Original Research

Interpersonal Coordination between Female Soccer Players: Leader-Follower Roles within a Collision-Avoidance Task

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Background/Purpose

Return to sport decision-making may be improved by assessing an athlete's ability to coordinate movement with opponents in sport. The purpose was to investigate whether previous injuries associated with female soccer players' interpersonal coordination during a collision avoidance task. The authors hypothesized that external perturbations would disrupt the strength and stability of coordinated movement, and that individuals with a history of injury would be less likely to recover coordinated movement.

Study Design

Cross-Sectional

Methods

Nine female athletes with a history of lower extremity injuries and nine without injuries were paired into dyads. Each dyad completed twenty trials of an externally paced collision-avoidance agility task with an unanticipated perturbation. Participant trajectories were digitized and analyzed using cross-recurrence quantification analysis (CRQA) to determine the strength and stability of interpersonal coordination dynamics. Trials in which participants with injury history assumed leader or follower roles within each dyad were then used to study how dyadic coordination varied across task stages (early, perturbation, and late) using linear mixed effect models. Cohen's d effect sizes were calculated to demonstrate magnitude of differences. In exploratory analysis, psychological readiness (i.e., self-reported knee functioning, fear of injury, and risk-taking propensity) was evaluated for their association with leader-follower status.

Results

Perturbation disrupted the strength (R2=0.65, p<0.001, early=49.7±1.7, perturbation=41.1±1.7, d=0.39) and stability (R2=0.71, p < 0.001, early=65.0±1.6, perturbation=58.0±1.7, d=0.38) of interpersonal coordination regardless of leader-follower status. Individuals with injury history failed to restore coordination after the perturbation compared to control participants (injury=44.2.0±2.1, control=50.8±2.6, d=0.39). Neither demographic nor psychological measures were associated with leader-follower roles (B=0.039, p=0.224).

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Conclusion

Individuals with a history of lower extremity injury may have a diminished ability to adapt interpersonal coordination to perturbations, possibly contributing to a higher risk of re-injury.

Level of Evidence

3

INTRODUCTION

With an estimated 240 million players in over two hundred countries and territories, soccer is often considered the world's most popular sport.[1] High rates of injury (30.3 injuries/1000 hours) result in socioeconomic and quality of life burdens,[2] and they have motivated decades of research and practical efforts towards primary and secondary injury prevention. The nature of soccer involves high-intensity movements, coordinated action between teammates, and evasive collision-avoidant actions with opponents. This contributes to the majority of lower extremity injuries occurring through non-contact mechanisms (60-90%), which primarily include hamstring strains, anterior cruciate ligament (ACL) tears, and ankle sprains.[2,3] Once an individual experiences injury, they are at increased risk for future injuries,[4] a risk that is often attributed to faults in neuromuscular control strategies.[2,5,6] Yet, isolated environments used in testing neuromuscular control are not representative of games in which players continuously interact with other independent actors (i.e., interpersonal dynamics). While there is a body of literature that supports the importance of controlling interpersonal dynamics to team success,[7-12] whether and how previous injuries influence interpersonal dynamics remains unclear.[2]

Sports are complex systems composed of an intricate network of continuously evolving tasks and environments.[12-14] Athletes often face challenging interpersonal interactions and perturbations from their environment that require them to adapt their movements.[15] For example, athletic movements are influenced by the movements of other players. Higher injury rates in defensive players[16-18] are theorized to occur in part because defenders need to react quickly to evasive offensive strategies.[16,18] In a sense, defenders must follow their opponents lead. Furthermore, psychological constructs, such as confidence, fear of pain-related movement, and self-efficacy, are risk factors in sport-related injury,[19-24] indicating that there are complex interactions between physical capacity and psychological readiness. Interestingly, female athletes frequently perceive the risk of re-injury as beyond their control,[22] suggesting athletes are unprepared to control the 'chaotic' environment of sport.[25] These findings challenge the construct validity of rehabilitation and return to sport protocols that fail to recreate the complex sport environment or elicit comparable behavioral demands.[13,25-28] This protocol shortfall may be a contributor to the elevated risk of re-injury upon returning to sport after rehabilitation. Return to sport decision-making may be improved with a screening tool to assess an athlete's ability to control interpersonal dynamics in a continuously evolving task, and to determine whether psychological factors influence interpersonal dynamics.[13,27]

