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Coordination and variability during anticipated and unanticipated sidestepping

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ABSTRACT

Background: Numerous investigations have attempted to link the incidence and risk of non-contact anterior cruciate ligament injuries to specific intrinsic and extrinsic mechanisms. However, these are often measured in isolation.

Research question: This study utilizes a dynamical systems approach to investigate differences in coordination and coordination variability between segments and joints in anticipated and unanticipated sidestepping, a task linked to a high risk of non-contact anterior cruciate ligament injuries.

Methods: Full body, three-dimensional kinematics and knee kinetic data were collected on 22 male collegiate soccer players during anticipated and unanticipated sidestepping tasks. A modified vector coding technique was used to quantify coordination and coordination variability of the trunk and pelvis segments and the hip and knee joints.

Results: Sagittal and frontal plane trunk-pelvis coordination were more in-phase during unanticipated sidestepping. Sagittal plane hip-knee and hip (rotation)-knee (flexion/extension) coordination were more in-phase with the knee dominating the movement during unanticipated sidestepping ($P < 0.05$). Coordination variability was greater in unanticipated sidestepping for trunk (flexion)-pelvis (tilt), trunk (lateral flexion)-pelvis (obliquity), hip (flexion/extension)-knee (flexion/extension) and hip (rotation)-knee (flexion/extension) ($P < 0.05$). In unanticipated sidestepping where there is limited time to pre-plan the movement, multiple kinematic solutions and high coordinative variability is required to achieve the task.

Significance: Our results suggest that coordination becomes more in-phase and the variability of this coordination increases as a function of task complexity and reduced planning time as that which occurs in unanticipated sporting task scenarios. Consequently, injury prevention programs must incorporate perceptual components in order to optimise planning time and coordinate appropriate postural adjustments to reduce external knee joint loading and subsequent injury risk in sport.

1. Introduction

A significant body of research has been dedicated toward understanding the underlying mechanisms and counter-measures of non-contact anterior cruciate ligament (ACL) injuries. In-vivo, in-vitro and in-silico research have identified that elevated and combined peak knee extension, valgus and internal rotation moments while the knee is in an extended posture (i.e. $< 20^\circ$) increase ACL strain [1]. Non-contact ACL injuries typically occur during sidestepping and single leg landing; tasks which are characterized by sudden redirections of whole-body centre of mass concurrent with rapid accelerations or decelerations of the body [2].

Team-based sports often require athletes to perform these dynamic

tasks under high temporal and visuospatial demands in response to external stimuli (i.e. a ball, team member, opponent). These external stimuli require rapid and precise reactions, and as such, time constraints associated with these dynamic movements may lead to altered joint biomechanics and elevated loading at the knee, which has been shown in unanticipated sidestepping tasks [3–5]. Understanding the effect of anticipation on postural adjustments is important to further the body of knowledge toward how both performance and safety can be enhanced during unanticipated sporting tasks.

Modifiable risk factors of ACL injury risk [1,6] include control of whole body centre of mass via dynamic trunk and pelvis control [7,8], hip flexion and internal rotation [9], dynamic knee valgus [10], knee flexion angle [11,12] and foot strike posture [13]. However, the

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majority of research associated with lower limb biomechanics and ACL injury have reported on the kinematics/kinetics of lower extremity joints in isolation, rather than addressing the interaction between them [14]. A dynamical systems approach may therefore provide greater insight into the state of the system (i.e. injured, uninjured, high risk, low risk) by assessing the complex interactions between segments/joints (eg. trunk-pelvis, hip-knee) during dynamic sporting tasks. Coordination from a dynamical system approach describes the integration of the individual degrees of freedom into functional units. Bernstein's principles [15] outline two key factors when determining the state of a system. The first is that, coordination between many joints/segments can be organized in a number of different ways to achieve the same task. Secondly, the variability of coordination is important as it provides a metric into the variety of the coordination patterns utilized. It is important to note that coordination variability differs from end-point variability (i.e. task goal). In the context of sidestepping, end-point variability may encompass approach velocity and change of direction angle. It has been shown that with reference to overuse injury, coordinative variability is desirable as this describes an adaptable and flexible system [16]. In the context of both performance and acute injury in team sports, a certain level of coordinative variability may be desirable to evade an opponent and distribute joint loading.

Therefore, the purpose of this study was to determine if differences in coordination and coordination variability exist when time constraints (i.e. anticipated versus unanticipated) occur in sporting tasks in order to understand the role of the organization of the degrees of freedom in ACL injury risk. It was hypothesized that during unanticipated sidestepping: 1) trunk-pelvis and hip-knee coordination patterns would differ from anticipated sidestepping; and 2) there would be increased variability in trunk-pelvis and hip-knee couplings during the stance phase compared with their anticipated counterparts due to the increased complexity of the task.

