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Segment coordination and variability among prospectively injured and uninjured runners

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ABSTRACT
Coordinative variability (CAV) and underlying coordinative patterns are potential running-related overuse injury (RROI) mechanisms, but prospective analyses are needed. This study compared lower limb CAV and coordinative patterns between prospectively injured and uninjured runners. Knee, shank, and ankle kinematics were collected for 39 recreational runners at the beginning of a 6-month follow-up period. Subjects were classified as injured (n=21) or controls (n=18) based on RROI incidence during follow-up. CAV was quantified using modified vector coding. Time spent in each coordinative pattern category was quantified using binning frequency analysis. Coordinative patterns were classified as mechanically unsound if underlying joint/segment motions opposed anatomically allowable running motion. Wilcoxon Rank-Sum tests compared CAV and binning frequencies between groups within different stance portions for knee-shank, shank-ankle, and knee-ankle couplings ($\alpha \leq 0.05$). During initial-stance, the injured group displayed significantly greater knee-ankle CAV (effect size (ES)=1.1), knee-shank CAV (ES=0.97), and greater frequency of mechanically unsound knee-shank (ES=0.72) and shank-ankle (ES=0.63) motion. During mid-stance, the injured group displayed lower frequency of mechanically sound knee-ankle motion (ES=0.31). In late-stance, the injured group displayed greater shank-ankle CAV (ES=0.11). Mechanically unsound coordinative patterns along with greater knee-ankle and shank-ankle CAV potentially lead to RROI.

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KEYWORDS
Running injury; vector coding; coordination variability; lower extremity; coordination patterns

Introduction

Elucidation of individual risk factors associated with running gait has been the focus of running-related overuse injury (RROI) investigations. Peak joint kinematics are commonly investigated as potential RROI mechanisms (Ferber et al., 2010; McClay & Manal, 1998; Messier et al., 1991; Williams III et al., 2001). However, traditional analyses of peak angles alone may not reflect the relative motion between anatomically and mechanically linked lower extremity joints and segments, like shank internal rotation and ankle eversion. Examining the coordination of the shank and ankle together may more adequately reflect soft tissue strain at the knee and torsional loading within the shank than examining peak ankle eversion alone (McClay & Manal, 1997). Therefore, examining relative motion between joints and segments may provide crucial insight to RROI susceptibility.

Interactions between joints and segments of the lower limb such as the knee, shank, and ankle are characterized by continuous and dynamic coordination patterns (Turvey, 1990). Variability in these joint or segment coordinative patterns during locomotion is known as coordinative variability (CAV) (Chang et al., 2008; Hamill et al., 2012; Hamill et al., 1999; Stergiou & Decker, 2011). CAV affects stress exerted on the musculoskeletal system, making it an important consideration to RROI aetiology. Such stress can be functional or injurious (Hamill et al., 1999; Heiderscheit et al., 2002; Miller et al., 2008; Stergiou & Decker, 2011). Studies investigating associations between CAV and RROI from a dynamical systems perspective suggest that adaptable biological systems achieve optimal movement by displaying greater CAV via multiple coordinative patterns (Hamill et al., 1999; Miller et al., 2008). However, exhibiting variability beyond a certain threshold could also be injurious, as evidenced among female recreational runners with patellofemoral pain (Cunningham et al., 2014) and in a recent systematic review (Baida et al., 2018). Conversely, movement performed using a restricted set of coordinative patterns has been theorized to load a specific group of soft tissue structures similarly and repeatedly. This may potentially increase risk for overuse injury, though such a causal link is yet to be established (Hamill et al., 1999). Restricted CAV in runners with a history of iliotibial band syndrome (Miller et al., 2008) or symptomatic patellofemoral pain (Hamill et al., 1999; Heiderscheit et al., 2002) is evidence that such restriction may be injurious. Unfortunately, it is difficult to discern from existing retrospective evidence whether CAV contributes to or is the effect of pain in symptomatic runners. For example, mechanical changes such as increased stiffness in response to pain may result in decreased CAV (Hodges & Tucker, 2011). Alternatively, exploring multiple movement pathways to re-optimize movement following RROI may result in increased CAV (Baida et al., 2018). Thus, prospective studies like the current study are necessary to investigate the role of CAV as an RROI mechanism.

Greater variability, presently considered functional (Stergiou & Decker, 2011), may be dysfunctional if the movement is characterized by mechanically unsound coordinative

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patterns of underlying joints and segments. Mechanically sound coordinative patterns result when the knee, shank, and ankle move as they are anatomically linked. During the first half of the stance phase in running, mechanically sound motion involves calcaneal eversion accompanied by shank internal rotation, which allows the knee to flex (McClay & Manal, 1997). Mechanically sound motion in the second half of stance phase involves the reversal of these motions. If coordinated motions were disrupted, movement would be less than optimal, or unsound. Directionality of motion cannot be discerned or understood from CAV alone (Chang et al., 2008). CAV in conjunction with mechanically unsound coordinative patterns may result in loading to soft tissue structures unprepared to experience such stresses (Tepavac & Field-Fote, 2001), and may eventually diminish the health of the biological system. Thus, expanding on previous investigations (Hamill et al., 1999; Heiderscheit et al., 2002; Miller et al., 2008), a comprehensive study of CAV in conjunction with the assessment of coordinative patterns is necessary to fully understand the effects of CAV on RROI (Needham et al., 2014).

Mechanically unsound motion between the knee, shank, and ankle could be related to multiple common RROI, including patellofemoral pain syndrome and iliotibial band syndrome (Heiderscheit et al., 2002; Messier et al., 1991; Miller et al., 2008). The purpose of this study, therefore, was to examine segment coordination between the knee, shank and ankle, anatomical sites with high RROI incidence (Hamill et al., 2012), and compare CAV and coordinative patterns between prospectively injured and uninjured recreational runners. Since restricted variability may increase RROI risk by repeatedly loading the same set of soft tissue structures (Hamill et al., 1999), it was hypothesized that prospectively injured runners would display less CAV compared with uninjured controls. It was further hypothesized that the injured runners would display more mechanically unsound coordinative patterns.

