guide rehabilitation interventions following reconstruction.

Keywords

Anterior Cruciate Ligament injury; Coordination; Balance; Relative phase; Cross-recurrence quantification analysis

The timeline from anterior cruciate ligament reconstruction (ACLR) to completion of post-surgery rehabilitation and return to sport clearance has been accelerated in recent years. This is partly due to advances in graft reconstruction and fixation to restore joint stability to near pre-injury levels and a strong emphasis on the progression through the acute and subacute phases of patient rehabilitation [1]. However, unilateral deficits and asymmetries in neuromuscular control persist after the athlete is cleared to participate in sport for up to 24 months post-reconstruction [2, 3]. Asymmetries in neuromuscular control significantly increase risk of second ACL injury, but this factor is not well understood [4]. Improvement of rehabilitation protocols to address sensorimotor deficits in this population require further understanding of the underlying mechanisms that contribute to neuromuscular control of the involved lower extremity.

Athletic actions (i.e., jumping, landing and pivoting/cutting during running) require the functional organization of groups of muscles and associated neural and connective tissues into autonomous units termed *coordinative structures*. These coordinative structures must maintain a blend of stability and flexibility that enable the athlete to effectively perform in a variety of contexts [5]. The knee joint plays an important role in the modulation and transfer of neural inputs to function between other components in the lower kinetic chain—specifically providing a conduit for the transmission of sensory (i.e., proprioceptive) information between various joints (e.g., ankle and hip) during athletic maneuvers. Disruption to the flow of sensory information that results from an ACL rupture may decrease the quality of sensory feedback in the lower extremity, or even sever the informational link completely. This disruption to sensory pathways may lead to a reduction in neuromuscular control and a destabilization of coordinative structures leading to impaired motor performance.

One way to measure the extent to which sensory information is compromised following ACLR is through measures of coordination performance (i.e., *relative phase*) during multi-joint postural coordination tasks [6, 7]. Relative phase (ϕ) quantifies the difference in the *phase angles* of two oscillating joints and can be used to describe the relational positioning of the joints in their respective cycles. The standard deviation of ϕ ($SD\phi$) is indicative of coordination stability (lower $SD\phi$ indicates greater stability). The primary benefits of employing such tasks with patients following ACLR compared to previous tasks that have allowed for quantifying the relative phase between lower limb joints in this population [8, 9] are (1) the postural coordination task is a closed-chain task that can be utilized throughout the various stages of athlete rehabilitation, and (2) if decreased coordination stability is observed in patients following ACLR during such an elementary postural control task then it follows that these deficits would impact stability in complex athletic actions as well. Thus, this task has the potential to provide a proof-of-concept for development of a clinical assessment tool to identify deficits throughout the time-course of rehabilitation.

The purpose of this study was to determine whether sensorimotor deficits that follow ACLR persisted following clearance for return to sport, and in turn, whether they would compromise ankle-hip coordination during performance of a unipedal postural coordination task. Based on previous work we hypothesized that, following ACLR, individuals would exhibit less stable coordination patterns (higher $SD\phi$) than uninjured controls [9, 10]. This effect was predicted to be more pronounced during a low movement-frequency condition, as the slower, sustained movements performed in this condition were expected to be more challenging. $SD\phi$ alone cannot parse out the underlying causes for changes in stability as these effects could be isolated to two independent, but not exclusive, mechanisms—a decrease in the strength of joint coupling (i.e., a lower deterministic coupling causing a decrease in coordination between ankle and hip angular excursions over time) or an increase in neuromotor noise [11]. Therefore, we also employed a nonlinear time series analysis, cross-recurrence quantification (CRQ), to examine the time-correlated activity between the ankle and hip. CRQ provides a measure of stability that can distinguish between the possible underlying causes of stability change. Accordingly, we hypothesized that the decreased coordination stability present in patients following ACLR would result from both weaker coupling and noisier ankle-hip patterns than those observed in the performance of the matched controls.

