POSTURAL CONTROL AND STEPPING KINEMATICS OF MULTIDIRECTIONAL GAIT INITIATION

By

Kuanting Chen
Bachelor of Science, 2018
Baylor University
Waco, Texas

Submitted to the Graduate Faculty of
Harris College of Nursing and Health Sciences
Texas Christian University
in partial fulfillment of the requirement
for the degree of

MASTER OF SCIENCE

In

Kinesiology
(Motor Control)

May 2023

POSTURAL CONTROL AND STEPPING KINEMATICS OF

MULTIDIRECTIONAL GAIT INITIATION

A Thesis for the Degree

Master of Science

By

Kuanting Chen

Thesis Approved By:

Adam C. King

Dr. Adam C. King, Major Professor

Joshua Carr

Dr. Joshua C. Carr, Committee Member

Dr. Phillip Esposito, Committee Member

Emily Lund

Dr. Emily Lund, Associate Dean for Research

Harris College of Nursing & Health Sciences

Table of Contents

CHAPTER 1: INTRODUCTION **1**

SIGNIFICANCE 4
STATEMENT OF PURPOSE 4
RESEARCH QUESTIONS 5
HYPOTHESES 5
DEFINITIONS 6

CHAPTER 2: REVIEW OF LITERATURE **7**

AIMS 7
MOTOR CONTROL 7
Dynamical (Ecological) systems theory *8*
POSTURAL CONTROL 11
Anticipatory Postural Adjustments *12*
Factors affecting APAs *12*
GAIT INITIATION 15
Gait Initiation and APAs *16*
Gait initiation and Kinematic *18*
Gait Initiation and Obstacle Negotiation *19*
LIMB PREFERENCE 20
Gait Initiation and Leg Dominance *22*

CHAPTER 3: METHOD **24**

PARTICIPANTS 24
INSTRUMENTS 25
EXPERIMENTAL PROCEDURES 26
DATA PROCESSING 28
STATISTICAL ANALYSIS 30

CHAPTER 4: RESULTS **31**

TEMPORAL VARIABLES 31
ANTICIPATORY POSTURAL CONTROL VARIABLES 34
STEPPING CHARACTERISTICS 39

CHAPTER 5: DISCUSSION **44**

STEPPING DIRECTIONS AND POSTURAL CONTROL CHARACTERISTIC 44
STEPPING DIRECTIONS AND STEP CHARACTERISTICS 47
THE OBSTACLE NEGOTIATION ON POSTURAL CONTROL AND STEPPING KINEMATICS 48
THE STEPPING LEG AND MULTIDIRECTIONAL GI 50
LIMITATIONS 51
CONCLUSION 51

REFERENCE **53**

APPENDIX A **64**

APPENDIX B **65**

ABSTRACT **66**

List of Figures

Figure 2.1 9

Figure 3.1 27

Figure 3.2 29

Figure 4.1 33

Figure 4.2 38

Figure 4.3 39

Figure 4.4 43

List of Tables

Table 3.1 24

Table 4.1 32

Table 4.2 36

Table 4.3 41

Chapter 1: Introduction

Gait initiation (GI) is a movement that transitions an individual from static upright standing to steady state walking and can be separated into a preceding anticipatory postural adjustment (APA) phase and a step execution phase. During the APA phase, the contraction of postural control muscles counteracts with upcoming postural perturbations and positions the body into a mechanical advantageous location for more efficient center of mass translation. In the step execution phase, the two legs function in a synchronized manner for dynamic balance and forward translation of the center of mass. Although GI is often performed without conscious planning, the organization of APA and stepping movement requires a coherent integration of the central nervous system for information processing and the muscular system for postural and limb controls (Yiou et al., 2017). Practically, the ability to adapt the postural control and movement aspects of GI to various task and individual constraints is critical to locomotive functions (Yiou et al., 2012). Maladaptation, such as abnormal organization of APA and incorrect coupling of the APA to the stepping motion, can impair GI resulting in falls and freezing of gait (Callisaya et al., 2016; Maslivec et al., 2020; Nutt et al., 2011). In daily living activities and sport movements, individuals encounter demands to adapt GI to multiple stepping directions, a need to clear an obstacle, and individual's leg dominance.

