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Trunk, pelvis and lower limb coordination between anticipated and unanticipated sidestep cutting in females

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ABSTRACT

Background: Emerging research has suggested a plausible relationship may exist between lower limb coordination and musculoskeletal injury. A small number of studies have investigated the link between coordination and anterior cruciate ligament (ACL) injury during sidestep cutting. While prior work has shown unanticipated sidestep cutting to exhibit a more 'at risk' kinematic profile compared to anticipated tasks, a detailed understanding of the coordination between multiple joints and how they differ during unanticipated actions is lacking, particularly in females.

Research question: The purpose of this study was to observe the difference in trunk, pelvis and lower limb coordination and coordination variability during a dynamic, sidestep cutting task under anticipated and unanticipated conditions in a healthy female cohort.

Methods: Three-dimensional motion analysis data were recorded during anticipated and unanticipated sidestep cutting for nineteen healthy female participants (age, 24 ± 3yrs; height, 164 ± 5 cm; and weight, 58 ± 6 kg). Vector coding methodology was used to calculate coordination and coordination variability values and statistical parametric and non-parametric mapping was used to comprehensively determine differences between anticipated and unanticipated conditions.

Results: Differences were observed between anticipated and unanticipated conditions in the hip flexion – knee abduction angle (89 % of stance), hip rotation – knee abduction angle (55 % of stance), knee flexion – knee abduction angle (81–83 %, 86 % and 88–89 %) and knee flexion – ankle flexion angle (14–18 %) coupling angles. Differences in coupling angle variability were also observed with only one cluster of significance seen in hip abduction – knee abduction variability (27–30 % of stance).

Significance: Healthy females exhibit significant differences in lower limb coupling angles and coupling angle variability between anticipated and unanticipated sidestep cutting. Interventions aimed at reducing ACL injury risk may need to consider that anticipated and unanticipated sidestep cutting tasks present unique demands, and therefore should both be trained specifically.

1. Introduction

Human movement requires the complex organization of multiple degrees of freedom to form coordinated action. Task performance is inherently linked to the underlying organisation of movement, and advances in how this organisation is quantified has increased the ability of researchers, and in turn practitioners, to decipher human movement. Generally, coordination can be considered in two parts [1]; 1) the organisational pattern between multiple joints or segments to form goal directed action and 2) the variance within the pattern utilised. Previous work has suggested that variance in joint coordination is normally seen in healthy individuals, allowing motor patterns to be both stable and repeatable, yet flexible enough to adapt to task constraints [2,3].

There is a plausible relationship between lower limb musculoskeletal injury and variance in joint coordination, as previous work has shown differences in joint coordination variability between injured and

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uninjured populations [2,4]. With the rates of anterior cruciate ligament (ACL) rupture increasing in recent years [5,6], mechanisms of injury have continued to gain interest in motor control research [7,8]. Additionally, whilst ACL rupture is more likely to occur in females [9] they are still a population that is underrepresented in motor control literature. Epidemiological studies show most ACL ruptures are non-contact in nature, occurring during dynamic sporting movements like sidestep-cutting and single leg landings [10–12]. Additionally, competitive sport requires individuals to adapt their movement and react to constantly changing stimuli and these unanticipated movements are believed to play a key role in ACL rupture [13]. A relatively large body of work has investigated knee joint angles and moments during unanticipated movements, showing differences in key biomechanical variables associated with increased ACL load, such as decreased knee flexion angle and increased knee abduction angle and moment [14,15]. Additionally, video analysis has shown altered trunk motion to be associated with incidence of ACL injury [11,12]. However, these studies observe kinematics and kinetics of the lower limb joints independently, rather than addressing the relationship between them.

A recent paper by Weir et al. (2019) quantified intersegment coordination by employing a vector coding approach to calculate coupling angle and coupling angle variability (e.g. trunk-pelvis and hip-knee), between anticipated and unanticipated side-step cutting. These authors found preliminary evidence of altered coupling angles and increased coupling angle variability between conditions, suggesting coordination and coordination variability may play a role in lower limb musculoskeletal injury. However, Weir and colleagues (2019) only investigated a male cohort, so it is unknown if these findings can be generalised to a female population. Additionally, the statistical approach used by Weir and colleagues (2019) was unable to determine differences in coupling angles between conditions across the entire stance phase.