Therefore, this investigation focused on whether factors such as injury history and psychological readiness associate with interpersonal dynamics. To do so, interpersonal interactions were examined during a novel agility-based task during which participant dyads coordinated their movements along intersecting paths. The task included perturbations designed to temporarily disrupt coordination. To quantify the predictability (i.e., "strength") and duration (i.e., "stability") of interpersonal coordination during a collision avoidance task, this study used cross-recurrence quantification analysis (CRQA), an analytic approach used to describe distinct dynamics between two interacting people.[27] The authors hypothesized that participants would naturally assume *de facto* leader-follower roles within dyads and would develop and retain a highly coordinated movement pattern. Additionally, it was hypothesized that external perturbations would disrupt the strength and stability of their coordinated movement, and that individuals with a history of injury would be less likely to recover coordinated movement than controls. To explore the degree to which a player's psychological outlook may have influenced movement pattern coordination within the task, differences in psychological measures between dyad members were characterized. The authors hypothesized that individuals with histories of injury and lower psychological readiness would predict the *de facto* follower within each dyad.

METHODS

EXPERIMENTAL DESIGN

This study used a cross-sectional design with each dyad completing twenty trials within a single visit. Independent variables were leader-follower status (with/without injury history) and task stage (early, perturbation, and late).

PARTICIPANTS

High-school and collegiate female soccer players in the geographical area (metropolitan area with population >250k) were recruited via flyers, communication with coaching and athletic trainers, and word-of-mouth recruitment. To be eligible, participants had to be actively playing on a high school or collegiate soccer team and between the ages of 15 and 25. Participants were excluded if they self-reported a current injury that limited participation in soccer or an inability to run 30 minutes with multiple changes in direction. All adult participants provided written and verbal informed consent, while legal guardians gave written and verbal informed consent on behalf of minor participants.

Additionally, minors provided written and verbal assent to participate before completing any study procedures. Our University Institutional Review Board approved this study.

INDEPENDENT VARIABLES AND MEASURES

As predictor variables, a range of psychological and physical measures were measured. Self-reported knee function was assessed using the International Knee Documentation Committee (IKDC) Subjective Knee Evaluation, developed by Irrgang et al.[29,30] This scale has demonstrated high reliability and validity in measuring knee function in athletic populations.[29,30] Fear of movement was measured using the Tampa Scale of Kinesiophobia (TSK-11), created by Woby et al.[31] The TSK-11 has been validated for its reliability in capturing fear-related constructs in musculoskeletal disorders.[31,32] Psychological readiness for sport was assessed using the Anterior Cruciate Ligament Return to Sport after Injury (ACL-RSI) scale, authored by Webster et al.[33] This scale has been widely used to measure athletes' emotion, confidence, and risk appraisal when returning to sports and has shown strong psychometric properties, including a Cronbach's alpha of 0.92.[34,35] Risk-taking propensity was assessed using the General Risk Propensity Scale (GRiPS), which is considered reliable for measuring risk-taking behaviors in athletic contexts.[36] Physical activity level was also recorded using the Tegner Activity Score (TAS), developed by Briggs, et al.,[37,38] and perceived task workload was recorded using the NASA Task Load Index (NASA-TLX) by Hart & Staveland.[39] Both TAS and NASA-TLX have been validated for their reliability and responsiveness in athletic and high-workload settings, respectively.[37-39]

DEPENDENT VARIABLES AND MEASURES

Cross recurrence quantification analysis (CRQA) is particularly useful for uncovering distinct dynamics between two interacting people[40] and analyzing data from a complex dynamic systems perspective. For instance, CRQA has been used in prior work to examine interpersonal motor coordination in the context of dyadic problem-solving,[41] supra-postural task demands,[42] developmental disability,[43] and dance.[44] The methodological details and mathematical description of CRQA have been documented extensively elsewhere.[40,45,46] In brief, CRQA quantifies the shared locations (i.e., cross-recurrence) of two time-series in a reconstructed phase space. These shared locations (in time and space) are illustrated as dark points on cross-recurrence plots (CRPs; as shown in Figure 1d). The resultant structure and patterns in CRPs (e.g., the number and length of diagonal lines in the plot) can then be quantified to describe how the two time-series unfold together over time and reveal information about the coordination of the systems under study. Furthermore, an extension of CRQA, diagonal-wise cross-recurrence (DWCR),[40] permits the quantification and analysis of leader-follower dynamics within an interacting dyad (i.e., whether one member of the dyad is leading the coordinated behavior).

Strength of Coordination. In this study, CRQA was used to determine coordination strength as defined by determinism (DET) and mean line length (MEANLINE). DET was the percentage of recurrent points that formed diagonal lines in the CRP. Higher DET indicated more deterministic coordination between members of a dyad with stronger and more frequent coupling (as opposed to random). High DET suggested that the system transitioned less frequently between different states and tended to remain within recurrent patterns for longer durations, indicating the participant's locations unfolded similarly over time without falling out of synchronization. MEANLINE indexed how long the average cross-recurring trajectory was,[47] with higher MEANLINE indicating that dyads achieved more continuous, or longer duration, coordination on average.