Method

Participants

Twenty-two females following primary, unilateral ACLR with hamstrings tendon or bone-patellar tendon-bone autografts participated (M age 16.7 ± 2.4 years; M height 164.2 ± 6.9 cm; M weight 70.1 ± 11.8 kg). All had completed rehabilitation and were cleared to return to sport participation by their physical therapist and surgeon ($M = 8.5 \pm 2.5$ months from surgical reconstruction to time of testing, and all athletes participated in the experiment within four weeks of their return to sport date). All athletes reported to be completely pain free when participating in activities of daily living. Exclusion criteria included prior history of additional ACL injury, recent injury to the spine, hips, ankles or contralateral knee in the last 12 months, or failure to return to prior sport. Twenty-two athletes with no prior history of injury were used as a control group (M age 16.6 ± 2.3 years; M height 164.0 ± 5.8 cm; M weight 59.4 ± 8.1 kg). They had no recent history of injury to the spine, hips, knees or ankles in the past 12 months, reported no pain during activities of daily living, and were matched to achieve the same proportion of dominant to non-dominant legs as the ACLR group. The operational definition of the *dominant leg* was the leg the participant would use to kick a ball as far as possible.

Apparatus

Participants were instrumented with 37 retro-reflective markers on the sacrum, PSIS, sternum and bilaterally on the shoulder, elbow, wrist, ASIS, greater trochanter, mid thigh, medial and lateral knee, tibial tubercle, mid shank, distal shank, medial and lateral ankle, heel, dorsal surface of the midfoot, lateral foot (5th metatarsal) and toe (between 2nd and 3rd metatarsals). Three-dimensional motion data were recorded by a ten-camera digital motion capture system (Motion Analysis Corp., Santa Rosa, CA) and post-processed with *EVaRT* (Version 4 Motion Analysis Corp., Santa Rosa, CA) and *Matlab* (Mathworks, Inc., Natick, MA) software.

Procedure

Participants gave informed consent prior to participation. The Institutional Review Board approved all procedures. Participants first completed a standing reference trial. For the postural coordination task, participants stood on a single leg and tracked the anterior-

posterior (AP) movement of a square target (15.7 cm horizontal $\times$ 15.7 cm vertical, subtending $8.92^\circ \times 8.92^\circ$ visual angles) presented on a computer monitor at eye level, 1 m away. The target oscillated at either a low (0.2 Hz) or high (0.7 Hz) frequency. Participants tracked the target with the head and maintained a constant perceived distance between the head and target by moving in synchrony with and matching the amplitude of the target oscillations (apparent amplitude = 44 cm). This amplitude was slightly higher than the largest amplitude (35 cm) used in previous studies [6, 7]. Participants were not explicitly instructed to produce oscillations about the ankle or hip, nor were they instructed to adopt a particular coordination pattern. The coordination patterns they produced were thus spontaneously selected to serve the goal of tracking the target (Figure 1). A successful trial constituted completion of 10 oscillation cycles while maintaining the position of the foot on the floor. If the subject lost balance during the trial prior to the completion of 10 cycles, data collection continued until 10 uninterrupted, steady state cycles were completed. All participants were able to meet this criterion on each trial. Only the subset of data corresponding to the 10 completed cycles was analyzed. Four randomized trials (two frequencies on each leg) were performed. Only data from the injured leg of the ACLR group, and matched leg of the control group, were analyzed. Data were sampled at 60 Hz.

Data reduction and analysis

Kinematic data were filtered in *Matlab* using a low-pass Butterworth filter (5 Hz cut-off frequency) based on a residual analysis. Custom *Matlab* routines (modified from KineMat Toolbox [12]) were used to quantify sagittal plane ankle and hip joint angles. Data for approximately 10% of all participants (four total trials) were too irregular (i.e., the peak-to-peak coupling between the ankle and hip was not quantifiable) to permit objective extraction of joint angle peaks required for relative phase calculations (one trial each for two participants following ACLR and two control participants). These trials were replaced with group averages for the current analyses.

Relative phase analysis—The coordination of ankle and hip excursions was calculated by measures associated with hip-ankle ϕ using customized *Matlab* routines. The previously filtered joint position and velocity data were smoothed using a time window of 0.42 sec to facilitate identification of peaks in the time series. Phase angles (θ_i) were calculated from the smoothed time series according to $\theta_i = \arctan(\dot{x}_i / \Delta x_i)$, where $\dot{x}_i$ is angular velocity at sample i (normalized by the trial mean angular frequency, which was determined using a peak-picking algorithm to identify the mean number of oscillation cycles per unit time), and Δx_i is the angular displacement at sample i (angular position at sample i minus the trial mean angular position). Continuous ϕ was calculated at each sample as the difference between the ankle and hip phase angles, $\phi_i = \theta_{\text{ankle}} - \theta_{\text{hip}}$. The within-trial mean ϕ (ϕ_0) for each time series was obtained by averaging the ϕ time series for a given trial. The within-trial SD ϕ for each ϕ time series was computed.