Therefore, the purpose of this study was to observe the difference in trunk, pelvis and lower limb coordination and coordination variability during a sidestep cutting task under anticipated and unanticipated conditions in a healthy female cohort, across the entire stance phase. Based on previous research [8] we hypothesised that;

1. Trunk – pelvis and hip – knee coupling angles would be significantly different between anticipated and unanticipated conditions across the stance phase.
2. Trunk – pelvis and hip – knee coupling angle variability would be increased across the stance phase of the unanticipated condition compared to the anticipated condition, due to increased task complexity.

2. Methods

2.1. Participants

Nineteen healthy, recreationally active females (age, 24 ± 3yrs; height, 164 ± 5 cm; and weight, 58 ± 6 kg), were recruited to participate in this study. All participants had experience competing in multidirectional sports (e.g. Soccer, Australian Rules football and gymnastics), however, participant inclusion was not limited to a single sport to aid with recruitment. Participants were required to have had no history of lower limb injury requiring surgical intervention, and no lower limb injury sustained within the last six months. Prior to data collection, ethical approval was gained by the Australian Catholic University, Human Research Ethics Committee (ethics register number: 2015−11 H) and all participants provided written informed consent.

2.2. Data collection

Participants were required for a single session and completed all testing barefoot. Although these sidestep cutting tasks are typically performed while wearing shoes in sporting environments, having the participants barefoot allowed exposure of the foot for direct placement of reflective markers on anatomical landmarks, as seen in prior published work [16]. Forty-three reflective markers [16] were adhered to each participant's skin on various anatomical locations of the torso (sternum, spinous process of 7th cervical vertebra, spinous process of mid-thoracic vertebra and left and right acromion), pelvis (left and right anterior superior iliac spines and posterior superior iliac spines), upper limbs (left and right medial and lateral elbow and distal radius and ulna) and lower limbs (medial and lateral femoral epicondyles, malleoli, first and fifth metatarsal-phalangeal joints, calcaneus and three additional markers on each thigh and shank segment). Marker trajectories were recorded using a nine camera Vicon system (Vicon, Oxford metrics Ltd., Oxford, United Kingdom) sampled at 200 Hz, with ground reaction forces recorded using two ground-embedded force plates (Advanced Mechanical Technology Inc., Watertown, MA, USA) sampled at 1000 Hz [16].

Due to the inherent difficulty in achieving successful trials with run-and-cut tasks, especially under unanticipated conditions, a task was chosen that mimics the demands and biomechanical profile as per previous research [16–18]. The task required participants to execute a forward jump off a 0.31 m box placed 1.35 m from the centre of the force plate, landing on a single limb and immediately side cutting at approximately 45°, guided by floor markings. During the anticipated conditions, participants were instructed to side cut to either the right or left prior to performing the task. During the unanticipated condition, a timing gate system (Fusion Sport, Sumner Park, Australia) was used to provide a randomised 'left' or 'right' stimulus, approximately 450 ms prior to initial contact with the force plate. This time delay is similar to previously published works [16,19] and is within suggested temporal restraints for unanticipated cutting tasks [20]. Additionally, our analysis showed the time delay was small enough to elicit a substantial increase in failed trials during the unanticipated condition (sucessful trials were 88 % ± 11 vs 43 % ± 16, $p < 0.001$), yet large enough to allow successful completion of the task. If the 'left' gate light was triggered, participants landed on their right leg and cut to the left, if the 'right' gate light was triggered, participants landed on their left leg and cut to the right.

For a trial to be considered successful, the participant's entire foot was required to land within the edges of the force plate. Additionally, the cut needed to be in the correct direction with the correct limb, within the floor markings indicating the 45° cutting angle. Four successful trials of each task and condition were needed to calculate joint variability [21].