Regarding the direction of GI, previous evidence showed that in a simulated cafeteria and department store setting, 35% to 50% of gait initiation was not directed forward (Glaister et al., 2007), and in sport setting, a soccer athlete can perform up to 800 non-forward gaits in a game (Taylor et al., 2017). Multidirectional GI is relevant in daily life; for example, an individual might perform lateral GI to avoid an upcoming shopping cart in a busy grocery store aisle, and an athlete might need to initiate locomotion in a diagonal pattern to a defense position. The investigation of lateral stepping by Patla et al. (1993) discovered that individuals performed lateral stepping with less weight shift and required less time in weight shift comparing to forward GI. Recently, Inaba et al. (2020) expanded the stepping directions to nine ranging from forward to posterior and found decreased mediolateral (ML) and anteroposterior (AP) center of pressure (COP) displacement during APA phase in response to the lateral shift in stepping directions. However, the step initiation task in the study was taking only one step toward the designated direction while facing the same direction and without any arms swing (Inaba et al., 2020). From an experimental perspective, this movement eliminates the confounding influence of the upper limb motions and truck rotation in the investigation of movement kinematics but does not resemble real-life GI. Since the movements in real-life GI, like arm swing, served specific purposes in gait stability (Meyns et al., 2013), the investigation of the anticipatory postural responses in multidirectional GI should not limit the motion of the upper limbs.

Moreover, in multidirectional GI, stepping kinematics are likely to be influenced by the task constraint of stepping direction. The demand of stepping toward various directions imposes different constraints from forward GI and requires the individual to emerge an innovative movement solution to complete the task. Vallabhajosula et al. (2013) who investigated the stepping kinematics alterations among healthy, elderly adults and individual with Parkinson's disease in multidirectional GI presented potentially decreasing trends of step distance, step duration, and step velocity as the stepping direction shifted laterally. To our knowledge, Vallabhajosula et al. (2013) were the only group that evaluated the multidirectional GI in the real-life context involving a complete transition to steady walking and unrestricted body motions, yet they did not report statistical analysis on the directional effect due to the focus of the study. Further evaluation regarding the effect of stepping directions on stepping kinematics is needed to obtain a comprehensive understanding of the GI adaptation in response to various stepping directions.

Another maladaptation of GI that can lead to falls relates to obstacle negotiation. In everyday life, the need for obstacle negotiation is frequent. For example, when walking into a room full of children's toys or stepping into a house with an elevated door frame. The act of obstacle negotiation in GI requires increased vertical displacement of the stepping leg, increased horizontal projection of the center of mass, and prolonged step duration in order to clear the obstacle (Chien et al., 2018; Shin et al., 2015). These movement alterations had shown to create larger postural perturbations and demand a greater ML COP displacement in APA phase and a greater step length to counteract the perturbations to maintain postural stability (Yiou, Fourcade, et al., 2016; Zettel et al., 2002). Although forward GI with obstacle negotiation has been examined in forward GI (Yiou, Artico, et al., 2016; Yiou, Fourcade, et al., 2016; Zettel et al., 2002), the obstacle negotiation in multidirectional GI can exhibit different postural control and stepping kinematics, which are novel in the literature and beneficial for improving task specificity in gait rehabilitation.

Lastly, the performance asymmetry between limbs in selective motor tasks, also known as limb dominance, can act as an individual constraint and influence the GI task. Differed from the handedness where the dominant hand possesses consistent superior fine motor performance, the leg dominance is characterized by the task. When performing a motor task with the lower limbs, the mobilizing and manipulating leg is the dominant leg, while the stabilizing and supporting leg is the non-dominant leg (Sadeghi et al., 2000). For example, in a soccer kick, the leg performing the kicking motion is the dominant leg, and the planting leg is the non-dominant leg (King & Wang, 2017). In the context of GI, the distinction between dominant and non-dominant leg is less understood because the functions of each leg during GI are alternating and not characterized by precise manipulation and stability control. However, previous evidence had shown the effect of leg dominance on the asymmetry of lateral impulse production (Dessery et al., 2011), COP displacements, and center of gravity velocity in the APA phase of GI (Yiou & Do, 2010). These findings not only provide information of leg dominance in forward GI but also support the possible effect of leg dominance on multidirectional GI.