Cross-recurrence quantification—The unfiltered, non-smoothed ankle and hip joint angle time series were submitted to CRQ [13–16]. CRQ is a multivariate nonlinear analysis in which time-correlated activity between two signals (in this case sagittal motion of ankle and hip joint angular position) is quantified by embedding the pair of time series in a multidimensional, time-delayed embedding space. Each time series was embedded in a three-dimensional and a four-dimensional space for the 0.7 Hz and 0.2 Hz conditions, respectively, based on false nearest neighbors analysis and using the original signal and time-delayed copies of it as dimensions $x(t)$, $x(t + \text{delay})$, $x(t + [2 \times \text{delay}])$, and so forth. Delays of 25 and 100 data points were used for the 0.7 Hz and 0.2 Hz conditions, respectively (a delay of one-quarter cycle of a sinusoid guarantees the minimal average mutual information between points separated by that distance and, accordingly, results in

nearly orthogonal dimensions in embedding space [17]). Inclusion radii for considering points recurrent in the embedding space were 15% and 26% of the maximum distance separating points in the embedding space for the 0.7 Hz and 0.2 Hz conditions, respectively. These values optimize the sensitivity of identifying recurrent points without oversaturating the cross-recurrence matrix. Percent cross-recurrence (%CREC), the percentage of shared joint angular positions in the embedding space, is quantified by tracking when the two time series are in similar locations (i.e., the embedded configuration of one time series is within the radius of the embedded configuration of the other). %CREC has demonstrated to be inversely proportional to noise magnitude in simulations [13] and under empirical manipulations of noise [14]. The length of the longest sequence of consecutive recurrent configurations, cross-maxline (CML), is sensitive to changes in the strength of coupling between two signals, independent of changes in noise magnitude [13–15]. Percent cross-determinism (%CDET) provided a measure of coordination regularity between the two joints.

Statistical analysis—The dependent measures (ϕ_0 , $SD\phi$, %CREC, %CDET, and CML) were submitted to 2 (ACLR vs. control group) $\times$ 2 (low vs. high frequency) mixed-model ANOVAs with $\alpha = .05$. Bonferroni-corrected paired-samples *t*-tests for follow-up comparisons were employed where appropriate.

Results

Mean ankle-hip relative phase (ϕ_0)

All participants produced anti-phase ($\phi \approx 180^\circ$) coordination on every trial ($M = 182.30^\circ \pm 9.66^\circ$ for the ACLR group and $M = 181.03^\circ \pm 6.51^\circ$ for the control group, and overall 95% confidence interval of $179.90^\circ - 183.42^\circ$). ϕ_0 values greater than 180° indicate that both groups exhibited a slight phase lead by the ankle. No instances of in-phase ($\phi \approx 0^\circ$) coordination occurred, nor did any transitions from anti-phase to another phase mode. ANOVA revealed no significant effects ($ps > .05$).

Ankle-hip coordination stability ($SD\phi$)

A group $\times$ frequency interaction was observed [Figure 2; $F(1,42) = 4.12$, $p = .049$] for $SD\phi$. Post-hoc analyses revealed a significant difference between the ACLR and control group only during the low-frequency condition [$t(21) = 4.07$, $p = .001$; $M = 33.84^\circ \pm 13.79^\circ$ and $21.87^\circ \pm 5.23^\circ$, respectively]. No other comparisons were significant ($ps > .008$, the adjusted significance level).

CRQ

A significant group main effect was present for %CDET, $F(1,42) = 4.39$, $p = .042$, indicating a greater tendency for the hip and ankle trajectories produced by controls to share patterns of consecutive data points, compared to the ACLR group ($M = 99.46\% \pm 0.36\%$ and $99.27\% \pm 0.44\%$, respectively). The interaction was not significant ($p > .05$).

Significant main effects of frequency were present for %CREC [$F(1,42) = 63.63$, $p < .001$], CML [$F(1,42) = 22.94$, $p < .001$], and %CDET [$F(1,42) = 111.34$, $p < .001$]. %CREC was greater during the low-frequency ($M = 8.43\% \pm 4.11\%$) than the high-frequency ($M = 3.47\% \pm 1.61\%$) condition. CML was also higher during the low-frequency than the high-frequency condition ($M = 230.43 \pm 149.71$ and 122.45 ± 60.60 , respectively). %CDET was greater in the low-frequency ($M = 99.75\% \pm 0.24\%$) than high-frequency ($M = 98.96\% \pm 0.54\%$) condition, indicating that ankle and hip trajectories shared patterns of consecutive data points more often during the low-frequency condition.