Stability of Coordination. Where DET and MEANLINE characterized diagonal line structures and represented the strength of coordination between dyads over time, laminarity (LAM) and trapping time (TT) characterized vertical line structures and represented temporal persistence or stability of each participant's location while the other participant's location varied over time. LAM was the percentage of recurrent points that formed vertical line structures in the CRP. Higher LAM indicated a greater redundancy in the system, indicating persistence or stability in the observed recurrent patterns without changing coordination strategy. TT was the average length of time that the dyad remained trapped within laminar points. Higher TT indicated a longer period where one member of the dyad was "trapped" with respect to the other's location over time (i.e., temporal persistence).

EXPERIMENTAL PROCEDURES

Screening Procedures and Dyad Assignment. An initial screening survey was used to gather self-reported demographic information about participants, including their years of soccer experience, physical activity level, and pertinent self-reported injury history. Injury history was operationally defined as history of lower extremity surgery (lifetime) or lower extremity injury resulting in >two weeks of lost time from participation in soccer within the prior six months.

Individuals with a history of injury and those without were deliberately paired into dyads. From the participant pool, dyads were randomly assigned using anonymized scheduling with 1:1 assignment. Participants from each group self-scheduled their visits to a scheduling block using an online scheduling software (Calendly, Remote, www.calendly.com). Participants were blinded to factors determining group allocation (i.e., injury history, years of soccer experience).

Participant Setup. When participants arrived at their study visit, they were outfitted with retroreflective markers, which were adhered to boney landmarks on the pelvis and thorax. Participants were randomly assigned to one of two marker sets including the following landmarks (set 1: bilateral ASIS, bilateral PSIS, C7 spinous process, and right twelfth rib; set 2: bilateral ASIS, bilateral iliac crest, and median sacral crest). Two marker sets were used to differ-

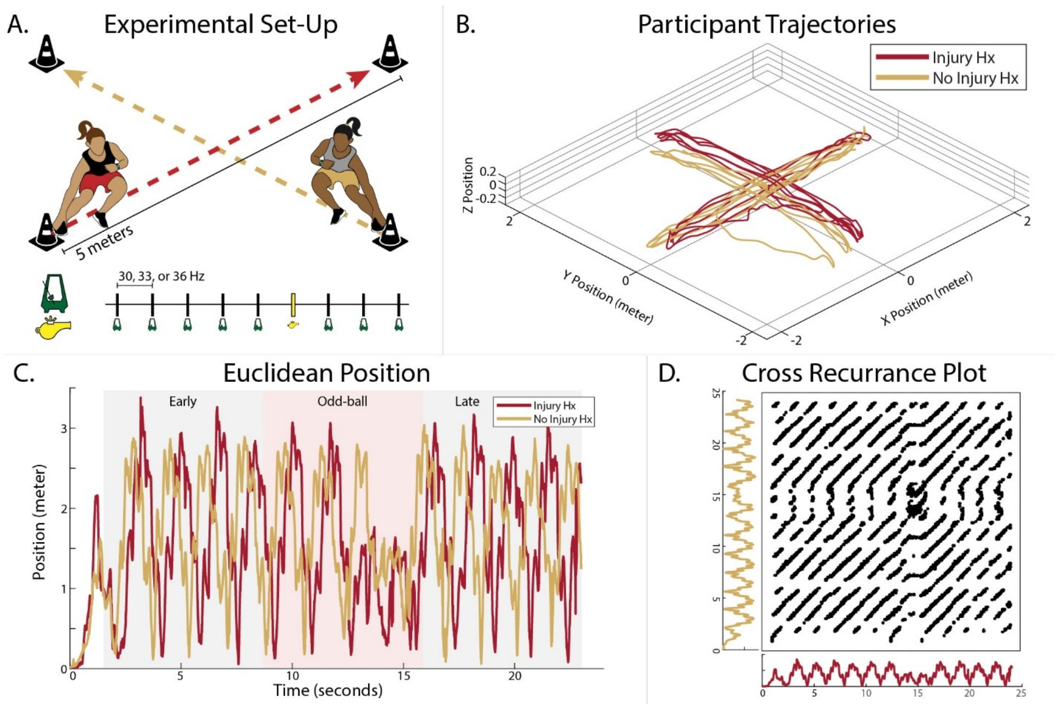

Figure 1. A. Schematic of collision-avoidance task. Upon oddball tone (whistle) within the audio, participants would make a 90 degree turn at the center and continue the task (e.g., red would follow gold path and vice versa). B. Raw Cartesian position of the dyad movement. C. Euclidean displacement of participant position. D. The time series subjected to CRQA analysis, producing the cross-recurrence plot.