2.3. Data analysis

Marker data were low-pass filtered using a fourth order, zero-lag Butterworth filter (Mathworks, Natick, USA) with a cut-off frequency of 8 Hz, determined via residual analysis [16]. Using OpenSim [22], a 35 degree-of-freedom (DOF) musculoskeletal model [23] was scaled to each participant's anthropometry via a static trial. Joint angles were computed using a global optimisation inverse kinematics approach [24]. Recent work has shown there to be no difference between left and right lower limb biomechanical variables for similar tasks [25,26], therefore only the right leg trials were analysed. Joint angle data across the stance phase, defined as the period when the vertical ground reaction force exceeded 10 N, were linearly time-normalised to 101 points (0–100% of stance) for further analysis.

To quantify coordination, joint couplings were computed using a modified vector coding method [27]. This method computed the resultant coupled angle (between 0°- 360°, however, note that 360° was excluded as it is defined as the same angular value as 0°) using the orientation to the right horizontal of two adjacent data points on the joint angle-angle plot (see supplementary digital content for further explanation of methodology). Whilst there is a very large scope of joint-coupling angles that could be investigated, we have chosen to focus on those likely to be more relevant to ACL injury. As there is no consensus in which coupling angles to investigate in reference to ACL injury, the coupling angles investigated in this study were based on a comprehensive coverage of the approaches from previously published work [8,21,28], with additional couplings of interest included. The joint coupling angles were: trunk flexion – pelvis tilt, trunk lateral flexion – pelvis obliquity, trunk rotation – pelvis rotation, hip flexion – knee flexion, hip flexion – knee adduction, hip adduction – knee adduction, hip rotation – knee flexion, hip rotation – knee adduction, hip rotation – knee rotation, knee flexion – knee adduction, knee rotation – knee abduction, knee flexion – ankle flexion and knee adduction – ankle inversion. To establish typical coupling angles across the stance phase, the circular mean was computed for each time node across the four trials. In accordance with previous research [29] we classified coupling angles as in-phase (both segments rotating in the same direction) or anti-phase (segments rotating in opposite directions), as well as identifying proximal or distal dominancy (which segment was rotating at a faster rate). To compute joint coupling variability, the circular standard deviation was calculated for each time node across the four trials, for each participant. The group mean and standard deviation of each time node was then calculated giving a non-angular measure of between trial variability for each condition.

2.4. Statistics

A paired circular *t*-test [30] was conducted to compare anticipated and unanticipated coupling angle data. In order to analyse the differences between conditions across the entire stance phase, statistical parametric mapping (SPM) techniques [31] were utilised. To our knowledge, SPM has never been validated for use with circular data. The