Collectively, a gap in the literature exists with respect to the effect of stepping direction, obstacle negotiation, and leg dominance on the anticipatory postural control and stepping characteristics during GI. In order to maintain movement functionality in daily living, individuals must modulate GI to the constant changing environmental and task demands. Therefore, the aim of this study was to investigate how APA properties and stepping kinematics in GI change in response to various stepping directions, a need of obstacle negotiation, and individual's leg dominance.

Significance

A comprehensive knowledge of the postural control and movement alterations in response to the directional, obstacle negotiation, and leg dominance constraints provides valuable information for rehabilitation specialist and researcher to enhance the movement programs for gait training and improve the design of assistive devices. Thus, individuals who are participating a gait retraining program can be more adaptable to the environment and less restricted in daily living. Being able to clear an obstacle when initiating gait also lowers the risk of fall and improves accessibility in daily living. Moreover, understanding the effect of lower extremity limb preference on multidirectional GI can expand our knowledge on motor asymmetry and structural lateralization.

Statement of Purpose

This study aimed to investigate the effect of stepping direction, obstacle negotiation, and leg dominance preference on gait initiation by evaluating anticipatory postural control properties and stepping kinematics. The primary purpose was to expand the current knowledge on the anticipatory postural and movement adaptations in GI when exposed to directional variances, obstacle negotiation, and leg dominance. A secondary purpose was to provide practical knowledge for movement specialists and researchers to improve current gait training regimes and a foundation for future research in gait initiation.

Research Questions

There were two research questions to this study. First, what was the effect of stepping directions, obstacle negotiation, and leg dominance on anticipatory postural control and stepping kinematics during gait initiation? Second, what was the potential interaction effect of stepping directions, obstacle negotiation, and leg dominance on anticipatory postural control and stepping kinematics during gait initiation? In another words, would the obstacle impact the postural control and step kinematics universally in all stepping directions, or would the leg dominance influence the postural control and step kinematics uniformly in all stepping directions?

Hypotheses

It was hypothesized that the characteristics of APA would be scaled to the predicted magnitude of postural perturbations associated with stepping directions and obstacle negotiation. Specifically, we predicted that initiating gait laterally would result in decreased APA magnitude in both AP and ML directions. The stepping kinematic variables were expected to be decreased based on the findings of Vallabhajosula et al. (2013). The presence of the obstacle would result in a universal increase in APA and stepping kinematic metrics due to the need to counteract the additional postural perturbations and change for the technique used to clear the obstacle. Leg dominance was likely to influence only some aspects of the movement. It was hypothesized that the dominant leg would have greater APA magnitude and longer APA duration but have no effect on the stepping kinematics.

Definitions

Gait initiation (GI) - The phase from upright static standing to the steady state walking. It contains two phases, the anticipatory postural adjustment phase and the step execution phase.

Anticipatory postural adjustment (APA) – Occurs prior to the stepping motion. Postural muscle contractions prepare the body to minimizing upcoming postural perturbations.

Step execution phase – Indicates the stepping phase of the gait initiation. In this study, it includes all movements from the swing leg heel off to the swing leg heel strike.

Multidirectional gait initiation – Gait initiation in the non-forward direction.

Postural control – Describes the strategy used to maintain positions of body segments with considerations of external forces, mechanical properties of the body, and neuromuscular forces .

Stepping kinematics – The movements in the step execution phase of the gait initiation. It composes all movements from the swing leg heel off to the swing leg heel strike.

Obstacle negotiation – An act to overcome an obstacle in gait initiation.

Limb preference – Tendency to subjectively prefer the use of a consistent limb in performing selective tasks.

Leg dominance – Superior motor performance of a selective leg that can be objectively measured.

Center of mass – The point represents the center of the distribution of body mass.

Center of pressure – The point on the supporting surface where the distribution of the ground reaction force is summed into a single point of application.

Chapter 2: Review of Literature

Aims

The following synthesis of literature will provide the conceptual and methodological framework of GI in the realm of human motor control. First, motor control theories are presented with a focus on the ecological dynamics and task specificity. Next, the postural control mechanism (APA) used to counteract perturbation associated with voluntary movements is discussed. The final section will highlight the current understanding of gait initiation in the context of various constraints.