Abbreviations: Hx, History.

entiate participants in data processing. Prior to testing participants completed a static calibration trial while standing in the anatomical position.

Data Acquisition and Procedures. A twelve-camera motion capture system (Raptor E-Digital Cameras, Motion Analysis Corporation, Santa Rosa, CA) captured participant location and maker trajectories with a sampling frequency of 120 Hz throughout each agility task trial. Data were acquired using Cortex software (v. 7.10, Motion Analysis Corporation, Santa Rosa, CA). Participant markers were visible throughout the agility task course, which was centered within a 25 ft^2 capture area.

Four pylons were organized in a square with 3.5-meter sides (5-meter hypotenuse) (Figure 1a). The task involved running diagonally across the square area, following paths that intersected perpendicularly, necessitating that participants avoid colliding with each other. Each trial lasted for 24 seconds and included a three-second countdown at the beginning.). The trials were paced using custom audio tracks featuring a metronome set to play at one of three frequencies: 30, 33, or 36 beats per minute (Hz). Each track contained an oddball tone—a whistle sound—randomly inserted in place of a metronome beat. Upon hearing this whistle, participants were instructed to execute a sharp 90-degree turn before continuing along their intersecting paths. Tracks and direction of the turn were selected at random (using a custom MATLAB script [v. R2019b, MathWorks, Natick, MA]) for each trial to prevent participants from anticipating the pace.

Prior to beginning the experiment, each participant was asked to complete one practice trial by running between the pylons to a sample audio track. They did so independently, without the other participant on the course. To ensure uniformity in the participants' experience, participants were provided standardized instructions using a script that emphasized the importance of timing their movements to reach each pylon synchronously with the metronome beats. A total of twenty trials were conducted for each pair of participants (dyad), incorporating two-minute rest breaks between trials and a longer 5-minute break after completing half of the trials. This structure was intended to mitigate fatigue and maintain the quality of the data collected.

DATA PROCESSING AND REDUCTION

Following data collection, Cortex software (v. 7.10, Motion Analysis Corporation, Santa Rosa, CA) was used to fill marker gaps, identify unnamed markers, and prune ghost markers. Center of mass trajectories were calculated for each participant and trial using Visual 3D software (C-Motion, Germantown, MD) using bilateral PSIS and bilateral ASIS markers for each participant and exported in cartesian coordinate planes (Figure 1b). The three-dimensional cartesian coordinate paths were then collapsed into two dimensions as Euclidean displacement using a custom MATLAB (v. R2019b, MathWorks, Natick, MA) script (Figure 1c).

CROSS-RECURRENCE QUANTIFICATION ANALYSIS AND DIAGONAL WISE CROSS-RECURRENCE ANALYSIS

Resultant center of mass trajectories of the two members of the interacting dyad from each trial were then subjected to CRQA (Figure 1d) to index coordination strength (DET and MEANLINE) and stability (LAM and TT) as described above. It is important to note that recurrence metrics are not absolute quantities. Thus, the *relative* pattern of change is considered most important for achieving the aims of this study.

To determine leader follower dynamics, DWCR considers a narrower band of the entire CRP, resulting in a window around the main diagonal line of the plot where x = y (i.e., line of incidence).[42] In the current study, this window was restricted to ± 1.5 seconds around the line of incidence for each trial. Recurrence points that fell on the line of incidence represented moments where the two time-series exhibited 0-lag synchronization over consecutive samples. Recurrence points that fell on diagonal lines above or below the line of incidence indicated situations where one time-series was revisiting a state previously occupied by the other at a given time delay (i.e., >0 lag in either direction). In other words, members of the dyad were coordinated with a lag (i.e., one was leading the other). MAXLAG is a metric of DWCR that indexed the lag at which cross-recurrence was highest within the set window around the line of incidence. Accordingly, a MAXLAG of 0 indicated that the most frequent dyad interaction was perfect synchrony (i.e., occupying the same space at the same time). A positive or negative MAXLAG indicated that the maximum number of recurrent points in a single diagonal fell above or below the line of incidence and that similarities in dyad movement occurred most frequently with a lag (i.e., one participant was leading/following the other).