Methods

Subjects

Fifty-five healthy recreational runners were voluntarily enrolled for a minimum of 6-months in this longitudinal study. During this follow-up period, subjects engaged in their own running programme while reporting training and RROI occurrence weekly through an online survey. Subjects who failed to provide weekly responses for at least 6-months with less than 80% compliance were excluded from the analysis, yielding a final sample size of thirty-nine. Inclusion criteria required subjects to: 1) be between the ages 18–60 years; 2) have no history of lower back or lower limb surgeries; 3) have returned to normal running volume for at least 8-weeks if an RROI was sustained in the previous 6-months; 4) have 2 years of running experience; and 5) a minimum weekly running volume of 10 miles·week^{-1} for at least the past 3-months. Prior to data collection, the subjects gave written-informed consent and completed a physical activity readiness questionnaire. All procedures were approved by the Indiana University Institutional Review Board.

At the end of follow-up, subjects were classified as injured or controls based on whether they sustained an RROI during the minimum 6-month surveillance period. RROI was defined as any running-related pain experienced in the lower back and/or lower limbs that caused them to stop or modify training for a minimum of one day (Bovens et al., 1989; Marti et al., 1988). This definition excluded delayed onset of muscle soreness (DOMS). Survey responses of RROI occurrence were assessed by a trained clinician ensuring they qualified as an RROI.

Experimental protocol

Subjects completed a three-dimensional gait analysis at baseline. Retro-reflective markers were placed on the subjects at anatomical locations on the lower extremity consistent with published standards (Sutherland, 2002). A two-second standing calibration trial was captured as subjects stood still with arms across their chest. This was followed by practice trials across an 18 m level runway at a speed of 4 m·s^{-1} (±5%) prior to data collection. This criterion speed was slightly faster than the average preferred speed (3.71 ± 0.54 m·s^{-1}), but no subjects reported discomfort or showed signs of difficulty performing this speed. Three-dimensional position of the markers was recorded at 240 Hz by nine motion capture cameras (Oqus 400+, Qualysis AB, Göthenburg, Sweden) while subjects ran across the runway. Gait speed was measured using two infrared break beam sensors (TC-Gait, Brower Timing System, Draper, UT, USA) placed 6 m apart, within the centre of the collection volume. Data collected from this centre section of the collection volume were used for analysis. Five successful trials for each limb consisting of a single stance phase per trial were retained for analysis (Hafer et al., 2016; Needham et al., 2014). Trials were deemed successful if subjects: ran within ±5% of the target speed, did not modify their speed between timing sensors (speed was considered modified if the difference between the peaks of the anteroposterior ground reaction forces exceeded 50 N), did not modify their stride to target the force platform (1200 Hz, AMTI, Inc., Watertown, MA, USA), and landed on the force platform with their whole foot. Trial-to-trial speed differences were recorded to determine variance in speed across trials.

Data reduction and processing

Three-dimensional marker positions were tracked using Qualisys Track Manager (Qualisys AB, Göthenburg, Sweden). The global coordinate system was defined as: *X*-axis as mediolateral (right = positive), *Y*-axis as anteroposterior (anterior = positive) and *Z*-axis as vertical (upward = positive). Raw kinematic data were exported to Visual 3D (C-Motion Inc, Rockville, MD, USA) for processing and were filtered using a bi-directional, 4th-order, Butterworth lowpass filter with zero lag and a cut-off frequency of 12 Hz. Joint angles (Figure 1) for the knee (sagittal plane), ankle (frontal plane) and shank (transverse plane) were calculated with reference to the proximal segment. The maxima (knee extension, shank internal rotation, ankle inversion) and minima (knee flexion, shank external rotation, ankle eversion) were extracted from the timeseries of each trial and subject, then the average of each group was calculated to