2. Methods

2.1. Participants

Twenty two male collegiate team sport athletes (20.3 ± 1.2 yrs, 1.82 ± 0.08 m, 72.3 ± 7.9 kg) participated in a single biomechanical testing session. This cohort was chosen as ACL injuries typically occur in team sport athletes and this cohort would be familiar sidestepping sporting tasks. A power analysis from previous research [4,17,18] revealed that to achieve 80% power at an alpha criterion level of 0.05, a minimum of 16 participants were required for comparison. All athletes were free from injury at the time of testing and had no history of serious lower extremity injury or surgery within the previous year. Approval for this research was gained from the University Institutional Review Board and written informed consent for all participants was obtained.

2.2. Experimental setup

Kinematic data were recorded using an 11-camera motion capture system (Qualysis, Inc., Gothenburg, Sweden) sampling at 240 Hz synchronously with ground reaction forces from a 1.2×0.6 m force platform at 1200 Hz (AMTI, Watertown, MA). Participants were fitted with 42 14 mm retroreflective markers as per a customised trunk and lower limb kinematic marker set and model [19,20]. Markers placed on the medial and lateral femoral condyles were used alongside a functional knee axis to define knee joint centers and knee axes orientation [19]. A functional method was also used to define hip joint centers [19]. Anatomical landmarks of the lower limb were tracked using rigid marker clusters placed on the thigh and leg [21]. All participants wore standardized footwear provided by the laboratory.

2.3. Protocol

Participants were asked to complete a random series of anticipated and unanticipated run, run-stop and sidestepping tasks using their dominant limb. Dominant limb was determined by asking participants which leg they would kick a soccer ball with or land from a jump. All participants were right limb dominant. Run and run-stop tasks were used for task randomization to limit predictability of the unanticipated sidestepping tasks and were not used formally in analysis. Symbols representing these tasks (i.e. arrow or stop sign) were displayed on a 1.65 m television screen at the end of a 20 m runway. Participants were instructed to run at $4.0 \pm 0.5 \text{ m s}^{-1}$ down the runway and perform the task displayed on the screen. During these tasks, the screen either displayed the task prompt before the initiation of the run (anticipated) or it appeared at ipsilateral limb toe off prior to contacting the force platform with the dominant leg to perform the task (unanticipated). An unanticipated task prompt was triggered by the athlete running through a set of timing gates. Participants were given approximately 30 s of rest between tasks to minimize any effects of fatigue. End-point variability/task completion was controlled for both anticipated and unanticipated sidestepping tasks such that results could only be interpreted with reference to condition and not task execution. As such, sidestepping trials were considered successful if the athletes' average approach velocity was $4.0 \pm 0.5 \text{ m s}^{-1}$ [22] and they contacted a black line $\pm 10^\circ$ marked on the ground at 45° with the contralateral limb upon exit of the sidestep manoeuvre.

2.4. Data reduction

Kinematic trajectories and ground reaction forces were filtered with a zero-lag fourth-order low pass Butterworth filter at 14 Hz. This cut-off frequency was selected based on residual analysis and visual inspection. Three-dimensional kinematic and kinetic data were calculated using a customised lower body model compliant with the International Society of Biomechanics (ISB) standards for the reporting of data [23]. Data processing was performed using Visual 3D software (C-motion, Inc., Rockville, MD).

2.5. Data analysis

Mean spatial-temporal, kinetic and segment/joint coordination and coordination variability were calculated for seven trials each of anticipated and unanticipated sidestepping. Spatial-temporal variables included pre-contact velocity (average pelvis centre of mass velocity in the last stride prior to foot strike of the sidestep) and change of direction angle (angle between the two centre of mass position vectors from dominant limb toe off to contralateral limb foot strike) [20]. External knee flexion, valgus and internal rotation moments were calculated during the stance phase and normalized to body mass and height. Stance was defined using the vertical ground reaction force from $> 10 \text{ N}$ to $< 10 \text{ N}$. Segment/joint coordination and coordination variability were calculated using a modified vector coding technique [24] for each participant and each sidestepping condition during stance. Angle-angle plots were created for motion between adjacent segments and joints (i.e. hip, knee, pelvis and trunk) over stance.

