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Head-Trunk Coordination and Coordination Variability During Anticipated and Unanticipated Sidestepping

A Thesis Presented

by

SAMUEL R. ZEFF

Submitted to the Graduate School of the

University of Massachusetts Amherst in fulfillment

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Kinesiology

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ABSTRACT

HEAD-TRUNK COORDINATION AND COORDINATION VARIABILITY DURING ANTICIPATED AND UNANTICIPATED SIDESTEPPING

MAY 2020

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Directed by: Professor Richard van Emmerik

INTRODUCTION: Sensory systems within the head provide us with rich perceptual information and may require complex control of the head during locomotion when changing direction. Head position in space is maintained by head on trunk motion as well as lower extremity kinematic modifications, such as increased knee flexion and increased stance time in order to facilitate shock attenuation and reduce vertical CoM displacement. It has been established that the body organizes its degrees of freedom of the trunk, pelvis and lower extremities differently during anticipated and unanticipated sidestepping, which raises the question of how these modifications affect head control during change of direction tasks.

METHODS: Fourteen collegiate soccer players performed 7 anticipated and 7 unanticipated sidestepping tasks. Kinematic data were recorded using an 11-camera motion capture system (Qualysis, Inc., Gothenburg, Sweden) sampling at 240 Hz. Head and trunk orientation was quantified at penultimate toe off. A modified vector coding analysis was used to quantify the coordination and coordination variability between the head and trunk during the anticipated and unanticipated side-stepping trials. Differences in head-trunk orientation and coordination pattern frequencies were assessed with a paired t-test with an $\alpha = 0.05$. One-dimensional statistical parametric mapping (SPM1D) was used to compare coordination variability waveforms.

RESULTS: The head ($p < 0.01$, ES = 0.82) and trunk ($p < 0.05$, ES = 0.59) were significantly more oriented toward the new travel direction during anticipated compared to unanticipated sidestepping. No significant differences in transverse or sagittal plane coordination were observed throughout the change of direction stride. However, during unanticipated sidestepping we observed significantly reduced in-phase head-trunk coordination during the preparatory phase in the sagittal ($p = 0.04$, ES = 0.63) and transverse ($p = 0.02$, ES = 0.73) planes but did not find differences in the stance or post-transition phases. Coordination variability did not differ between anticipated and unanticipated conditions. Irrespective of planning time, greater transverse plane coordination variability was observed during the flight phases compared to the stance phase ($p < 0.01$) of the change of direction stride. Sagittal plane coordination variability was significantly greater during the preparatory phase than the stance phase ($p < 0.01$), and stance phase coordination variability was significantly greater than post-transition phase variability ($p < 0.01$).

SIGNIFICANCE: Our results suggest differences in coordination between the head and trunk between anticipated and unanticipated sidestepping emerge during the preparatory phase of the change of direction stride, from penultimate step toe off to transition step heel strike. Anticipated and unanticipated sidestepping are different tasks, but individuals are consistent in the way the head-trunk coupling is controlled. Relating variability to task goals may allow for a better understanding of the beneficial aspects of variability observed at the head.

GLOSSARY

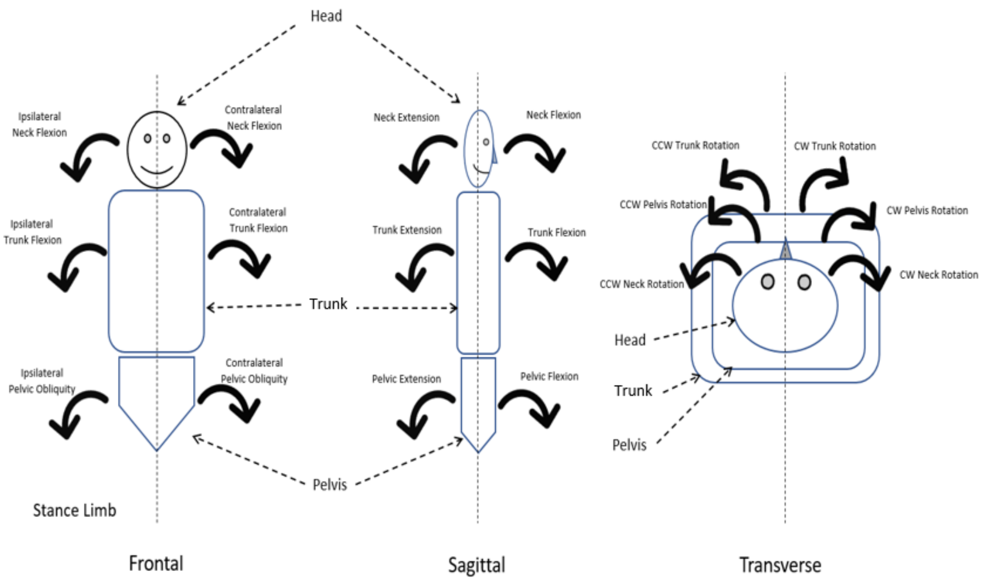

Figure 1: Tri-Planar Definitions of Head, Trunk and Pelvic Motion. The trunk represents the thorax-ab region of the body. The term obliquity is used to describe pelvic motion in the frontal plane to the ipsilateral and contralateral sides relative to the stance leg while lateral flexion can be used to describe neck and trunk motion. The stance leg will be specified. In the transverse plane, the neck trunk and pelvis can rotate clockwise (CW) and counter-clockwise (CCW).

Trunk – Thorax-abdominal region of the body. Throughout the literature, the term trunk has been used to describe the thorax, thorax-ab, and thorax-ab-pelvic region of the body. Throughout this document, the term trunk will be used strictly to define motion of the thorax-ab region when appropriate (Figure 1). In circumstances where the original authors of an adapted figure use the term to represent something other than the thorax-ab region, the figure caption will provide the correct term.

Obliquity – Term used to describe pelvic motion in the frontal plane. Ipsilateral pelvic obliquity would refer to the pelvis being lower on the stance leg side and higher on the contralateral side in the frontal plane.

Frankfort Plane – a plane referenced to anatomical landmarks of the head which closely aligns with the earth's surface during quiet stance, from the inferior limit of the orbit of the eye to the center of the vestibular canals.

Center of Mass (CoM) – the concentrated point where the body mass can be considered for the entire body as well as each body segment

Center of Pressure (CoP) – The weighted average of all pressures over the surface of the area in contact with the ground, most commonly represented as the point under the feet where the vertical ground reaction force (GRFv) is exerted

Base of Support (BoS) – The total surface area where a virtually projected CoM can be contained to maintain upright posture, defined by the outer boundaries.

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CHAPTER 1
INTRODUCTION

1.1 Background

The control of head position in space requires the integration of multiple sensory systems, mainly visual, vestibular and somatosensory. The head contains both visual and vestibular systems. Visual information allows for the perception of self-motion and obstacle avoidance with distant objects, while vestibular information allows for the sensation of angular and translational accelerations. The vestibulo-ocular reflex (VOR) and vestibulocollic reflex (VCR) collectively allow for a stable visual field and stable head position within space, respectively (Hirasaki, Moore, Raphan, and Cohen, 1999; Imai, Moore, Raphan, and Cohen, 2001; Moore, Hirasaki, Cohen, and Raphan, 1999). Somatosensory information from neck proprioceptors allows for the detection of changes in muscle length and thus the position of the head relative to the trunk (Pettorossi and Schieppati, 2014). A stable head facilitates a stable visual field as well as the optimization of vestibular input.

The trunk plays a vital role in Center of Mass (CoM) control, as well as providing a stable platform for the head during locomotion (Cromwell, Newton, and Carlton, 2001; Pozzo, Berthoz, and Lefort, 1990; Romkes and Bracht-Schweizer, 2017). During walking and running, trunk motion oscillates around an equilibrium point in space, with a trunk flexion angle maintained within a few degrees in the sagittal plane (Pozzo et al., 1990; Romkes et al., 2017). At moderate to fast walking speeds, sagittal plane head motion is compensatory for vertical CoM translation (Hirasaki et al., 1999; Moore et al., 2001) while transverse plane head motion is compensatory for angular transverse plane motion of the trunk (Imai et al., 2001). While compensatory out-of-phase head motion occurs in the sagittal and transverse planes, the head tends to move in-phase with the trunk in the frontal plane (Pozzo, Levik, and Berthoz, 1995). The out-of-phase motion during running is also characterized by more dominant trunk motion in the transverse plane and more dominant head motion in the sagittal plane (Lim et al.,2020).

Throughout the stride cycle, the trunk oscillates twice in the sagittal plane, while only oscillating once in the frontal and transverse planes due to gait related events (Romkes et al., 2017). Despite large head on trunk motion, there is relatively little head in space motion during walking with compensatory motion occurring at a similar frequency to trunk motion in the sagittal and transverse planes (Hirasaki et al., 1999; Imai et al., 2001; Moore et al., 2001; Moore et al., 1999; Pozzo et al., 1990). Like the trunk, the head motion in the up-down direction is dependent on the step frequency, while frontal and transverse plane motion are both dependent on the stride frequency at faster walking speeds (Thorstensson et al., 1984, Hirasaki et al., 1999; Imai et al., 2001; Moore et al., 2001).

Lower extremity changes in joint and segmental motion may reduce head motion both with and without a visual task (Busa et al., 2016; Hamill, Derrick, and Holt, 1995; Lim et al., 2017; Mulavara, Verstraete, and Bloomberg, 2002). Accelerations at the head are attenuated relative to accelerations at the shank, primarily achieved through active modifications at the knee during late stance (Busa et al., 2016; Hamill et al., 1995; Lim et al., 2017). With increased visual acuity demands, it has previously been reported that individuals increase knee flexion angle and increase double support time during walking (Mulavara, Verstraete, and Bloomberg, 2002), and increase knee and hip flexion angle as well as stride frequency during running (Lim et al., 2017). These kinematic modifications are suggested to facilitate shock attenuation (Busa et al., 2016; Hamill et al., 1995), reduce vertical CoM displacement and overall head motion (Lim et al., 2017; Mulavara et al., 2002).

To successfully change direction, the CoM must move beyond the lateral Base of Support (BoS) in the desired travel direction (Patla et al., 1999). With adequate planning time a *stepping strategy* can be implemented to redirect the CoM, where a more medial penultimate step results in reduced CoM acceleration toward the transition limb, allowing for a wider transition step relative to the CoM to increase the vertical ground reaction force vector (GRFv) angle in the new direction of travel (Patla et al., 1999). With reduced planning time a *hip strategy* is implemented to redirect the CoM (Patla et al., 1999). Without sufficient planning time to modulate penultimate step width, a more lateral penultimate step is taken, similar to straight running foot position (Lee et al., 2017; Patla et al. 1999). To redirect the CoM in a new travel direction, the hips are thrust toward the new travel direction commonly seen with trunk orientation away from the new travel direction in the frontal plane (Lee et al., 2017; Mornieux et al., 2014; Patla et al., 1999; Weir et al., 2019). During unanticipated change of direction tasks, increased trunk rotation and lateral trunk flexion in the opposite direction of travel, decreased hip flexion, increased hip abduction, and increased knee flexion are commonly reported as well as significant differences in vertical CoM displacement (Besier et al., 2001; Brown, Palmieri-Smith, and McLean, 2009; Mornieux et al., 2014; Wyatt et al., 2019).

Anticipatory rotations of the head are also observed during change of direction tasks. Under normal conditions with adequate planning time, participants align their head with the new travel direction prior to aligning the rest of their body during sidestepping tasks (Hollands et al., 2001; Patla et al., 1999). When individuals are asked to walk around a curved trajectory, gaze and head direction are aimed toward future heading direction, even in darkness without visual cues (Authie et al., 2015; Bernardin et al., 2012; Grasso et al., 1996, 1998). While Cinelli and Warren (2012) have shown these anticipatory head rotations are neither sufficient nor necessary, they are typically observed in natural conditions both along curved trajectories (Authie et al., 2015; Bernardin et al., 2012; Grasso et al., 1998) and during sidestepping tasks (Hollands, Sorensen, and Patla 2001; Patla et al., 1999). This head direction alteration prior to changes in heading direction has been observed with adequate planning time, but may not be as prevalent during unanticipated change of direction tasks. Mornieux et al. (2014) reported that, on average, the head was less rotated in the new direction of travel during unanticipated sidestepping conditions. However, the authors used range of motion assessments at discrete time points to present these findings, which may not provide the full information regarding the changes in the movement pattern of the head during a change in direction.

The body's individual segments can be organized in a number of different ways during sidestepping tasks. In a dynamical systems approach, the organization and re-organization of the many degrees of freedom in the body occur through a process of self-organization in which changes are not implemented in a top-down approach, but where the system components organize in a task-dependent manner. When assessing the state of a system, two of Bernstein's principles can be implemented (Bernstein, 1967). First, coordination between many joints/segments can be organized in a number of different ways to achieve the same task. Second, the variability of coordination is important as it provides a metric into the variety of coordination patterns utilized. It is important to note that coordination variability differs from end-point variability. In the context of sidestepping tasks, end-point variability may be approach velocity and change of direction angle while coordination variability refers to the variability of the segmental couplings utilized to achieve task goals (Weir et al., 2019).

Dynamical systems theory has provided a language to describe and quantify complex movement patterns. When performing a complex task, the body must be flexible and adaptable. This requires stable patterns and qualitative transitions. These stable patterns are known as attractors, defined by a set of points in the state space (Kelso, 1995). When an attractor becomes unstable, it will undergo a phase transition via a bifurcation, defined as a qualitive change in the attractor structure (Kelso, 1995). To quantify specific attractors, collective variables known as order parameters describe pattern formation as well as their evolution. The relative phase between segments and joints has been identified as an order parameter and is used to describe the underlying dynamics of the system (Diedrich and Warren, 1995; Li, Van Den Bogert, Caldwell, van Emmerik, and Hamill, 1999). Control parameters, such as frequency or velocity, can induce a shift in the relative phase at a critical transition point. In the context of the walk-to-run transition, as gait speed (the control parameter) increases a critical point is reached where the relative phase of ankle-hip and ankle-knee coupling angles (order parameters) become energetically costly and the attractor dynamics become unstable, initiating the transition to running (Diedrich et al., 1995).

The coordination literature has quantified task-dependent joint coupling to better understand the effects of aging and disease. In healthy individuals, transverse plane trunk-pelvis relative phase is dependent on gait speed, with more in-phase motion at slower walking velocities and more anti-phase motion at faster walking velocities (van Emmerik and Wagenaar, 1996; van Emmerik et al., 2005; van Emmerik et al., 1999; Wagenaar and, Beek, 1992). Changes in these coordination patterns during walking have been observed in those with movement disorders. van Emmerik et al. (1999) had newly diagnosed patients with Parkinson disease perform a treadmill walking task at a range of walking speeds while assessing the relative phase of trunk-pelvis transverse plane motion. Compared with healthy controls, Parkinson's disease patients had significantly reduced changes in the mean relative phase and lower coordination variability. Reduced trunk-pelvis relative phase in the transverse, frontal and sagittal plane has also been reported in older adults across a range of walking speeds (van Emmerik et al., 2005). The relative phase pattern is not inherently good or bad, but instead represents a stable pattern at a specific frequency or velocity. At slower walking velocities, transverse plane trunk-pelvis in-phase motion represents a more stable pattern until it reaches a critical transition point, where the relative phase shifts to a more anti-phase pattern. However, reductions in anti-phase coordinative patterns with aging and disease may represent the *locking of the degrees of freedom* to simplify the control task (Hamill, Palmer, and van Emmerik, 2012; Lipsitz et al., 2002; Vereijken et al., 1992).

Weir et al. (2019) assessed trunk-pelvis and hip-knee coordination and coordination variability using methods from dynamical systems theory to better understand the role of the organization of degrees of freedom during anticipated and unanticipated sidestepping. During unanticipated side-stepping tasks, there is more in-phase motion as well as an increase in variability for the trunk-pelvis and hip-knee coupling angles compared to anticipated sidestepping. By reducing planning time, task difficultly increases which may have resulted in the locking of the degrees-of-freedom to simplify the control task.

The coordination variability literature provides a means of describing the complexity in terms of the intrinsic dynamics and stability of specific patterns (Kelso, 1995). Attractors are inherently stable at specific velocities or frequencies, but as they approach transition points they become unstable and the relative phase variability increases (Kelso, 1984). While too much variability may characterize unstable attractors, too little variability can also be detrimental as variability may also play a functional role in regards to overuse injuries and the adaptability of the system (Hamill et al., 2012). The loss of complexity hypothesis stated by Lipsitz et al. (2002) suggests a lack of variability may be a characteristic of dysfunction in performance, frailty due to injury or disease. Reduced coordination variability has been reported during running between the thigh-shank relative phase in patients with patellofemoral pain (Hamill et al., 1999) and between the trunk-pelvis relative phase in patients with low back pain (Seay, van Emmerik, and Hamill, 2011a). During unanticipated sidestepping, increased trial to trial coordination variability between the trunk-pelvis and thigh-shank relative phase was found compared to anticipated sidestepping (Weir et al., 2019), which may reflect problems in control of the degrees of freedom due to temporal constraints (Hamill et al., 2012). There appears to be an optimal range for variability, as too little variability may suggest a more constrained movement pattern, while excessive variability may interfere with functional actions (Fetters, 2010; Hamill et al., 2012). In the context of sidestepping with reduced planning time, attractors may not have enough time to settle on a desired pattern and may constantly be in an unstable mode. The increased variability may be the result of the subject attempting to move to a more stable coordination pattern (Kelso, 1995).

1.2 Statement of the Problem

Athletes are often required to rapidly respond to external stimuli under high temporal demands. Despite the importance of perceptual information obtained through sensory systems within the head, our current knowledge of how the head is controlled in space during sport-specific tasks is limited. During treadmill walking and running, head position in space is maintained by compensatory head-on-trunk motion, predominantly led by the trunk in the transverse plane and the head in the sagittal plane (Hirasaki et al., 1999; Imai et al., 2001; Moore et al., 1999; Moore et al., 2001, Pozzo et al., 1990, Lim et al., 2020). In addition, lower extremity modifications such as increased stride frequency and knee flexion angle (Boyer and Nigg, 2004; Busa et al., 2016; Edwards, Derrick, and Hamill, 2012; Hamill, Derrick, and Holt, 1995) reduce vertical CoM displacement and facilitate shock attenuation and reduce transmission to the head (Busa et al., 2016; Lim et al., 2017; Mulavara et al., 2002).

During change of direction tasks, head position changes precede heading position in the transverse plane when walking along a curved trajectory (Authie et al., 2015; Bernardin et al., 2012; Grasso et al., 1998) and during sidestepping tasks (Hollands et al., 2001; Patla et al., 1999). However, when assessing the peak magnitude of head reorientation during anticipated and unanticipated sidestepping tasks, the head is less orientated toward the new travel direction when planning time is reduced (Mornieux et al., 2014). During change of direction tasks, head position is assessed in the transverse plane with a primary emphasis on temporal motion onset relative to other segments of the body. Little is known regarding the changes in the relationship between the head and trunk throughout the sidestepping motion.

With reduced planning time during sidestepping tasks, a modified control strategy with altered kinematics and CoM displacement has been observed (Fox, 2018; Wyatt et al., 2019). When performing an unanticipated sidestepping task, significant reductions in anterior-posterior and medio-lateral CoM displacement, as well as significant increases in vertical CoM displacement have been reported compared to anticipated sidestepping tasks in male athletes (Wyatt et al., 2019). Head, trunk, pelvis, hip and knee range of motion assessments have been used to quantify differences between tasks such as anticipated and unanticipated side stepping (Besier et al., 2001; Brown et al., 2009; Byrne et al., 2018; Houck, Duncan, and Haven 2006; Lee et al., 2017; Lee et al., 2013; McLean et al., 2004; Mornieux et al., 2014) but do not capture the temporal development of specific movement patterns. Coordination and coordination variability analyses have the potential to reveal differences in upper body and lower extremity segmental coupling changes during unanticipated sidestepping (Weir et al., 2019). Collectively, more in-phase coupling angles have been reported during unanticipated sidestepping, suggesting individuals are locking the degrees of freedom to simplify the control task (Vereijken et al., 1992; Weir et al., 2019). Additionally, increased coordination variability suggests a more unstable pattern when performing a sidestepping task with reduced planning time.

Walking and running are different tasks and while there is a significant body of literature on head motion during change of direction tasks at a variety of walking speeds, our understanding of head motion throughout anticipated and unanticipated sidestepping tasks at running speeds is limited. Whole-body modifications are commonly seen to facilitate head control during forward locomotion but may differ during change of direction tasks. Reducing planning time further changes sidestepping kinematics but their relationship to head motion control remains unknown.

1.3 Specific Aims

- **Aim 1: Assess head and trunk orientation in the transverse plane during anticipated and unanticipated sidestepping**

  Hypothesis 1: During unanticipated sidestepping, the head and trunk will be less oriented toward the new travel direction in the transverse plane compared to anticipated sidestepping at the penultimate step toe off.

  Rationale: During unanticipated sidestepping, Lee et al. (2017) found trunk reorientation to occur during the transition step, while an earlier reorientation was found during anticipated trials. Weir et al. (2019) reported that that trunk-pelvis and thigh-shank coordination were more in-phase when sidestepping with reduced planning time, which may suggest a reduction in out-of-phase movement between the head and trunk. This would be in agreement with Mornieux et al. (2014), who found the head to be less oriented in the new travel direction during unanticipated sidestepping when compared with anticipated conditions.

- **Aim 2: Assess head-trunk coordination in the transverse plane during anticipated and unanticipated sidestepping**

  Hypothesis 2: During anticipated sidestepping, the head and trunk will have a more trunk dominant coordination pattern in the transverse plane compared to unanticipated sidestepping.

  Rationale: During treadmill running with a visual task, head-trunk coupling was predominantly driven by trunk motion in the transverse plane (Lim et al., 2020). These findings may provide insights into the preferred segment dominancy used during anticipated sidestepping. However, during unanticipated sidestepping a more in-phase pattern between the trunk-pelvis was found compared to anticipated sidestepping

(Weir et al., 2019), which may provide insights into the coordination pattern utilized when planning time is reduced.

- **Aim 3: Assess head-trunk coordination in the sagittal plane during anticipated and unanticipated sidestepping**

  This aim is exploratory and therefore does not have a formal hypothesis. During forward locomotion while walking at slower velocities, sagittal plane head motion compensates for sagittal plane trunk motion, and while walking at preferred velocities, sagittal plane head motion compensates for CoM motion in the up-down direction (Hirasaki et al. 1999; Pozzo et al., 1999) While treadmill running with a visual task, head (flexion/extension)-trunk (flexion/extension) coupling was predominantly anti-phase throughout a range of visual tasks (Lim et al. 2020). However, during unanticipated sidestepping a more in-phase pattern between the trunk-pelvis was found compared to anticipated sidestepping (Weir et al., 2019). Based on current knowledge it is difficult to predict how the head-trunk coupling in the sagittal plane will behave during anticipated and unanticipated sidestepping.

- **Aim 4: Assess coordination variability between the head and trunk during anticipated and unanticipated sidestepping without an explicit goal in the new travel direction**

  Hypothesis 4: During unanticipated sidestepping, there will be an increase in coordination variability between head-trunk relative phase in the transverse and sagittal planes, compared to anticipated sidestepping.

  Rationale: Weir et al. (2019) observed an increase in trunk-pelvis and hip-knee coordination variability between during unanticipated compared to anticipated sidestepping.

1.4 Significance of Thesis

Understanding how the body organizes its degrees of freedom to facilitate head position in space allows for contributions to several bodies of literature. Currently, there is a limited amount of work regarding how head position in space is controlled during change of direction tasks at higher speeds. While the published work provides a strong starting point, many questions remain open regarding how we are able to coordinate complex tasks in sport-specific settings. This thesis will contribute to the foundational development of head control literature during more dynamic tasks by considering the entire human body as a cohesive unit rather than assessing segments or joints in isolation. The primary emphasis of sidestepping literature is anterior cruciate ligament (ACL) injury risk with reduced planning time due to the high incidence rate and financial burden following injury. This body of literature highlights altered control strategies to facilitate change of direction placing high loads on the ACL. By considering the modified control strategies in the context of head control, a more thorough understanding of the underlying mechanisms behind lower extremity kinematics may be achieved.

The proposed study will also provide the building blocks to better understand the effects of concussion on sport performance. A concussion is a traumatic brain injury that effects vestibulo-ocular function, anticipatory postural adjustments and coordinative function, leaving athletes at an increased injury risk for both musculoskeletal injury and additional head trauma following return to play (Howell, Lynall, Buckley, and Herman, 2018; McCrory et al., 2017). Perceptual systems within the head provide individuals with rich information and may require more complex control of the head to continue to obtain accurate information. Future concussion studies can utilize information obtained from this thesis to better understand if modifications to head control may be part of the increased injury risk following return to play. Therefore, this thesis aims to better understand the consequences of whole-body kinematic modifications on head control during anticipated and unanticipated sidestepping tasks.

CHAPTER 2
LITERATURE REVIEW

2.1 Visual, Vestibular and Proprioceptive Systems

The control of head position in space requires the integration from multiple sensory systems, mainly visual, vestibular and somatosensory. The head contains both visual and vestibular systems. Visual information allows for the perception of self relative to objects within space, self-motion and obstacle avoidance with distant objects, while vestibular information allows for the sensation of angular and translational accelerations. Somatosensory information from neck proprioceptors allows for the detection of changes in muscle length and thus the position of the head relative to the trunk.