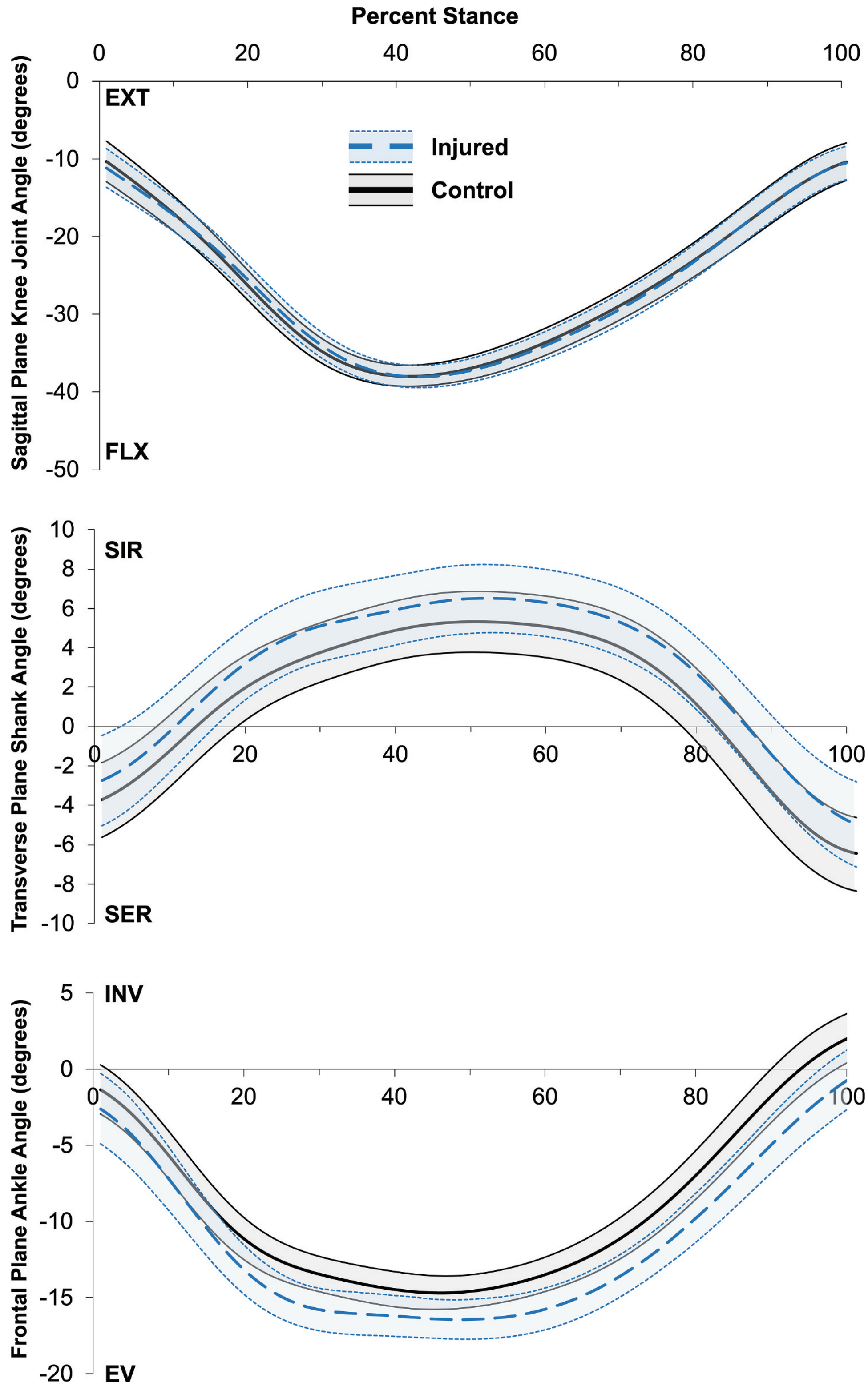

Figure 1. Group mean and standard deviation knee, shank, and ankle angles over 0%-100% of the stance phase. Thicker lines represent the mean of the injured group (blue) and uninjured control group (black). Thin lines represent ±1 standard deviation. The joint motions represented are knee extension (EXT) and flexion (FLX) (top), shank internal rotation (SIR) and external rotation (SER) (middle), and ankle inversion (INV) and eversion (EV) (bottom).

compare the peak joint angle-magnitudes between groups. Force platform data were used to identify gait events of heel strike and toe-off of the stance phase using a 20 N vertical force threshold. Stance phase was time normalized from initial contact (0%) to toe-off (100%). Stance was divided into three portions: initial-stance (0–33%), mid-stance (34–66%), and late-stance (67–100%) to compare coordinative patterns and CAV within each portion between groups. Data from the affected leg for the injured group and the matched side from randomly selected control group subjects were exported to MATLAB (Release 2018b, MathWorks, Natick, MA, USA) for circular data analysis.

CAV was quantified at the knee, shank, and ankle using a continuous circular analysis measure known as vector coding. Vector coding describes intersegmental coordination by constructing angle-angle plots of the concerned couples (i.e., two mechanically linked joints or segments). Angle-angle plots present the angle-time series of the proximal structure on the horizontal axis and the distal structure on the vertical axis, yielding a single data point at each instant of time (Freedman Silvernail et al., 2018). The angle-angle plots provide information regarding the changes in relative joint and/or segment positions throughout stance while conserving the directionality and magnitude of the coupling relationships (Miller et al., 2010) and enabling inferences on original positional signals of segmental couples (Freedman Silvernail et al., 2018).

Angle-angle plots of each trial were created for three couples: knee-shank, shank-ankle, and knee-ankle (group mean data presented in Figure 2). A modified vector coding method adapted from Needham et al. (2014) was applied to this kinematic data in MATLAB using the circular statistics toolbox. A coupling angle was subtended from a vector constructed between two consecutive data points within the angle-angle plot, relative to the right horizontal. Coupling angles and CAV were computed for each instant of stance. Circular statistics was used to calculate the mean and standard deviation of the coupling angles to present values between 0° and 360° (Berens, 2009). Average coupling angles were computed for each instant of stance across trials for each subject. CAV was computed as the circular standard deviation of the coupling angle across trials for each subject. A linear average of CAV ($CAVi_{avg}$) was computed for each instant of stance across subjects to present the time-series of the group mean variability during the stance phase for each couple of interest.

A histogram of coupling angle magnitudes was also created to compare coordinative patterns between injured and control groups. This binning frequency analysis, as suggested by Needham et al. (2015), was completed by categorizing the coupling angles into one of eight coordination pattern category bins based on their magnitude (Table 1). Categories were defined as antiphase (rotational motion of joints or segment was in the opposite direction relative to one another) and inphase (rotational motion of joints or segment was in the same direction relative to one another) during motions of both proximal and distal dominance in both positive and negative directions (Table 1). The total frequency (i.e. count) of coupling angles in each coordination pattern category represents the proportion of total time spent in that motion during the stance phase, presented as a percentage. Category names were qualitatively described and interpreted as being mechanically sound or