Coordination patterns were classified into in-phase with proximal dominance, in-phase with distal dominance, anti-phase with proximal dominance and anti-phase with distal dominance (Fig. 1) [25]. In order to understand which patterns were most prevalent, the percentage of stance from which each coordination pattern emerged was quantified using frequency plots. Coordination variability was calculated as the standard deviation of the vector connecting corresponding consecutive time points of the angle-angle plots across all trials in each condition using circular statistics [24]. Based on the ACL loading mechanisms identified in the literature [1,6], the following intra-limb couplings from the stance limb were examined: 1) trunk (flexion/extension)-

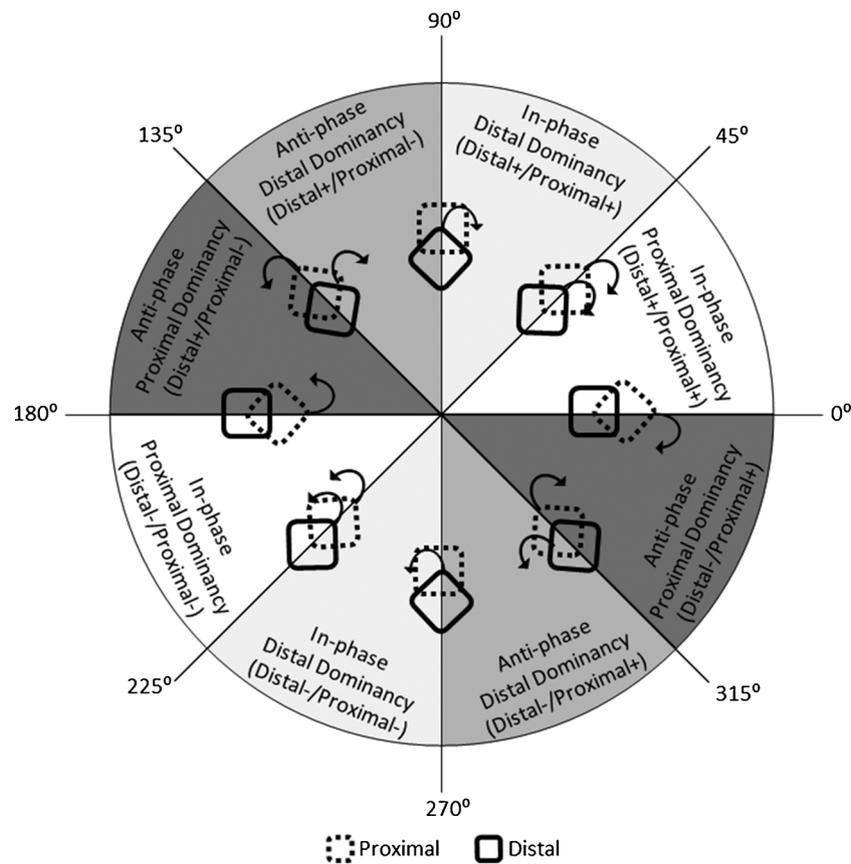


Fig. 1. Polar plot showing the coordination pattern classification as described by Needham et al., (2015). Visual illustrations at each 45° interval of coupling angle show coordination patterns between the proximal (dashed box) and distal (solid box) segments.

pelvis (anterior tilt/posterior tilt), 2) trunk (lateral flexion)-pelvis (obliquity), 3) trunk (rotation)-pelvis (rotation), 4) hip (flexion/extension)-knee (flexion/extension), 5) hip (rotation)-knee (flexion/extension), and 6) hip (rotation)-knee (abduction/adduction).

2.6. Statistical analysis

Differences in spatial temporal variables and coordination pattern frequencies over stance in anticipated and unanticipated sidestepping were assessed with paired t-tests with an $\alpha = 0.05$. As this was an exploratory study, a correction factor was not applied to account for the number of statistical tests conducted. Cohen's *d* effect sizes were calculated and defined as small (0.2), moderate (0.5) and large (0.8) [26]. Discrete statistical analyses were conducted in SPSS (IBM SPSS Statistics 22, SPSS Inc., Chicago, IL).

One-dimensional statistical parametric mapping (SPM1D) was used to compare mean moment and coordination variability waveforms over stance [27]. The scalar output SPM t-statistic curves were calculated for each time point over stance forming a statistical parametric map. The temporal smoothness based on the average temporal gradient of the data curve was then estimated using random field theory [27]. Statistical significance was achieved when the value of the test statistic breached the threshold above which only 5% of the data would be expected to reach had the SPM t curve resulted from an equally smooth random process.

3. Results

No differences were observed for approach velocities of 4.4 m s^{-1} (SD 0.3) in anticipated and 4.4 m s^{-1} (SD 0.3) in unanticipated sidestepping tasks ($P = 0.67$, $ES = 0.1$). Change of direction angle,

however, was 40.3° (SD 4.0) in anticipated which was greater than the 35.1° (SD 5.7) change of direction angle observed in unanticipated sidestepping ($P < 0.001$, $ES = 1.1$). No differences were observed in peak external knee joint moments. However, externally applied knee flexion moments were greater in unanticipated sidestepping than anticipated sidestepping from 0 to 2% of stance ($P = 0.049$). Knee valgus moments were greater in unanticipated sidestepping compared with anticipated sidestepping from 23 to 36% of stance ($P = 0.001$). No differences were observed in internal rotation knee moments (Fig. 2).