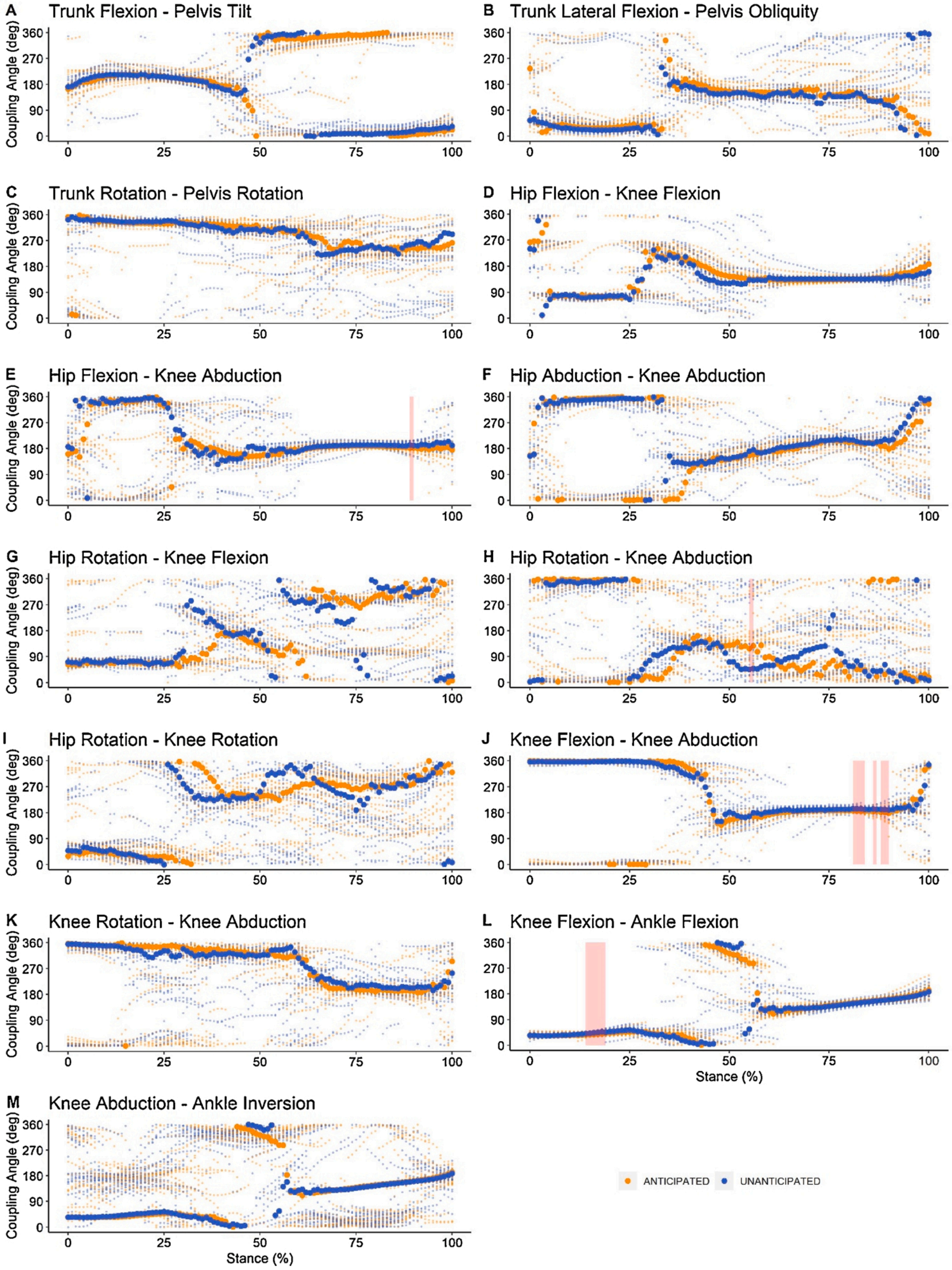

Fig. 1. Coupling angles across the stance phase of anticipated and unanticipated sidestep cutting. Larger points show the group mean coordination pattern, smaller points show individual participant patterns. Light red shaded bars show clusters of significant difference between anticipated and unanticipated tasks. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

nature of circular data creates problems with standard linear statistics because (i) 0° and 360° are essentially the same value, (ii) when angular data are expressed in polar coordinates, the radius is constrained to a constant value, and (iii) when angular data are expressed in Cartesian coordinates the shortest path between two points is not a straight line, but rather a circular arc. These difficulties are comprehensively dealt with for 0D (scalar) data, often using approximate convergences rather than explicit solutions [30], but the validity of these solutions has not been extended to 1D circular data (i.e. angular data that changes in 1D time). Moreover, since we are unaware of any existing 1D Von Mises random number generators, we would be unable to validate parametric solutions even if they exist. Therefore, in this paper, rather than explicitly validating SPM for 1D circular data, we instead employed non-parametric inference [32], which is valid for all 1D statistics, irrespective of the underlying data distribution [33].

Nevertheless, we partially validated our approach as follows. Firstly, validation of an existing implementation of a paired test for circular 0D data (“meandir.test.R”, [34]) was conducted by randomly generating 10,000 paired samples of random, circular 0D Von Mises datasets of various sample sizes and confirming that that these random data adhered to the theoretical cumulative distribution function. The test was then adapted for 1D data by computing the test statistic at each point in the 1D trajectory and non-parametric inference [33] was used to assess the significance of the 1D test statistic trajectory.

A paired *t*-test was conducted to compare anticipated and unanticipated coupling angle variability data. Unlike the coupling angle, variability data is not considered circular, therefore use of SPM is considered valid [33,34]. As this was an exploratory study, the alpha level was set to 0.05 for all comparisons.