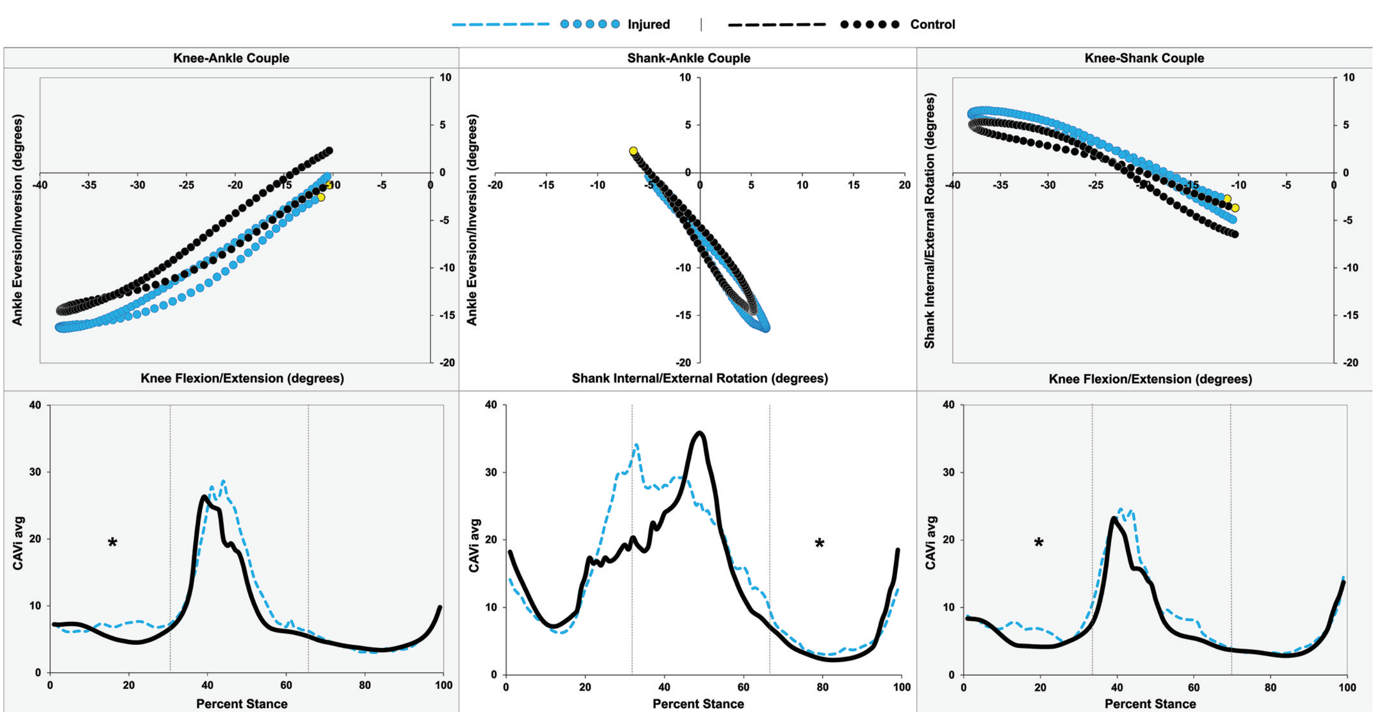

Figure 2. Angle-angle plots (top row) and linear average coordinative variability (CAVi avg; bottom row) during the stance phase for the knee-ankle (left column), shank-ankle (middle column), and knee-shank (right column) coupling relationships of the injured group (blue) and uninjured control group (black). The angle-angle plots include the proximal joint or segment on the x-axis and the distal joint or segment on the y-axis. Initial contact in the angle-angle plots is represented by the yellow dot. The vertical dashed lines included with the CAVi avg separate stance into initial (0%-33%), mid (34%-66%), and late (67%-100%) portions of the stance phase. * indicate a significant difference in CAVi avg between groups during the indicated portion of the stance phase ($p < 0.05$).

Table 1. Coordinative pattern categories for coupling angles (γ) and the relative motions for each coupling relationship that demonstrate each coordinative pattern. Coupling angles were binned into each coordinative pattern category based on their magnitude. Categories were defined according to Needham et al., 2015 (Needham et al. 2015). The relative motion associated with each coordinative pattern was defined by the right hand rule (i.e. antiphase = (+)(-) or (-)(+); inphase = (+)(+) or (-)(-); distal phase coordination patterns occur when motion is dominated by distal segment or joint motion; proximal phase coordination pattern occurs when the motion is dominated by the proximal segment or joint motion). Abbreviations are: P = Proximal segment motion, D = Distal segment motion, FLX = knee flexion, EXT = knee extension, SIR = shank internal rotation, SER = shank external rotation, EV = ankle eversion, INV = ankle inversion. *indicates that motion is mechanically sound because the relative joint motions consistent with anatomy, eg: during mid-stance, the ankle everts, allowing the shank to internally rotate and the knee to flex. If the ankle remained in inversion motion, the shank would not be able to internally rotate enough to allow the knee to flex. Thus, FLX-EV and SIR-EV are mechanically sound motion whereas FLX-INV and SIR-INV are mechanically unsound.

	Coordinative Pattern	Coupling Angle	Knee-Ankle	Shank-Ankle	Knee-Shank
i	Inphase Proximal Dominance	$0° \leqslant \gamma \leqslant 45°$ (+P,+D), $180° \leqslant \gamma \leqslant 225°$ (-P,-D)	EXT – INV* FLX – EV*	SIR – INV SER – EV	EXT – SIR FLX – SER
ii	Inphase Distal Dominance	$45° \leqslant \gamma \leqslant 90°$ (+P,+D), $225° \leqslant \gamma \leqslant 270°$ (-P,-D)	EXT – INV* FLX – EV*	SIR – INV SER – EV	EXT – SIR FLX – SER
iii	Antiphase Distal Dominance	$90° \leqslant \gamma \leqslant 135°$ (-P,+D), $270° \leqslant \gamma \leqslant 315°$ (+P,-D)	FLX – INV EXT – EV	SER – INV* SIR – EV*	FLX – SIR* EXT – SER*
iv	Antiphase Proximal Dominance	$135° \leqslant \gamma \leqslant 180°$ (-P,+D), $315° \leqslant \gamma \leqslant 360°$ (+P,-D)	FLX – INV EXT – EV	SER – INV* SIR – EV*	FLX – SIR* EXT – SER*

unsound per the right hand rule (Table 1). That is, mechanically sound motion included the following coordinative patterns that are anatomically linked with polarity defined per the right hand rule: knee flexion (FLX, negative)-shank internal rotation (SIR, positive)-ankle eversion (EV, negative), or knee extension (EXT, positive)-shank external rotation (SER, negative)-ankle inversion (INV, positive). Given that these motion patterns occur together due to the anatomy of the knee and ankle joints, any coordinative pattern opposing these patterns was operationally defined as mechanically unsound.