To achieve the aims of the study, both CRQA and DWCR were performed on windows of the data surrounding the odd-ball tone. As such, each trial was divided into three, non-overlapping seven-second temporal windows (e.g., early, odd-ball, late), to examine the effect of the perturbation on the stability of the leader-follower relationship. Trials with an odd-ball tone occurring outside of the middle seven-second temporal window (i.e., odd-ball stage) were excluded so as not to corrupt the early and late temporal windows (50 of 170 trials). CRQA and DWR were completed using custom R scripts in RStudio (v 1.4.1106, RStudio, Inc., Boston, MA). CRQA parameters were determined for each trial using the routine of Coco and Dale.[40] Radius was adjusted per trial to achieve a fixed recurrence rate between with a lower bound of 2.25% and upper bound of 2.5%, following prior recommendations.[47] Embedding dimension ranged from 4 - 10 (5.17 ± 1.04), delay ranged from 3 – 51 (24.85 ± 5.75), and radius ranged from 0.24 – 0.74 (0.39 ± 0.08). Prior to phase space reconstruction and CRQA calculations, signals were centered about their respective means. MAXLAG values for each stage of each trial were extracted from DWCR and used to assign participants within each dyad the leader or follower designation. Because leader-follower status is an emergent property of dyad interaction, leader-follower status was used to reallocate groups for statistical analysis. In other words, each trial was characterized in the context of whether the participant with a history of injury or the control became the *de facto* follower. Furthermore, within each dyad, the majority leader was determined using counts of leader-follower status (whomever led for most of the 20-trials).

STATISTICAL ANALYSIS

To ensure adequate data for CRQA, a minimum of 120 trials were included based on recommendations from previous authors.[42,43] Differences in demographic and self-reported function were assessed using independent *t*-tests, while coordination strength and stability were evaluated with a linear mixed effect model. In this model, leader-follower status, stage, and their interaction were fixed effects and each dyads' trial were random effects. Tukey's Honestly Significant Difference Test confirmed differences between groups and stages. Cohen's d effect sizes were calculated to demonstrate magnitude of differences, interpreted as small (⩾0.2), medium (⩾0.5), or large (⩾0.8) effects. Lastly, participant descriptors were used to determine leader-follower status using logistic regression, including participant descriptors that were statistically different within dyads as predictor variables. *A priori* this could have included age, height, weight, years playing experience, IKDC, ACL-RSI, TSK-11, and GRiPS. All data met assumptions of normality of residuals. No violations of sphericity (Mauchly test) were observed. Due to the experiment's novel statistical analysis, a traditional power analysis was not possible for the primary analyses. Observed power from these analyses is provided in Supplement 1. Secondary analyses using logistic regression were underpowered and should be considered exploratory. Statistical Analysis Software (SAS) v 9.4 (SAS Institute, Cary, NC) was used for all statistical analyses, with a significance level of $p<0.05$.

RESULTS

A total of eighteen women's collegiate soccer athletes between the (age = 19.7 ± 1.6 years) were recruited for and enrolled in this study. Participant demographics and self-reported function are presented in Table 1. Participants with a history of lower extremity injury reported lower ACL-RSI scores compared to their uninjured control counterparts (*d* = -1.15 [0.16, 2.15]). Participants with lower extremity injury were heterogenous regarding injuries. Reported histories included primary unilateral ACL reconstruction (n = 2), bilateral ACL reconstruction (n = 2), unilateral meniscectomy (n = 1), hamstring strain (n = 1), ankle syndesmosis sprain (n = 1), Lisfranc fracture (n = 1), and avascular necrosis of sesamoid bones of great toe (n = 1). One dyad completed only ten trials due to the participant's aggravation of low back pain that was not disclosed prior to beginning the task but was reported after the 10th trial. Available data from this dyad were retained because both participants had still met inclusion criteria and group allocation was not affected.

Table 1. Participant Demographics (mean ± SD)

	Overall	Control	History of Injury	*t*	*p*
Age (years)	19.7 ± 1.63	19.3 ± 1.3	20.1 ± 2.0	0.99	0.339
Height (cm)	168.5 ± 5.2	168.8 ± 6.0	168.2 ± 4.9	-0.22	0.829
Mass (kg)	65.42 ± 5.83	65.0 ± 6.3	65.8 ± 6.0	0.27	0.792
Experience (years)	15.2 ± 1.84	15.1 ± 1.9	15.3 ± 2.0	0.24	0.812
Dominant Limb (% right)	94%	100%	89%		
Position	5 forward 3 midfielder 8 defender 2 goalie	1 forward 3 midfielder 3 defender 2 goalie	4 forward 5 defender		
Time from injury (months)			14.0 ± 11.1		
IKDC	92.20 ± 10.28	97.33 ± 4.74	88.12 ± 12.29	-2.109	0.060
ACL-RSI	87.30 ± 21.43	97.78 ± 4.41	76.66 ± 25.52	-2.446	**0.039**
TSK- 11	17.00 ± 4.55	15.67 ± 3.64	18.33 ± 5.15	1.269	0.223
GRiPS	22.4 ± 6.17	22.11 ± 5.95	22.56 ± 6.69	0.149	0.883
NASA-TLX	49.04 ± 10.34	49.50 ± 8.88	48.58 ± 12.16	-0.184	0.348

Abbreviations: SD, standard deviation; IKDC, International Knee Documentation Committee; ACL-RSI, Anterior Cruciate Ligament – Return to Sport after Injury; TSK-11, Tampa Scale of Kinesiophobia; GRiPS, General Risk Propensity Scale; NASA-TLX, NASA Task Load Index.