The vestibular organs are highly sensitive receptors that respond to angular and translational accelerations and can be found within the inner ears on each side of the head. The vestibulo-ocular reflex (VOR) enables a stable visual field by providing compensatory eye movement following head perturbations (Moore et al., 2001; Moore et al., 1999; Raphan and Cohen 2002). Angular head accelerations are sensed by semicircular canals, and generate compensatory eye movement via the angular vestibulo-ocular reflex (aVOR) (Hirasaki et al., 1999a; Imai et al., 2001; Moore et al., 1999). Meanwhile, linear accelerations of the head stimulate otoliths, contributing to the linear VOR (lVOR), commonly seen during the vertical translation of the head during locomotion (Hirasaki et al., 1999a; Imai et al., 2001; Moore et al., 1999). While compensatory eye motion can be made by both the aVOR and lVOR, different responses are seen at a range of viewing distances (Moore et al., 2001; see section 2.4 for more details). It is important to note that while the same otolith response will occur due to head tilt and translational acceleration, information from other sensory modalities such as the visual and proprioceptive systems will differ.

Proprioceptive information at the neck allows for sensing the head location relative to the trunk. Neck musculature is highly concentrated with muscle spindles, facilitating sensitive information regarding muscle length. The vestibulocollic reflex (VCR) and cervico-collic reflex (CCR) help stabilize the head in space through vestibular and muscle spindle stimulation. The VCR helps compensate for angular and translational motion by moving the head in the direction opposite of angular or translational motion, while the CCR maintains head position relative to trunk as muscle spindles detect change in length in the neck (Peterson et al., 1985). When the head is rotated in a single plane, semicircular canals that correspond with that specific plane are stimulated and provide the vestibular nuclei with information regarding the change in head position. Neural signals carry out the response to stimulate the appropriate neck musculature to counter the rotation and maintain appropriate head posture.

The integration of information from multiple systems provides a more complete picture regarding postural orientation and location within the environment. The simple task of tilting the head backwards will stimulate the otoliths in a similar way as if an individual was falling backwards. The integration of proprioceptive information at the neck, in addition to visual information provides the system with rich information allowing for a more accurate representation of self-motion.

2.2 Upper Body Kinematics During Walking and Running

The trunk plays a vital role in the control of the CoM during locomotion in all three planes. Kinematic analysis shows the oscillatory dynamics of the trunk and pelvis throughout locomotion, with two full oscillations at the trunk and pelvis per stride cycle within the sagittal plane (Romkes and Bracht-Schweizer 2017; Thorstensson et al., 1984), while one full oscillation is observed in the frontal and transverse plane per stride cycle at a range of walking speeds (Romkes et al., 2017) (Figure 2)

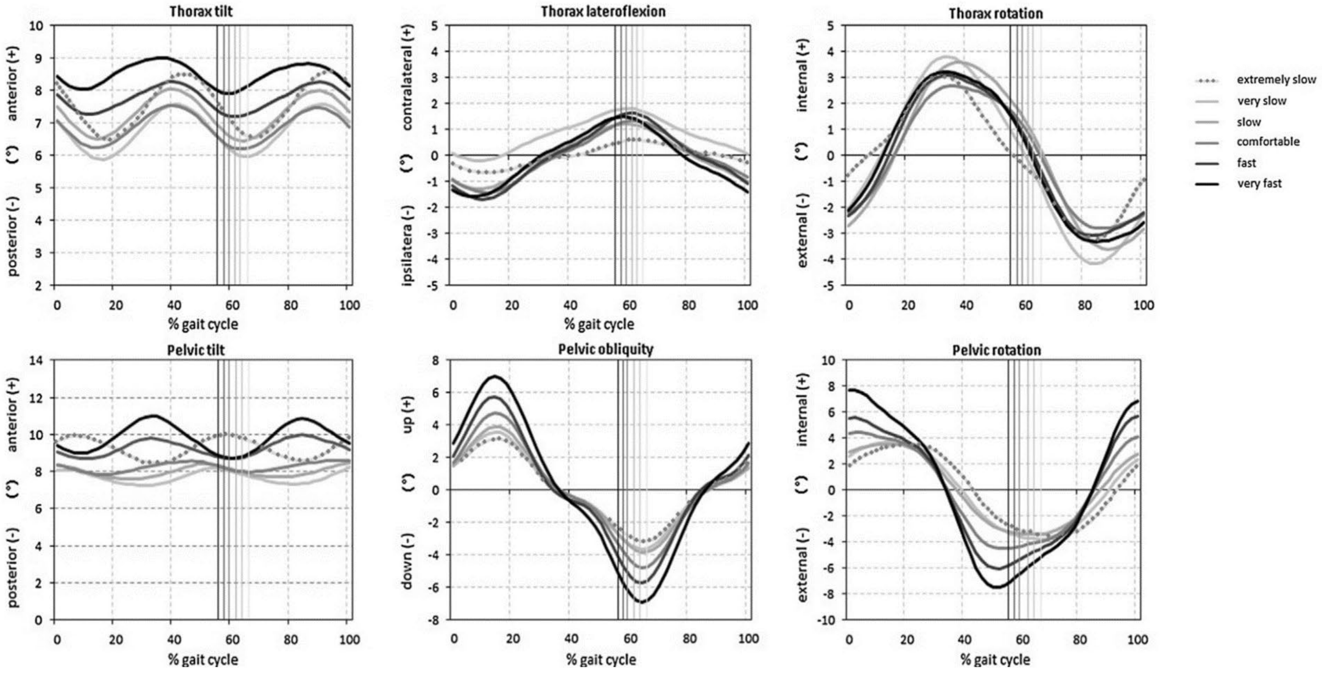


Figure 2: Three-Dimensional joint and segment rotations at several preferred walking speeds. The left, middle and right column display data from the sagittal, frontal and transverse planes, respectively. Thorax and pelvic tilt can be considered flexion (positive) and extension (negative) in the sagittal plane. The vertical lines indicate toe off, separating stance from swing phase. Figure adapted from Romkes et al. (2017).

2.2.1 Trunk and Pelvis Kinematics

2.2.1.1 Sagittal Plane

Trunk flexion oscillates around an equilibrium point in space, maintaining a flexed position throughout the stride cycle (Pozzo et al., 1990; Romkes et al., 2017). During walking, a maximal flexion angle is seen during double support, with a minimal flexion angle during single support, highlighting the subtle oscillatory trunk dynamics during walking (Figure 2) (Romkes et al., 2017; Thorstensson et al., 1984). During mid-stance, the trunk reaches its most flexed position, decreasing its flexion angle until toe off where the trunk increases its flexion angle again (Thorstensson et al., 1984). A similar trend is seen at the level of the pelvis, with predominantly in-phase motion between the trunk and pelvis during walking near preferred walking speeds (Romkes et al., 2017).

During running, a similar oscillatory trend is observed at the trunk and pelvis. The trunk maintains a flexed position throughout the stride cycle, with the least flexed position at or just prior to heel strike (Elliot and Roberts 1980; Thorstensson et al., 1984). Throughout stance, trunk flexion angle increases, reaching the maximal flexion angle at mid-to-late stance (Elliot and Roberts 1980; Thorstensson et al., 1984). At toe off, trunk flexion angle is reduced as the cycle continues (Elliot and Roberts 1980; Thorstensson et al., 1984). Similar to the trunk, the pelvis oscillates twice, maintaining a flexed position throughout the stride cycle (Novacheck, 1998). During the absorption phase, the least pelvic flexion is observed but pelvic flexion angle increases through stance, reaching the most flexed position at toe off (Novacheck 1998). Collectively during both walking and running the trunk and pelvis maintain an anteriorly flexed position in the sagittal plane, facilitating forward locomotion (Novacheck 1998; Thorstensson et al., 1984).

2.2.1.2 Frontal Plane

During walking, ipsilateral pelvic obliquity facilitates foot clearance of the contralateral limb during the swing phase of gait (Romkes et al., 2017) (Figure 1). The trunk tends to move anti-phase relative to the pelvis in the frontal plane during the initial portion of single support to control CoM motion through contralateral flexion toward the stance limb (Romkes et al., 2017) (Figure 2). As the swing limb begins to contact the ground, the pelvis approaches a more neutral position along with the trunk (Romkes et al., 2017). During running, a similar trend is present, with peak ipsilateral trunk flexion limb at early to midstance during the weight acceptance phase (Novacheck, 1998). A less sinusoidal pattern is seen at the pelvis during running. At heel strike, ipsilateral pelvic obliquity is seen but approaches a near horizontal position at midstance, then approaches contralateral obliquity to facilitate toe clearance of the initial stance limb (Novacheck, 1998).

2.2.1.3 Transverse Plane

During walking at higher speeds, the trunk and pelvis move in an out-of-phase pattern, suggested to minimize whole body motion in the transverse plane (Hinrichs, 1990) (Figure 3) . From mid-to-late stance, the stance leg (right leg) provides a propulsive force against the ground, facilitating forward locomotion, while simultaneously the swing leg (left leg) moves forward. To extend the stride length, a "pelvic step" may be taken, seen as a clockwise pelvic rotation to allow for a more anterior left foot position.

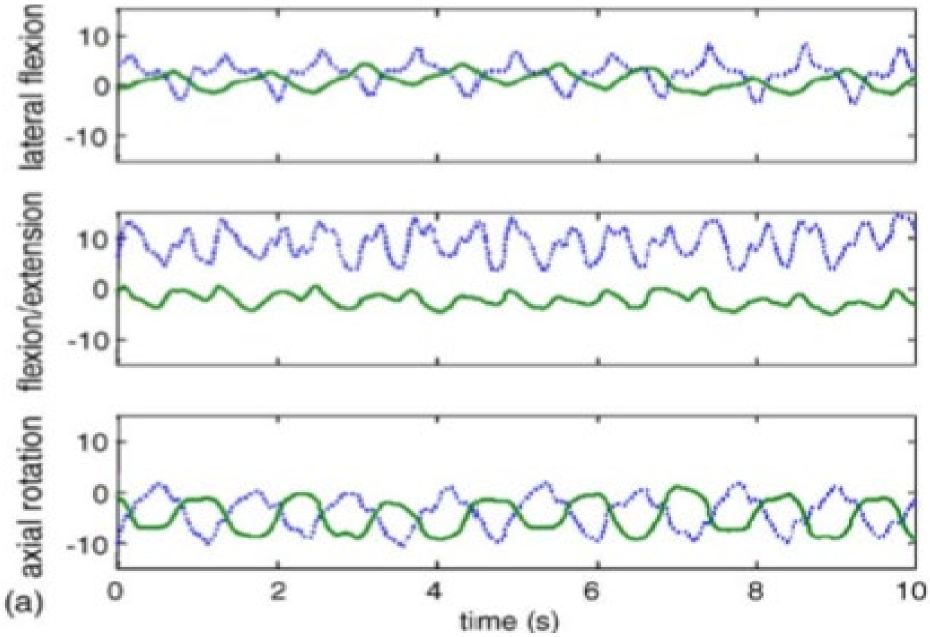


Figure 3: Trunk (solid line) and pelvis (dashed line) motion during treadmill walking at 1.2 ms^{-1} in healthy individuals in the frontal plane (lateral flexion), sagittal plane (flexion-extension) and transverse plane (axial rotation). Adapted from van Emmerik et al. (2005).

During running, a less clear cut relation between the trunk and pelvis is present. The arms tend to counter leg motion, with trunk motion closely following, producing one full oscillation per stride (Figure 4). While Figure 4 depicts angular momentum, a similar visual trend is seen in trunk and pelvis kinematics during treadmill running at 3.8 ms^{-1} (Seay, van Emmerik, and Hamill 2011a). However, describing trunk-pelvic motion in terms of angular momentum may provide us with a better understanding of the kinematics; when the angular momentum of the arms and trunk were summated and plotted against the summated angular momentum of the legs and pelvis, a clear relationship is present (Hinrichs, 1987) (Figure 4). Pelvic and lower extremity angular momentum is countered via counterclockwise trunk and upper extremity arm motion, producing a counterclockwise moment (Hinrichs, 1987; van Emmerik et al., 2005). As a result, minimal deviations in the whole body CoM are present. Motion at the pelvis facilitates propulsive motion to continue locomotion while motion at the trunk for momentum regulation allows for arm motion to counter-balance lower extremity momentum in both walking at higher speeds and during running (Hinrichs 1987; Romkes et al., 2017; van Emmerik et al., 2005).

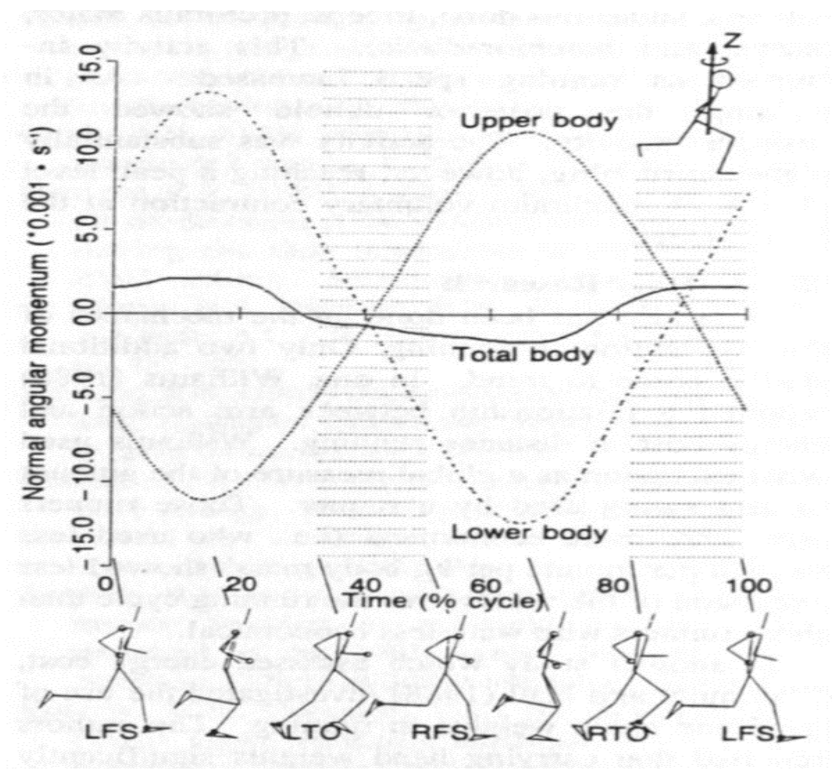


Figure 4: Mean angular momentum of the upper body (head, arms and trunk), lower body (pelvis and legs) and whole body in the transverse plane while running 4.5 ms^{-1}. Adapted from Hinrichs (1987).

2.2.2 Center of Mass Movements

During both walking and running, the center of mass shows two full vertical oscillations per stride cycle, reaching the lowest point during the double support phase in walking (Thorstensson et al., 1984) and during stance in running (Figure 5). During walking, the CoM reaches its highest point during the middle of single support phase, while in running, the CoM reaches its highest point when airborne.

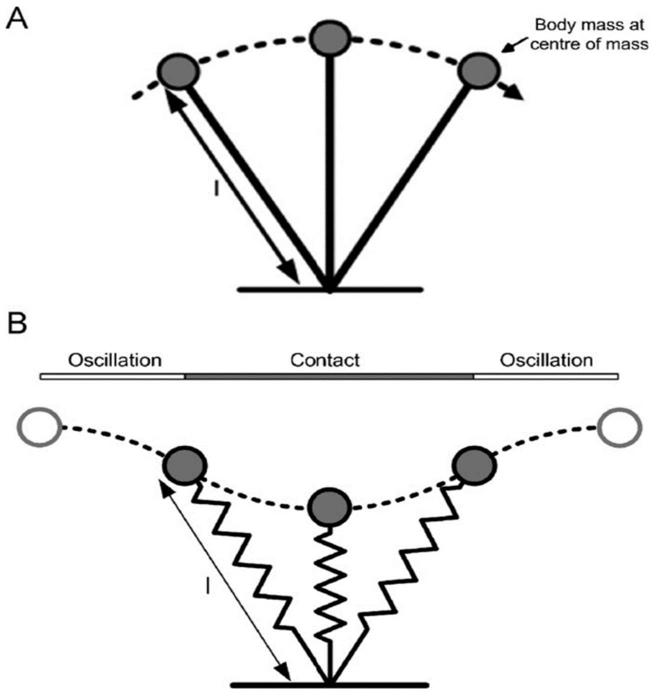


Figure 5: The inverted pendulum model for walking (A) and spring-mass model for running (B) illustrates the different mechanisms involved in moving the body's CoM forward. Both models provide a snapshot of the single support phase of walking and running. l = initial spring length. Adapted from Delattre, Lafortune, and Moretto (2009).

Lateral CoM motion shows a single oscillation during a stride cycle in both walking and running (Thorstensson et al., 1984) (Figure 6). During stance the CoM moves along the medial border of the center of pressure (CoP) of the support limb (Thorstensson et al., 1984; Winter 1995).

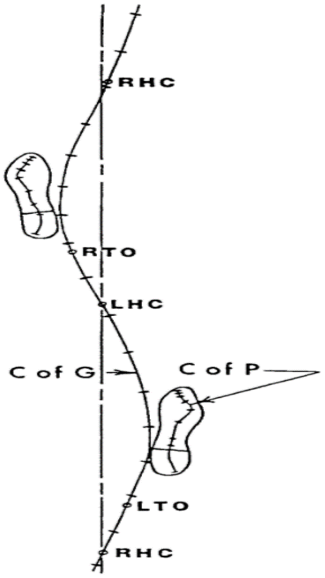


Figure 6: Whole body center of gravity (CoG) and CoP relationship during level walking. Shortly following right heel contact (RHC), swing phase of gait is initiated as left toe off (LTO) while the CoG moves toward the stance foot. Throughout the gait cycle, the CoG must remain within the lateral boundaries of the CoP. RHC – right heel contact, LHC – left heel contact, RTO – right toe off. Adapted from Winter (1995).

2.3 Change of Direction Segmental Kinematics and Center of Mass Motion During Walking and Running and Segmental Kinematics when Changing Direction

2.3.1 Center of Mass Motion During Walking and Running

CoM motion in the frontal plane is mainly dictated by foot placement but can also be modulated via hip abduction. To maintain forward locomotion, the CoM must be contained within the lateral borders of the BoS (Winter, 1995). The BoS area depends on the specific phase of gait in walking and running. During walking a larger BoS is present during the bipedal stance phase, where two feet are in contact with the ground while during the swing phase there is only a single foot support surface. During running, stance phase contains only a single foot while swing phase is airborne with no ground contact. Once foot placement is established, modifications at the ankle and hip can correct for destabilizing force imbalances to keep the CoM within the lateral border of the BoS (Winter, 1995). Subtalar inversion moves the CoP laterally to reduce the lateral component of the GRF acting on the CoM (Winter, 1995). To modulate CoM motion, increased hip abduction at the supporting hip during stance aids in more medial trunk motion, allowing for the maintenance of the CoM within the BoS (Winter, 1995).

The control of whole body mediolateral CoM precedes the reorientation of the rest of the body during change of direction tasks while walking (Patla et al., 1999) and running (Wyatt et al., 2019). The difference between the position of the CoP and CoM during stance dictates the magnitude and direction of CoM acceleration (Winter, 1995). To change direction, the CoM must move beyond the lateral border of the BoS in the intended new direction of travel. Two strategies are often seen, with either a “step strategy” or a “hip strategy”. During a step strategy, advanced knowledge of the change of direction is typically required two steps prior to the transition step. A more medial penultimate step allows for a decrease in CoM acceleration in the opposite direction of travel by decreasing the GRFv angle (Patla et al., 1999) (Figure 7). A wider transition step is then taken relative to the CoM position to increase the GRFv angle in the new direction of travel, redirecting the CoM towards the new travel direction (Patla et al., 1999). Lee et al. (2017) found individuals' penultimate foot opposite the direction of the sidestep during anticipated sidestepping (Figure 8). In doing so, the penultimate step began to shift the CoM toward the new travel direction prior to the transition limb making contact with the ground. As a result, a more upright trunk position is maintained, oriented in the new direction of travel (Lee et al., 2017). During change of direction tasks at higher speeds, greater inertia requirements may lead to a penultimate step opposite the new direction of travel, while at lower speeds, a more medial penultimate step is still seen, but remains on the intended new direction of travel (Patla et al., 1999; Lee et al., 2017). Collectively, a stepping strategy is represented by a more medial penultimate step, thus reducing the medial GRFv requirements from the transition limb to shift the CoM to a new travel direction (Wyatt et al., 2019). However, without sufficient planning time to modulate the penultimate step width, a more lateral penultimate step is taken, similar to normal running foot position (Patla et al., 1999, Lee et al., 2017). Following penultimate toe off, the CoM is moving opposite the intended travel direction with greater velocity (Patla et al., 1999) (Figure 7).

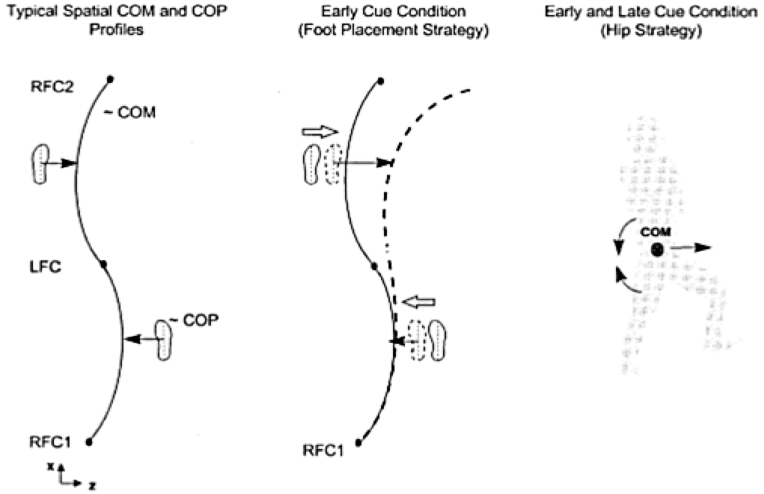


Figure 7: CoM and CoP trajectories during a foot and hip strategy during sidestepping to the right while walking. On the left, the typical CoM trajectory during forward locomotion. The middle figure displays a more medial penultimate step that reduces the CoM acceleration toward the transition limb, thus reducing the GRFv requirements to move the CoM in the new direction of travel, which in this case is to the right. With reduced planning time, the CoM and CoP look similar to forward locomotion (left figure) which requires a hip strategy to move the CoM toward the new travel direction. Adapted from Patla et al. (1999).

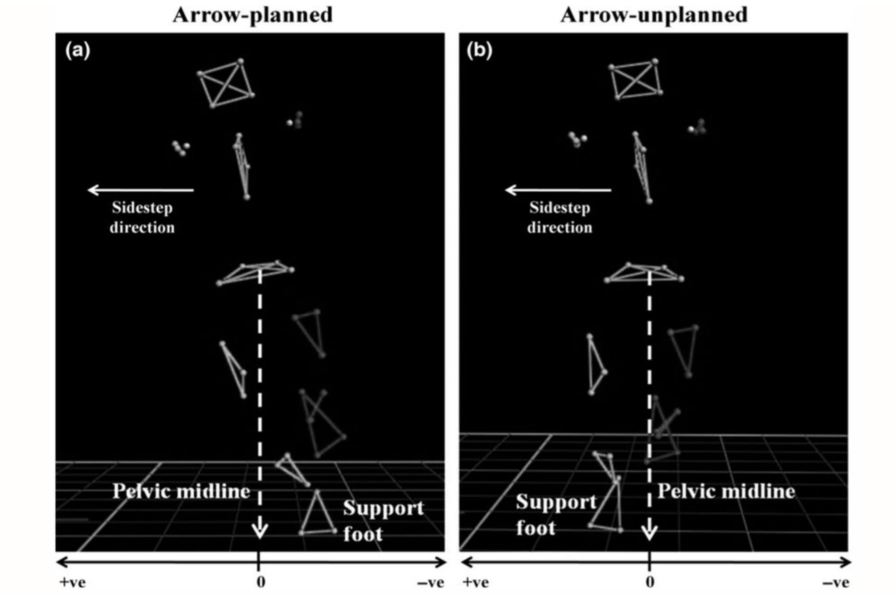


Figure 8: Frontal views examples of a stepping strategy during sidestepping while running. Anticipated (a) and unanticipated (b) anterior view snapshots of the penultimate step during a sidestep directed to the right while running. During the anticipated condition (arrow-planned), the penultimate step is opposite the midline, shifting the CoM toward the new direction of travel prior to the transition step. During the unanticipated condition (arrow-unplanned), the penultimate step is on the same side as the intended new travel direction, which accelerates the CoM toward the transition limb. Adapted from Lee et al. (2017).