Statistical analysis

A sample size estimate using data from Cunningham et al. (2014) indicated 18 subjects in each group would be required to obtain 0.8 statistical power ($\alpha < 0.05$). Shapiro-Wilk tests revealed a non-normal distribution of the demographic data (except height and body mass), kinematic data, coordination patterns, and CAV. Therefore, Wilcoxon Rank-Sum tests ($\alpha < 0.05$) were conducted to identify differences between groups in demographics (age, weekly mileage at baseline and during follow-up, years of running experience), peak joint and segment angles, joint ranges of motion, $CAVi_{avg}$ for all coupling relationships during each separate portion of the stance phase, and binning frequencies of coupling angles during each stance phase. Chi-square test was used to compare sex distributions between groups, with the Yates correction applied to account for a relatively small sample size. Parametric-independent samples t-tests were conducted to identify differences between groups in height and body mass. A One-Way Circular ANOVA using the Watson-Williams two sample test of the null hypothesis (Berens, 2009) was performed to determine differences in coupling angle magnitudes between groups. Cohen's d effect sizes were calculated for linear averages of peak joint and segment angle magnitudes and ranges of motion, CAV, and binning frequencies to determine the degree to which each of these variables may be an RROI mechanism. Effect sizes for statistical tests were defined as small = 0.2–0.49, medium = 0.-5–0.79, large = ≥0.8 (Cohen, 2013).

Results

The sample included 39 subjects categorized into the injured group (n = 21) and control group (n = 18). Demographics for both groups are presented in Table 2. No differences were found between groups in demographics, weekly mileage at baseline and during follow-up, and years of running experience ($p > 0.05$).The control group had 50% fewer females compared with the injured group, though not statistically significant ($p > 0.05$) (Table 2). The distribution of RROI sustained in the injured group are presented in Table 3. The compliance rate for the injured group pre-injury and control group throughout follow-up was 93.13% and 81.67%, respectively. The variance in speed across trials was similar between groups ($p = 0.54$, $d = 0.22$).

Discrete analysis of joint and segment angle-time series (Figure 1) revealed no significant differences between groups for peak joint angle magnitudes or joint and segment ranges of

Table 2. Group mean(standard deviation) of demographic and weekly running mileage variables for the injured and uninjured control groups. Weekly mileage at baseline was a self-reported estimate over the previous 3-months, collected at the enrolment appointment. Weekly mileage from first week of follow-up was collected by the weekly online survey, and so it may better represent the baseline running frequency than the self-reported estimate from the previous 3-months. Weekly mileage during follow-up was recorded weekly in the online survey and refers to the weeks prior to injury for the injured group and all weeks throughout follow-up for the control group. Differences in sex distribution between groups was assessed with a Chi square test; differences between groups in all other demographics were assessed with t-tests.

	Injured, n = 21	Controls, n = 18	*p value*	*Cohen's d*
Sex (Male/Female)	M = 5 (24%), F = 16 (76%)	M = 10 (56%), F = 8 (44%)	0.08	0.27
Age (years)	32.38 (11.68)	31.11 (9.62)	0.98	0.12
Height (metres)	1.71 (0.08)	1.73 (0.09)	0.48	0.23
Mass (kilograms)	65.69 (9.87)	70.04 (15.46)	0.31	0.33
Weekly mileage at baseline (miles per week)	22.4 (13.96)	22.08 (12.18)	0.83	0.02
Weekly mileage from first week of follow-up (miles per week)	14.04 (7.83)	19.76 (13.27)	0.12	0.52
Weekly mileage during follow-up (miles per week)	14.72 (8.99)	19.8 (12.9)	0.17	0.45
Years of Running Experience	8.69 ± 6.40	10.02 ± 6.55	0.53	0.20

Table 3. Distribution of reported injuries at anatomical regions in the lower limb within the sample. Some subjects sustained more than one injury, resulting in an injury count greater than the injured sample size (n = 21).

Anatomical region	Number of injuries	Percentage of total injuries (%)
Knee	5	20
Shank	4	16
Ankle	1	4
Hip	2	8
Thigh	5	20
Pelvis	2	8
Foot	6	24

Table 4. Group mean (standard deviation) of the stance phase peak joint and segment angle magnitudes, average joint and segment motions, and ranges of motion for the knee, shank, and ankle. Average joint and segment motion was calculated as the average value across the stance phase. * indicates a significant difference between groups ($p < 0.05$).

	Injured (°)	Controls (°)	*p* value	*Cohen's d*
Peak Ankle Eversion	−17.22(5.54)	−15.06(6.69)	0.28	0.35
Peak Ankle Inversion	0.22(3.95)	2.91(6.07)	0.25	0.53
Peak Shank Internal Rotation	7.12(5.12)	5.64(6.60)	0.44	0.25
Peak Shank External Rotation	−6.56(5.27)	−7.14(8.04)	0.79	0.09
Peak Knee Flexion	−38.17(4.61)	−38.06(3.95)	0.66	0.03
Average Ankle motion*	−11.34(5.09)	−9.09(5.27)	<0.01	0.43
Average Shank motion*	2.86(3.52)	1.54(3.64)	<0.01	0.36
Average Knee motion	−25.51(9.02)	−26.43(9.09)	0.80	0.10

motion (Table 4). However, frontal average ankle ($p < 0.01$; $d = 0.43$) and average transverse shank ($p < 0.01$; $d = 0.36$) angle magnitudes were significantly different between groups.