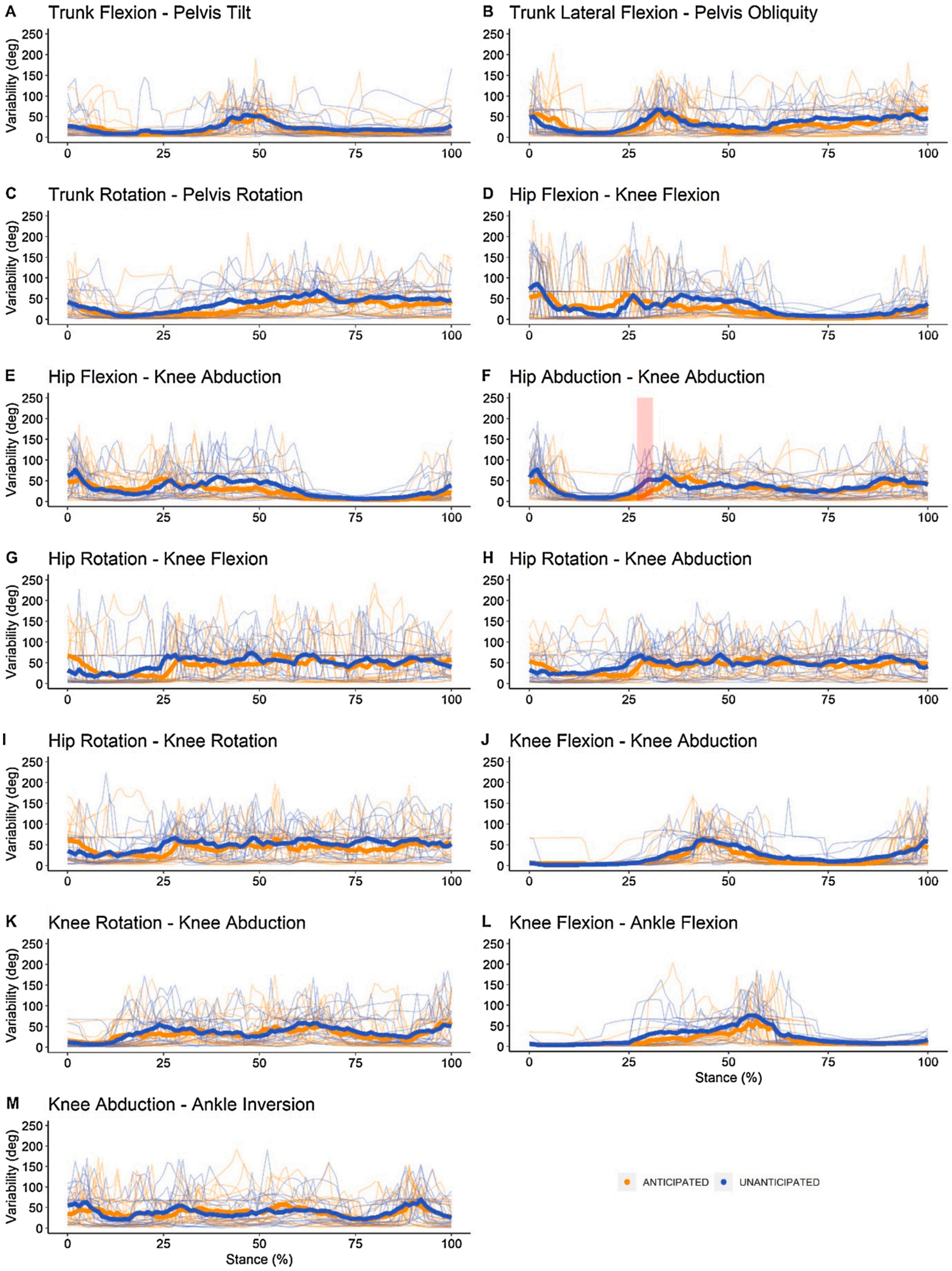

Fig. 2. Coupling angle variability across the stance phase of anticipated and unanticipated sidestep cutting. Thicker lines indicate the group mean variability, thinner lines show individual participant variation across all trials. Light red shaded bars show clusters of significant difference between anticipated and unanticipated tasks. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Results