When a stepping strategy fails, a hip strategy is often seen, with an increase in hip abduction from the transition limb shifting the CoM towards the new direction of travel enabling a new travel direction (Patla et al., 1999; Lee et al., 2017). When a hip strategy is used, increased lateral trunk flexion in the opposite direction of travel is often observed (Patla et al., 1999; Lee et al., 2017). Wyatt et al. (2019) found a decrease in mediolateral CoM motion, with increases in anterior and vertical CoM displacement when planning time was reduced in both male and female collegiate athletes (Figure 9). CoM velocity and displacement was assessed throughout both the preparatory phase (penultimate toe off to transition limb heel strike) and stance phase (transition limb heel strike to transition limb toe off) to further explore the effects of anticipation on sidestepping. During the preparatory phase, there were significant differences in mediolateral and anterior CoM displacement (Figure 10). During both the preparatory and stance phase, decreased medial CoM velocity and an increase in downward vertical

CoM velocity was found as a function of reduced planning time (Wyatt et al., 2019). Collectively, these findings highlight the influence of planning time on whole body kinematics, with the greatest CoM differences in the preparatory phase with reduced planning time (Wyatt et al., 2019; Lee et al., 2017). With reduced planning time, a hip strategy is implemented during the stance phase to facilitate CoM motion in the new direction of travel, manipulating whole body kinematics and kinetics (Lee et al., 2017; Mornieux et al. 2014; Patla et al., 1999; Weir et al., 2019).

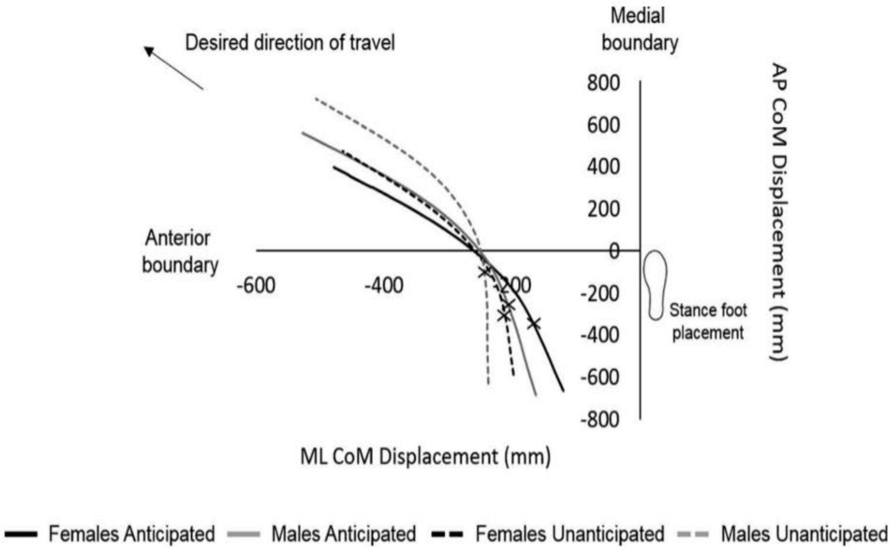


Figure 9: Whole-body AP and ML CoM path with respect to AP and ML boundaries of the right stance foot for the preparatory phase and stance phase during anticipated and unanticipated sidestepping between males and females. X's on the CoM path represent a transition point from the preparatory to stance phase. Adapted from Wyatt et al. (2019).

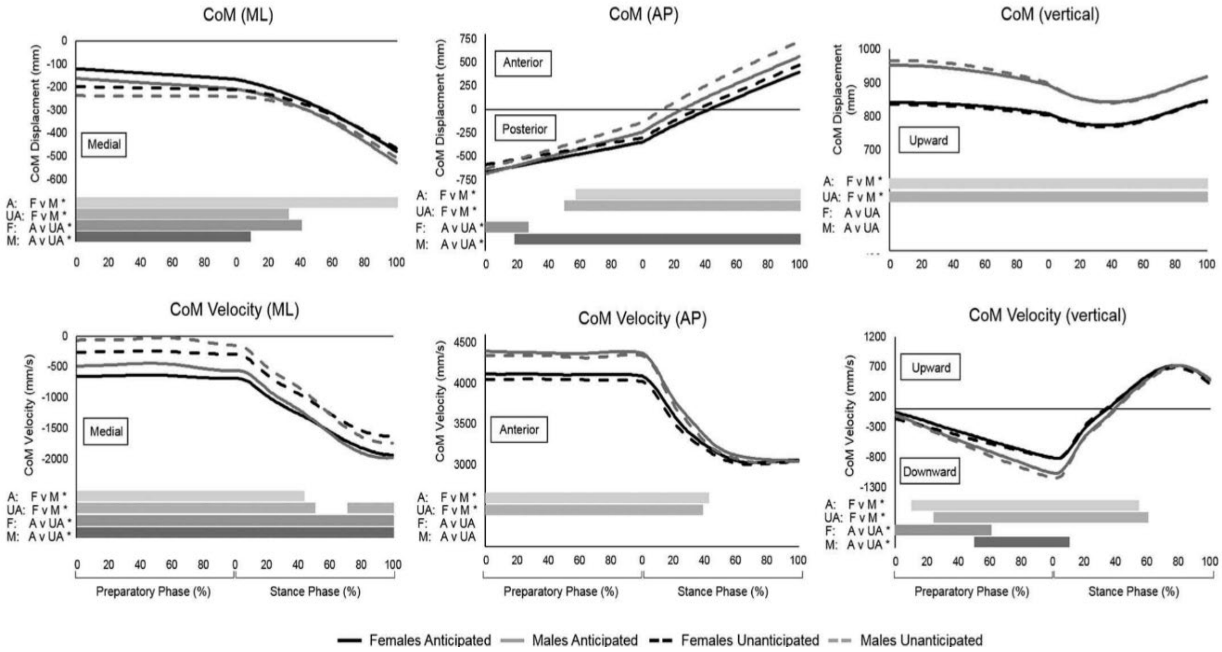


Figure 10: Time-normalized CoM displacement from the stance foot and CoM velocity during preparatory (Penultimate toe off to transition step heel strike) and stance phases (transition step heel strike to transition step toe off) of anticipated (A) and unanticipated (UA) sidestepping for males (M) and females (F). Shaded bars indicate periods of statistical significance. Adapted from Wyatt et al. (2019).

2.3.2 Change of Direction Segmental Kinematics at the Upper Body During Running

Change of direction segment and joint kinematics have primarily been assessed in the context of anterior cruciate ligament (ACL) injury, with injury mechanisms occurring in the frontal and transverse planes at the knee, while it has been suggested that sagittal plane forces are not sufficient to cause ACL injury (McLean et al., 2004). Frontal and transverse plane motion of the trunk, pelvis and knee have been assessed more extensively, while the body of literature in the sagittal plane is less developed.

2.3.2.1 Frontal Plane

Change of direction maneuvers require a medially directed GRFv to facilitate direction change. A more medial penultimate step allows for a more upright trunk posture in the frontal plane (Houck et al., 2006; Lee et al., 2017; Mornieux et al., 2014). With a more lateral penultimate step, a hip strategy is implemented during stance, associated with the trunk oriented in the opposite direction of travel in the frontal plane (Houck et al., 2006) (Figure 11). During unanticipated sidestepping reduced ipsilateral pelvic obliquity is seen during the penultimate step (Byrne et al., 2018) (Table 1).

Table 1: Comparison of Mean (SD) pelvis kinematics in the frontal plane at toe off of the penultimate step during straight run, planned sidestep, and unplanned sidestep. Participants ran between 4.5 and 5.5 ms^{-1} with a change of direction angle of 45° Negative value denotes ipsilateral pelvic obliquity. Adapted from Byrne et al. (2018).

*significant different to straight run

^significant difference between planned and unplanned sidestep

Variable	Straight Run	Planned Sidestep	Unplanned Sidestep
Pelvic Obliquity	-8 (3.3)	-15(5.1)*	-7(4.3)^

During the weight acceptance phase at the transition limb, the main differences between anticipated and unanticipated sidestepping can be seen by the initial starting posture (Figure 11; Houck et al., 2006; Weir et al., 2019). While the overall trend of motion in the frontal plane is similar, the initial orientation at heel strike is less oriented toward the new direction of travel when planning time is reduced (Weir et al., 2019). During anticipated sidestepping, a more neutral pelvic orientation is seen, with stance limb (transition limb) ipsilateral pelvic obliquity at heel strike, increasing throughout the weight acceptance phase (Figure 12; Weir et al., 2019). During unanticipated sidestepping, the pelvis maintains ipsilateral pelvic obliquity throughout stance (Weir et al., 2019). During anticipated side-stepping the initial posture at the trunk is more favorable for change of direction at heel strike of stance already oriented towards the new direction of travel, while during unanticipated sidestepping, the trunk is oriented in the opposite direction of travel at heel strike (Weir et al., 2019).

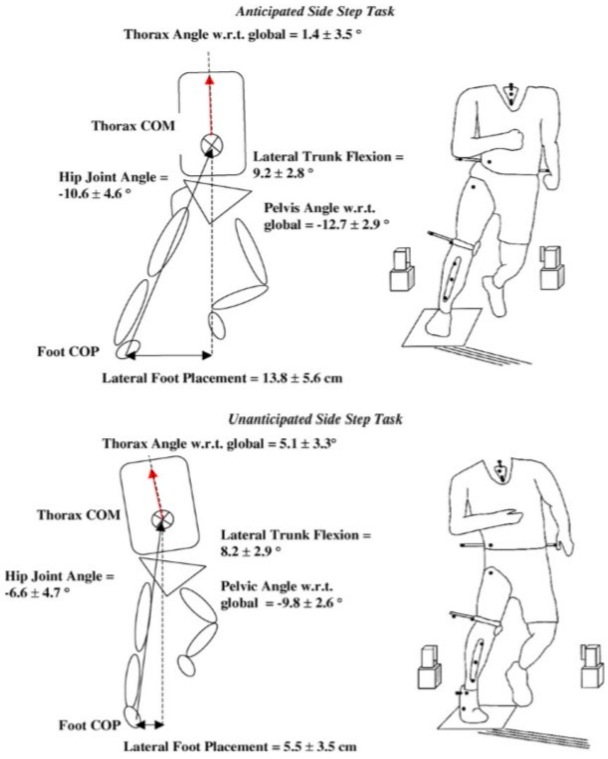


Figure 11: Average lateral foot placement, hip, trunk, pelvis and thorax angle values (+/- standard deviation) during anticipated and unanticipated sidestepping in the frontal plane during the transition step. All joint angles were calculated with respect to the global reference frame. Adapted from Houck et al. (2006).

To investigate frontal plane kinematics, Houck et al. (2006) had participants perform unanticipated sidesteps while walking at speeds ranging from 1.9-2.1 ms^{-1}, responding to an arrow display. A significantly larger lateral trunk orientation opposite the new direction of travel was observed during unanticipated sidestepping. However upon further analysis, the authors concluded that the trunk and pelvis move as a single segment, suggesting trunk orientation was not due to an increase in lateral trunk flexion, but instead a change in foot placement and hip abduction angles. It has been suggested a decreased lateral foot placement and hip abduction angle may be responsible for the increased lateral trunk orientation (Houck et al., 2006). While demands may differ between walking and running, a more in-phase coordination pattern between the trunk and pelvis has been reported during unanticipated sidestepping while running (Weir et al., 2019) (See Section 2.6.4).

2.3.2.2 Transverse Plane

The transition to a new travel direction requires the reorientation of the body from a forward position to a new direction. During forward locomotion, at footstrike the trunk is rotated with the chest and shoulders directed towards the stance leg (Hinrichs 1987). During change of direction tasks, the trunk is oriented away from the intended travel direction, but more so during unanticipated conditions (Mornieux et al., 2014) (Table 2). During anticipated conditions, prior knowledge of the sidestep direction was given. The additional conditions varied the time the stimulus was given before initiating the sidestep from 850-500 ms. The peak knee abduction moment typically happens during the weight acceptance phase of the transition limb. The authors did not find significant differences between anticipated and the 850 ms condition, which they concluded suggests 850 ms is adequate planning time to perform a sidestepping maneuver at the given speed and angle.

Table 2: Mean (SD) values of trunk rotation at time of peak abduction movement during sidestepping with reduced planning time. Participants ran 5 +/- 0.2 ms^{-1} while performing a 45° sidestep. Negative values indicate orientation away from new travel direction. Adapted from Mornieux et al., (2014).

*expresses a significant difference

[b] compared to the 850 ms sidestepping condition

	Anticipated	850 ms	600 ms	500 ms
Trunk rotation (°)	-4.8 (11.0)	-3.3 (11.1)	-7.3 (10.3) *[b]	-8.8 (9.9)*[b]

2.3.2.3 Sagittal Plane

For both anticipated and unanticipated sidestepping, trunk flexion angle increases throughout stance, with an increased trunk flexion angle during unanticipated conditions (Weir et al., 2019) (Figure 12). An increase in the pelvic flexion angle can be seen throughout the weight acceptance phase, though the pelvic flexion angle decreases following the weight acceptance phase. While significant differences in the trunk and pelvic flexion angle have been reported during both anticipated and unanticipated sidestepping when compared to straight running, no significant differences have been reported between anticipated and unanticipated sidestepping (Byrne et al., 2018).

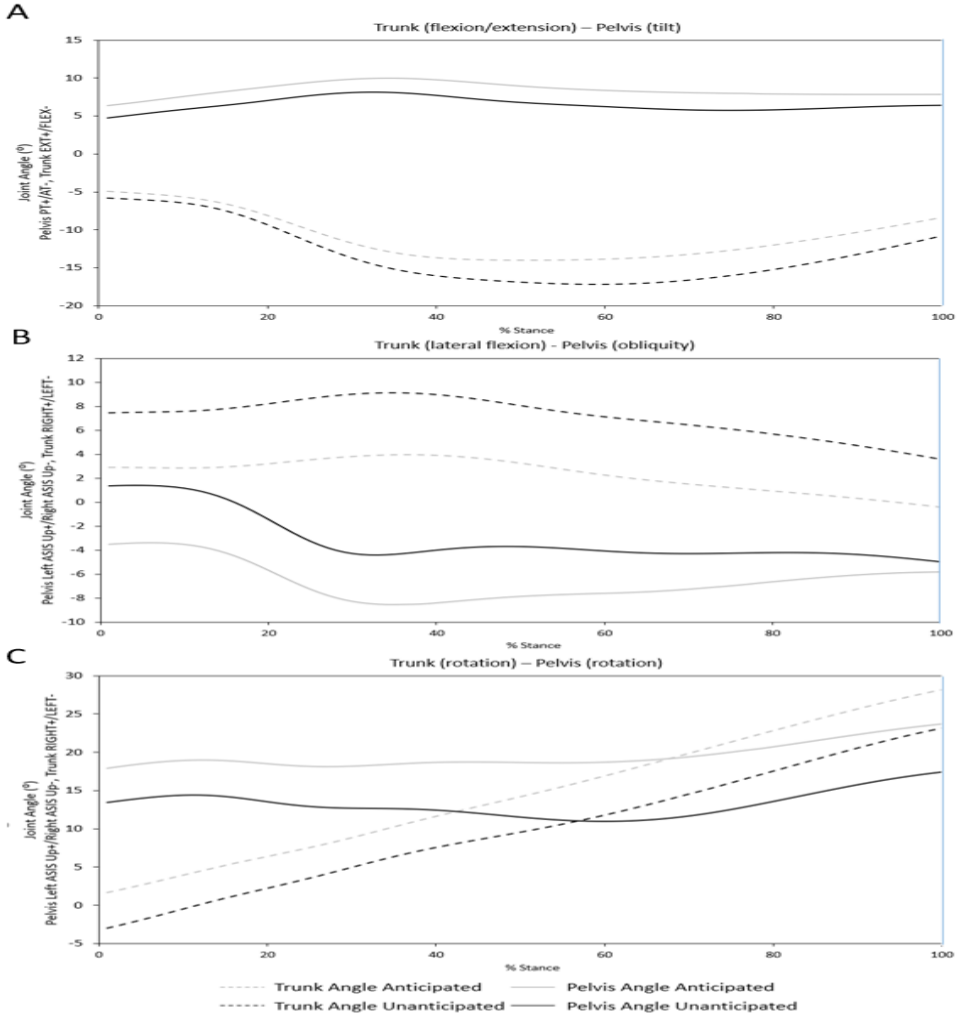


Figure 12: Trunk and pelvis segment kinematic patterns during the stance phase of anticipated (grey) and unanticipated (black) sidestepping for the sagittal (A), frontal (B), and transverse planes (C). AT = anterior tilt, PT = posterior tilt, FLEX = flexion, EXT – extension, ASIS = anterior superior iliac spine, LF = lateral flexion, C = clockwise, AC = anti-clockwise. Adapted from Weir et al. (2019)

2.4 Head Stabilization in Space During Straight Path Locomotion

During locomotion, we do not see complete stabilization of the head in space, but instead an intermittent position around discrete angular positions, accomplished by large head relative to trunk motion (Hirasaki et al., 1999; Imai et al., 2001; Moore et al., 1999; Moore et al., 2001; Pozzo et al., 1990). The Frankfort plane closely aligns with earth's surface and may be used as a set-point for the head, where the head has been shown to oscillate around this plane with and without visual information (Pozzo et al., 1990). Ultimately the position of the head is goal-directed (Bloomberg, Reschke, Huebner, and Peters, 1992) and dependent on the line of sight, but has been shown to maintain a specific head fixation distance (HFD) (Moore et al. 1999; Moore et al. 2001; Pozzo et al., 1990) (Figure 13). Gaze is stabilized through a combination of head and eye compensation for translational and angular movement. An angular or translational perturbation to the head may cause the head to counter rotate, mediated by the VCR, which maintains head position in space within a few degrees (Hirasaki et al., 1999; Imai et al., 2001; Moore et al., 1999; Moore et al., 2001; Pozzo et al., 1990); in addition VOR adjustments allow for compensatory eye movements in response to head movement to align gaze with desired visual information (Moore et al., 1999; Moore et al., 2001).

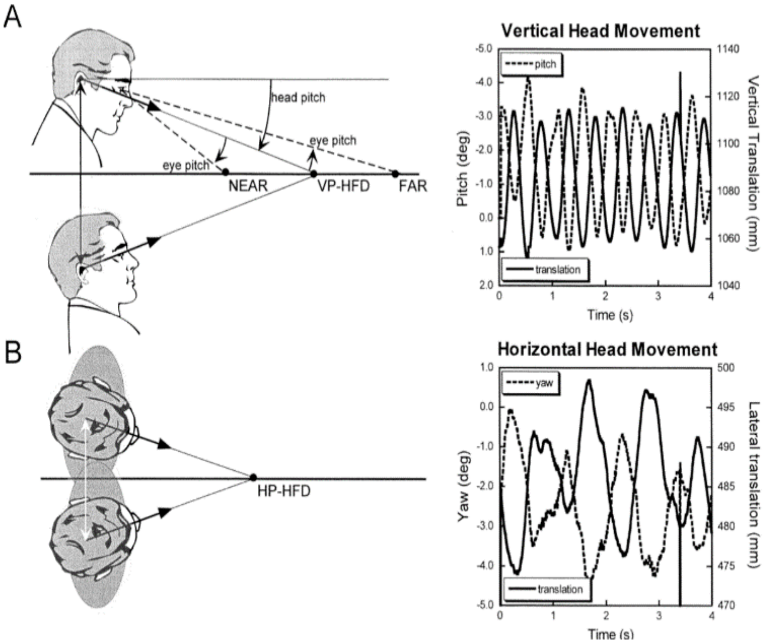


Figure 13. Illustration of compensatory vertical and horizontal head motion while treadmill walking at 1.67 ms^{-1}. Vertical head translation occurred at a frequency twice that of horizontal head translation. Both a vertically projected head fixation distance (VP-HFD) and horizontally projected head fixation distance (HP-HFD) were maintained in space through compensatory head relative to trunk motion. The HFD in both the vertical and horizontal planes was calculated from the average intersection of the projected naso-occipital axes with the respective plane over a series of stride cycles. In the sagittal plane, the direction of compensatory eye motion is dependent on viewing distance (See Figure 15). Adapted from Moore et al. (2001).

The head and trunk have been shown to vertically translate in a similar fashion at a range of walking speeds (Hirasaki et al., 1999) (Figure 14). While walking at speeds between 0.6-2.2 ms^{-1}, the vertical translation ranged from amplitudes of 10-35 mm (20-70 mm peak to peak amplitudes), with amplitudes increasing at speeds up to 2.0 ms^{-1}, before declining as the maximal step length is reached (Hirasaki et al., 1999). Similar findings have been reported, with a mean vertical head translation peak to peak amplitude of 48 mm and 53-60 mm at moderate (1.39 ms^{-1}) and fast (1.78-1.87 ms^{-1}) walking speeds, respectively (Bloomberg et al., 1992; Murray, 1967). Additionally, a mean lateral head translation peak to peak amplitude of 50 mm and 58 mm at moderate (1.39 ms^{-1}) and fast (1.87 ms^{-1}) walking speeds has been reported, respectively (Murray, 1967). It is important to note, Hirasaki and colleagues reported the peak amplitude, while the other authors reported the peak to peak magnitude of displacement. The reported studies presented treadmill walking data, though a similar vertical translation has been found during over ground walking from 1.4-1.8 ms^{-1} (Imai et al., 2001). No significant difference have been found between the head, upper and lower trunk regarding the vertical accelerations during walking (Kavanagh, Barrett, and Morrison, 2006; Waters, Morris, and Perry, 1973). This suggests the head, thorax and pelvis vertically translate in a similar fashion.

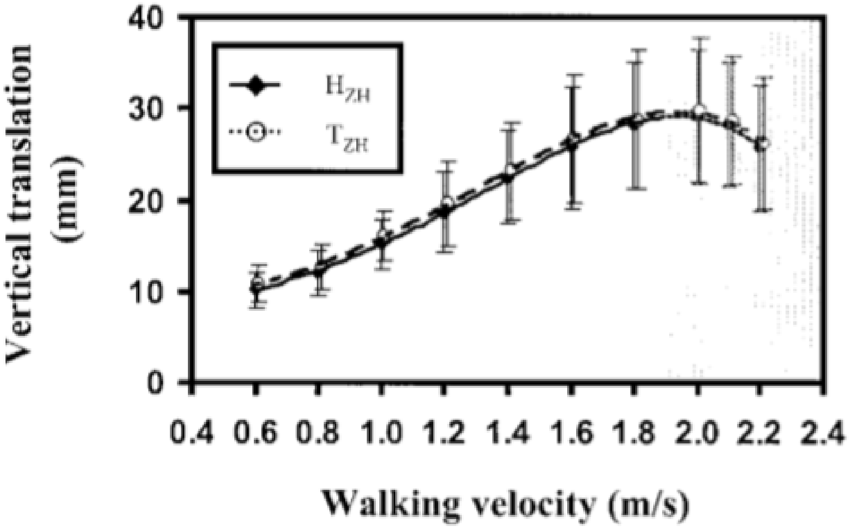


Figure 14: Vertical head (H_{ZH}) and trunk (T_{ZH}) translation changes relative to walking velocity. Adapted from Hirasaki et al. (1999).

The body translates (Figure 5) and angularly rotates (Figure 2) at different frequencies in each plane of motion. To better understand how gaze compensates for translational and angular perturbations, Moore et al. (2001) had participants fixate on an environment-fixed target 0.25-2.0 m from the eye while walking on a treadmill at 1.67 ms^{-1}; assessing both vertical and horizontal head and eye compensatory movements. The authors found different compensatory mechanisms in the transverse and sagittal planes as a function of viewing distances (Figure 15). The HP-HFD remained between the subject and target at all viewing distances which suggests the aVOR is compensatory for head rotation, while the target location relative to the VP-HFD location varied dependent on viewing distance. With near targets, the VP-HFD was beyond the target, which suggests the lVOR is providing the compensatory eye movements. Collectively, this suggests that the aVOR is mainly compensatory for horizontal eye movements at target distances 0.25-2.0 m while both the aVOR and lVOR allow for compensatory vertical eye movements, depending on viewing distance. When viewing distances were less than 1 m, the visual target was between the participant and their vertical HFD, but when viewing distances were greater than 1 m, the vertical HFD was between the participant and the visual target. The authors suggest translational motion stimulated compensatory eye motions at viewing distances less than 1 m, but angular motion was the main driver of compensatory eye motions at viewing distances greater than 1 m. However, in the horizontal direction all visual targets persisted beyond the horizontal HFD suggesting head rotation in the transverse plane stimulated compensatory eye motion.

During locomotion, the oscillatory nature of the head is dependent on specific gait events, with vertical head and trunk motion occurring at twice the frequency of mediolateral head motion (Grossman et al., 1988; Hirasaki et al. 1999; Imai et al. 2001; Moore et al. 2001) (See Figure 16). The head vertically oscillates once per step and horizontally oscillates once per stride (Murray, 1967). At walking speeds ranging from 1.2-1.8 ms^{-1} , the compensatory sagittal plane head motion is dependent on the step frequency, while frontal and transverse plane motion are dependent on the stride frequency (Hirasaki et al. 1999; Imai et al. 2001; Thorstensson et al., 1984; Moore et al. 2001) (Figure 15).