Differences in trunk-pelvis coordination pattern frequency during stance were primarily observed in the sagittal and frontal planes (Fig. 3). In the sagittal plane, anti-phase coordination with trunk dominance (pelvis anterior tilt/trunk extension) was lower in unanticipated sidestepping compared with anticipated sidestepping ($P = 0.003$, $ES = 0.67$). In the frontal plane, anti-phase coordination with pelvis dominance (left ASIS up/left lateral flexion) was greater in anticipated sidestepping than unanticipated sidestepping ($P = 0.008$, $ES = 0.67$). In-phase trunk ($P = 0.049$, $ES = 0.52$) and in-phase pelvis ($P = 0.029$, $ES = 0.45$) (right ASIS up/left lateral flexion) were both greater in unanticipated sidestepping than anticipated sidestepping.

During unanticipated sidestepping, there was an increase in knee dominant motion of the hip (flexion/extension)-knee (flexion/extension), hip (rotation)-knee (flexion/extension) and hip (rotation)-knee (abduction/adduction) couplings (Fig. 4). In-phase coordination with knee dominance (knee flexion/hip flexion) was greater in unanticipated sidestepping compared with anticipated sidestepping during early stance ($P = 0.048$, $ES = 0.28$). During mid-stance, anti-phase coordination with hip dominance (knee flexion/hip extension) was lower in unanticipated sidestepping compared with anticipated sidestepping ($P = 0.049$, $ES = 0.54$). In-phase coordination with knee dominance (knee extension/hip external rotation) was greater in unanticipated

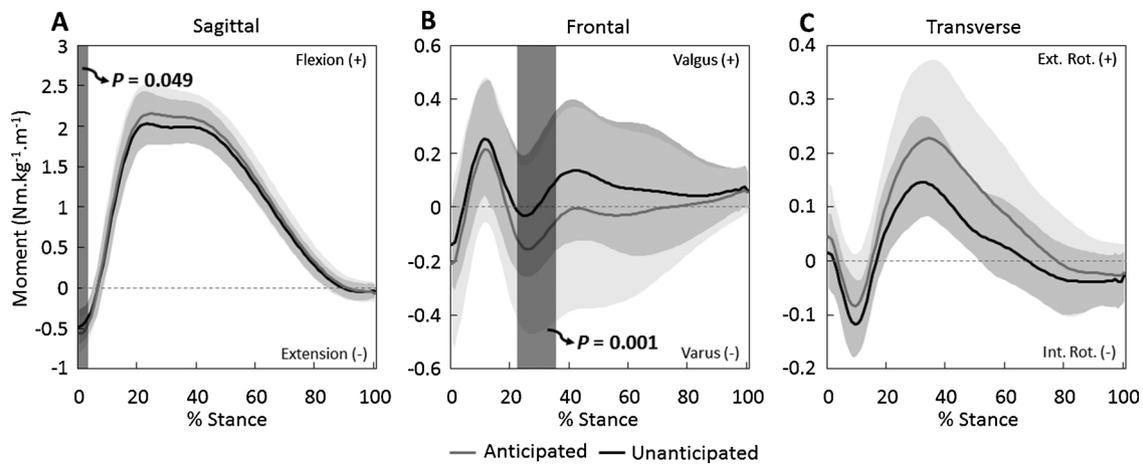


Fig. 2. Average external knee flexion/extension (A), valgus/varus (B) and internal/external rotation (C) moments during anticipated (grey) and unanticipated (black) sidestepping. Shaded regions on the graph indicate statistical significance at $P < 0.05$ from SPM1d analyses.

sidestepping compared with anticipated sidestepping during mid-stance ($P = 0.041$, $ES = 0.40$). During mid to late stance, there was greater anti-phase motion with knee dominance (knee adduction/hip external rotation) in unanticipated sidestepping compared with anticipated sidestepping ($P = 0.015$, $ES = 0.64$). There were no differences in hip internal rotation and knee abduction coupled motion (i.e. dynamic knee valgus posture) between tasks.

Higher coordination variability was observed from 7 to 8% of stance for trunk (flexion-extension)-pelvis (tilt) ($P = 0.049$) and 77–83% of stance for trunk (lateral flexion)-pelvis (obliquity) ($P = 0.001$) during unanticipated sidestepping compared with anticipated sidestepping. No differences were observed in the transverse plane (Fig. 5).