Table 2. Simple Leader-Follower Frequency Analysis

	Frequency	Percent (%)
Control	73	60.8
History of Injury	47	39.2
Total	120	100

LEADER-FOLLOWER STATUS

Using MAXLAG to dichotomize the leader-follower of each trial indicated that the roles were unstable within participant dyads (i.e., the individual leading often flipped from trial to trial). However, the participant with a history of injury was the follower in 60.8% of trials (in individual dyads, the incidence of this occurrence ranged from 40–70%) (Table 2). The control participant was the majority leader in 7 of the 9 dyads.

COORDINATION STRENGTH AND STABILITY

Results of the linear mixed effect model demonstrated a significant interaction effect between group (leader/follower) and task stage (R^2 = 0.65, p < 0.001) for DET (Figure 2a). When individuals with a history of injury were the follower, *post hoc* testing revealed lower DET during the perturbation (i.e., odd-ball stage, d = 0.52 [0.19, 0.85]) and late stage (d = 0.34 [0.01, 0.67]) compared to the early stage. In contrast, when control participants were the follower, *post hoc* testing revealed lower DET only during the perturbation compared to both early (d = 0.46 [0.05, 0.87]) and late stages (d = 0.55 [0.14, 0.97]). Furthermore, DET in the late stage was lower when individuals with a history of injury were the follower compared to controls (d = 0.39 [0.02, 0.76]).

Results of MEANLINE analysis demonstrated a significant interaction effect between group and task stage (R^2 = 0.67, p < 0.001) with *post hoc* testing revealing shorter MEANLINE during the perturbation compared to early stage (d = 0.40 [0.08, 0.73]) when individuals with history of injury were the follower, and late stage (d = 0.46 [0.05, 0.86]) when control participants were the follower (Figure 2b). Furthermore, MEANLINE in the late stage was shorter when individuals with a history of injury were the follower compared to controls (d = 0.37 [0.00, 0.74]).

Results of the LAM and TT analyses both demonstrated significant stage effects (LAM: R^2 = 0.71, p < 0.001; TT: R^2 = 0.87, p < 0.001). *Post hoc* testing revealed lower LAM and shorter TT occurring within the perturbation compared to the early stage (LAM: d = 0.38 [0.12, 0.63]; TT: d = 0.24 [-0.01, 0.50]) and late stage (LAM: d = 0.22 [-0.03, 0.47]; TT: d = -0.16 [-0.03, 0.36]) regardless of group (Figure 2c-d).

PREDICTING LEADER-FOLLOWER STATUS

The ACL-RSI score was the only metric of self-reported function that differed between groups. Binary logistic regression with predictor variable ACL-RSI was not predictive of leader-follower status (B = 0.039, p = 0.224, Exp(B) = 1.039). Figure 3 presents visualization of these data for all dyad pairs. For descriptive purposes, demographic and self-reported metrics are presented by majority leader-follower roles for logistic regression (Table 3).

DISCUSSION

In this study, the strength and stability of interpersonal coordination in a collision-avoidance task were examined among female soccer athletes. By assessing leader-follower status and contrasting coordination strength and stability with the dyads, there are three key findings. First, all participants experienced disruption in their coordinated actions due to the external perturbations, indicating the in-