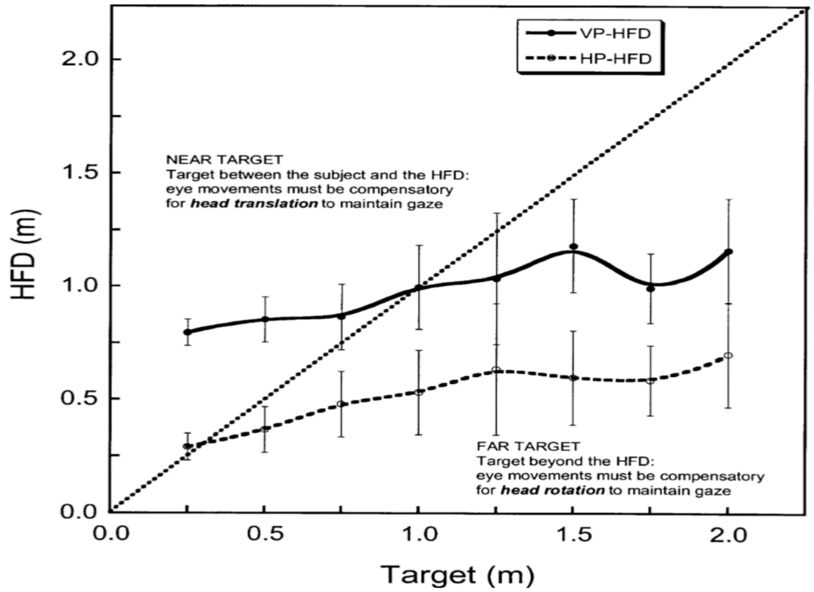


Figure 15: HFD relative to target location while walking at 1.67 ms^{-1} at a range of viewing distances. Adapted from Moore et al., (2001).

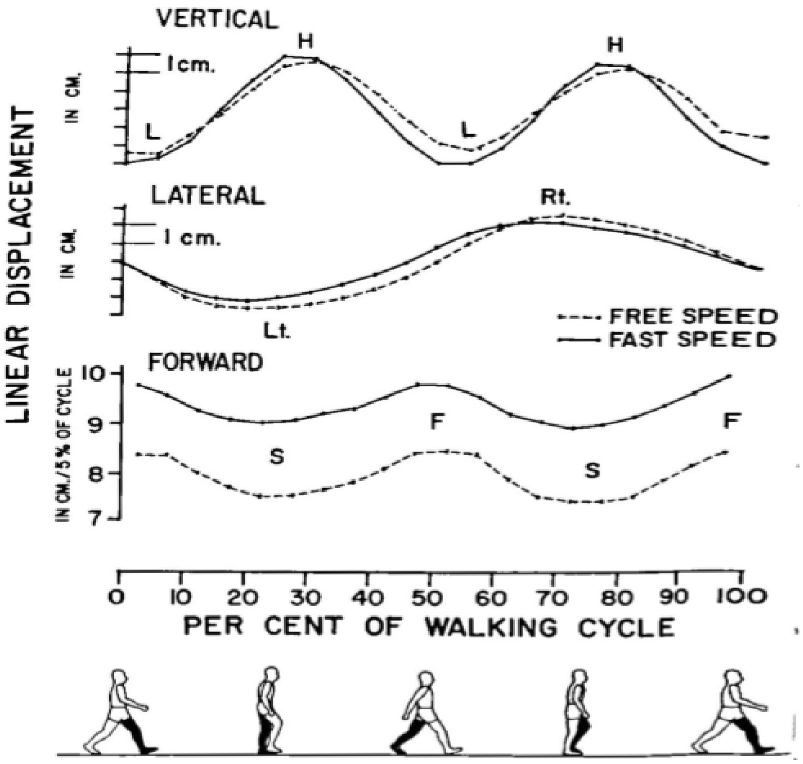


Figure 16: Tri-planar translational motion of the head at preferred (1.51 ms^{-1}) and fast (2.18 ms^{-1}) walking speeds. Adapted from Murray (1967).

During both treadmill (Moore et al., 2001, Hirasaki et al., 1999) and over ground (Imai et al., 2001) walking, translational motion at the head stimulates the VCR, producing compensatory head motion to maintain a head position in space. Lateral head translation occurs at a frequency exactly half of the vertical head translation (Moore et al., 1999, Moore et al., 2001, Imai et al., 2001, Hirasaki et al., 1999). Sagittal and transverse plane head motion in space is maintained within a narrow range, while trunk motion in space, and head motion related to trunk motion rotate at larger ranges (Imai et al., 2001, Moore et al., 2001) (Figure 17). At typical adult walking speeds, ranging from 1.4-1.8 ms^{-1}, the compensatory effect is suggested to be due to stimulation of otoliths, producing an lVCR (Moore et al., 2001, Imai et al., 2001, Hirasaki et al., 1999,).

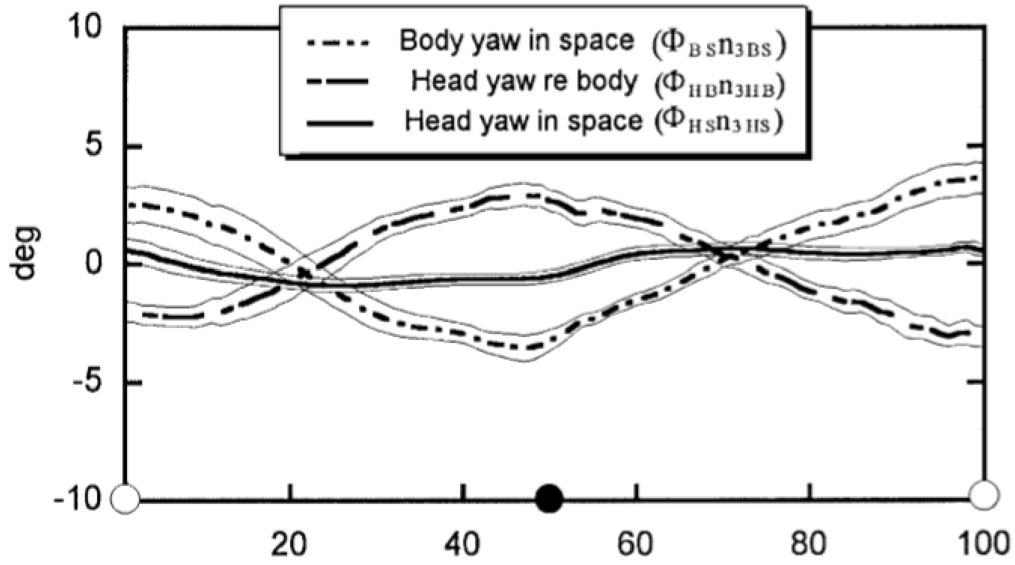


Figure 17: Head and Body (Trunk) transverse plane motion throughout a gait cycle while walking at faster walking speeds (1.4-1.8 ms^{-1}). Body yaw in space completes a full oscillation once per stride. Head yaw relative (re) to body compensates for body yaw in space, allowing minimal deviations of head yaw in space. Open and closed circles represent heel strike. Adapted from Imai et al. (2001).

The demands placed on the VCR are largely dependent on walking speed, as walking speed can be modulated by changing both step length and step frequency. Individuals tend to increase walking speed by increases in step length from 1.2-1.8 ms^{-1} (Hirasaki et al., 1999). In doing so, participants increase the vertical CoM displacement throughout the gait cycle and rely more heavily on the lVCR to maintain vertical head position in space (Hirasaki et al., 1999). However, at walking velocities 0.6-1.2 ms^{-1}, step length does not significantly change, while step frequency changes to increase walking speed. At these slower speeds, head motion does not compensate for translational motion, but instead for changes in trunk angle throughout the gait cycle, suggesting angular vestibular information is used to maintain head posture in the sagittal plane through the aVCR (Hirasaki et al., 1999). Collectively this suggests that both angular and translational information may be used by the vestibular system to maintain head posture at different walking speeds, with translational information utilized more heavily at walking speeds greater than 1.2 ms^{-1} (Moore et al., 1999, Moore et al., 2001, Imai et al., 2001, Hirasaki et al., 1999). However, little is known regarding the angular information used by the vestibular system at faster velocities.

In the frontal plane, the trunk laterally shifts toward the support limb during each step, with increased lateral trunk flexion toward the support limb. The head moves in-phase to the trunk during locomotion in the frontal plane. During a series of dynamic balancing tasks that decreased the medio-lateral BoS, Pozzo et al. (1990) found that head position was maintained relative to earths horizontal in the frontal plane.

Collectively these findings highlight that specific gait events, as well as visual tasks, place different demands on the vestibular system and the corresponding change in eye movements in different planes (Grossman et al., 1988; Hirasaki et al., 1999; Moore et al., 2001; Imai et al., 2001).

2.4.1 The Influence of Visual Task Constraints on Head Stability

Lower body alterations maintain head stability both with and without a visual task (Busa et al. 2016; Hamill et al., 1995; Lim et al., 2017; Mulavara et al., 2002). Individuals are able to stabilize the head and attenuate shock at a wide range of stride lengths and stride frequencies, primarily through active modulation during late stance (Busa et al., 2016; Hamill et al., 1995; Lim et al., 2017). To study the effect of visual feedback on head stability and shock attenuation, Busa et al. (2016) had participants run at 3.1 ms^{-1} at their preferred speed under 5 stride frequency conditions (+/- 0, 10, and 20% of preferred stride frequency) under two visual conditions, with and without visual feedback of head-gaze orientation. To maintain running speed, an inverse relationship between stride length and frequency was present (i.e. increase in frequency results in decrease in length). Individuals were able to modulate the amount of impact shock at the head across a range of stride frequencies (-10% - +20% preferred), but had significantly larger magnitudes and integrated power of tibia and head accelerations with extreme reductions in stride frequency (-20% preferred). Visual feedback of head gaze orientation resulted in an increase in the active adjustments during late stance to reduce head accelerations and overall head motion.

To further explore the effect of visual feedback, Lim et al., (2017) had participants run at their preferred speed while receiving real-time feedback while visual angle was reduced through decreasing box sizes. The size of the static box, initially set by a 21° vertically and horizontally subtended visual angle, decreased by increments 3° for 7 trials (visual angle ranged from 21°- 3° for all trials). By decreasing the size of the box, Lim and colleagues were able to increase head stability demands. As head stability demands increased, head motion and vertical CoM displacement decreased, while stride frequency, hip flexion*, and knee flexion increased (Figure 18). These findings highlight that individuals make active adjustments during late stance at their preferred running speed to stabilize head orientation with increased visual task demands.

During treadmill walking, Muluvara et al. (2002) had participants perform gaze stabilization tasks such as focusing on a central point target (low visual acuity demands) or reading numeral characters (high visual acuity demands). With increased visual acuity demands, they found an increase in head pitch motion despite no significant difference in trunk pitch or trunk vertical translation, and increased knee flexion. Collectively these studies suggest head stability requires whole body modifications. With increased head stability demands, individuals increase stance time, thereby decreasing the amount of vertical CoM translation. Additionally, the increase in knee flexion may utilize the human body's shock attenuation capacity. The knee joint may act as a low pass filter, facilitating shock attenuation from the impact shock to the head (Edwards et al., 2012). The human body attenuates shock primarily by mechanisms at the knee joint (Derrick, Hamill, and Caldwell, 1998; Edwards et al., 2012). With increased flexion at the knee, active muscle tissue may play a more active role in shock attenuation, preventing a larger range of frequencies found at the impact shock to be transmitted to the head (Boyer et al., 2004;

*increased at impact, decreased at takeoff

Edwards et al., 2012). Together, this suggests an increase in knee flexion angle increases the shock attenuation characteristics of the body, thus minimizing large accelerations at the head.

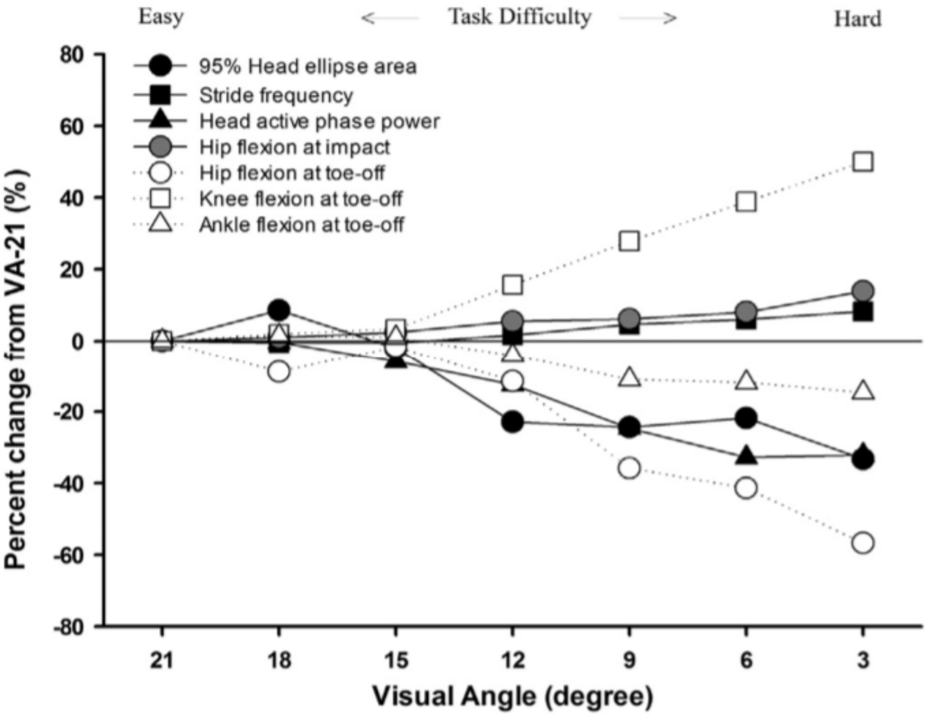


Figure 18: Mean percent change for key dependent variables as visual task demand difficulty increased while treadmill running. Adapted from Lim et al. (2017).

2.5 Anticipatory Changes to Head Kinematics during Directional Changes

Spatial and temporal anticipation of eye movement, followed by the head is often found toward the new travel direction (Bernardin et al., 2012; Grasso et al., 1996, 1998a, 1998b; Hollands, Ziavra, and Bronstein 2004; Hollands, Patla, and Vickers 2002; Imai et al. 2001). Gaze shifts greater than 15° often require head movements following initial eye saccade (Fuller, 1992). Motion of the head precedes heading direction, followed by the trunk (Patla et al., 1999), and then the pelvis (Bernardin et al., 2012). Several studies had participants change direction or turn in darkness and continued to find a change in the head direction preceding the heading direction during the turn, suggesting aligning the head with the new travel direction initiates a *steering synergy* where head motion initiates a chain of motor commands (Authie et al., 2015; Grasso et al., 1998). With head rotation in the new direction of travel, the visual and vestibular systems are aligned, as well as proprioceptive information that can be used as an egocentric reference frame to change whole body direction.

Hollands et al. (2002) had participants perform anticipated turns at 30 and 60 degrees with the head fixed to the trunk via blocks, requiring enbloc movements. With the head fixed to the trunk, the authors found individuals realigned their trunk with the new direction of travel in a shorter period of time. The direction of travel is suggested to be controlled by fixating the goal, then aligning the head and body with gaze direction, suggesting people follow their eyes and head.

Vallis and Patla (2004) had participants perform voluntary and involuntary head perturbations in an attempt to better explain the role of the head in steering. Participants were instructed to continue walking straight ahead; during the voluntary head perturbation, participants were instructed to realign gaze with an environment fixed target in the periphery while involuntary head perturbations were implemented via a pressurized head apparatus. The authors found involuntary head perturbations caused the participants to deviate from the straight path in the direction of perturbation, while voluntary head perturbations provided no significant deviation. The authors concluded that a steering synergy was released following an unexpected head perturbation but suppressed with voluntary head motion. However, during the voluntary head perturbation, the participants were given an explicit visual goal, providing the system with self-to-object information, while the involuntary perturbation did not include an explicit goal.

Cinnelli and Warren (2012) further explored the role of explicit targets during change of direction and concluded that head reorientation is neither sufficient nor necessary to change direction when the change of direction target is within 55° of the current travel path. Two visual strategies can be implemented to determine heading direction. The optic flow strategy is used based on the visual angle between the goal and one's current heading direction, specific to optic flow. Alternatively, the egocentric direction strategy is based on the angle between the goal direction and the foot-centered locomotor axis. The authors concluded that people do not follow their head, suggesting head movement during steering may be a byproduct of gaze shifts to fixate the goal or intended walking direction. Instead, steering is controlled by closing the angle between the direction of the goal and the current direction of travel, independent of head orientation.

While anticipatory head reorientation may not be sufficient or necessary, it is still observed in conditions in the absence of a visual goal (Bernardin et al., 2012). Bernardin and colleagues had participants memorize a high curved, medium curved and continuous curved trajectory before performing the pre-cued trajectories in an environment free of notable landmarks. The authors found the head to precede the trunk which preceded the pelvis during all conditions both temporally and spatially. Interestingly, the authors also found the leading foot to precede the pelvis, suggesting both a top-down and bottom-up approach are used during larger and medium sized curves. While changing direction can be accomplished throughout a single stride (Patla et al., 1999), walking around a curved trajectory requires multiple strides and is comprised of small turns and straight walking which utilizes the oscillatory mechanics between the head and body (Imai et al., 2001). Changing direction involves mediolateral CoM initiation in the new travel direction followed by head, and then whole body reorientation (Patla et al., 1999). However, the stance foot provides a stable support for the CoM, and therefore may be required to anticipate the CoM, which is located near the pelvis.

With less time available while running the head tends to be less oriented in the new direction of travel throughout the preparatory and weight acceptance phase of stance during a sidestepping task. Mornieux et al. (2014) had participants run 5 $^{+}/_{-}$ 0.2 ms^{-1} while performing a 45° sidestep while a visual stimulus in the direction of travel would turn on at specific time points (Figure 19).

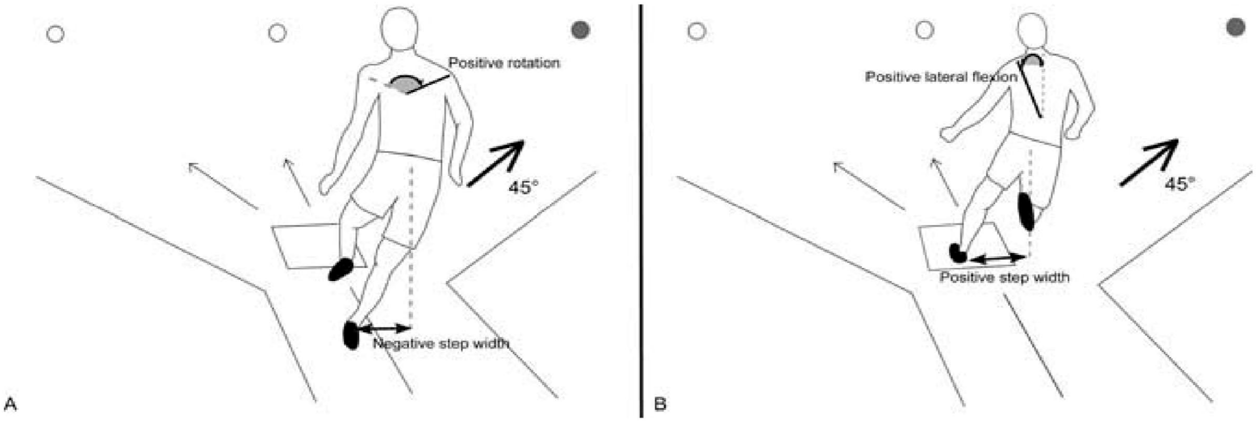


Figure 19: Schematic representation of protocol for sidestepping study. Participants were instructed to change direction toward the light stimuli in one of the three directions under four temporal conditions. During the anticipated condition, participants were aware of which light would turn on before the start of the run. For the other three conditions, the light stimulus would turn on 850, 600 and 500 ms before ground contact. All trials were randomized. A = penultimate step. B = Transition step. Adapted from Mornieux et al. (2014).

Head rotation is influenced by time available, and while a reduction in head orientation in the new travel direction was present for both conditions with reduced planning time, only the 600 ms condition produced significant differences while the 500 ms condition did not during both the penultimate step and transition step (Table 3). While noticeable changes in change of direction mechanics are seen below the head with reduced planning time (Lee et al., 2017; Patla et al., 1999; Weir et al., 2019), it is likely that head motion onset may be reduced with decreased planning time (Mornieux et al., 2014).

Table 3: Mean (SD) values (°) of head rotation during the penultimate step and at the time of the peak knee abduction moment during the transition step. Larger values indicate greater orientation toward new direction of travel. The authors concluded the anticipated and 850 ms condition were not significantly different and should both be considered anticipated conditions. Adapted from Morniuex et al. (2014).

*expresses a significant difference ($p < 0.05$)

[a] significant difference compared to the Anticipated and 850 ms sidestepping condition

Time Point	Anticipated	850 ms	600 ms	500 ms
Penultimate Step	11.1 (9.1)	10.9 (9.9)	6.5 (10.5) *[a]	6.9 (7.1)
Transition Step	18.0 (11.3)	17.6 (13.1)	13.3 (13.5)*[a]	13.5 (11.5)

2.6 Coordination and Variability

2.6.1 Dynamical Systems

"The study of biological systems under the lens of self-organizing systems, the components of a system create new patterns in a self-organized fashion" – J.A. Scott Kelso

A dynamical systems approach provides researchers with a means to better untangle human movement dynamics by not considering the system in terms of computerized functions, but instead view it as a pattern-forming, open self-organized system governed by nonlinear dynamical laws (Kelso, 1995). Open in the sense that the subsystems can interact with the environment, and self-organized in the sense that the subsystems' intrinsic properties determine pattern formation (Kelso, 1995). While traditional viewpoints consider variability to be detrimental to performance, a dynamical systems perspective sheds light on the importance of variability in the transition to different stable patterns.

Complex physical systems show stable patterns and qualitative transitions, and from a dynamical systems perspective, allow for the classification of stable patterns and critical transition points (Schöner and Kelso, 1988). These stable patterns are known as attractors, defined by a set of points in the state space (Kelso, 1995). When an attractor becomes unstable, it will undergo a phase transition via a bifurcation, a qualitive change in the attractor structure (Kelso, 1995). To quantify specific attractors, collective variables known as order parameters describe pattern formation as well as their evolution. The behavior of biological systems can be quantified through the order parameter, a low-dimensional collective variable which represents the organization of the system. Phase relations between body segments can be considered order parameters as they reflect the interaction between components of the system. Modification of control parameters, such as frequency or velocity, can induce a shift in order parameters at a critical transition point. Phase transitions between order parameters occur once the attractor becomes unstable and the system bifurcates to a new attractor. An attractor represents a series of focal points within the state space where neighboring solutions converge following perturbation. A bifurcation is a rapid jump from one attractor to another.

Systemic reorganization toward a more stable pattern requires bifurcation, where a qualitative change in the order parameter occurs. As the system approaches a transition, critical fluctuations emerge, where the variability within the system increases and also exhibits critical slowing down (where the relaxation time required to recover from a perturbation increases). The system also has a tendency to display hysteresis (a directional response where the transition does not happen at similar values of the control parameter when scaling up and down) (Kelso, 1995). In the study of human movement, greater variability has shown the system is closer to a phase transition, with less variability highlighting a more stable pattern in bimanual coordination (Kelso, 1984; Kelso et al. 1981), and during the walk to run transition in locomotion (Diedrich et al., 1995). A lack of relative phase variability also been shown in older populations, individuals with low back pain and Parkinson's disease patients in both walking (van Emmerik et al. 2005; van Emmerik et al. 1999) and running (Seay et al., 2011b), suggesting age and disease to reduce the adaptability of the system.

Head, trunk, pelvis, hip and knee range of motion assessments have been used to quantify differences between tasks such as anticipated and unanticipated side stepping (Besier et al., 2001; Brown et al., 2009; Byrne et al., 2018; Houck et al., 2006; Lee et al., 2017; Lee et al., 2013; McLean et al., 2004; Mornieux et al., 2014) but do not capture the development of specific movement patterns. Bernstein's principles outline two key factors in determining the state of the system, where redundant degrees of freedom are used to achieve the same task while separately, the variability of coordination provides a metric into the variety of coordination patterns utilized (Bernstein, 1967). From this perspective, analysis of coordination and variability through relative phase analysis may provide deeper insights into the state of the system.

2.6.2 Coordination

Human movement is composed of a series of subsystems that have locally defined properties, brought together to complete specific goals in a coordinated pattern. From a dynamical systems perspective, principles of coordination emerge from the interaction of the underlying degrees of freedom in the system. Bernstein defined coordination as a problem of mastering the redundant degrees of freedom involved in a particular movement, or reducing the number of independent variables to be controlled (Bernstein, 1967; Turvey, 1990). It is possible to organize different degrees of freedom in the same way to achieve the same purpose and organize the same degrees of freedom in a different way to achieve a different purpose (Turvey, 1990).

Walking and running are different tasks but similar coordinative patterns emerge when comparing the two tasks at the same speed (Li et al., 1999). When learning a new task, or when planning time is reduced the system may lock the degrees of freedom to simplify the control task (Vereijken et al., 1992; Weir et al., 2019). Biological systems are equipped with excess, in the sense that with injury, we are still able to ambulate through the environment but may possess less complexity in our actions. A loss of complexity hypothesis brought forth through the work of Lipsitz et al. (2002) suggests that with aging and disease, less complexity may be linked to a reduction in the degrees of freedom, and with this reduction there is also a decrease in variability (Figure 20).