Motor Control

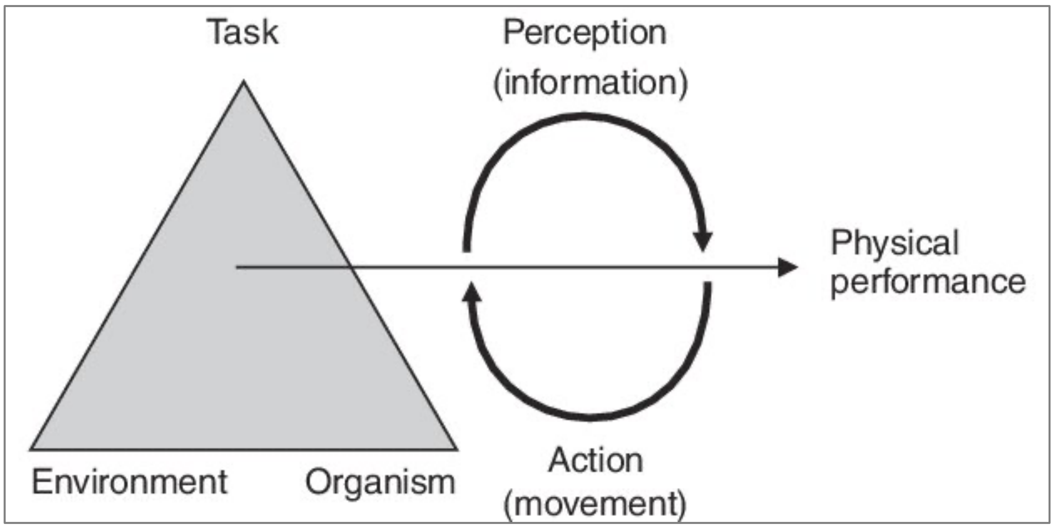
The study of motor control concerns about the key factors influencing movement pattern organization and movement generation. Understanding movements organization and, more importantly, what factors affect changes in movement outcome will improve the efficacy of skill learning, clinical rehabilitation, and performance training. Various motor control theories have been formulated since the beginning of 20th century with origins traced back to Sir Charles Sherrington, a neurophysiology, who established the foundation for the reflex theory suggesting that reflexes are the building blocks of complex behavior (Cano-de-la-Cuerda et al., 2015). Accordingly, the organizing of behavior occurs through compound reflexes or chained action in which a stimulus provokes a response, and this response is transformed into the stimulus of the next response. As further knowledge of the structure and function of the CNS were discovered, motor control theories shifted toward an emphasis on the role of the CNS in movement planning and execution. Two prominent theories emerged in this period, the hierarchical theory and the motor program theory. Both perspectives stress the importance of top-down control with the CNS serving as the command center sending movement programs to the peripheral effectors in order to accomplish movement tasks (Roller et al., 2013). These two theories received significant attention in the field of motor control, skill acquisition and motor development. However, the motor program theory was greatly challenged by the emerging ecological/dynamical systems theory (Summers & Anson, 2009). Pioneers of dynamic systems theory, Turvey, Fitch, and Tuller (1982), questioned the existence of the homunculus-type entity (a miniature version of the individual in the brain) who selected motor program features from a movement memory library stored and then played it down to the cortical and spinal level.

Dynamical (Ecological) systems theory

Dynamical systems theory emphasizes the role of intrinsic dynamics formed by the structural and functional constraints of individual in shaping movement outcome (Summers & Anson, 2009). In this context, the movement performer is considered as a self-organizing system, and the constraints can be viewed as boundaries or features that limit the motion of the individual (Newell, 1986). Specifically, the coordination structure of the self-organizing system is automatically adjusted to stable movement pattern under constraints, which means this system does not require constant involvement of higher control center, the brain. There are three constraints: organismic constraints, environmental constraints, and task constraints. Organismic constraints pertain to the characteristics of performer; examples include body mass, height, strength, and sensitivity to the sensory inputs. Environmental constraints are generally recognized as the constraints that are independent to the task and not interacted by the organism when performing the task. The temperature, gravity, natural light, and sounds are examples of environmental constraints. Task constraints focus on the goal of the activity and the specific rules to the activity. All tasks have goals that are related to the outcome of the action. The rules specify configurations of action, for example, in a doorknob turning motion, knowing the direction of the knob-turn will significantly affect the position and orientation of forearm at the time of grasping (Herbort & Butz, 2010). In summary, the perception of these constraints provides opportunities for actions (Fajen et al., 2008; Warren, 1990). (Figure 2.1) In another words, the movement outcomes are constrained by the organism, environment, and task.