Vector coding analysis revealed significantly greater CAV in the injured group during initial-stance for the knee-ankle and knee-shank coupling relationships and late-stance for the shank ankle relationship (Figure 2; also see Table, Supplemental Digital Content 1 for mean CAV values for each group, p-values, and Cohen's d effect sizes). One-way Circular ANOVA ($\alpha < 0.05$) revealed no differences in coupling angle magnitudes between groups ($p > 0.05$).

The results of the binning frequency analysis (Figure 3; Table 1 lists the definitions of each bin) indicated whether a specific coordination pattern was performed for a significantly greater proportion of stance phase (i.e. more frequently) in one group than the other. For the knee-ankle coupling relationship, the injured group displayed significantly less frequent inphase EXT-INV (mechanically sound) during mid-stance, knee extension dominancy ($p = 0.01$; $d = 0.31$) but significantly more frequent inphase FLX-EV (mechanically sound) during mid-stance, knee flexion dominancy ($p = 0.03$; $d = 0.68$) than the control group (Figure 3). For the knee-ankle coupling, the control group displayed more frequent

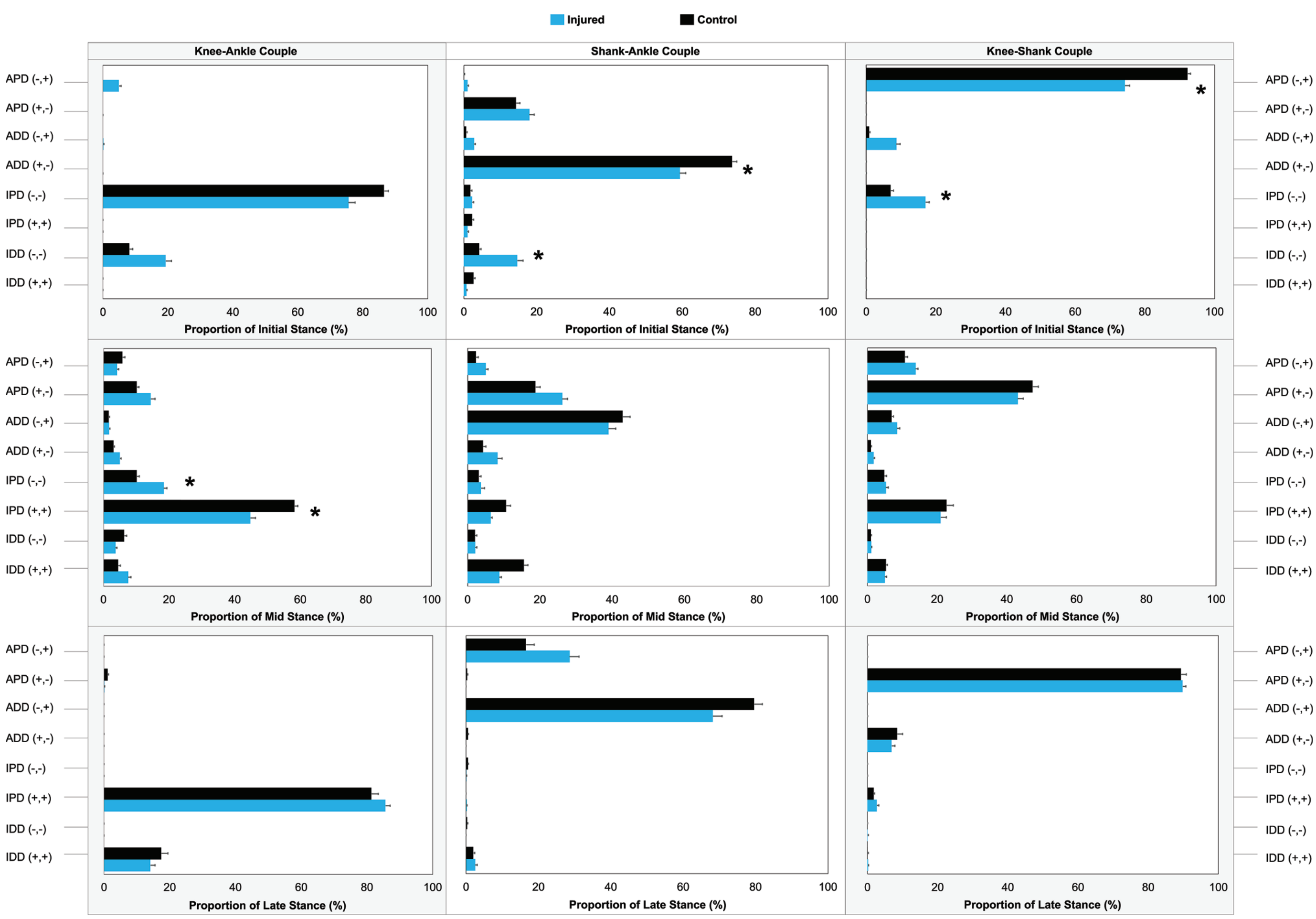

Figure 3. Histograms of the binning frequency analysis for the knee-ankle (left column), shank-ankle (middle column), and knee-shank (right column) coupling relationships of the injured group (blue) and uninjured control group (black). The top, middle, and bottom rows are the initial (0%-33%), mid (34%-66%), and late (67%-100%) portions of the stance phase, respectively. Bars represent the proportion of time spent in each coordinative pattern category (category descriptions provided in Table 1) as a percentage of the given portion of stance. Error lines indicate the standard error of the mean. APD-antiphase proximal dominancy, ADD-antiphase distal dominancy, IPD-inphase proximal dominancy, IDD-inphase distal dominancy. * indicates a significant difference between groups ($p < 0.05$).