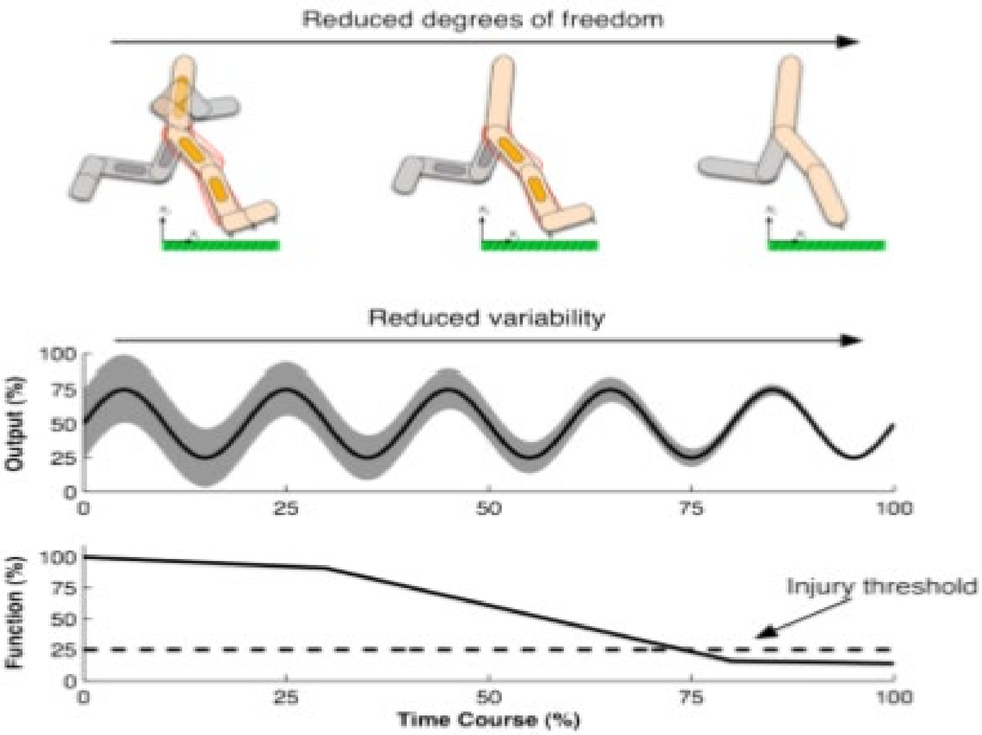


Figure 20: Loss of complexity hypothesis based on the work of Lipsitz et al. (2002). Top panel shows a reduction in the degrees of freedom used over time to accomplish the same task, explained graphically by the middle panel. A reduction in the degrees of freedom utilized is associated with a reduction in variability in the system. The bottom figure relates degrees of freedom and variability to functionality, with a reduction in variability related to a reduction in functionality. Over time, the reductions seen may relate to disease, injury and injury risk. Adapted from van Emmerik et al. (2013).

Age related changes in gait have been well documented, with a major emphasis on the changes at the lower extremity and their influence on the reduction in gait speed and stride length (Murray, 1967). However, a growing body of literature highlights the importance of trunk-pelvis motion, and the relationship to gait stability (van Emmerik and Wagenaar, 1996; Hinrichs, 1987; Murray, 1967; Stokes, Andersson, Forssberg 1989; Wagenaar and Beek, 1992). The phase relationship between the trunk and pelvis is dependent on gait speed, with a more in-phase relationship at lower velocities, and more anti-phase relationship at higher walking velocities (Wagenaar and Beek, 1992). During human locomotion, the pelvic step increases stride length through greater transverse plane motion of the pelvis, starting between 0.75 (Stokes et al., 1989) and 1.0 ms^{-1} (van Emmerik and Wagenaar, 1996; Wagenaar and Beek, 1992) in healthy participants. The counter rotation between the trunk and pelvis may reduce whole body angular momentum (Figure 4), allowing for more stable gait (Hinrichs, 1987; Stokes et al., 1989).

A more in-phase transverse plane trunk-pelvis motion during walking has been observed in stroke (Wagenaar and Beek 1992) and Parkinson's disease patients (van Emmerik et al., 1999), and with aging (van Emmerik et al., 2005; Murray, 1967), as well as with lower back injury during walking and running (Seay et al., 2011a). McGibbon and Krebs (2001) had young and older participants walk over ground at their preferred speeds and found no age-related differences in trunk-pelvis ranges of motion in the sagittal plane but did find different leading strategies between age groups, with younger participants displaying a pelvis leading strategy while older participants displayed a trunk leading strategy. When controlling for walking speed with young, middle aged and older individuals, van Emmerik et al. (2005) found a reduction in pelvic motion in the frontal, sagittal and transverse planes, as well as a reduction in trunk motion in the sagittal plane as a function of age. Interestingly the authors found an increase in transverse trunk motion, but a reduction in compensatory motion between the trunk and pelvis in older individuals.

When assessing the effect of low back pain on pelvis-trunk coordination during walking and running, Seay et al. (2011a) found a more in-phase movement pattern between the trunk and pelvis in the transverse plane in individuals with a history of low back pain compared to healthy controls. With reduced planning time, a reduction in the degrees of freedom utilized has been observed with more in-phase trunk-pelvis and hip-knee motion during an unanticipated sidestepping task (Weir et al., 2019). These findings highlight the loss of complexity by locking the degrees of freedom to simplify the control task seen with a reduced system capacity either with aging, disease or a reduction in planning time.

2.6.3 Coordination Variability

An increase in coordination variability can pinpoint unstable patterns near a transition point (Kelso, 1984), but variability may also play a functional role in regards to overuse injuries and the adaptivity of the system (Hamill, Palmer, and van Emmerik 2012). The traditional view of variability is based on the concept of end point variability, which greatly differs from coordination variability (Hamill et al., 2012). End-point variability refers to the task goal, which in the context of pistol shooting may involve pistol aiming location prior to pulling the trigger (Arutyunyan, Gurfinkel, and Mirskii 1969). Coordination variability refers to the variability in the joint and segment coupling strategies used to achieve a task goal. When comparing novice and expert marksmen, Arutyunyan et al. (1969) found experts to have less end-point variability, while coordination variability of the shoulder, elbow and wrist was greater than novice marksmen. These findings highlight the differences between coordination variability and end-point variability.

Variability can be both beneficial and adaptive, with a reduction in variability commonly seen in aging and disease (van Emmerik et al., 1999; Hamill et al., 1999; Seay et al., 2011b). Trunk-pelvis coordination was examined in patients recently diagnosed with Parkinson's disease during treadmill walking as speed incrementally increased, and then decreased by 0.2 ms^{-1} from 0.2 ms^{-1} to 1.4 ms^{-1} (van Emmerik et al., 1999). A significantly smaller adaptation in coordination and reduced coordination variability was seen in Parkinson's disease patients compared to healthy controls, which the authors concluded may be a more sensitive metric to assess patients compared to traditional gait parameters (van Emmerik et al., 1999). A similar protocol was used during the walk to run transition to assess the effect of low back pain on coordination and coordination variability, with treadmill speeds ranging from 0.8 to 3.8 ms^{-1} (Seay et al., 2011b). Individuals with low back pain showed reduced coordination variability (Seay et al., 2011b). During a running study comparing healthy individuals with individuals with patellar femoral pain, patients with patellar femoral pain showed a reduction in coordination variability throughout the entire stride cycle, with the most observable differences during terminal stance (Hamill et al., 1999) (Figure 21). In the context of injury, and injury prevention, the narrow range of movement patterns may result in repeated stress to a segment or joint, and may provide insight into the underlying cause of injury (Hamill et al., 1999; Hamill et al., 2012). The authors suggest lower coordination variability may be an indicator of pathology (Hamill et al., 2012).

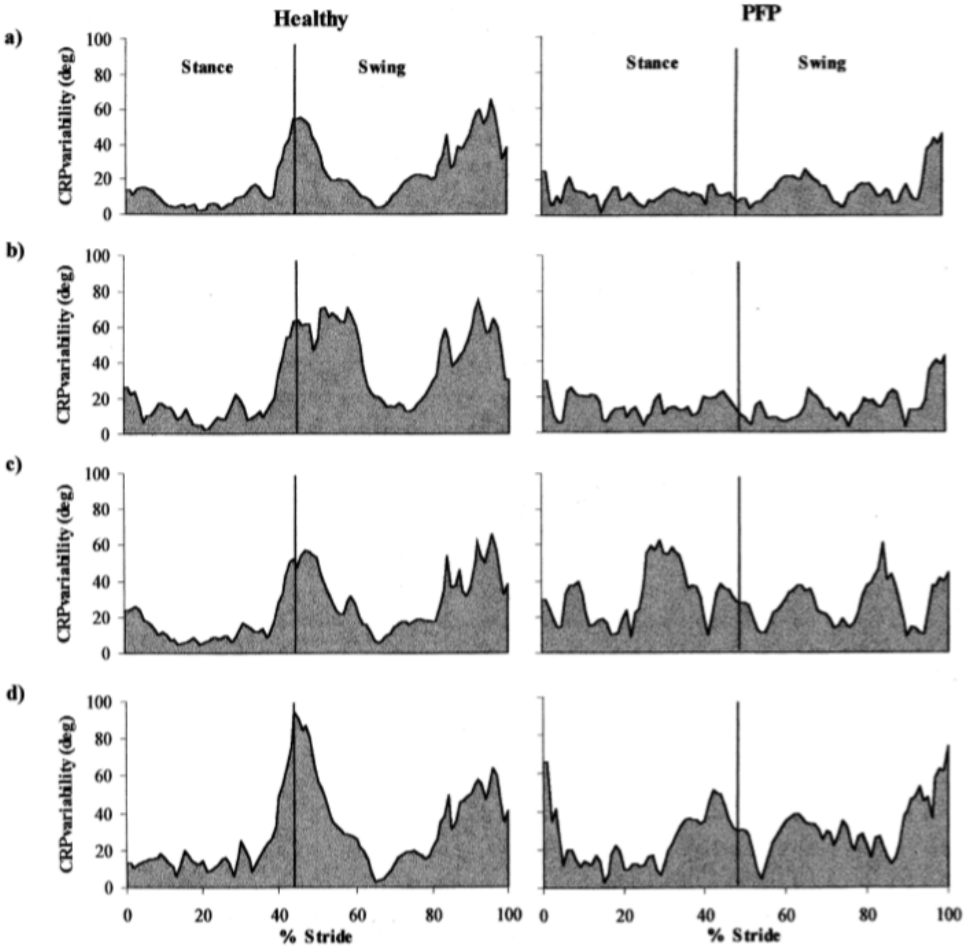


Figure 21: Continuous Relative Phase (CRP) variability of lower extremity coupling during running in healthy individuals and individuals with patellofemoral pain (PFP). The vertical line separates stance phase from swing phase during running. There were significant differences in the variability during terminal stance in healthy compared to PFP. Throughout the entire stride cycle, the PFP group displayed less variability. a: thigh flexion/extension – tibia rotation , b): thigh rotation – tibia rotation, c): thigh abduction/adduction – tibia rotation, d): tibia rotation -foot eversion/inversion. Adapted from Hamill et al. (1999).

Regarding variability, it appears there may be an “optimal” range, where too little variability suggests that a reduced number of movement patterns may result in overuse of specific tissues, and an inability to appropriately respond to a perturbation (Hamill et al., 2012; Weir et al., 2019) . However, too much variability may also be detrimental also highlighting an injured state (Figure 22).

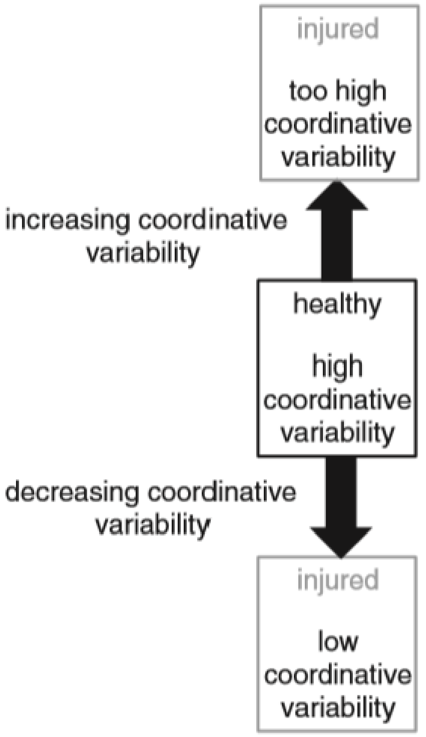


Figure 22. A schematic illustrating the theoretical relationship between high and low variability. Adapted from Hamill et al. (2012).

2.6.4 Coordination and Coordination Variability Assessments During Side-Stepping

The majority of side-stepping literature places a major emphasis on kinematics and kinetics of the lower extremity joints in isolation, rather than assessing the interaction between the joints of interest (Brown, Brughelli, and Hume, 2014; Fox, 2018). Non-contact ACL injuries typically occur during sidestepping or single leg landing tasks, commonly the result of rapid redirection of whole body CoM during the weight acceptance phase (Besier et al., 2001; Cochrane, Lloyd, Buttfield, Seward, and McGivern, 2007), with female athletes at a higher risk than males (Griffin, Garrett, and Huston 2000). A growing body of literature utilizes coordination and variability analysis during anticipated and unanticipated sidestepping (Pollard, Heiderscheit, van Emmerik, and Hamill, 2005; Pollard, Stearns, Hayes, and Heiderscheit, 2015; Weir et al., 2019). Multiple complex coordination patterns are needed to successfully change direction, which requires a large kinematic solution space. With reduced planning time, more in-phase coupling between the trunk-pelvis and hip-knee segments has been observed, with an increase in coordination variability (Weir et al., 2019). By manipulating the time available to plan a movement, the task complexity increases, displaying significant differences in joint coupling and coupling variability (Weir et al., 2019).

Gender differences in ACL risk have also been reported, with women at an increased injury risk, possibly due anatomical differences between males and females (Griffin et al., 2000). However, when assessing the coupling variability, females have a decrease in coordination variability prior to ACL injury with an increase in coordination variability following ACL reconstruction during the same sidestepping task (Pollard et al., 2005; 2015). Decreased variability in intralimb coupling may highlight a less flexible system, with a reduction in pattern flexibility or adaptability increasing overuse injury risk through repetitive loading (Hamill et al., 1999).

2.6.5 Quantifying Coordination and Coordination Variability

Visual graphical inspection has been used in an attempt to quantify the phasic relation between segments but does not provide a quantifiable metric (Stokes et al., 1989). To quantify coordination and coordination variability, the three primary methods are relative phase (DRP), continuous relative phase (CRP) and vector coding (VC) (van Emmerik et al., 2013). DRP calculation is relatively simple, extracting the relative timing of two corresponding peaks from different time series. However, DRP is limited as it only provides a discrete measure of coordination. When assessing signals where coordination can change within the cycle, CRP and VC may be more suitable options. CRP allows for the extraction of higher order metrics between two segments or joints by quantifying the coordination between two oscillations based on the difference in their phase plane angles, though this requires to construction of a phase plane and extraction of phase plane angles. The phase plane is often constructed from position-velocity or angular position-angular velocity data. DRP provides a single discrete event in a time series while CRP allows for the quantification of coordination across an entire movement cycle, such as a stride cycle during walking or running (van Emmerik et al., 1999; Li et al., 1999). The construction of the phase plane enables the assessment of both velocity and displacement of the joint or segment.

CRP and DRP can be used to assess the spatial-temporal coordination between segment angles while manipulating a control parameter such as walking velocity to better understand the effects of aging and disease (van Emmerik and Wagenaar, 1996; van Emmerik et al., 1999; Li et al., 1999). To quantify coordination variability, the between-cycle standard deviation of the CRP can be taken from a normalized gait cycle. While higher order dynamics of the system can be extracted from CRP analysis, this also requires a sinusoidal pattern and is difficult to interpret when the question of interest mainly deals with spatial phasing. Instead, a modified vector coding (VC) analysis, originally presented by Sparrow, Donovan, van Emmerik, and Barry (1987), allows for the classification of a coordination pattern with both sinusoidal and non-sinusoidal data and may be more clinically applicable (Chang, van Emmerik, and Hamill, 2008; Needham, Naemi, and Chockalingam, 2014, 2015). Coupling angles, extracted through circular statistics from angle-angle plots (Figure 23), allow for more information regarding the development of the movement. While CRP provides the relative phase, VC can clarify the different coordination patterns such as in-phase, anti-phase and with proximal or distal dominancy based on spatial changes (Chang et al., 2008; Needham et al., 2014, 2015). It is important to note that CRP and vector coding do not always provide the same relevant information (Miller, Chang, Baird, van Emmerik, and Hamill, 2010). When both a CRP and VC analysis were performed on the same dataset, differences in coordination and coordination variability patterns suggest that the comparison between CRP and VC should be used with caution (Miller et al., 2010). While CRP may provide a more complete metric for variability, a VC technique may be preferable when assessing sidestepping coordination. The coupling angle extracted from VC provides direction information about the movement patterns without the need for higher order variables. CRP requires a sinusoidal signal to accurately capture the coordination and coordination variability while VC has the capacity to handle non-sinusoidal signals, which may be present during anticipated and unanticipated sidestepping. Lastly, VC may be more clinically interpretable; while the higher-order variables from CRP may be more sensitive to subtle changes, they may not be as easily translated at a clinical level (van Emmerik et al., 2013).

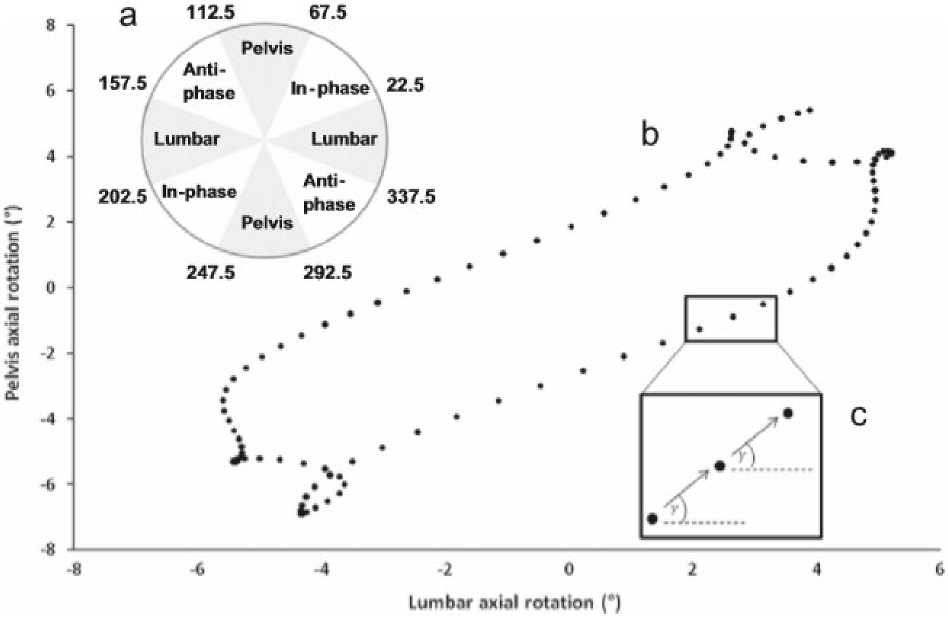


Figure 23: (a) Polar plot adapted from Chang et al. (2008) to quantify the coupling angle through a modified vector coding technique. (b) Angle-angle diagram of pelvic-lumbar coordination in the transverse plane of the mean of 10 participants while walking at their preferred speed. (c) Coupling angle (γ_i) determined by the vector orientation between two adjacent data points in time relative to the right horizonal. Adapted from Needham et al. (2014).

CHAPTER 3
METHODS

3.1 Introduction

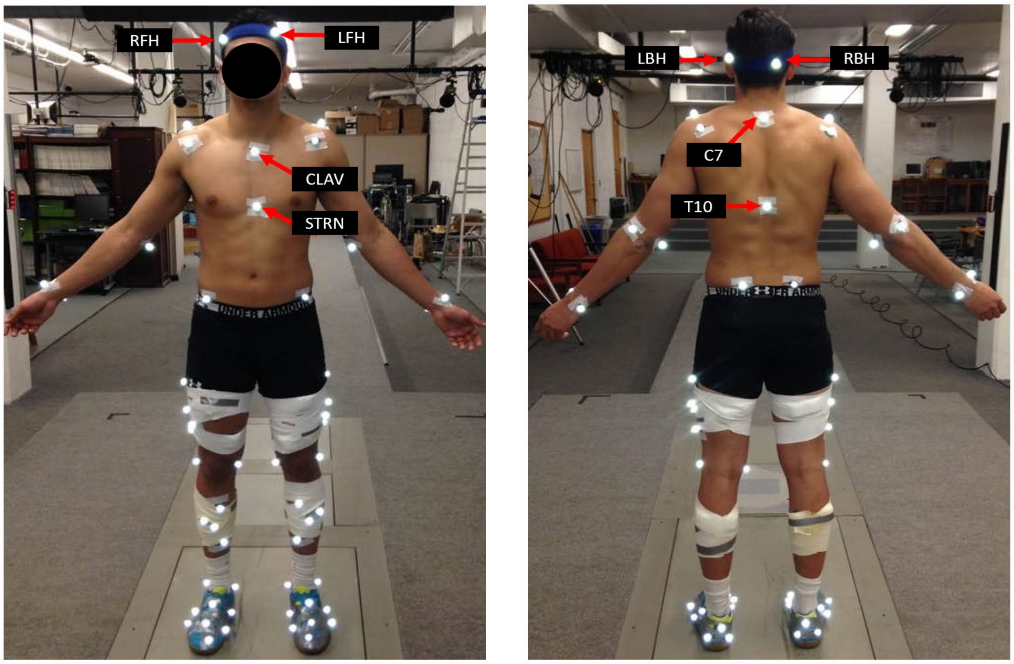
This study was a secondary analysis of the data published by Weir et al. (2019). The original purpose was to identify if coordination and coordination variability differences exist when planning time was reduced in sport-specific tasks to better understand the role of the organization of the degrees of freedom in ACL injury risk. The primary objective of this thesis was to better understand how the body's degrees of freedom organize themselves during sidestepping tasks with and without reduced planning time in collegiate athletes in regard to head control. Whole-body modifications are commonly seen to facilitate head control during forward locomotion, but kinematic differences are present during sidestepping tasks with and without reduced planning time compared to forward locomotion and their relationship to head motion control remains unknown.

3.2 Participants

Fourteen male collegiate athletes 18-25 years of age with no physical or neurological disorders were recruited to participant in this study. 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.

3.3 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 70 14-mm retroreflective markers as per a customized head, trunk and lower limb kinematic marker set and model (Weir et al., 2019). Four markers were fixed to the head via a head band. Four markers were placed on the suprasternal notch, xiphoid process, C7 and T10 to define the trunk (Figure 24). Markers were placed on the shoulder, elbows and wrists, with clusters placed on the pelvis, thigh, shank and feet to calculate segmental and whole body CoM. All participants wore standardized footwear provided by the laboratory.



Anterior

Posterior

Figure 24: Anterior and posterior views of market set up to define the head and trunk. RFH - Right Front Head, LFH - Left Front Head, RBH - Right Back Head, LBH - Left Back Head, CLAV – Suprasternal notch, STRN – xiphoid process, C7 - Cervical vertebrae 7, T10 - Thoracic vertebrae 10.

3.4 Protocol

Participants were asked to complete a 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. 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 this 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 (Figure 25). Participants were instructed to run at 4.0 ± 0.5 ms^{-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 non-dominant limb (penultimate step) limb toe off prior to contacting the force platform with the dominant leg to perform the task (unanticipated) (Figure 25b). 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. Sidestepping trials were considered successful if the athlete's average approach velocity was 4.0 ± 0.5 ms^{-1} and they contacted a black line ± 10° marked on the ground at 45° with the contralateral limb upon exit of the sidestep maneuver. A total of 7 anticipated and 7 unanticipated sidestepping trials were collected for each participant.

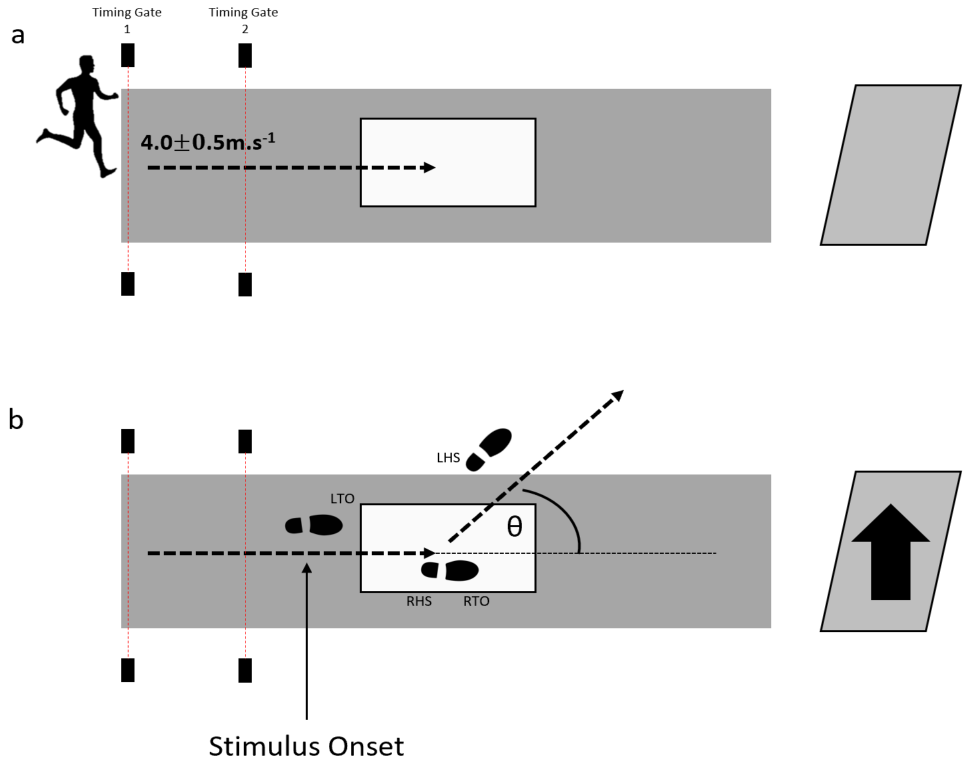


Figure 25: Sidestepping Protocol. Participants were instructed to run at 4.0 ± 0.5 ms^{-1} and perform a task present on the screen. (a) During unanticipated trials, a blank screen would be present prior to passing through the timing gaits. (b) A stimulus on screen would be present at penultimate step toe off, instructing the participant to change direction. For anticipated sidestepping tasks, the task prompt on the screen would be present at the start of the trial. Trials were considered successful with an approach velocity of 4.0 ± 0.5 ms^{-1} and a change of direction angle (θ) of 45°± 10° (LTO – left toe off, RHS – right heel strike, RTO – right toe off, LHS – left heel strike).