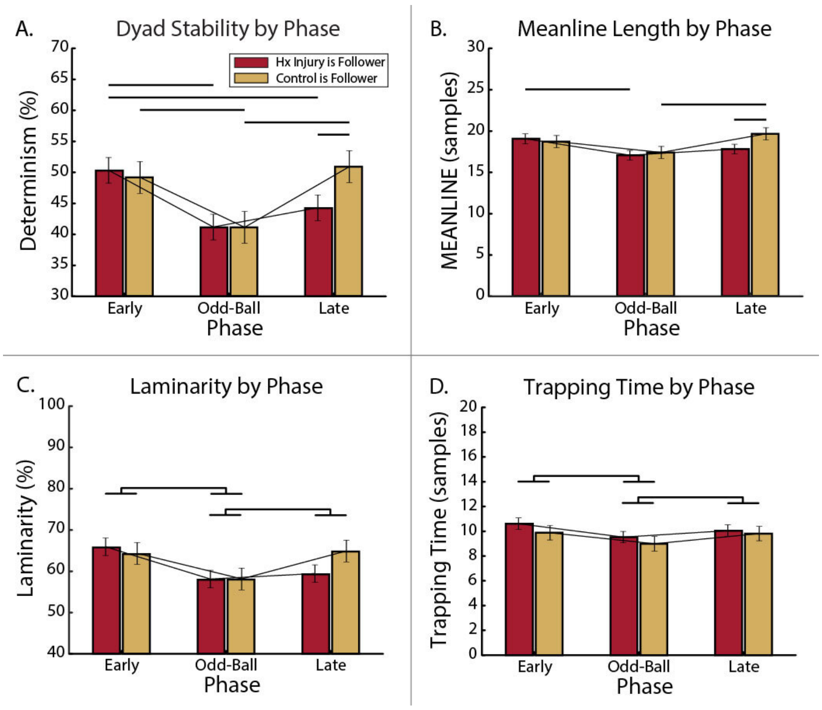

Figure 2. Windowed analysis by leader-follower status through each stage of the collision-avoidance task for outcomes of (A) DET, (B) MEANLINE, (C) LAM, and (D) TT. Error bars depict standard error of measurement. Connecting bars indicate relative change for each group (History of Injury, Control) through each stage. Statistically significant differences are present for group*stage interaction comparisons with horizontal lines. Statistically significant differences are present for stage main effects with brackets.

Abbreviations: Hx, History.

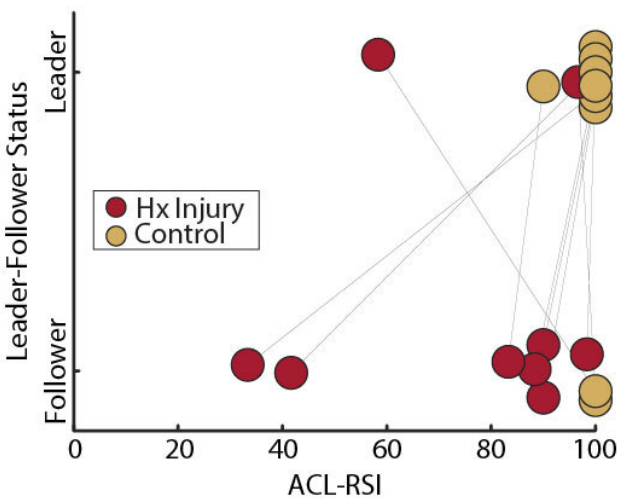

Figure 3. Majority leader-follower status by ACL-RSI score. Group allocation indicated by circle color. Black lines connect the participants within each dyad.

fluence of external factors on dyadic coordination in sport. Second, despite the initial disruption, all participants were able to regain stable coordinated actions, demonstrating dyadic adaptation to the temporary disruption and a return to the task. However, third, those participants with a history of injury faced challenges in restoring the strength of this coordination after the perturbation, whereas control participants did not, indicating a weaker coupling when the previously injured participants attempted to follow the control participant's actions. These findings provide evidence for the value of measuring interpersonal dynamics in soccer and offer insights into how injury history can affect both the strength and stability of interpersonal coordination during sport.

A large body of literature in sport sciences supports the idea that controlling interpersonal dynamics in sport is critical to team success.[7-12] Despite this, few investigators have employed CRQA to study interpersonal coordination and leader-follower dynamics in sport. To our knowledge, the available literature demonstrates that dyads of people typically converge upon highly stable coordinated behavior when given a shared motor task.[44,48] Furthermore, a more dominant individual almost always emerges to lead dyadic coordination.[8,15] Commonalities between these works and the current paradigm include stable interpersonal coordination despite task complexity, limited practice, and *de facto* leader-follower dynamics. With recent evidence suggesting that injuries occur more often in players who assume defensive roles[16,18] that require them to adapt movements to external perturbations (e.g., evasive action by opponent),[8,12,15] the authors sought to determine whether unexpected events (perturbations) would influence interpersonal coordination strength and stability.