inphase EXT-INV (mechanically sound) during mid-stance, knee extension dominancy ($p = 0.01$; $d = 0.31$) but less frequent inphase FLX-EV (mechanically sound) during mid-stance, knee flexion dominancy ($p = 0.03$; $d = 0.68$) than the injured group. For the shank-ankle coupling relationship (Figure 3), the injured group displayed more frequent inphase SER-EV (mechanically unsound) during initial-stance, ankle eversion dominancy ($p = 0.04$; $d = 0.63$) than the control group. The control group displayed more frequent antiphase SIR-EV (mechanically sound) during initial-stance, ankle eversion dominancy than the injured group ($p = 0.02$; $d = 0.73$). For the knee-shank coupling relationship (Figure 3), the injured group displayed more frequent inphase FLX-SER (mechanically unsound) during initial-stance knee flexion dominancy than the control group ($p = 0.02$; $d = 0.72$). The control group displayed more frequent antiphase FLX-SIR (mechanically sound) during initial-stance knee flexion dominancy than the injured group ($p < 0.01$; $d = 1.17$).

Discussion

The purpose of this study was to determine whether segment coordination patterns and variability are related to RROI development. Contrary to our hypothesis and previous evidence (Hamill et al., 1999; Heiderscheit et al., 2002; Miller et al., 2008), the injured group displayed significantly greater CAV than the uninjured control group for each coupling relationship during either initial or late-stance. However, in line with our prediction, the injured group displayed mechanically unsound movement patterns compared with the uninjured control group for some coordinative patterns and portions of stance but also engaged in mechanically sound motion, like the control group, for other coordinative patterns and portions of stance. Unsound patterns were observed for the knee-shank and shank-ankle coupling relationships during initial-stance. Additionally, the injured group displayed mechanically sound knee extension-ankle inversion coupling during mid-stance significantly less often than the control group, given that the knee flexion-ankle eversion motion was mechanically sound for this specific portion of stance. The injured and control groups displayed similar movement patterns within late-stance that were mechanically sound motion for each coupling relationship. Investigating coordinative movement patterns in conjunction with CAV provides novel information regarding the potential role of these factors as RROI mechanisms.

Analysing peak joint angles was not sufficient to identify potential RROI mechanisms in this prospective study. Our statistical analysis showed no significant differences in peak joint angle magnitudes between groups. However, average shank and ankle motions over the entirety of stance were significantly different between groups. The shank and ankle were more internally rotated and everted, respectively, throughout the stance phase in the injured group, which explains the significantly greater average shank and ankle motion compared with the control group. These greater shank and ankle angles throughout stance may have resulted in greater rotational stresses at the knee (Fischer et al., 2018; Hintermann & Nigg, 1998) given that knee flexion angles throughout stance were nearly identical between groups. Also, significantly greater average shank and ankle motion magnitudes across stance for the injured group but similar average knee motion between groups may have influenced coordinative interactions between these joints and segments differently for each group as reflected in the angle-angle plots (Figure 2). Alterations in these coordinative interactions were not captured by solely analysing peak joint angle magnitudes. The relatively high incidence of RROI at the knee compared with other anatomical regions in our sample (Table 3) might reflect the musculoskeletal stresses incurred from these altered joint and segment interactions in the absence of statistically different or "excessive" peak angle magnitudes.

The injured group displayed greater CAV compared to the control group during initial and late-stance, periods during which the limb is transitioning from initial contact to mid-stance, and from late-stance to toe-off, respectively (see Figure 2, also see Table, Supplemental Digital Content 1). Transitioning between initial contact to mid-stance and from late-stance to toe-off require alterations in coordination patterns (Heiderscheit et al., 2002) due to rapid changes in joint and segment positions. For example, transitioning from initial contact to mid-stance demands a rapid transition from ankle inversion at heel-strike to ankle eversion during mid-stance. As the ankle rapidly everts, the shank begins to internally rotate, enabling the knee to move from extension at initial contact to flexion during mid-stance. Towards the end of mid-stance, as the ankle begins to invert in preparation for toe-off, the shank reverses motion and begins to externally rotate allowing the knee to reverse from flexion to extension. The magnitude of CAV during these rapid changes in joint and segment positions may be important to musculoskeletal stress. Greater knee-ankle and knee-shank CAV observed in the prospectively injured versus control group here during initial-stance, and greater shank-ankle CAV during late stance suggests it may have exacerbated musculoskeletal stress increasing risk of RROI. Additionally, musculoskeletal stress during such transitions may also increase stress if the underlying coordination is disrupted or unsound. The binning frequency analysis indicated that injured runners displayed a greater frequency of mechanically unsound inphase knee-shank motion during initial-stance. Thus, instead of being adaptive, this heightened CAV displayed by the injured group during this transition phase may have increased RROI susceptibility because the coordinative pattern was mechanically unsound. Engaging in mechanically unsound coordinative patterns more frequently during initial-stance may have resulted in abnormal stresses to soft tissue structures. This stress, occurring due to the unsound coordinative pattern itself, may have been compounded in knee-shank coordination by the greater CAV experienced.