3.5 Data Analysis

Marker data were initially processed in Qualisys Tracking Manager (Qualisys, Gothenburg, Sweden). All the markers were labeled and gap filled (when appropriate). A residual analysis was performed on kinematic trajectories for the head and trunk separately to determine the appropriate cut off frequency. Once an appropriate cut-off frequency was determined, tracked marker data and ground reaction forces were exported to Visual 3D software (C-motion, Rockville, MD), where data filtering and processing was performed. A zero-lag fourth-order low pass 14 Hz Butterworth filer was applied. A complete stride, from left toe off to left heel strike was used to export normalized head and trunk segment angles, as well as vertical CoM motion of the trunk, relative to the global coordinate system.

Mean spatial-temporal, segment orientation, segment range of motion, and segment/joint coordination and coordination variability were calculated for seven trials for anticipated and unanticipated sidestepping. Spatial-temporal variables included pre-contact velocity (average pelvis CoM velocity at penultimate toe off) and change of direction angle (angle between the two CoM position vectors from dominant limb toe off to contralateral limb foot strike during change of direction stride) (Donnelly, Lloyd, Elliott, and Reinbolt, 2012). Segment orientation was calculated independently for the head and trunk as the angular position in the transverse plane at penultimate step toe off relative to the global coordination system. Segment range of motion was calculated independently for the head and trunk using transverse plane angular position data relative to the global coordinate system as the maximum value minus the minimum value across the entire gait cycle from left toe off to left heel strike. Segment/joint coordination and coordination variability were calculated using a modified vector coding technique for each participant and each sidestepping condition throughout the entire stride from left toe off to left heel strike (Equations 1-9) (Figure 26) (Chang et al., 2008).

3.5.1 Coupling Angle Calculation

The following procedures follow the modified vector coding technique developed by Chang et al., (2008).

Coupling angles (y_i) were calculated for each instant (i) from a normalized stride cycle based on the consecutive proximal segment angles ($\theta_{P(i)}, \theta_{P(i+1)}$) and consecutive distal segment angles ($\theta_{D(i)}, \theta_{D(i+1)}$) (Figure 23).

Equation 1: Calculation of coupling angle based on consective proximal and distal segment angles part 1

$$y_i = Atan\left(\frac{\theta_{D(i+1)}-\theta_{D(i)}}{\theta_{P(i+1)}-\theta_{P(i)}}\right) * \frac{180}{\pi} \qquad \theta_{P(i+1)} - \theta_{P(i)} > 0$$

Equation 2: Calculation of coupling angle based on consecutive proximal and distal segment angles part 2

$$y_i = Atan\left(\frac{\theta_{D(i+1)}-\theta_{D(i)}}{\theta_{P(i+1)}-\theta_{P(i)}}\right) * \frac{180}{\pi} + 180 \qquad \theta_{P(i+1)} - \theta_{P(i)} < 0$$

Equation 3: Calculation of coupling angle part 3

$$y_i \begin{cases} y_i = 90 & \theta_{P(i+1)} - \theta_{Pi} = 0 \quad and \;\; \theta_{D(i+1)} - \theta_{Di} > 0 \\ y_i = -90 & \theta_{P(i+1)} - \theta_{Pi} = 0 \quad and \;\; \theta_{D(i+1)} - \theta_{Di} < 0 \\ y_i = -180 & \theta_{P(i+1)} - \theta_{Pi} < 0 \quad and \;\; \theta_{D(i+1)} - \theta_{Di} = 0 \\ y_i = undefined & \theta_{P(i+1)} - \theta_{Pi} = 0 \quad and \;\; \theta_{D(i+1)} - \theta_{Di} = 0 \end{cases}$$

Equation 4 allows for coupling angle (y_i) correction to present a value between 0° and 360°

Equation 4: Coupling angle correction

$$y_i \begin{cases} y_i + 360 & y_i < 0 \\ y_i & y_i \geq 0 \end{cases}$$

3.5.2 Average Coupling Angle and Coordination Variability Calculation

As the coupling angle is directional, the average coupling angle ($\bar{y}_i$) was then calculated based on the average vertical ($\bar{y}_i$) and horizontal ($\bar{x}_i$) components at each instant using circular statistics (Batschelet 1981).

Equation 5: Average coupling angle based on horizontal components

$$\bar{x}_i = \frac{1}{n}\sum_{i=1}^{n} \cos y_i$$

Equation 6: Average coupling angle based on vertical components

$$\overline{y}_i = \frac{1}{n}\sum_{i=1}^{n} \sin y_i$$

To correct for the average coupling angle ($\bar{y}_i$), Equation 7 was applied to present a value between 0° and 360°

Equation 7: Correction for average coupling angle

$$\overline{y}_i \begin{cases} Atan\frac{\overline{y}_i}{\overline{x}i} * \frac{180}{n} & x_i > 0, y_i > 0 \\ Atan\frac{\overline{y}_i}{\overline{x}i} * \frac{180}{n} + 180 & x_i < 0 \\ Atan\frac{\overline{y}_i}{\overline{x}i} * \frac{180}{n} + 360 & x_i > 0, y_i < 0 \\ 90 & x_i = 0, y_i > 0 \\ -90 & x_i = 0, y_i < 0 \\ undefined & x_i = 0, y_i = 0 \end{cases}$$

Equation 8 was used to calculate the length of average coupling vector $\overline{r}_i$

Equation 8: Calculating length of average coupling angle

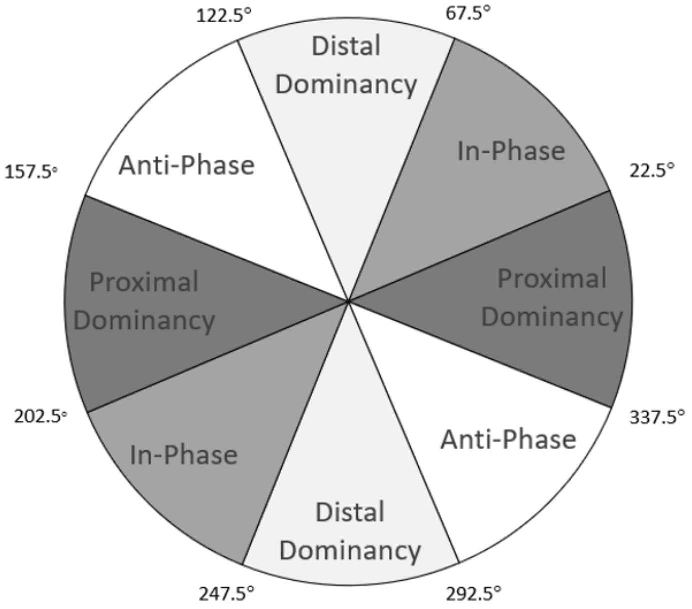
$$\overline{r}_i = \sqrt{\bar{x}_i^{\,2} + \bar{y}_i^{\,2}}$$

Lastly, Equation 9 was used to calculate coupling angle variability CAV_i

Equation 9: Calculating Coupling Angle Variability

$$CAV = \sqrt{2(1 - \overline{r}_i)} * \frac{180}{\pi}$$

Angle-angle plots were created for motion between the head and trunk in the transverse and sagittal planes. Coordination patterns were classified into in-phase, proximal dominancy, anti-phase, distal dominancy (Figure 26). 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 (Equation 9). Based on the plane dependent relationship between the head and trunk, the following couplings were examined: 1) head (rotation) – trunk (rotation) and 2) head (flexion/extension) – trunk (flexion/extension).



Coordination Pattern	Coupling Angle Definition
Anti-Phase	$112.5° \leq \gamma < 157.5°$, $292.5° \leq \gamma < 337.5°$
In-Phase	$22.5° \leq \gamma < 67.5°$, $202.5° \leq \gamma < 247.5°$
Proximal Dominancy	$0° \leq \gamma < 22.5°$, $157.5° \leq \gamma < 202.5°$, $337.5° \leq \gamma < 360°$
Distal Dominancy	$67.5° \leq \gamma < 112.5°$, $247.5° \leq \gamma < 292.5°$

Figure 26: Polar plot showing coordination pattern classification as described by Chang et al. (2008).

Hypothesis 1 predicts when performing a sidestepping task with reduced planning time, both the head and trunk will be less oriented toward the new travel direction in the transverse plane compared with performing the same sidestepping task with adequate planning time. The dependent variable for this analysis will be the discrete measure of head and trunk orientation at penultimate toe off. Differences in head and trunk orientation during anticipated and unanticipated sidestepping will be assessed with a paired t-test with an $\alpha = 0.05$.

Hypothesis 2 predicts when performing a sidestepping task with reduced planning time, coordination between the head and trunk will be less trunk dominant in the transverse plane compared with performing the same sidestepping task with adequate planning time. The dependent variables for this analysis will be head-trunk coupling angle. A binning method, as described by Chang et al., (2008) will be used to determine the coordination pattern. Differences in coordination pattern frequencies during anticipated and unanticipated sidestepping will be assessed with a paired t-test with an $\alpha = 0.05$.

Hypothesis 3 is exploratory and will assess coordination between sagittal plane head and trunk motion during anticipated and unanticipated sidestepping. The dependent variable for this analysis will be head-trunk coupling angle. A binning method, as described by Chang et al., (2008) will be used to determine the coordination pattern. Differences in coordination pattern frequencies during anticipated and unanticipated sidestepping will be assessed with a paired t-test with an $\alpha = 0.05$.

Hypothesis 4 predicts an increase in coordination variability between head-trunk relative phase in the transverse and sagittal plane during unanticipated sidestepping compared with anticipated sidestepping. The dependent variables for this analysis will be head-trunk coupling angle variability. One-dimensional statistical parametric mapping (SPM1D) will be used to compare coordination variability waveforms during anticipated and unanticipated sidestepping (Pataky, Robinson, and Vanrenterghem, 2013).

3.6 Statistical Analysis

Differences in the means and standard deviations spatial-temporal variables, orientation, range of motion and coordination pattern frequencies throughout the stride cycle will be assessed with paired t-tests with an $\alpha=0.05$. Cohen’s d effect sizes will be calculated and defined as small (0.2), moderate (0.5) and large (0.8) (Cohen, 1988). For all data means, standard deviations and 95% confidence intervals (CI) will be presented.

One-dimensional statistical parametric mapping (SPM1D) will be used to compare coordination variability waveforms over stance (Pataky et al., 2013). The scalar output SPM t-statistic curves will be 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 will then be estimated using random field theory (Pataky et al., 2013). Statistical significance is achieved when the value of the test statistic breaches 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.

CHAPTER 4
RESULTS

4.1 Demographics

We examined spatial-temporal variables, coordination and coordination variability on 14 male collegiate soccer players (20.14 ± 1.82 yrs, 1.82 ± 0.07 m, 71.76 ± 6.27 kg).

4.2 Spatial-Temporal Variables

No statistically significant differences were observed between approach velocities at the penultimate step (left toe off) ($p = 0.61$, ES = -0.14) (*Table 4*). Change of direction angle was greater during anticipated compared to unanticipated conditions ($p < 0.001$, ES = 1.45) (*Table 5*).

Table 4: Change of direction velocity throughout the change of direction stride. The velocity was calculated at each gait event.

Change of Direction Velocity				
Gait event	Anticipated Mean (SD)	Unanticipated Mean (SD)	P	ES
Left Toe Off	4.52 (0.37)	4.58 (0.24)	0.61	-0.14
Right Heel Strike	4.21 (0.29)	4.30 (0.39)	0.49	-0.19
Right Toe Off	3.96 (0.44)	3.90 (0.37)	0.38	0.24
Left Heel Strike	3.84 (0.40)	3.77 (0.36)	0.20	0.36

Table 5: Change of direction angle calculated from the angle of the two center of mass position vectors from left toe off to left heel strike

Change of Direction Angle			
Condition	Angle ° (SD)	p	ES
Anticipated	40.45 (4.87)	< 0.001	1.17
Unanticipated	33.87 (5.16)		

4.3 Static Calibration

A standing calibration was performed to determine local segment coordinate systems. The tri-planar change in head and trunk angle with respect to the global coordinate system was based off a static calibration angle of 0°. The following data presented represent orientation change with respect to the static calibration and should be interpreted as such.

4.4 Head and Trunk Orientation

Significant differences in head (p = 0.009, ES = 0.82) and trunk (p = 0.047, ES = 0.59) orientation at penultimate toe off during anticipated and unanticipated sidestepping were observed (*Table 6*). The greater mean head angle during anticipated sidestepping (10.21°) compared to unanticipated sidestepping (5.90°) indicated the head was more oriented toward the new travel direction when adequate planning time was provided. The greater negative trunk angle during unanticipated sidestepping (-8.42°) compared to anticipated sidestepping (-5.59°) indicates the trunk was more oriented toward the opposite direction of travel when planning time was reduced.

Table 6: Transverse plane head and trunk orientation (°) at penultimate toe off. Negative values indicate orientation opposite the new direction of travel

Segment	Condition	Mean(°) (SD)	95% CI	p	Effect Size
Head	ANT	10.21 (1.37)	5.77, 18.77	**0.009**	0.82
	UNANT	5.90 (2.20)	-0.22, 9.89		
Trunk	ANT	-5.59 (1.58)	-6.64, 2.43	**0.047**	0.59
	UNANT	-8.42 (1.55)	-8.66, -4.37		

4.5 Head and Trunk Coordination

Head and trunk coordination was assessed in both the transverse and sagittal planes. Segment coupling pattern was assessed throughout the entire change of direction stride, as well as during the preparatory, stance and post-transition step phases of the change of direction stride.

4.5.1 Transverse Plane

4.5.1.1 Transverse Head and Trunk Kinematics

Despite significantly different initial head position at penultimate toe off, there were no observed differences in transverse plane head reorientation trajectories during the change of direction stride as an effect of planning time (Figure 27). However, there was delayed trunk reorientation when planning time was reduced during the preparatory phase. Initial trunk reorientation is seen during anticipated sidestepping at approximately 5% of the change of direction stride. During unanticipated sidestepping, the trunk rotates towards the opposite direction of travel before reorienting toward the new direction of travel at approximately 10% of the change of direction stride (*Figure 27*). Throughout the stance phase, we did not observe differences in trunk reorientation. During the post-transition phase, the trunk continues to rotate towards the new travel direction during anticipated conditions but appears to stop rotating during unanticipated conditions despite continued head reorientation toward the new direction of travel.

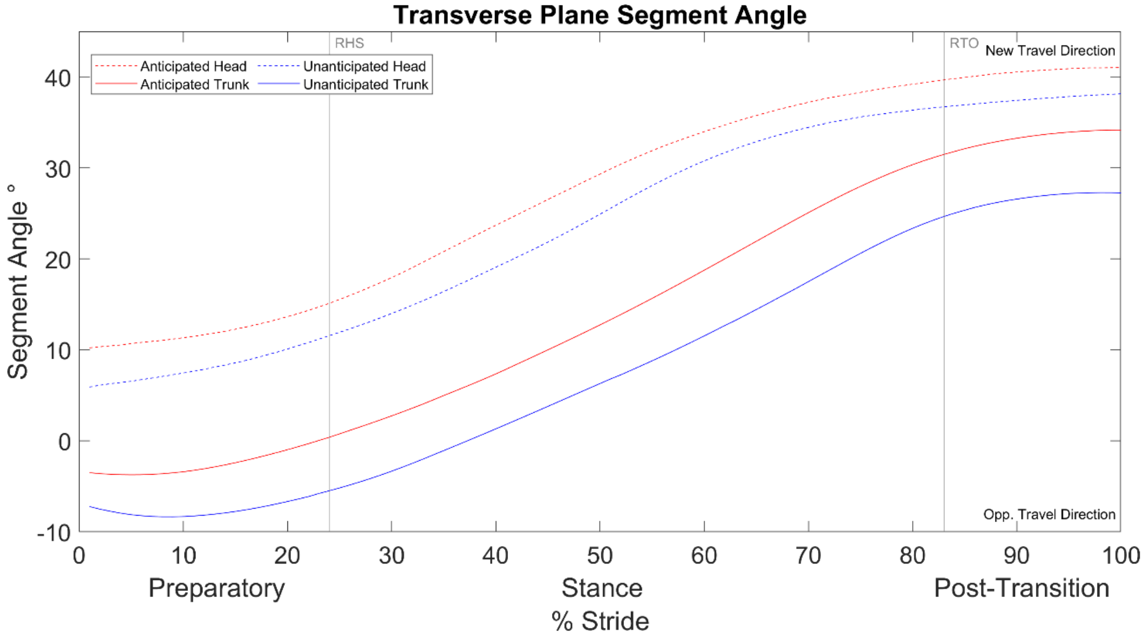


Figure 27: Transverse plane head and trunk segment angles. Positive values indicate new travel direction while negative values indicate the opposite direction of travel.

4.5.1.2 Transverse Head and Trunk Coordination

Throughout the change of direction stride, transverse plane head and trunk rotations were predominantly in-phase with the second largest percentage of trunk dominancy during anticipated and unanticipated sidestepping. No significant differences in head and trunk coupling pattern frequencies were observed between anticipated and unanticipated conditions throughout the change of direction stride (*Table 7*). Adequate planning time had a small effect on in-phase coupling pattern frequency (p = 0.25, ES = 0.32), while reducing planning time had a small effect on trunk dominant coupling pattern frequency throughout the change of direction stride (p = 0.23, ES = -0.33).

Table 7: Transverse plane head and trunk couple binning percentage means during anticipated and unanticipated sidestepping across the entire change of direction stride.

	Transverse Plane			
	Frequency (95% CI)			
	Anticipated (%)	Unanticipated (%)	p	ES
Trunk	24.36 (18.34, 30.37)	27.29 (22.08, 32.49)	0.23	-0.33
In-Phase	59.43 (51.49, 67.37)	55.71 (49.80, 61.63)	0.25	0.32
Anti-Phase	5.29 (3.80, 6.78)	4.71 (3.20, 6.23)	0.63	0.13
Head	10.93 (6.59, 15.26)	12.29 (8.84, 15.73)	0.60	-0.14

When assessed during the individual phases of the change of direction stride, we found significant differences in coupling pattern frequencies during the preparatory phase (Figure 28). During the preparatory phase, the primary coordination pattern remains in-phase for both anticipated and unanticipated conditions, with greater in-phase coordination during anticipated trials compared to unanticipated trials (p = 0.02, ES = 0.73) (Table 8). Planning time had a moderate effect on head dominancy, with greater head dominancy coupling pattern frequency during unanticipated compared to anticipated trials (p = 0.07, ES = -0.53). Throughout the stance phase, the predominant coordination pattern remains in phase, followed by the trunk dominant pattern. No statistically significant differences with very small effect sizes were observed throughout the stance phase in the transverse plane. During the post-transition phase an initial trunk dominant coordination pattern shifts towards an in-phase and then head dominant coordination pattern (*Figure 28*). No differences were reported for the frequencies of trunk dominancy between anticipated and unanticipated conditions. Small effects were observed during the post-transition phase, with greater in-phase coupling pattern frequencies during anticipated sidestepping compared to unanticipated sidestepping (p = 0.16, ES = 0.40) and reduced head dominancy during anticipated sidestepping compared to unanticipated sidestepping (p = 0.19, ES = -0.37).

Table 8: Transverse plane head and trunk couple binning percentage means during the preparatory, stance and post-transition phases of the change of direction stride.

	Preparatory			
	Frequency (95% CI)			
	Anticipated (%)	Unanticipated (%)	p	ES
Trunk	13.50 (4.31, 22.69)	18.64 (8.09, 29.19)	0.25	-0.32
In-Phase	**58.50** **(44.84, 72.16)**	**44.36** **(31.33, 57.38)**	**0.02**	**0.73**
Anti-Phase	11.14 (3.69, 18.59)	10.43 (4.95, 15.91)	0.88	0.04
Head	16.86 (5.88, 27.83)	26.57 (14.13, 39.02)	0.07	-0.53
	Stance			
	Frequency (95% CI)			
	Anticipated (%)	Unanticipated (%)	p	ES
Trunk	23.64 (15.25, 32.04)	24.64 (18.69, 30.59)	0.76	-0.08
In-Phase	68.79 (60.00, 77.57)	69.50 (61.26, 77.74)	0.84	-0.06
Anti-Phase	1.29 (0.08, 2.49)	0.64 (-0.50, 1.78)	0.34	0.27
Head	6.29 (1.50, 11.07)	5.21 (-0.67, 11.10)	0.73	0.09
	Post-Transition			
	Frequency (95% CI)			
	Anticipated (%)	Unanticipated (%)	p	ES
Trunk	46.00 (28.61, 63.39)	49.14 (31.50, 66.79)	0.60	-0.14
In-Phase	30.14 (16.84, 43.44)	22.14 (11.77, 32.52)	0.16	0.40
Anti-Phase	7.50 (2.17, 12.83)	9.21 (2.36, 16.07)	0.59	-0.15
Head	15.93 (2.62, 29.23)	19.50 (6.95, 32.05)	0.19	-0.37

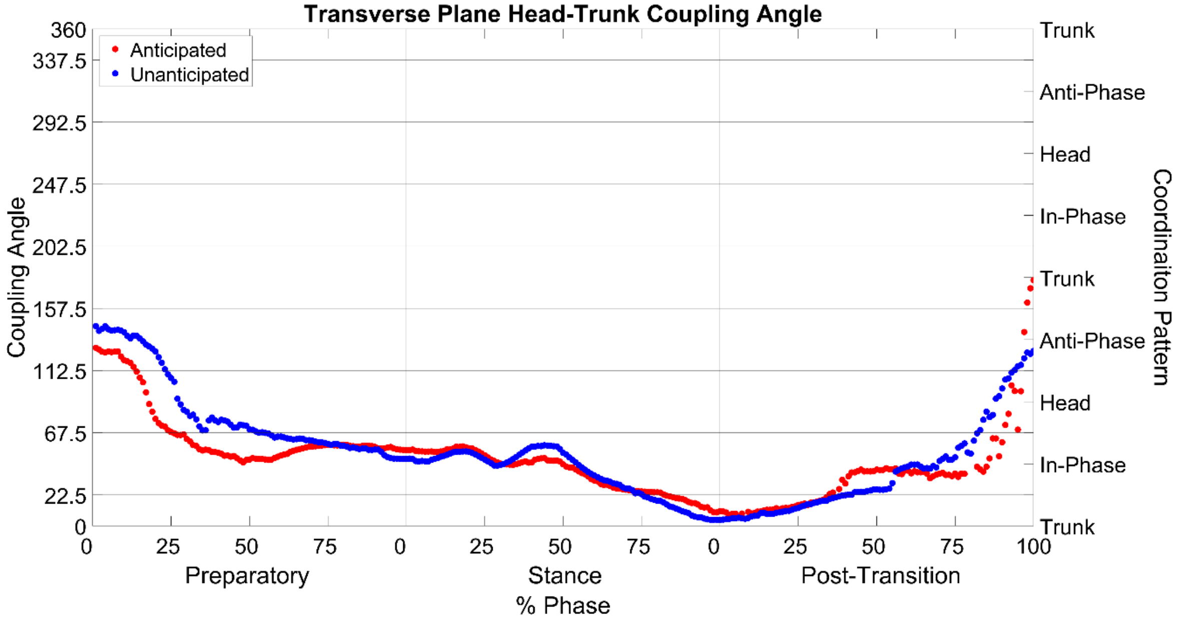


Figure 28: Transverse plane mean head and trunk coupling angle during anticipated and unanticipated sidestepping.

4.5.2 Sagittal Plane

4.5.2.1 Sagittal Head and Trunk Kinematics and Center of Mass Vertical Displacement

Throughout the change of direction stride, the head maintained a more extended posture compared to the initial static calibration (See section 4.3), ranging from 4-10°, with reduced extension during unanticipated sidestepping (*Figure 29*). During the preparatory phase, the head extension orientation decreased during unanticipated conditions, while a subtle increase in head extension orientation change was observed during anticipated conditions. Throughout the stance and post-transition phases, similar head flexion/extension orientation patterns were observed between anticipated and unanticipated conditions.