Significant differences were observed in multiple coupling angles between anticipated and unanticipated tasks (Fig. 1). Differences seen in the hip flexion – knee abduction coupling angle (89 % of stance, $p < 0.05$, Fig. 1.E.) fell within the same 'in-phase proximal dominant' pattern. Differences seen in the hip rotation – knee abduction coupling angle (55 % of stance, $p < 0.05$, Fig. 1.H.) showed the anticipated condition to have an 'anti-phase distal dominant' pattern, while the unanticipated condition had an 'in-phase distal dominant' pattern. Differences seen in the knee flexion – knee abduction coupling angle (81–83 %, 86 % and 88–89 %, $p < 0.05$, Fig. 1.J.), showed both conditions to adopt an 'in-phase proximal dominant' pattern, until 89 % of stance where the anticipated condition transitioned to an 'anti-phase proximal dominant' pattern. Differences seen in knee flexion – ankle flexion coupling angle (14–18 %, $p < 0.05$, Fig. 1.L.), showed both conditions to adopt an 'in-phase proximal dominant' pattern until 18 % of stance where the unanticipated condition transitioned to an 'in-phase distal dominant' pattern. In regards to coupling angle variability, only one cluster of significance was seen in the hip abduction – knee abduction coupling angle at 27–30 % of stance ($p = 0.01$, Fig. 2.F), indicating the unanticipated condition to have an increased amount of variability.

4. Discussion

This is the first study to investigate the difference in trunk-pelvis and lower limb coordination and coordination variability during anticipated and unanticipated versions of a sidestep cutting task, in a healthy female cohort. In partial support of our first hypothesis, we observed significant differences in hip-knee coupling angles at various points of stance phase, however no significant differences were observed in trunk-pelvis coupling angles. Our second hypothesis was also partially supported by our results, with the hip abduction – knee abduction coupling angle displaying higher variability in the unanticipated task.

To our knowledge, only one prior study has compared anticipated and unanticipated vector coding coordination data [8]. Our results show good agreement with reported coupling angle and variability values from Weir and collegues [8]. This study utilised the same SPM approach [33,35,36] to analyse variability data and, similar to Weir and collegues [8], saw minimal differences in coupling angle variability between anticipated and unanticipated conditions. While Weir and collegues [8] reported differences in trunk flexion – pelvis tilt (7–8 % of stance), trunk lateral flexion – pelvis list (77–83 % of stance), hip flexion – knee flexion (0–2 % of stance) and hip rotation – knee flexion (0–4 % of stance) variability, the current study only found differences in hip abduction – knee abduction (27–30 % of stance) variability. These contrasting findings may be due to differences in task and population, as previous work has suggested differences between male and female movement variability [7].

An important difference between this work and that of Weir and collegues [8] is the analysis method employed for coupling angle data. Weir and collegues [8] used an approach to interpret their coupling angle data, whereby each data point is characterised by a coordination 'pattern', then the frequency of each pattern is calculated. This approach is consistent with previous work [29], however, is in contrast to our approach, as we employed a novel statistical method for analysing coupling angle data which makes use of statistical non-parametric mapping [33,35,36]. This new approach allows inference between conditions to be made on the coupling angles themselves, across the entire time series. To assess the influence of the analysis approach, we also performed the same analysis used by Weir [8] on our coupling angle data (see supplementary digital content.docx, Table 1, the table shows mean pattern frequency for each coupling angle and associated p value between anticipated and unanticipated conditions). Overall, we obtained some similar findings to those observed by Weir and collegues [8]. For example, very similar pattern frequencies were noted within the hip flexion – knee flexion and hip rotation – knee flexion coupling angles (see supplementary digital content.docx, Table 1). Whilst it is impossible to know which analysis technique gives the most valid results, the time-varying approach used in this work has some key differences to previous studies [8,29]. Such previous work has classified coupling angle data into one of eight coordination patterns [29], thus, resulting in a reduction in resolution, which in turn can corrupt the data signal [37]. Additionally, while the measure of pattern frequency obtained by this method can suggest dominance of a strategy across stance, it inherently lacks the ability to determine a difference in the coordination pattern between conditions or the time point of when these differences could occur, as the resulting statistic addresses differences in frequency rather than the coupling angles themselves [37]. Another unavoidable aspect of this method is the need to perform multiple statistical comparisons within each variable. In our supplementary analysis we utilised the same approach, performing eight paired t-tests within each variable without any correction to the alpha level. Whilst numerous significant differences were observed using this approach, the multiple comparisons would have resulted in an increased chance of making a type one error. One of the major strengths of this project was the novel use of statistical non-parametric mapping with circular data. This has enabled the current analysis to be performed on joint coupling data for the first time, allowing inferences to be made between anticipated and unanticipated conditions, across the entire stance phase.