Coordinative patterns, not previously explored with regard to prospective RROI development, may provide insight to differences in movement patterns adopted by injured and uninjured runners that may contribute to RROI development. In the current study, both groups performed inphase (mechanically sound) knee-ankle motion with knee extension dominancy during mid-stance, although the injured group performed this sound motion less frequently than the control group (Figure 3). Thus, towards the end of mid-stance when knee extension is the dominant motion beginning around 45% of stance (Ferber & Macdonald, 2014) in preparation for toe-off, the injured group engaged in less frequent knee extension-ankle inversion motions (see Figure, Supplemental Digital Content 2). Additionally, the injured group performed inphase (mechanically sound) knee-ankle motion with knee flexion dominancy during mid-stance more frequently than the control group. However, despite this motion qualifying as mechanically sound, it may not have been protective from injury among the injured group due to its higher frequency compared to that of the control group. Thus, frequency and patterns of knee-ankle couplings engaged in by the injured group may have increased susceptibility to RROI whereas those engaged in by the control group may have enabled them to remain below a critical injury threshold (Hamill et al., 2012). This finding points to the possibility that a certain frequency of engaging in specific coordinative behaviours may be more protective from RROI than others.

Comparing the present study with investigations of symptomatic runners may reveal a difference in CAV before and during injury. Prospectively injured runners in the current study exhibit greater CAV across different coupling relationships. This result is consistent with another study comparing symptomatic runners with controls (Cunningham et al., 2014). However, it is in contrast with other investigations demonstrating symptomatic runners exhibited restricted CAV for different coupling relationships compared with controls (Hamill et al., 2012; Heiderscheit et al., 2002; Hein et al., 2012). Consider the knee (flexion/extension) – ankle (eversion-inversion) couple for comparison purposes: In our study, the prospectively injured group displayed greater CAV for the knee-ankle coupling relationship during initial-stance phase, suggesting greater CAV for this couple may be related to RROI development. However, using methods of analyses and reporting CAV magnitudes similar to the present study, Cunningham et al. (2014) found no significant differences in the knee flexion – ankle inversion couple between runners diagnosed with current patellofemoral pain and their healthy counterparts. The difference in results between studies may suggest that CAV changes in response to injury-related discomfort or pain. These changes in CAV may persist post injury, which would affect the inferences made from retrospective evidence regarding CAV as an RROI mechanism (Miller et al., 2008). We take caution in making these inferences, however, given that differences in sample demographics and experimental protocol may influence such a comparison. Nonetheless, these differing trends in existing literature are interesting and warrant further research into CAV and coordinative patterns before, during and post RROI.

This study has some limitations. Five stance phases were used to analyse coordination variability, which is consistent with previous overground running studies employing vector coding (Hafer et al., 2016; Needham et al., 2014). However, 8–10 strides was recommended to analyze coordination variability during treadmill running (Hafer & Boyer, 2017). Future studies should explore the number of overground trials required to minimize experience-related learning effects and trial-to-trial variability in CAV magnitudes. Weekly running mileage during follow-up was lower in the injured group compared to the control group in this study (Table 2), though not statistically significant. This relative difference is consistent with some previous research of mileage and RROI, but not others (Kluitenberg et al., 2016; Van Gent et al., 2007). Nonetheless, weekly running mileage and CAV may have compounding effects and should be investigated in future studies using similar methods and coordination patterns. Future studies should also analyse the potential effects of sex-based differences in CAV on risk of RROI. Considering the percent of males in the injured group and control group was 24% and 56%, respectively (Table 2), it is possible that sex-based anthropometric or biomechanical differences influenced the magnitude of CAV observed. However, to our knowledge, only two studies investigated sex-based differences in CAV (Boyer et al., 2017; Hannigan & Chou, 2019). One study included similar methods and coupling relationships (shank rotation-foot eversion specifically) as the present study and found no sex-based differences in CAV (Boyer et al., 2017). Neither of the two studies assessed how sex-based differences in CAV influence RROI risk.

Our sample size was smaller than some other prospective studies investigating gait-related mechanisms for RROI (Saragiotto et al., 2014). However, we met our sample size estimate and obtained medium to large effect sizes between groups for CAV (see Table, Supplemental Digital Content 1) and the coordination pattern results from the binning frequency analysis. Thus, our results closely represented the true effect of CAV and coordinative patterns between prospectively injured and uninjured runners. Medium-large effect sizes were found with the current sample size, however, further investigations using similar methodology with a larger sample must be conducted to affirmatively establish a causal relationship between CAV and coordination patterns to RROI development. Additionally, it may be that retrospective injuries in our sample influenced coordinative patterns and variability in our study compared with a sample of never-injured runners. Despite almost 84% of our sample reporting a retrospective injury, the distribution of retrospective injuries was similar between groups (injured group ($n = 21$): 33 retrospective injuries; control group ($n = 18$): 31 retrospective injuries; $p = 0.70$), which suggests that differences observed in CAV and coordination patterns in the present study likely reflects risk of future RROI. Further research in this area should focus on analysing CAV and coordinative patterns based on RROI type since retrospective evidence indicates that the magnitude of CAV might differ per RROI type (Baida et al., 2018). Potential differences in CAV magnitudes and coordination patterns could also be explored for injuries of differing severity (Supplemental Digital Content 3). A large scale, multicenter prospective study would be required to collect a sufficient sample size with each RROI type and severity level to compare CAV and coordinative patterns between RROIs.

Conclusions

Our study demonstrates a potential relationship between CAV and RROI, the nature of which may differ pre, during and potentially post RROI as seen from comparisons with previous investigations. However, CAV alone cannot appropriately determine RROI outcome. The coordinative patterns dictating directionality of constituting joints and segments may play a role in the impact of CAV on RROI development. Therefore, both CAV and coordinative patterns must be considered when analysing segment coordination as an RROI mechanism. Further, the interactions between segment coordination, sex, weekly running mileage, and injury severity must be explored to better understand them as RROI mechanisms.

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The authors declare no conflict of interest or professional relationships with companies or manufacturers who may benefit from this research. The results of the study are presented clearly, honestly, and without fabrication, or inappropriate data manipulation.

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