Hip-knee coordination variability in the sagittal plane was higher during unanticipated sidestepping compared with anticipated sidestepping from 0 to 2% of stance ($P = 0.036$). Hip (rotation)-knee (flexion-extension) coordination variability was higher in unanticipated sidestepping compared with anticipated sidestepping from 0 to 4% of stance ($P = 0.011$). There were no differences in hip (rotation)-knee (abduction-adduction) coordination variability (Fig. 6).

4. Discussion

The purpose of this study was to investigate differences in coordination and coordination variability in anticipated and unanticipated sidestepping to gain a better understanding of the organization of the degrees of freedom during these tasks and the role of this organization in ACL injury risk. In support of our first hypothesis, coordination patterns of the trunk-pelvis and hip-knee couplings differed between sidestepping conditions where we observed more in-phase coordination of the trunk-pelvis coupling in the frontal and sagittal planes and the hip (flexion/extension)-knee (flexion/extension) and hip (rotation)-knee (flexion/extension) couplings during the stance phase of unanticipated sidestepping. We also hypothesized that coordination variability would be higher in unanticipated sidestepping. This was supported by increased variability in frontal and sagittal plane trunk-pelvis coupled motion, hip (flexion/extension)-knee (flexion/extension) and hip (rotation)-knee (flexion/extension) coupled motion in unanticipated sidestepping.

4.1. Coordination

During both anticipated and unanticipated sidestepping, the trunk dominated the trunk-pelvis coupling in all three planes of motion. This is unsurprising given the multiple studies describing the large ranges of motion of the upper body during sidestepping tasks [7,28,29]. During unanticipated sidestepping there was greater in-phase trunk-pelvis

coordination in both the frontal and sagittal planes. This may be the result of locking the degrees-of-freedom due to the inability to appropriately coordinate the movement in the reduced amount of time available [16]. This may suggest that, when assessing trunk mechanics with respect to ACL injury risk, it should be measured during unanticipated sidestepping for more sensitive analyses.

Higher in-phase coordination with knee dominance was observed for both hip (flexion/extension)-knee (flexion/extension) and hip (rotation)-knee (flexion/extension) in unanticipated sidestepping. This difference primarily occurred during mid stance where knee flexion was greatest (see Fig. 4). Interestingly, we did not observe differences between tasks in hip internal rotation/knee abduction coupled motion which may quantify a dynamic knee valgus posture. This result that may be, in part due to the complexity of this posture which encompasses excessive hip internal rotation combined with knee extension and abduction [30]. The analysis of coordination of the hip and knee joints provided information regarding the lower extremity that was not evident in previous analyses of sidestepping. Coordination analysis indicated that in unanticipated sidestepping, the hip is not extended to propel the body forward in the same manner that is observed in anticipated sidestepping. As a consequence, the knee must generate the majority of propulsion. This may contribute to the elevated knee moments that were observed in unanticipated sidestepping. Additionally, much larger muscle forces are required to both counter loads and support this lower limb posture [31].

4.2. Coordination variability

During unanticipated sidestepping, athletes displayed higher sagittal and frontal plane trunk-pelvis coordination variability in early and late stance, respectively. Hip-knee coordination variability was greater in unanticipated sidestepping at, and just following foot strike. The greater coordination variability observed in unanticipated sidestepping is likely a result of utilizing more degrees of freedom in order to achieve the more complex task [15]. Additionally, the lower coordinative variability observed in anticipated sidestepping likely occurs because the weight acceptance phase occurs prior to the initiation of the change of direction in order to control the centre of mass toward the intended direction of travel [32]. Analysis of the dynamic knee valgus posture showed increased variability of the hip (rotation)-knee (flexion/extension) coupling but not hip (rotation)-knee (abduction/adduction) during unanticipated sidestepping during early stance.