Figure 2.1

Dynamical (Ecological) systems theory framework



Note. Movements are the emergent outcomes through the perception and action process that are constrained by the organism, environmental and task.

Practically, dynamical systems theory provides a multidimensional scope for practitioners to design training programs, rehabilitation plans, and augmented instructions with the consideration of ecological dynamics. Since movement performers are self-organizing system, movement practitioners often function as a facilitator in guiding self-organizing process and manipulating constraints to prepare the performer for various complex and fast-changing action demands. In sport performance training, one method of creating optimal learning is through manipulating the environment and movement goals in training to mimic the dynamic environmental and task constraints encountered in sports. This method is found to be a superior training regimen in a study examining the batting performance of experienced baseball athletes

(Gray, 2018); Gary showed the manipulation of task constraints (i.e., adding a barrier that must be hit over and adjusting barrier height and distance based on previous outcomes) in training can more effectively improve the post training batting test results in comparison to traditional training modalities which focus on perfect movement execution. Applying dynamic systems theory in sports has also been shown to improve decision making in rugby players (Passos et al., 2008), skill acquisition in interceptive sport athletes (Clark et al., 2018), and motor skill technique in non-expert university students (Moy et al., 2020).

Similarly, clinicians can assess injury and design rehabilitation plans through the lens of dynamic systems theory. It is well established that injury causation is multifactorial involving intrinsic risk factors like age, history of injury and strength and extrinsic risk factors like weather condition and ground surface (Meeuwisse, 1994). To address the readiness of an individual for the dynamic constraints, practitioners have proposed the use of ecological validity questionaries which coordinate one's cognitive and behavioral capacities with real-world demand situations (Gioia & Isquith, 2011). Ecological approach can also be implemented directly to the therapy setting. Studies have displayed a positive trend in improving motor performance for children with cerebral palsy when combining therapeutic intervention to the context of daily life settings (Ahl et al., 2005; Beckers et al., 2020).

Since the dynamic systems theory postulates the movement organization is shaped by the organismic, environmental and task constraints, researching dynamic systems theory needs to be task specific and conducted in a controlled environment. One component that is commonly investigated and also existing in all dynamic and static task is the postural control. Studying postural control can provide valuable insight into the influence of organismic, environmental and task constraints on the control of body configurations.

Postural Control

Body posture is the configuration of segments that are linked together by flexible joints and controlled by the neuromuscular system (Massion, 1994). This structure allows a high degree of movement variability and significant potential for movement (Stergiou & Decker, 2011). However, this structure is inherently unstable (Ivanenko & Gurfinkel, 2018). The strategy utilized to maintain the integrity of this structure and desired postural configuration is termed postural control.

Postural control has two primary functions – maintaining posture while performing intentional movements (antigravity function) and providing a reference frame for perception and action (Massion, 1994). The antigravity function counteracts perturbations associated with gravity and the change in motion of the center of mass. This function is presented in most of the daily tasks. For example, in static standing where the center of mass is demanded to be inside the base of support, the CNS generates a series of postural adjustments to create stability while maintaining upright standing (Hof et al., 2005). Similarly, in gait, the center of mass is controlled in an oscillating figure-eight manner to create dynamic stability (Tesio & Rota, 2019). For the reference frame function, the position and orientation of the body segments form a reference for calculating target locations in external world and facilitating the organization of movements (Massion, 1994). During upright reaching, the body processes visual and proprioceptive inputs from the surrounding environment and each body segment to optimize the organization of reaching motion (Saunders & Knill, 2003; Scheidt et al., 2005). In investigating the antigravity function, researchers study the postural control mechanism associated with counteracting perturbation in selective movement tasks, and the reference frame function is commonly examined in a context of feedbacks.

The CNS utilize two postural control strategies to counteract the perturbations associated with performing a task. Anticipatory postural adjustments (APAs) occur prior to the onset of the movement, while postural corrections during movement execution are termed compensatory postural adjustments (CPAs). An APA aims to minimize potential postural perturbations associated with the upcoming movement (Aruin, 2002; Latash, 2012) while the goal of CPAs relates to compensate for the insufficient preparatory adjustments made by APAs. Organizing APAs relies on the feedforward mechanism with predicted perturbations as the major source of information (Krishnan et al., 2012). On the other hand, CPAs integrate sensory feedback responses from the ongoing movement and provide movement corrections through reflexes, pre-programmed reactions, and voluntary motor actions (Knox et al., 2016; Latash, 2012). CPAs are characterized in all postural control task, while APAs are unique to the voluntary movements (Aruin, 2002). Therefore, it is important to characterize APAs when investigating postural control strategy in voluntary movements.