Using this new statistical non-parametric mapping approach, we found relatively few differences between anticipated and unanticipated conditions within our coupling angle data. This is perhaps surprising as unanticipated cutting tasks have been shown to exhibit a more 'at risk' biomechanical profile compared to anticipated cutting tasks, characterised by increased knee abduction angle and moment [14,15]. Therefore, it may be expected that a difference would be seen in the coordination pattern utilised between the two conditions in the current study. However, our results suggest otherwise. Although clusters of significant differences were seen in hip flexion – knee abduction (89 % of stance), hip rotation – knee abduction (55 % of stance), knee flexion – knee abduction (81–83 %, 86 % and 88–89 % of stance) and knee flexion – ankle flexion (14–18 % of stance), the coordination patterns within these clusters are either the same, or represent a difference during only 1% of stance, both of which may suggest no meaningful differences in coordination strategy between conditions.

This result, together with the large amount of variance observed both between and within participants for the majority of the joint couples (Figs. 1 and 2), suggests that a large kinematic solution space exists during sidestep cutting, regardless of anticipation.

5. Limitations

Our study investigated recreationally active, healthy females, thus our results should not be generalised to other populations. Further work may aim to establish if coordination strategies are prospectively associated with increased lower limb injury risk, as well as investigating 'high risk' groups such as adolescent females and ACL reconstructed individuals.

A recent reliability study showed eight trials were needed for coordination variability to stabilise during gait using vector coding data [38]. Although there is no consensus on appropriate number of trials for sidestep-cutting tasks [8,21,28], the approach used in this work is in line with previous work analysing vector coding with dynamic tasks [21,28]. Given the greater intensity of our task compared to walking, attempting to obtain eight complete trials (especially under unanticipated conditions) may have induced excessive fatigue in some participants, potentially contaminating our results. We acknowledge, however, that using four trials may have caused our estimates of variability at an individual level to be higher than those previously reported [8], potentially resulting in type two error. Additionally, our between subject variation within each task also appeared relatively high. While these results may be due to the nature of the specific tasks performed, they may also explain the minimal significant differences seen in variability between conditions. Thus future work is needed to determine the optimal number of trials for high impact tasks, such as sidestep-cutting.

Prior work has shown knee joint angles in the frontal and transverse plane to be more prone to error associated with soft tissue artefact [39]. While this cannot be completely eliminated, we used a global optimisation inverse kinematics algorithm to compute joint angles, which has been shown to be relatively robust to soft tissue artefact [24]. Additionally, the comparisons in this study were paired, and it is reasonable to expect that soft-tissue artefact be similar between the two conditions within each participant. Subsequently, we do not believe that this limitation influenced our primary conclusions.

6. Conclusion

We present the first data to investigate the difference in trunk, pelvis and lower limb joint coordination during a sidestep cutting task under anticipated and unanticipated conditions, in a healthy female cohort, across the entire stance phase. We found evidence that hip-knee coupling angles and coupling angle variability were significantly different between anticipated and unanticipated side-step cutting. Our data therefore supports the notion that anticipated and unanticipated side-step cutting require unique coordination strategies, and therefore should be trained as distinct components within interventions aiming to reduce risk of ACL injury.

Declaration of Competing Interest

No authors on this paper have any conflicts of interest to declare.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.gaitpost.2020.12.011.

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