4.3. Limitations

These results must be taken into context with task completion/end-

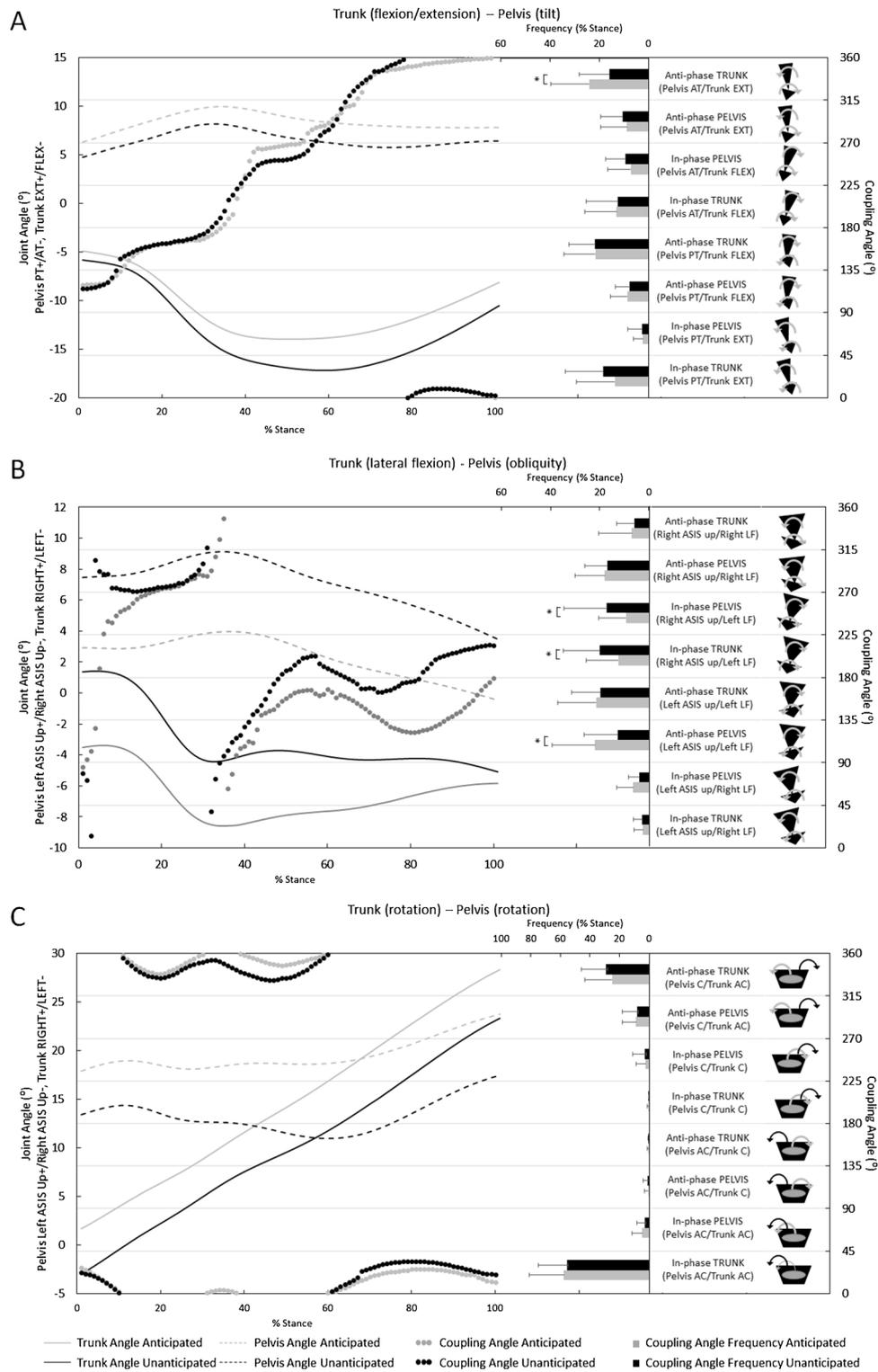


Fig. 3. Mean coupling angle for trunk-pelvis coordination (dotted lines), coordination pattern frequency (i.e. percentage of stance spent in each coordination pattern) (bars), trunk (dashed lines) and pelvis (solid lines) joint angles during the stance phase of anticipated (grey) and unanticipated (black) sidestepping for the sagittal (A), frontal (B), and transverse planes (C). AT = anterior tilt, PT = posterior tilt, FLEX = flexion, EXT = extension, ASIS = anterior superior iliac spine, LF = lateral flexion, C = clockwise, AC = anti-clockwise.

point variability. Although pre-contact velocities were matched between tasks, there was a statistically significant difference for the change of direction angle which may have influenced our results. This difference was, however, less than 5° which is comparable to that in other studies [4]. Female athletes have been shown to have lower coordination variability than their male counterparts during

unanticipated sidestepping and, as such, may have a wider difference in coordination patterns and coordination variability between anticipated and unanticipated sports tasks than observed in this study [33]. While vector coding allows the continuous measurement of two segments or joints with reference to one another, it only presents spatial information with no regard to temporal information [34]. Finally, this analysis was