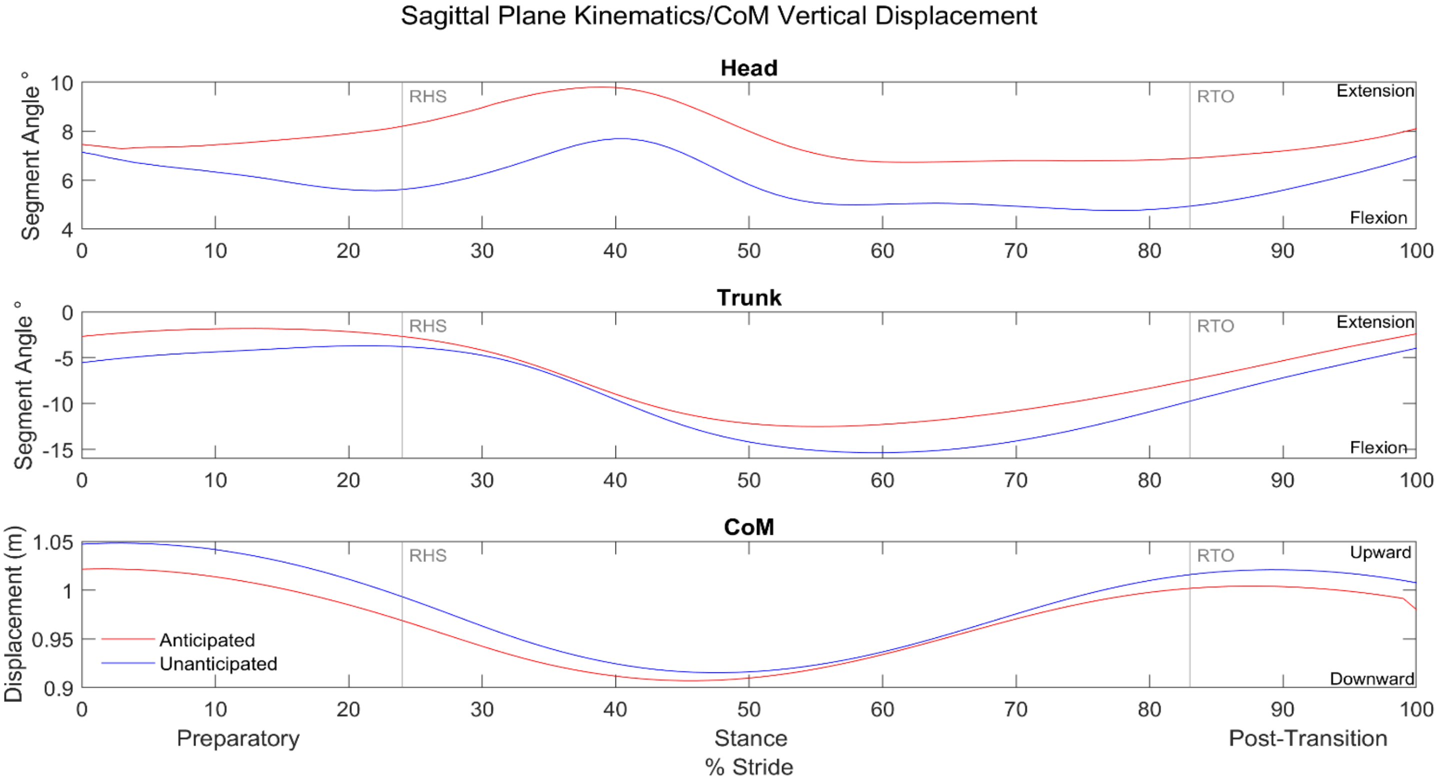


Figure 29: Sagittal plane head and trunk angle and center of mass vertical displacement during the change of direction stride. A neutral position of 0° was defined in the global coordinate system during static trials (See Section 4.3). Postive values indicate greater extension, and negative values indicate greater flexion relative to the global coordinate system. Center of mass displacement represented the vertical center of mass translation in meters with respect to the global coordinate system.

The trunk maintained a mean flexion angle relative to the initial static calibration throughout the change of direction stride, with a slightly greater mean flexion angle when planning time was reduced. During the preparatory phase, the trunk approached a less flexed position when planning time was reduced despite subtle extension followed by subtle flexion observed during anticipated conditions. Like the head, the trunk maintained similar flexion/extension patterns throughout the stance and post-transition phases during anticipated and unanticipated sidestepping.

Sinusoidal center of mass displacement, calculated as the whole-body center of mass vertical displacement in meters with respect to the global coordinate system, was observed, with the highest center of mass position observed during the flight phases (preparatory and post-transition) and lowest center of mass position observed during the stance phase. During anticipated conditions a compensatory head-to-center of mass relationship is observed; as the center of mass vertically translates upward, the head extension orientation decreases, and as the center of mass vertically translates downward, the head extension orientation increases. However during the preparatory phase, as the center of mass vertically translates downward, the head extension orientation decreases during unanticipated sidestepping. The compensatory head-to-center of mass relationship was not observed during the preparatory phase of unanticipated sidestepping but is maintained throughout the stance and post-transition phases.

4.5.2.2 Sagittal Head and Trunk Coordination

In the sagittal plane trunk dominancy was the primary coordination pattern throughout the change of direction stride, with modest amounts of head and trunk in-phase and anti-phase coordination during both anticipated and unanticipated sidestepping. Planning time had a moderate effect on coupling pattern frequency, with greater in-phase coordination during anticipated sidestepping compared to unanticipated sidestepping throughout the entire change of direction stride (p = 0.08, ES = 0.50) (Table 9). Small effects were observed on head dominancy, with greater head dominant coupling pattern frequency during unanticipated sidestepping compared to anticipated sidestepping (p = 0.19, ES = -0.37). No significant differences and effect sizes greater than 0.20 were observed for the anti-phase or trunk dominant coupling patterns across the entire stride.

Table 9: Sagittal plane head and trunk couple binning percentage during anticipated and unanticipated sidestepping across the entire change of direction stride.

	Sagittal Plane			
	Frequency (95% CI)			
	Anticipated (%)	Unanticipated (%)	p	ES
Trunk	45.64 (39.82, 51.47)	46.50 (39.29, 53.71)	0.82	-0.06
In-Phase	28.00 (21.50, 34.50)	22.86 (17.85, 27.86)	0.08	0.50
Anti-Phase	17.79 (13.48, 22.09)	19.14 (15.94, 22.34)	0.67	-0.12
Head	8.57 (6.39, 10.75)	11.50 (8.04, 14.96)	0.19	-0.37

Significant differences in coupling pattern frequency were observed during the preparatory phase (Figure 30), with greater in-phase coordination during anticipated sidestepping compared to unanticipated sidestepping (p = 0.04, ES = 0.63) (Table 10). Trunk dominancy was the primary coordination pattern throughout stance and the post transition stride during both anticipated and unanticipated conditions. No significant differences between anticipated and unanticipated sidestepping were observed during stance and the post-transition phase with very small effect sizes. During both anticipated and unanticipated sidestepping, the mean head-trunk coordination pattern was anti-phase by the end of the preparatory phase and trunk dominant by the end of the stance phase. However, the directionality of the mean phase angle as the head-trunk coordination approach the specific patterns differed between the two tasks (*Figure 30*).

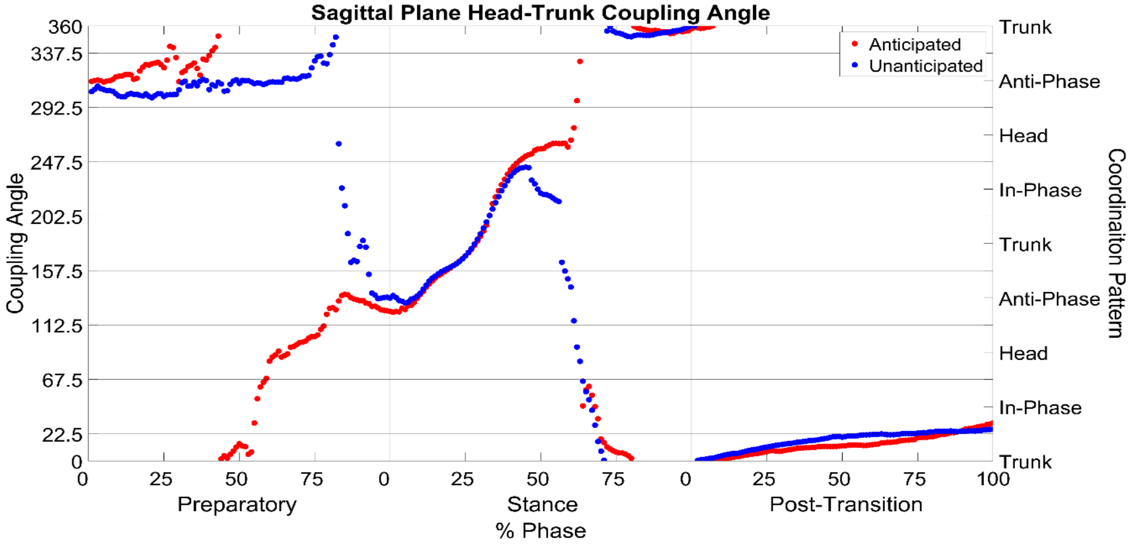


Figure 30: Sagittal plane head and trunk coupling angle during anticipated and unanticipated sidestepping.

Table 10: Sagittal plane head trunk coupling pattern frequency throughout the preparatory and stance phases of the change of direction stride. Binning percentages were taken from normalized data for each phase of the change of direction stride.

	Preparatory			
	Frequency (95% CI)			
	Anticipated (%)	Unanticipated (%)	p	ES
Trunk	36.79	29.93	0.51	0.18
	(24.08, 49.49)	(18.06, 41.79)		
In-Phase	**19.79**	**8.93**	**0.04**	**0.63**
	(12.80, 26.77)	**(4.56, 13.30)**		
Anti-Phase	26.57	34.71	0.35	-0.26
	(16.44, 36.71)	(23.14, 46.29)		
Head	16.86	26.43	0.24	-0.33
	(7.50, 26.21)	(14.41, 38.44)		

	Stance			
	Frequency (95% CI)			
	Anticipated (%)	Unanticipated (%)	p	ES
Trunk	42.07	42.93	0.83	-0.06
	(35.59, 48.55)	(35.46, 50.29)		
In-Phase	19.86	22.21	0.59	-0.15
	(14.21, 25.51)	(16.08, 28.35)		
Anti-Phase	25.14	22.00	0.35	0.26
	(18.93, 31.36)	(17.40, 26.60)		
Head	12.93	12.86	0.98	0.01
	(10.16, 15.70)	(9.22, 16.50)		

	Post-Transition			
	Frequency (95% CI)			
	Anticipated (%)	Unanticipated (%)	p	ES
Trunk	60.50	65.07	0.61	-0.14
	(44.12, 76.88)	(50.10, 80.04)		
In-Phase	34.71	34.93	0.98	-0.01
	(17.52, 51.91)	(19.96, 49.90)		
Anti-Phase	4.79	0.00	0.22	0.34
	(-1.80, 11.38)	(0.00, 0.00)		
Head	0.00	0.00	NaN	NaN
	(0.00, 0.00)	(0.00, 0.00)		

4.6 Coordination Variability

4.6.1 Transverse Plane Coordination Variability

No significant difference in transverse plane head and trunk coordination variability was observed as an effect of planning time (*Figure 31*). However significant differences between the individual phases of the change of direction stride were observed during both anticipated and unanticipated sidestepping (*Table 11*). There was significantly greater transverse plane head and trunk coordination variability during the preparatory phase compared to the stance phase ($p < 0.01$) and significantly greater coordination variability during the post-transition phase compared to the stance phase ($p < 0.01$). The preparatory and post-transition phases did not significantly differ ($p = 0.15$).

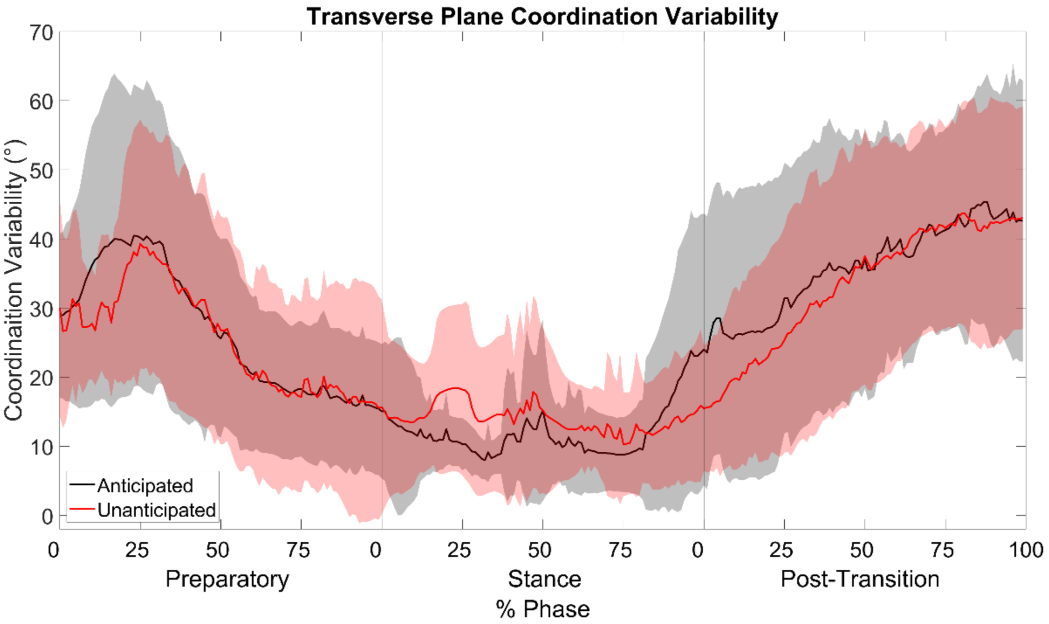


Figure 31: Head trunk transverse plane coordination variability calculated through statistical parametric mapping. The solid line represents the mean variability throughout stride. The light shaded regions represent the standard deviation of the variability for each condition. Dark shaded regions indicate areas of overlap where variability between both conditions occur.

4.6.2 Sagittal Plane Coordination Variability

No difference in sagittal plane head and trunk coordination variability was observed as an effect of planning time (*Figure 32*). Significant differences in the individual phases of the change of direction stride were observed, with significantly greater head and trunk coordination variability during the preparatory phase compared to the stance phase ($p < 0.01$) and post-transition phase ($p < 0.01$) (Table 11). Stance phase coordination variability was significantly greater than post-transition phase coordination variability ($p < 0.001$).

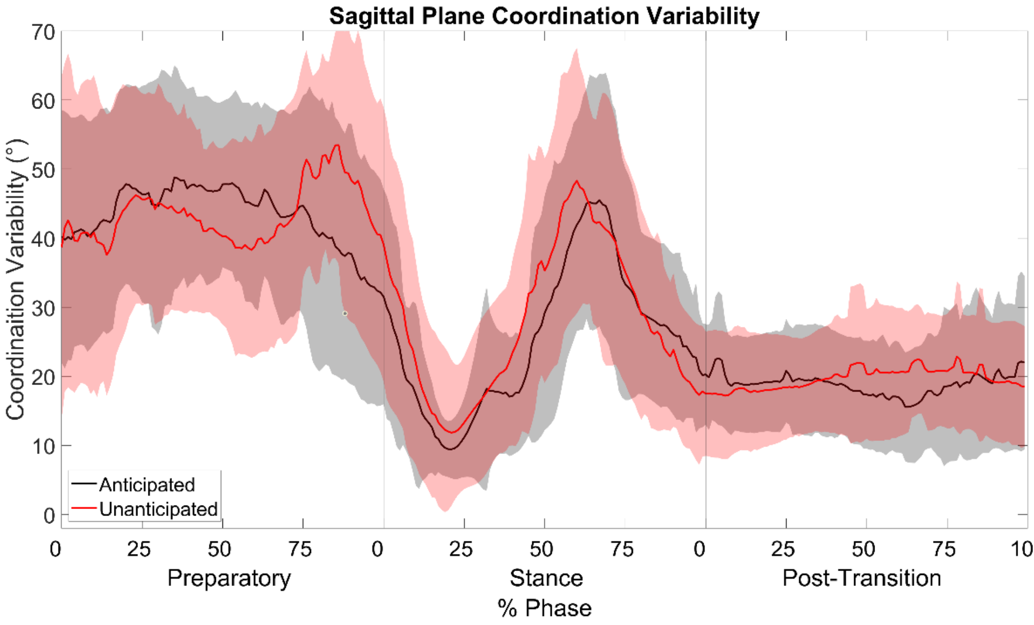


Figure 32: Head trunk sagittal plane coordination variability calculated through statistical parametric mapping. The solid line represents the mean variability throughout stride. The light shaded regions represent the standard deviation of the variability for each condition. Dark shaded regions indicate areas of overlap where variability between both conditions occur.

Table 11: Mean coordination variability (°) during anticipated and unanticipated sidestepping in the transverse and sagittal planes

	Preparatory	Stance	Post-Transition
Anticipated Transverse	26.90° ^{a}	12.05° ^{c}	35.74°
Unanticipated Transverse	25.62° ^{a}	14.10° ^{c}	33.19°
Anticipated Sagittal	43.32° ^{ab}	25.40° ^{c}	18.87°
Unanticipated Sagittal	43.45° ^{ab}	27.77° ^{c}	19.65°

Note: Main effect of phase of change of direction stride (* $p < 0.05$). ^{a} denotes significant differences between preparatory and stance means. ^{b} denotes significant differences between preparatory and post-transition means. ^{c} denotes differences between stance and post-transition means.

CHAPTER 5
DISCUSSION

The purpose of this study was to better understand head control during cutting maneuvers typically seen in many sporting activities. We approached this question specifically looking at the spatial development of head and trunk orientation and coordination during sidestepping tasks, and the effect of reduced planning time on head and trunk orientation and coordination during sidestepping tasks. In agreement with our initial hypothesis, during anticipated sidestepping the head and trunk were significantly more oriented toward the new travel direction compared to unanticipated sidestepping. While no significant differences in head and trunk coordination strategies were observed across the entire change of direction stride, statistically significant differences in coordination were observed during the preparatory phase of the change of direction stride with greater in-phase coordination during anticipated sidestepping in the transverse and sagittal planes. Interestingly, no significant differences in head and trunk coordination were observed in the sagittal and transverse planes during the stance phase despite significantly different coordination strategies previously reported at the lower extremity when comparing anticipated to unanticipated sidestepping tasks (Weir et al., 2019). We did not observe a locking of the degrees of freedom between the head-trunk in the transverse or sagittal planes during unanticipated sidestepping despite increased in-phase coordination previously reported when planning time was reduced (Weir et al., 2019). No significant differences in coordination variability were observed in both the transverse and sagittal planes. Anticipated and unanticipated sidestepping are different tasks in the context of whole body kinematics, kinetics, coordination and CoM control, but individuals are consistent in the way the coordinate their head and trunk during both sidestepping tasks.

5.1 Anticipatory Postural Adjustments

During change of direction tasks, the head direction precedes heading direction when walking along a curved trajectory (Authie et al., 2015; Bernardin et al., 2012; Grasso et al., 1998) and during sidestepping tasks (Hollands et al., 2001). Prior sidestepping studies had participants respond to a visual stimulus in the new direction of travel (Hollands et al., 2001; Mornieux et al., 2014; Patla et al., 1999), while our protocol involved a visual stimulus to change direction in the original direction of travel in the absence of specific visual cues in the new travel direction. Despite these differences, we observed similar findings; during anticipated sidestepping we found the head and trunk to be significantly more oriented toward the new travel direction compared to unanticipated sidestepping.

Aligning the head with the new travel direction may provide a natural frame of reference for visual and vestibular information (Pozzo et al., 1990). While multiple visual orientating strategies can be used to successfully navigate through the environment and change direction, it may be preferred to align gaze with the new travel direction in richly textured environments (Warren, Kay, Zosh, Duchon, and Sahuc, 2001). Despite previous reports of a "steering synergy" initiated by head reorientation to change travel direction (Grasso et al. 1996, 1998; Vallis and Patla, 2004), transverse plane head rotations found in our study may be a byproduct of gaze realignment to utilize optic flow in visual guidance during both anticipated and unanticipated sidestepping (Cinelli and Warren, 2012). The optic flow hypothesis suggests individuals shift gaze (which often includes head realignment) to align the focus of expansion with the intended travel direction while the egocentric direction hypothesis suggests individuals perceive the desired direction with respect to the body to orient towards the new direction of travel (Warren et al., 2001). In richly textured well-lit environments, it may be preferential to align the focus of expansion with the intended travel direction to enhance visual perception but both strategies can be used to navigate during change of direction tasks (Cinelli et al., 2012; Warren et al., 2001).

5.2 Coordination

We hypothesized a reduction in trunk dominant coordination during unanticipated sidestepping but found no statistically significant differences in transverse plane trunk dominant coupling pattern frequency between anticipated and unanticipated tasks. During both anticipated and unanticipated sidestepping, the head and trunk in the transverse plane moved in-phase throughout the change of direction stride with a substantial portion of trunk dominancy. The rationale for our hypothesis was based on earlier findings of a trunk dominant contribution to the transverse plane head and trunk coordination pattern observed during treadmill running with a visual task (Lim et al., 2020). Unlike forward locomotion, sidestepping requires the reorientation of the entire body toward the new travel direction which is likely responsible for the predominantly in-phase transverse plane coordination pattern during both anticipated and unanticipated sidestepping. Head reorientation onset often occurs prior to the trunk (Patla et al., 1999) and remains more orientated toward the new travel direction compared with the trunk at the penultimate step and throughout stance during sidestepping tasks (Mornieux et al., 2014), but as individuals progressed throughout the change of direction stride, coordination patterns become predominantly more trunk dominant from the preparatory phase to stance to the post-transition phase.

During the preparatory phase, in the transverse plane there was significantly less in-phase motion between the head and trunk in the unanticipated condition, with no difference in trunk dominancy but a trend towards greater head contribution. This is likely due to the delayed onset of trunk reorientation during the preparatory phase of the change of direction task, while head reorientation during unanticipated sidestepping followed a similar trajectory to anticipated sidestepping. During unanticipated sidestepping a hip strategy is implemented, often associated with significantly greater trunk lateral flexion in the opposite direction of travel. The interaction between frontal plane trunk motion and transverse plane reorientation may have played a role in this, but we can only infer the multi-planar interaction.

Sagittal plane head and trunk coordination was primarily trunk dominant throughout the change of direction stride, which likely aids in CoM control at specific gait events (Romkes et al., 2017; Thorstensson et al., 1984). The trunk maintained a flexed posture throughout the change of direction stride. Decreased trunk flexion prior to heel strike likely facilitated in the reduction of CoM momentum, and increased trunk flexion following heel strike facilitating forward acceleration of the CoM. The most notable sagittal plane kinematic differences between anticipated and unanticipated sidestepping were observed at the head during the preparatory phase (Figure 29), where head extension orientation subtly increased during anticipated sidestepping but decreased when planning time was reduced. We found small kinematic observational differences in trunk flexion, but the sagittal plane head orientation changes may be better explained with respect to CoM vertical displacement.

During forward locomotion, compensatory sagittal plane head motion relative to translational CoM motion allows for reduced perturbations to the visual field (Hirasaki et al., 1999; Moore et al., 1999; 2001; Pozzo et al., 1990). During anticipated sidestepping, a compensatory relationship between sagittal plane head orientation and vertical CoM displacement was observed throughout the entire change of direction stride (*Figure 29*). During the preparatory phase of unanticipated sidestepping, sagittal plane head orientation appeared to move in-phase with vertical CoM displacement, opposite of what was observed during anticipated sidestepping (*Figure 29*). This closely mimics a “strapped down” strategy where the head is fixed to the trunk, or a locking of the degrees of freedom (Lipsitz et al., 2002; Nasher, 1985). By reducing the degrees of freedom, the head and trunk can be considered a single segment, simplifying the control task but reducing the flexibility of head and trunk control. Head on trunk motion allows for reduced head in space motion, minimizing perturbations to the visual field. By reducing the degrees of freedom between the head and trunk in the sagittal plane during the preparatory phase, a simpler control task is achieved but visual perception may be compromised, though further testing is needed to validate this claim.

Similar to the transverse plane, there were no significant sagittal plane head-trunk coordination differences throughout the change of direction stride despite a moderate effect of greater in-phase head-trunk coordination during anticipated sidestepping. This is due to significantly greater in-phase coordination during the preparatory phase. Throughout the stance and post-transition phases, the predominant sagittal plane head trunk coupling pattern was trunk dominancy. Lim et al. (2020) found sagittal plane head-trunk coupling to be predominantly anti-phase during treadmill running with a visual task, with a substantial portion of the stride being trunk dominant. Trunk dominant sagittal plane head and trunk couples made up a substantial portion of the change of direction stride, with greater trunk dominant coordination during the stance and post-transition phases.

In the context of sidestepping literature, Weir et al. (2019) found significantly greater anti-phase sagittal plane trunk-pelvis coordination during anticipated sidestepping but reported no significant differences in transverse plane trunk-pelvis coordination throughout the stance phase of the change of direction stride. We did not observe significant coordination differences during the stance phase in both the sagittal and transverse planes. The different findings between our study and the one conducted by Weir et al. is not due to the different binning methods used to quantify coordination (Chang et al., 2008; Needham et al., 2014) but instead due to different demands placed on the head-trunk compared to the trunk-pelvis during sidestepping tasks (See appendix 2 for coupling pattern frequency using the Needham method).