The odd-ball tone in the middle stage of each trial disrupted task strength and stability regardless of leader-follower status; however, stability (DET) and strength (MEAN-

LINE) did not recover when participants with a history of injury were in the follower role. The lesser ability of individuals with history of injury to recover strong coupling to a leader's actions suggests that unexpected stimuli may disrupt interpersonal movement execution differently in previously injured individuals than in individuals without a history of injury. Within the limitations of these data (see below) and in the context of moderate and small effect sizes, the current results suggest that players with history of injury are apt to show less adaptable behavior or longer intervals to recover after injury. Given the unpredictable nature of sport and an understanding that history of injury significantly increases risk for future injury,[2,4] this finding is particularly interesting and worthy of further investigation, especially in the context of increasing neurocognitive demands and task complexity. Historically, many return-to-sport protocols do not replicate unanticipated stimuli or neurocognitive demands that athletes face upon returning to their sport, further indicating a need to consider these factors.[25,49]

The current efforts to determine which factors predicted leader-follower status were less informative. Although individuals with injury history more frequently assumed the follower role and reported lower confidence in returning to sport, their self-reported functioning was not found to associate with leader-follower roles. Injuries do not follow a traditional cause and effect model, but rather are multifactorial, influenced by interactions between people within the constraints of a particular physical and social environment.[50] Biopsychosocial constructs of confidence, knee-function, and risk-propensity are among many of the factors that were previously found to contribute to motor behavior and success in sport.[24,51,52] Lower confidence, fear of pain-related movement, and low self-efficacy are associated with failure to return to sport[21,24] and heightened risk of secondary injury in athletes,[23] although the mechanisms of the latter are unclear. Psychological readiness for sport, as measured by self-report instruments, differed between groups within this sample, but the hypothesis that leader-follower behavior would be predicted by biopsychosocial constructs was not supported. While beneficial, the use of patient reported outcome measures following injury are not all encompassing and the association of biopsychosocial factors with leader-follower status may be small due to the complex nature of sport and the many interacting constraints.

LIMITATIONS AND DIRECTIONS FOR FURTHER RESEARCH

The current study has limitations. The concept of this study was novel, making it difficult to assess the most descriptive measures of interpersonal coordination representative of sport. The task was meant to mimic on-field dynamics, but its cyclically repetitive nature may have still been a reductive representation of soccer play. Motion capture technology also necessitated that the study take place in a laboratory, threating ecological validity compared to on-field assessment. The repetitive perturbation, an odd-ball tone, was more predictable than are real sport conditions. While participants were randomly assigned to dyads, some participants had a prior relationship with their dyad partner, due to team or club dynamics. The influences of these social and psychological behavioral determinants may have contaminated this attempt to measure history of injury as the basis for leader-follower roles. These results with all female athletes may not be generalizable to male athletes. Enrollment was limited to females because they continue to suffer higher rates of soccer related injury than their male counterparts, making it particularly important l to identify biological and social factors responsible for those injuries.[50] Lastly, the attempt to measure differences in psychological readiness between players with and without history of injury may have been limited by the fact that participants with a history of lower extremity injury who return to sport have fewer psychological barriers than individuals who fail to return to play.[51,52] Finally, our ability to fully address the complexity of biopsychosocial factors amidst the many interacting constraints of sport were limited by our small sample size. Particularly, when there were no significant group differences on variables of interest, questions arise as to whether the current sample size was associated with insufficient statistical power. There is a clear need to replicate and extend this research by incorporating a complex system approach with larger samples of dyadic interpersonal relationships.

Table 3. Patient Reported Outcomes re-assigned by Leader-Follower Status

	Leader	Follower	*t*	*p*
Age (years)	19.67 ± 1.80	19.78 ± 1.64	0.137	0.893
Height (cm)	168.20 ± 5.79	168.77 ± 5.10	0.220	0.829
Weight (kg)	64.20 ± 7.18	66.64 ± 4.63	0.858	0.403
Experience (years)	15.44 ± 2.07	15.00 ± 1.80	-0.486	0.634
IKDC	93.49 ± 11.47	91.95 ± 9.27	-0.312	0.759
ACL-RSI	92.59 ± 13.49	81.85 ± 25.97	-1.101	0.287
TSK-11	17.00 ± 5.34	17.00 ± 3.91	0.00	1.000
GRiPS	21.11 ± 5.95	23.56 ± 6.44	0.836	0.415

Abbreviations: SD, standard deviation; IKDC, International Knee Documentation Committee; ACL-RSI, Anterior Cruciate Ligament – Return to Sport after Injury; TSK-11, Tampa Scale of Kinesiophobia; GRiPS, General Risk Propensity Scale

CONCLUSION

In this study, dyads of female soccer players successfully coordinated behavior during a collision-avoidance agility task. However, the strength and stability of their interpersonal coordination was disrupted by external perturbation, and individuals within these pairs with history of injury were less able to adapt when in the follower role than their counterparts without history of injury. Although additional work in this field is needed, diminished ability to recover coordinated behavior following an unanticipated stimulus may contribute to higher re-injury risk in athletes with previous lower extremity injury.

COMPETING INTERESTS

The authors report no competing interests.

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SUPPLEMENTARY MATERIALS

Supplemental File 1 - Observed Power

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