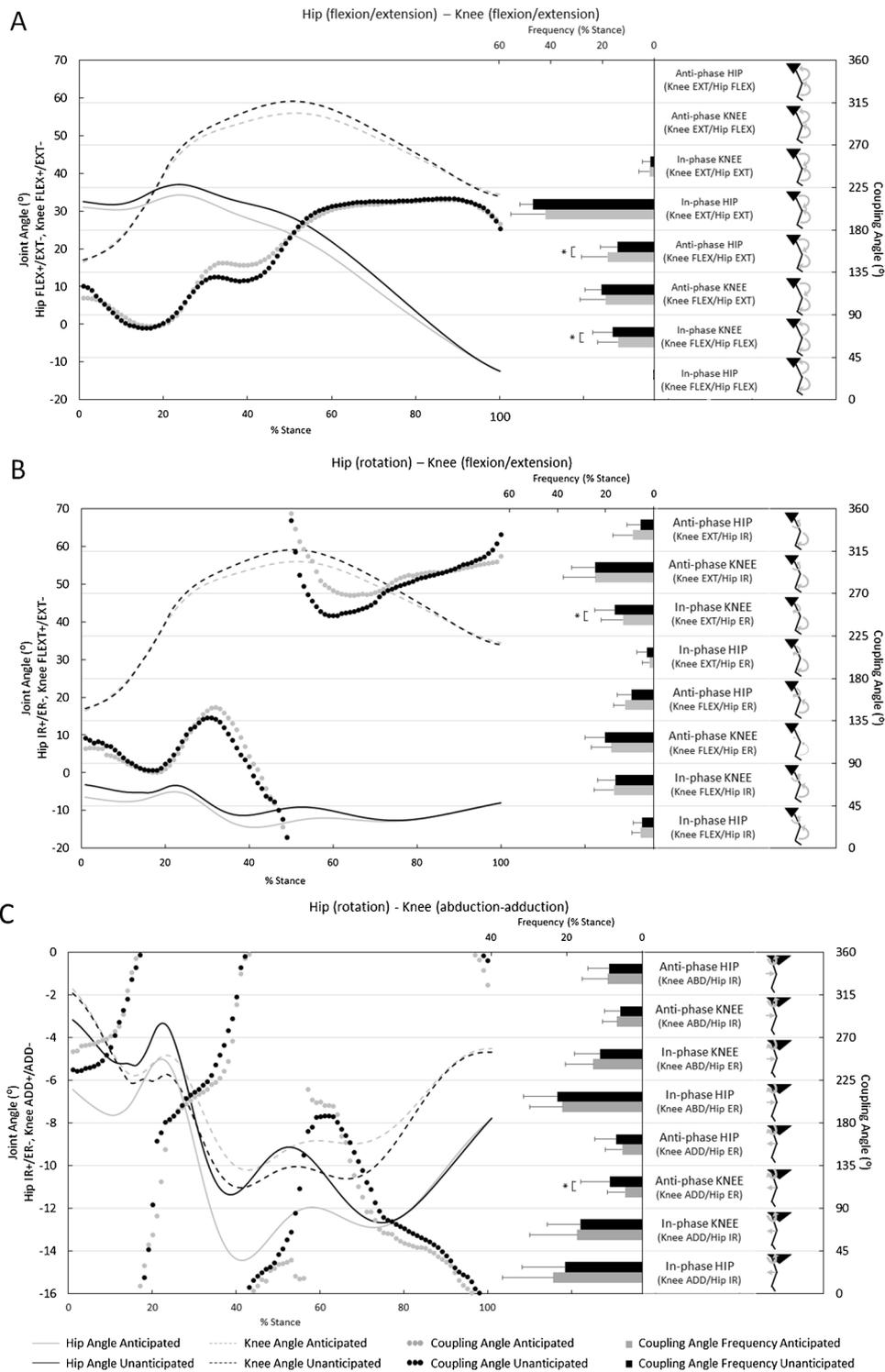


Fig. 4. Mean coupling angle for hip-knee coordination (dotted lines), coordination pattern frequency (i.e. percentage of stance spent in each coordination pattern) (bars), knee (dashed lines) and hip (solid lines) joint angles during the stance phase of anticipated (grey) and unanticipated (black) sidestepping for hip (flexion/extension) – knee (flexion/extension) (A) and hip (rotation) – knee (flexion/extension) couplings (B). FLEX = flexion, EXT = extension, IR = internal rotation, ER = external rotation, ABD = abduction, ADD = adduction.

only tested in healthy team sport athletes retrospectively. This is one of the first studies to investigate coordination variability with reference to acute injury, and therefore a continuum of low to high and healthy to unhealthy variability needs to be established through prospective research studies.