Discussion

The ACLR group exhibited lower coordination stability (higher $SD\phi$) than the control group during the low-frequency condition, accompanied by a significant group main effect for %CDET, with higher %CDET for the control than the ACLR group. Although small, the group differences are nonetheless meaningful. The reduced stability of low-frequency coordination patterns produced by the ACLR group was likely due to decreased regularity of the coupling between the ankle and hip (lower %CDET).

The $SD\phi$ and %CDET findings could reflect declines in proprioceptive functioning following ACL injury and reconstruction [18–24]. The absence of functional mechanoreceptors in the graft tissue may disrupt the coupling that coordinates oscillations of the ankle and hip [25–27], or diminish the capacity to produce stabilizing torques about the knee to resist torques imposed on the knee while oscillations occur about the ankle and hip. Failure to accurately register changing torques, loads and joint positions in the lower limb can disrupt coordination by reducing the ability to moderate forces acting on the lower limb through neuromuscular control of the hip and trunk. This may increase the risk for future lower extremity injury or degenerative conditions such as osteoarthritis [21, 28, 29].

The hypothesized group effects for %CREC and CML were not observed, so the results do not support the hypothesis that differences in coordination stability arise from differential levels of noise or coupling strength. However, higher values of %CREC, %CDET, and CML were observed in the low-frequency condition. This may be attributed to the challenge of producing sustained, graded muscle activity in the low-frequency condition, in comparison to the rapid bursts of muscle activity required in the high-frequency condition. It is possible that steady control results in an overly constrained and thus more rigid and potentially less adaptable pattern of ankle-hip coordination. This would limit balance performance, especially in athletes following ACLR, and may be a predictor of an individual's ability to regulate ankle-hip coordination using the knee. An absence of knee joint stability may represent a clinically significant impairment in an athlete seeking to return to high-level sports that require the ability to form robust coordinative structures to execute precise and dynamic movements, especially since the disruption of mechanoreception (i.e., proprioceptive sensitivity) in the ACL following such an injury is likely to persist.

The current task was a unipedal version of the bipedal task employed previously [6, 7]. In overall agreement with prior work examining performance of this unipedal task by professional ballet dancers, we observed only anti-phase ($\sim 180^\circ$ relative phase) ankle-hip coordination, regardless of target frequency [10]. This mode was chosen spontaneously; participants were not instructed to adopt any particular mode. Anti-phase was apparently the preferred mode for negotiating the particular constraints of this task. In-phase postural coordination is more energetically efficient than anti-phase, but in-phase may not permit the production of sufficient levels of torque required to track the target with the head while standing on one leg [30].

The development of measures sensitive to neuromuscular and proprioceptive deficits associated with ACL injury may aid in the delineation of ACL injury mechanisms, identification of predictors of ACL injury risk, and optimization of rehabilitation subsequent to ACL injury. The postural coordination task combined with relative phase and CRQ measures may be useful for identification of functional sensorimotor deficits associated with ACLR. Further prospective research is warranted to evaluate whether these identified deficits created a predisposition to initial ACL injury or, alternatively, that the traumatic nature of ACL injury initiates sensorimotor deficits which may warrant targeted

rehabilitation interventions. Further investigations should aim to determine the potential impact of these functional deficits on second ACL injury risk.

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Figure 1.

(a) Example of the postural coordination task. From left to right: 1) the participant is swaying in a posterior direction as the visual target oscillates towards her (bottom 1), 2) the participant is swaying in an anterior direction as the visual target oscillates away from her (bottom 2), and 3) the participants is returning to the posterior position as the target is again oscillating towards her (bottom 3), completing one complete oscillation/postural sway cycle, (b) time series of one anterior-posterior oscillatory cycle of the hip and ankle angular position, (c) sample time series of hip and ankle angular position for one complete trial (10 oscillations) during which frequency remained steady at 0.7 Hz for the duration of the trial with the dashed box indicating the time series in (b), and (d) sample time series of relative phase. The anti-phase pattern is apparent in (c) by the co-occurrence of peaks in hip angular position with valleys in ankle angular position, and vice versa, and in (d) by oscillations of relative phase ϕ about a mean of approximately 180°.

Figure 2.
 $SD\phi$ as a function of group and oscillation frequency.