5.3 Coordination Variability

We did not find significant differences in coordination variability between sidestepping tasks throughout the change of direction stride or within the individual phases of the change of direction stride when comparing anticipated sidestepping to unanticipated sidestepping. Weir et al. (2019) did not find differences in coordination variability during anticipated and unanticipated sidestepping during the stance phase between the trunk and pelvis in the transverse plane, which corresponds with our findings. In our study, greater transverse plane variability was observed during the initial portion of the preparatory phase, but decreased as the coordination settled on a more stable pattern during the transition from late preparatory phase to stance during both anticipated and unanticipated sidestepping. In the sagittal plane, significant differences between anticipated and unanticipated sidestepping trunk-pelvis coordination variability were previously reported from 7-8% of stance (Weir et al., 2019). When comparing the remaining 99% of stance in the sagittal plane, similarities are present when comparing head-trunk coordination variability to trunk-pelvis coordination variability. Coordination patterns settled during early stance before transitioning during mid-to-late stance to a new stable pattern; this was observed for both head-trunk and trunk-pelvis coordination. While different demands are placed on the lower extremities and trunk-pelvis compared to the head-trunk, greater variability is present during the transition from one stable pattern to another.

Irrespective of planning time we found significantly greater transverse plane head-trunk coordination variability during the flight phases compared to the stance phase, and in the sagittal plane. We also found greater variability during the preparatory phase, with reduced variability during the post-transition phase. The mean sagittal plane head-trunk coordination variability in the preparatory phase was significantly greater than the mean stance phase coordination variability, which was significantly greater than the post-transition phase coordination variability. The variability differences throughout the individual phases of the change of direction stride highlight head-trunk attractor dynamics transitioning toward more stable patterns (Kelso, 1995). Systemic reorganization toward a more stable pattern requires bifurcation, where a qualitative change in the coordination pattern occurs. As the system approaches a transition, critical fluctuations emerge, where the variability within the system increases. In the transverse plane, greater variability in the preparatory phase highlights the transition toward a more stable coordinative pattern late in the preparatory phase and throughout stance. As the system prepares for the transition from the change of direction to forward locomotion, another bifurcation occurs, noted by the increase in transverse plane coordination variability during the post-transition phase. Sagittal plane head-trunk coordination undergoes two transitions, with one occurring late in the preparatory phase, and another occurring in mid-to-late stance during both sidestepping tasks. Like the transverse plane, as sagittal plane head-trunk coordination shifted toward a more stable pattern, variability around the bifurcation point promoted pattern transition. Bernstein's principles state 1) the coordination between the head and trunk can be organized in a number of different ways and 2) the variability of coordination provide a metric into the variety of coordination patterns utilized. While this suggests greater variability may highlight greater adaptability of the head-trunk couples, we did not relate variability to performance outcome measures and therefore can only infer.

5.4 Limitations

Approach velocity in the forward direction was controlled (4.0 ± 0.5 ms^{-1}) but differences in mediolateral velocities have previously been reported when comparing anticipated to unanticipated sidestepping tasks (Wyatt et al., 2019). We therefore calculated and presented the velocity vectors, which accounts for anterior-posterior and mediolateral velocities. Change of direction velocities throughout the total stride did not differ (both in the anterior direction and the velocity vector), but there were statistically significant differences in change of direction angle between tasks which may have influenced our results. Differences reported were greater than 5°, which is larger than those previously reported during sidestepping tasks and may have placed different demands on the participants between anticipated and unanticipated sidestepping tasks (Besier et al., 2001). Visual stimulus location has the ability to evoke head motion in a given direction. Previous studies examining head motion during sidestepping tasks (Hollands et al., 2001; Mornieux et al., 2014; Patla et al., 1999) provided a visual stimulus in the new travel direction to prompt direction change. Our stimulus location was not in the new travel direction, and comparisons of head control between this study and previous ones should be made cautiously. Additionally, a stronger correlation between sagittal head orientation and vertical CoM displacement compared to sagittal head-sagittal trunk orientation when traveling at greater velocities has previously been reported (Hirasaki et al., 1999). Sagittal plane head trunk coordination variability data therefore may not be reflective of the head-trunk coupling itself as neck flexion/extension may be compensating for vertical CoM displacement.

5.5 Conclusion

Our findings provide novel insights into the spatial development of the head and trunk during sidestepping tasks. Significant differences in head and trunk control emerge during the preparatory phase of the change of direction stride during anticipated and unanticipated sidestepping, with significantly greater in-phase head-trunk coordination during anticipated tasks in both the transverse and sagittal planes. However, the segment responsible for coordination differences between tasks is dependent on the plane of movement. Transverse plane preparatory phase differences between tasks was due to differences observed at the trunk, while sagittal plane coordination differences were due to differences observed at the head. By the post-transition phase, coordination patterns shift toward a trunk dominant strategy in the sagittal and transverse planes during both anticipated and unanticipated sidestepping. The lack of differences in head-trunk coordination variability suggests that while anticipated and unanticipated sidestepping are different tasks in the context of whole body kinematics, kinetics, coordination and CoM control, individuals are consistent in the way they coordinate their head and trunk during both sidestepping tasks. There are different demands placed on the head compared to the lower extremities during change of direction tasks, but the link between lower extremity modifications on head control, as well as whether different lower extremity couples are present during the flight phases of the change of direction phase remains unknown. Future studies should explore how the differences in head control during anticipated and unanticipated sidestepping affect perceptual awareness during and following the change of direction tasks, if a link exists between head control and knee injury risk, and if concussion effects head control during sidestepping tasks.

APPENDIX A
FRONTAL PLANE KINEMATICS, COORDINATION AND VARIABILITY

A.1.1 Frontal Plane Head and Trunk Kinematics

Throughout the change of direction stride, the trunk followed a similar trajectory during both anticipated and unanticipated sidestepping, with a greater change in lateral flexion angle during unanticipated sidestepping. Greater frontal plane trunk stance lateral flexion was observed during unanticipated sidestepping, with the largest differences occurring during the stance phase highlighting the "hip strategy" to laterally shift the CoM toward the new travel direction (Houck et al., 2006; Patla et al., 1999) (Figure 33). During anticipated sidestepping during stance greater lateral flexion was also observed, but to a lesser extent. A more neutral head orientation was observed at penultimate toe off during unanticipated sidestepping compared to anticipated sidestepping. During the preparatory and stance phases, the head followed a similar trajectory during both anticipated and unanticipated sidestepping task. Increased ipsilateral lateral flexion was observed throughout the post-transition phase during anticipated sidestepping, but was reduced during unanticipated sidestepping.

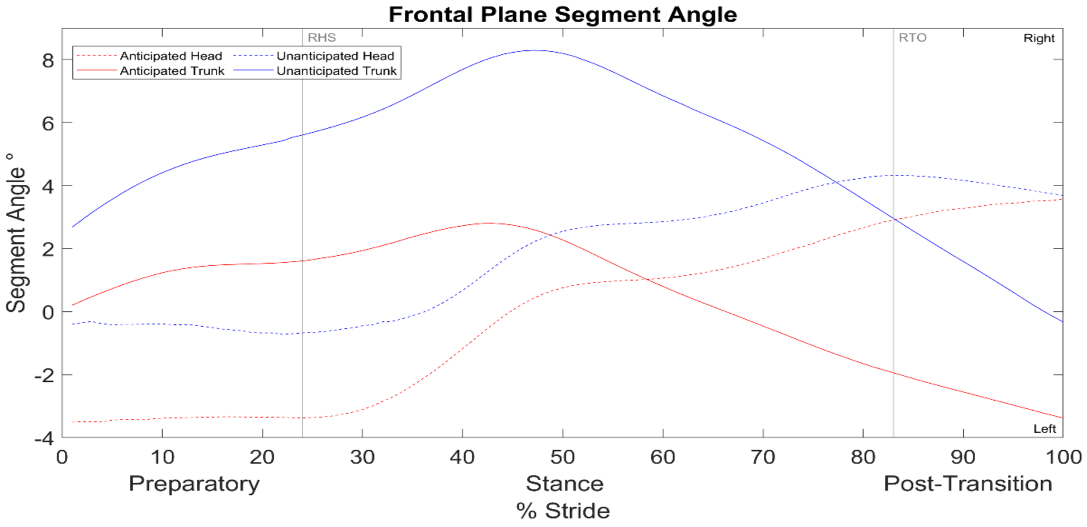


Figure 33: Frontal plane head and trunk kinematics throughout the change of direction stride. Positive values indicate orientation toward the right side of the body. Negative values indicate orientation toward the left side of the body.

A.1.2 Frontal Plane Head and Trunk Coordination

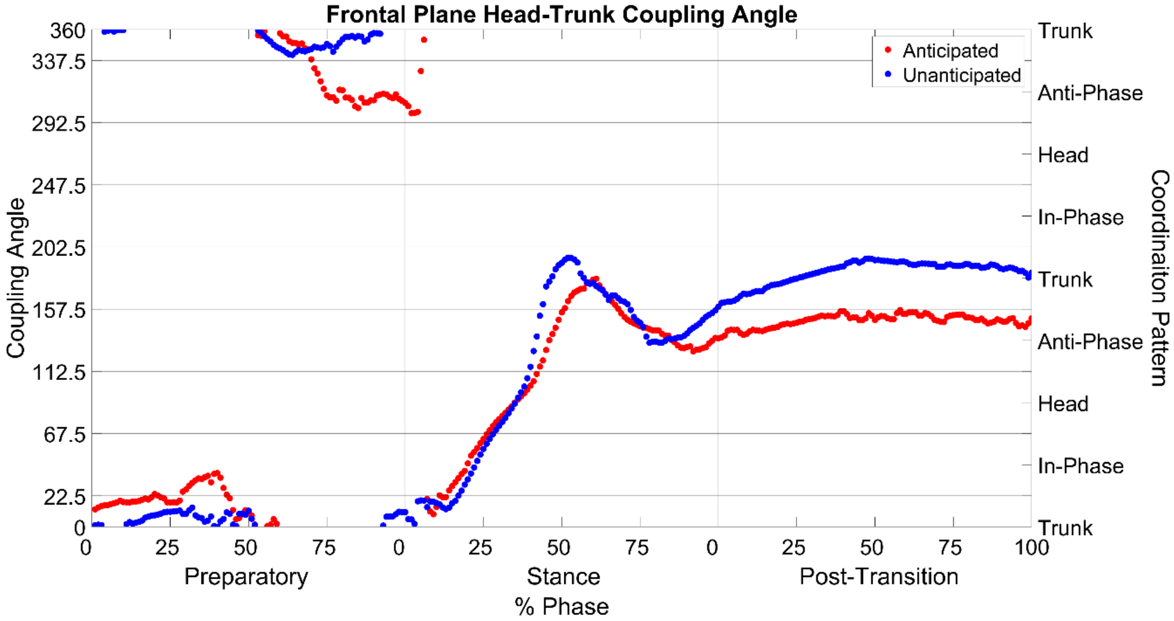


Figure 34: Frontal plane head and trunk coordination calculated through the binning method described by Chang et al. (2008).

Throughout the change of direction stride, frontal plane head and trunk coordination was predominantly trunk dominant (Figure 34**Error! Reference source not found.**). Statistically significantly greater head dominant coupling pattern frequencies were observed during anticipated sidestepping throughout the change of direction stride (p = 0.03, ES = 0.66) (Table 12). Reducing planning time had a small effect on increasing in-phase coupling pattern frequency compared to anticipated conditions (p = 0.12, ES = -0.44).

Table 12: Frontal plane binning frequency throughout the change of direction stride

	Frontal Plane			
	Frequency (95% CI)			
	Anticipated (%)	Unanticipated (%)	p	ES
Trunk	32.57 (27.13, 38.01)	34.36 (26.46, 42.25)	0.44	-0.21
In-Phase	18.93 (13.61, 24.25)	24.36 (19.91, 28.80)	0.12	-0.44
Anti-Phase	27.29 (22.90, 31.67)	26.07 (21.04, 31.11)	0.76	0.08
Head	**21.21** **(15.30, 27.13)**	**15.21** **(8.73, 21.70)**	**0.03**	**0.66**

Table 13: Frontal plane binning frequency for the individual phases of the change of direction stride

	Preparatory			
	Frequency (95% CI)			
	Anticipated (%)	Unanticipated (%)	p	ES
Trunk	31.79 (22.81, 40.76)	45.29 (31.90, 58.67)	0.10	-0.47
In-Phase	13.86 (3.70, 24.02)	22.21 (11.94, 32.49)	0.26	-0.31
Anti-Phase	**42.21** **(29.04, 55.38)**	**22.12** **(9.87, 34.42)**	**0.03**	**0.66**
Head	12.14 (5.96, 18.33)	10.36 (2.85, 17.86)	0.69	0.11
	Stance			
	Frequency (95% CI)			
	Anticipated (%)	Unanticipated (%)	p	ES
Trunk	22.43 (14.38, 30.48)	26.07 (18.15, 33.99)	0.17	-0.38
In-Phase	21.57 (13.72, 29.42)	24.36 (18.90, 29.81)	0.52	-0.18
Anti-Phase	29.43 (21.91, 36.95)	28.07 (21.07, 35.07)	0.78	0.08
Head	26.57 (17.75, 35.39)	21.50 (12.02, 30.98)	0.16	0.40
	Post-Transition Phase			
	Frequency (95% CI)			
	Anticipated (%)	Unanticipated (%)	p	ES
Trunk	38.93 (26.78, 51.08)	48.00 (30.62, 65.38)	0.36	-0.25
In-Phase	22.64 (6.85, 38.44)	32.07 (14.09, 50.05)	0.51	-0.18
Anti-Phase	28.29 (18.86, 37.71)	16.93 (3.50, 30.36)	0.27	0.31
Head	10.14 (0.03, 20.26)	3.00 (-2.05, 8.05)	0.28	0.30

During the preparatory phase of the change of direction stride, there was significantly greater anti-phase coupling pattern frequency during anticipated sidestepping (p = 0.03, ES = 0.66)(Table 13). Reducing planning time had a small effect on increasing trunk dominancy compared to anticipated sidestepping (p = 0.10, ES = -0.47). No significant differences were observed throughout the stance and post-transition phases.

A.1.3 Frontal Plane Coordination Variability

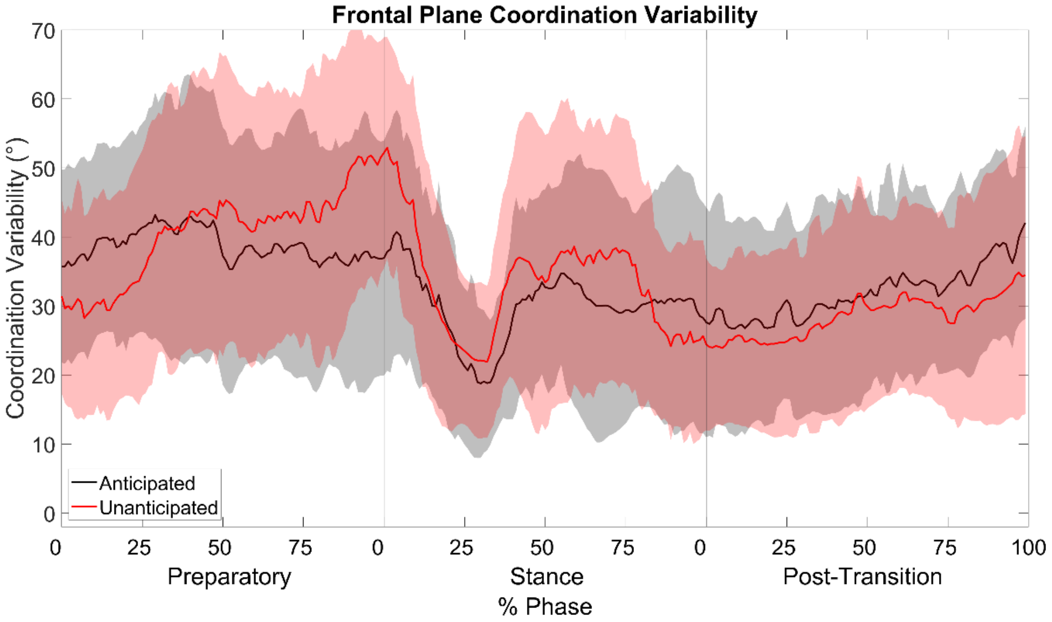


Figure 35: Frontal plane head-trunk coordination variability

No frontal plane head-trunk variability difference were observed as an effect of planning time. During anticipated conditions, the preparatory phase was significantly greater than stance ($p = 0.03$), while during unanticipated conditions, the preparatory phase was significantly greater than the post-transition phase ($p = 0.03$) (Table 14).

Table 14: Frontal plane head-trunk coordination variability

Frontal Plane Coordination Variability			
	Preparatory	Stance	Post-Transition
Anticipated	38.74° [a]	29.98°	31.82°
Unanticipated	40.57° [b]	33.28°	28.42°

Note: Main effect of phase of change of direction stride (* $p < 0.05$). [a] denotes significant differences between preparatory and stance means. [b] denotes significant differences between preparatory and post-transition means.

APPENDIX B
NEEDHAM ET AL. BINNING METHODS

Sagittal plane head trunk coupling pattern frequency throughout the preparatory and stance phases of the change of direction stride. Binning percentages were taken from normalized data for each phase of the change of direction stride.

A.2.1 Needham Transverse Plane

Table 15: Transverse plane binning frequency for the change of direction stride calculated with methods described by Needham et al. (2014)

	Transverse Plane			
	Frequency (95% CI)			
	Anticipated (%)	Unanticipated (%)	p	ES
In-Phase Trunk	56.86 (49.67, 64.05)	46.57 (41.84, 51.30)	0.053	0.57
In-Phase Head	32.14 (25.83, 38.46)	36.86 (31.65, 42.07)	0.249	-0.32
Anti-Phase Trunk	5.21 (2.92, 7.50)	9.71 (5.76, 13.67)	0.056	-0.56
Anti-Phase Head	5.79 (3.88, 7.69)	6.86 (5.60, 8.11)	0.373	-0.25

Table 16: Transverse plane binning frequency for the phases of the change of direction stride calculated with methods described by Needham et al. (2014)

	Preparatory			
	Frequency (95% CI)			
	Anticipated (%)	Unanticipated (%)	p	ES
In-Phase Trunk	43.64 (26.84, 60.45)	30.07 (13.86, 46.28)	.110	0.46
In-Phase Head	36.71 (21.76, 51.67)	42.29 (28.55, 56.02)	.331	-0.27
Anti-Phase Trunk	8.14 (2.73, 13.55)	11.14 (4.57, 17.72)	.529	-0.17
Anti-Phase Head	11.50 (5.56, 17.44)	16.50 (9.88, 23.12)	.169	-0.39
	Stance			
	Frequency (95% CI)			
	Anticipated (%)	Unanticipated (%)	p	ES
In-Phase Trunk	60.79 (51.62, 69.95)	54.93 (47.63, 62.23)	.333	0.27
In-Phase Head	36.00 (27.14, 44.86)	39.29 (32.82, 45.75)	.494	-0.19
Anti-Phase Trunk	2.21 (0.20, 4.22)	4.36 (-0.22, 8.93)	.468	-0.20
Anti-Phase Head	1.00 (0.02, 1.98)	1.43 (-0.33, 3.19)	.708	-0.10
	Post-Transition Step			
	Frequency (95% CI)			
	Anticipated (%)	Unanticipated (%)	p	ES
In-Phase Trunk	50.79 (32.50, 66.37)	41.79 (29.42, 54.15)	.190	0.37
In-Phase Head	19.14 (10.33, 27.95)	17.86 (10.91, 24.81)	.752	0.09
Anti-Phase Trunk	18.93 (5.33, 32.53)	25.36 (13.31, 37.40)	.347	-0.26
Anti-Phase Head	10.71 (1.88, 19.55)	15.00 (4.66, 25.34)	.193	-0.37

A.2.2 Needham Sagittal Plane

Table 17: Sagittal plane binning frequency calculated with methods described by Needham et al. (2014)

	Sagittal Plane			
	Frequency (95% CI)			
	Anticipated (%)	Unanticipated (%)	p	ES
In-Phase Trunk	40.36	38.07	.624	0.13
	(33.97, 46.75)	(33.39, 42.75)		
In-Phase Head	14.64	15.36	.786	-0.07
	(10.95, 18.34)	(12.53, 18.19)		
Anti-Phase Trunk	34.64	33.93	.848	0.05
	(27.89, 41.40)	(29.66, 38.20)		
Anti-Phase Head	10.29	12.64	.387	-0.24
	(8.02, 12.55)	(8.89, 16.39)		

Table 18: Sagittal plane binning frequency for the phases of the change of direction stride calculated with methods described by Needham et al. (2014)

	Preparatory			
	Frequency (95% CI)			
	Anticipated (%)	Unanticipated (%)	p	ES
In-Phase Trunk	25.07	20.14	.353	0.26
	(18.64, 31.51)	(11.00, 29.29)		
In-Phase Head	19.07	13.29	.283	0.30
	(10.29, 27.86)	(6.91, 19.66)		
Anti-Phase Trunk	36.57	35.07	.861	0.05
	(26.74, 46.40)	(23.42, 46.73)		
Anti-Phase Head	19.29	31.50	.189	-0.37
	(10.57, 28.00)	(19.59, 43.41)		
	Stance			
	Frequency (95% CI)			
	Anticipated (%)	Unanticipated (%)	p	ES
In-Phase Trunk	28.36	28.93	.878	-0.04
	(22.85, 33.87)	(22.17, 35.68)		
In-Phase Head	18.50	19.71	.672	-0.12
	(13.40, 23.60)	(15.45, 23.98)		
Anti-Phase Trunk	38.93	39.43	.908	-0.03
	(33.12, 44.74)	(33.63, 45.23)		
Anti-Phase Head	14.21	11.93	.409	0.23
	(10.48, 17.95)	(8.81, 15.05)		
	Post-Transition Step			
	Frequency (95% CI)			
	Anticipated (%)	Unanticipated (%)	p	ES
In-Phase Trunk	72.71	75.21	.811	-0.07
	(58.24, 87.19)	(62.16, 88.26)		
In-Phase Head	4.14	8.07	.438	-0.21
	(-0.87, 9.16)	(0.26, 15.89)		
Anti-Phase Trunk	23.14	16.71	.444	0.21
	(9.33, 36.96)	(3.51, 29.92)		
Anti-Phase Head	0.00	0.00	NaN	NaN
	(0.00,0.00)	(0.00,0.00)		

A.2.3 Needham Frontal Plane

Table 19: Frontal plane binning frequency calculated with methods described by Needham et al. (2014)

	Frontal Plane			
	Frequency (95% CI)			
	Anticipated (%)	Unanticipated (%)	p	ES
In-Phase Trunk	**23.29** **(16.53, 30.04)**	**33.86** **(26.04, 41.68)**	**0.01**	**-0.81**
In-Phase Head	17.93 (12.64, 23.21)	15.64 (11.48, 19.81)	0.532	0.17
Anti-Phase Trunk	35.57 (29.13, 42.01)	32.64 (25.93, 39.35)	0.421	0.22
Anti-Phase Head	23.21 (16.76, 29.66)	17.79 (11.63, 23.95)	0.153	0.41

Table 20: Frontal plane binning frequency calculated with methods described by Needham et al. (2014)

	Preparatory			
	Frequency (95% CI)			
	Anticipated (%)	Unanticipated (%)	p	ES
In-Phase Trunk	25.14 (14.13, 36.16)	38.71 (27.04, 50.39)	0.07	-0.54
In-Phase Head	11.43 (2.52, 20.33)	14.93 (4.63, 25.23)	0.57	-0.16
Anti-Phase Trunk	40.36 (28.35, 52.36)	36.86 (26.66, 47.05)	0.64	0.13
Anti-Phase Head	**23.07** **(15.71, 30.44)**	**9.50** **(3.79, 15.21)**	**0.02**	**0.72**
	Stance			
	Frequency (95% CI)			
	Anticipated (%)	Unanticipated (%)	p	ES
In-Phase Trunk	**18.07** **(9.69, 26.45)**	**27.50** **(18.21, 36.79)**	**0.01**	**-0.77**
In-Phase Head	22.64 (15.29, 30.00)	20.07 (14.31, 25.84)	0.58	0.15
Anti-Phase Trunk	29.00 (19.58, 38.42)	25.86 (18.52, 33.20)	0.47	0.20
Anti-Phase Head	30.29 (20.69, 39.89)	26.50 (17.21, 35.79)	0.47	0.20
	Post-Transition Step			
	Frequency (95% CI)			
	Anticipated (%)	Unanticipated (%)	p	ES
In-Phase Trunk	**17.93** **(8.07, 27.78)**	**52.36** **(36.97, 67.75)**	**< 0.01**	**-1.14**
In-Phase Head	18.21 (2.54, 33.89)	6.43 (1.26, 11.60)	0.24	0.33
Anti-Phase Trunk	49.86 (30.84, 68.88)	33.07 (19.94, 46.21)	0.27	0.31
Anti-Phase Head	13.93 (2.84, 25.02)	8.14 (-1.49, 17.77)	0.40	0.23

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