Anticipatory Postural Adjustments

Specifically, APAs are a series of muscle contractions organized by the CNS shortly prior to the onset of movement resulting in torques around the joint and shift in the center of mass to preserve postural integrity. These muscle activities are first documented by Belenkii and his colleagues (1967) using electromyography (EMG) on deltoid, spinal, and leg muscles while performing a rhythmic arm raising and dropping movement, and these postural control activities are termed anticipatory postural adjustments.

Factors affecting APAs

The CNS generates APAs based on three major factors: anticipated magnitude and direction of the perturbation, voluntary movements associated with the perturbation, and postural stability while performing the movement. The generation of precise APAs depends upon the prediction of the perturbation magnitude. In bilateral weight unloading task with various levels of self-generated perturbations, the timing and amplitude of the EMG signals of the postural control muscles demonstrate a positive correlation with the magnitude of the predicted perturbation (Aruin & Latash, 1995). The CNS's prediction will also be influenced by the previous experience with the perturbation. When the CNS is exposed to a novel perturbation, the generated APAs are less effective in minimizing the effect of perturbation; similarly, when the CNS is generating APAs for a series of repetitive perturbations, the APAs generated can more precisely counteract the postural perturbations (Kaewmanee et al., 2020). In addition to the absolute magnitude of the perturbation, the directional elements also affect the formation of APAs.

The CNS can organize APAs based on the direction of perturbation. The human body can sustain perturbations from all directions, and those perturbations require directional specific APAs to counteract. Aruin et al. (2001) were among the first to document this directional component. Their study identified direction dependent APAs patterns in the leg and trunk muscle groups in response to either frontal plane or rotational postural perturbations induced by performing a battery of voluntary tasks. Additional evidence has shown shifts in the Center of pressure (COP) – the point representing the position of ground reaction force – induced by APAs to be correlated with the direction of stepping during a multidirectional gait initiation task (Inaba et al., 2020b). In multidirectional gait initiation task, participants start walking to forward, diagonal, lateral, and posterior directions. Various stepping directions impose different directions of perturbation to the body. The results indicate that as the stepping directions become more lateral, both lateral and posterior shifts of COP during APA phase decrease. This study highlights the directional specificity element in organizing APAs during voluntary movements. Similar directional effect is also observed when the perturbation is induced by the external perturbations.

In investigating gait initiation in individuals with Parkinson's disease, the dropping of supporting platform under leg results in an improvement in APAs organization (Rogers et al., 2011). In a brief, the APA organizations depend on the predicted perturbation magnitude and the predicted direction of the perturbation, which emphasizes the importance of investigating APAs on a task-to-task basis especially when the motor task contains directional specific elements.

The second factor affecting the pattern of APAs consists of the magnitude of the motor action and the time available for organizing APAs. The relation between the magnitude of a motor action and the magnitude of APAs has been investigated in comparing the action of rapid horizontal abduction and finger flexion when unloading a weighted object attached to a balloon (Aruin & Latash, 1995). Since both actions are voluntary movement with inherent postural perturbations, both of these actions will result in APAs. However, the resultant APAs are scaled to the magnitude of the actions, meaning the APAs during finger flexion is smaller in magnitude comparing to the ones in rapid arm abduction. The time available for the proper development of APAs is termed the APA timing window (Berg & Strang, 2012). In the study of obstacle negotiation, an older population with high fall risk demonstrated a significantly longer APA timing window compared to a group with lower risk (Uemura et al., 2011). Under circumstance of shortened available time for APAs organization, suboptimal APAs may result in higher possibility of tripping and accidental falls. Additionally, when individuals perform rapid gait initiation the resultant APA window is shortened to compensate for the brief time allotted to propel the center of mass toward the stance leg (Caderby et al., 2014).