5. Conclusions

Sidestepping is a complex task that requires multiple, complex coordination patterns to achieve successful change of direction performance (e.g., evasion of opposition player). Consequently, there must be a large kinematic solution space. As task complexity increased in this study (i.e. reduced time to plan the movement in unanticipated

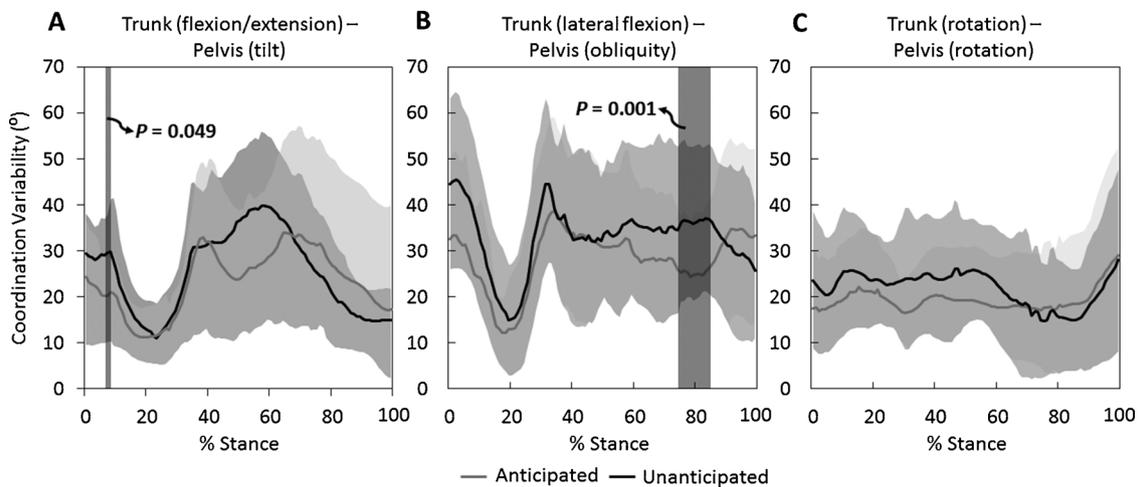


Fig. 5. Coordination variability during the stance phase of anticipated (grey) and unanticipated (black) sidestepping for the trunk-pelvis in the sagittal (A), frontal (B) and transverse (C) planes.

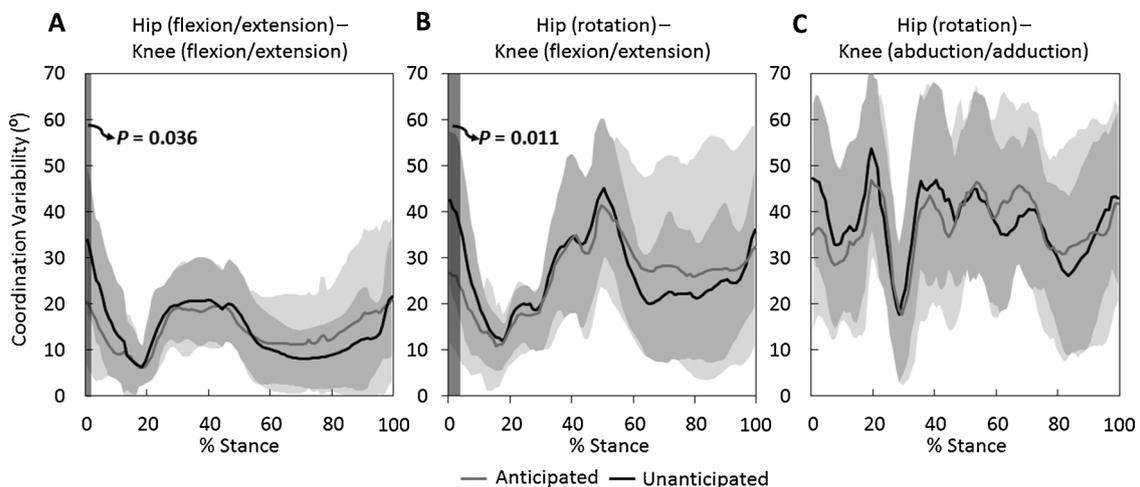


Fig. 6. Coordination variability during the stance phase of anticipated (grey) and unanticipated (black) sidestepping for the (A) hip (flexion/extension) – knee (flexion/extension), (B) hip (rotation) – knee (flexion/extension) and, (C) hip (rotation) – knee (flexion/extension) couplings. Shaded regions on the graph indicate statistical significance at $P < 0.05$ from SPM1d analyses.

scenarios), differences in coordination (i.e. greater in-phase coordination) emerged and variability of this coordination increased. While many studies have compared the mechanics of anticipated and unanticipated sidestepping, this study adds to this growing body of literature by describing the interaction between segments and joints from a dynamical systems perspective. These results highlight that: 1) anticipated and unanticipated sidestepping are not the same task: and, as such, 2) should be interpreted differently when assessing an athlete's risk of injury and when designing injury prevention protocols. Prophylactic training should incorporate perceptual training alongside traditional strength, balance and plyometric injury prevention training regimes in order to improve reaction time and enable athletes to optimally process sport related visual scenes to increase the time available to appropriately coordinate movement during sidestepping manoeuvres.

Conflict of interest

None.

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