The third factor influencing APAs formation is the stability of the body posture when the movement is initiated. Stability elements can be categorized into normal conditions like standing and seating, unstable conditions like standing on a foam pad or a balance beam, and very stable conditions like leaning against the wall. Under normal conditions, postural muscle contractions create nearly linear postural corrections. Unstable conditions, on the other hand, have nonlinear correlations, which mean the excessive APAs could become additional perturbations to the posture. Therefore, the magnitude and duration of APAs in unstable conditions are lessened to prevent overcompensation. This is documented when an individual is required to perform a spontaneous weight unloading task stand on an unstable platform, the APAs generated are attenuated to preserve postural integrity (Aruin et al., 1998). In very stable condition, the demand for APAs is decreased as the postural perturbations associated with the movements are lessened by the additional stability. The postural stability and the magnitude of APAs form an inverse relationship, with higher the stability resulting in lower APAs (Hall et al., 2010; Nam et al., 2017).

In conclusion, APAs play an important role in counteracting the postural perturbations in all self-paced voluntary actions. They are generated prior to the onset of action, and they rely on prediction of the perturbations as the source of information. As a result of that, the organization of APAs is influenced by the direction and magnitude of perturbation, the magnitude of the action, time allowed to generate APAs, and the postural stability while performing the action. Researchers have recognized the need to understand APAs in daily tasks like gait initiation because such knowledge provide enormous value in injury prevention and clinical intervention (Mornieux et al., 2014; Nutt et al., 2011).

Gait Initiation

Walking, as a form of transportation and exercise, is a critical measurement of health, daily functions, neurological control, and muscular strength (Mariani et al., 2010; Saint-Maurice et al., 2020; Wrisley & Kumar, 2010). The ability to walk can be affected by various factors including aging (Aboutorabi et al., 2015), neuromuscular diseases (Cameron & Wagner, 2011; Nonnekes et al., 2019), vision (Hallemans et al., 2010), and footwear (Menz et al., 2017). An important element of locomotion involves the transition from upright static standing to a steady walking pace and is termed gait initiation (Brenière & Do, 1991). Gait initiation is one of the most common yet challenging tasks in activity of daily living. To complete gait initiation, individuals need to generate two propulsive forces, one that propels the center of mass toward the stance leg and another that pushes the individual forward (Brenière & Do, 1991). Two elements of gait initiation have received considerable investigation – postural control and kinematic (spatial and temporal) element (Park et al., 2009). Postural control element investigates how the CNS counteracts various postural perturbations (internal moments, external ground reaction forces and gravitational forces) associated with gait initiation (Yiou et al., 2017). Kinematic element concentrates on the motion of the body segments in reference to the space and time. These two elements are examined in detail in the following sections.

Gait Initiation and APAs

The postural control strategy of interest in this study is the organization of APAs related with gait initiation. Researchers have utilized EMG and force plates to investigate postural variables in gait initiation. EMG provides a tool to measure muscle activity of the prime movers and postural control muscles to obtain an understanding of the timing and magnitude of muscle contractions generated to counteract the postural perturbations associated with gait initiation (Berg & Strang, 2012; Jacobs et al., 2009; Khanmohammadi et al., 2016; Lee et al., 2019). Practically, EMG sensors are often placed on tibialis anterior and gastrocnemius to assess muscle involvement in anterior-posterior movements (Park et al., 2009) and tensor fasciae latae, gluteus maximus and gluteus medius for the control of motion in medial-lateral direction (Wentink et al., 2013). The EMG signals are filtered and time normalized to examine the muscle activities during APAs phase. A force plate is used to accurately capture changes in magnitude and direction of applied forces. The COP - an imagery point that represents the concentration of ground reaction force in feet-ground contact (Chen et al., 2021) – is closely related to the APAs during gait initiation. A successful gait initiation requires a posterior shift in anteroposterior COP for forward propulsive leverage and a shift of mediolateral COP to the swing leg which promotes center of mass shift in the opposite direction, i.e., towards the stance leg (Honeine et al., 2016; Latash, 2012; Yiou et al., 2017). Evidence has shown that disease population who demonstrates trouble in gait initiation has shorten ML COP displacement, abnormal coupling of the COP and stepping, and abnormal amount of AP COP shifts (Jacobs et al., 2009; Nutt et al., 2011; Schlenstedt et al., 2018). With measuring tools like EMG and force plate, researchers can investigate factors that affect postural characteristics during gait initiation.

The organization of APAs during gait initiation can be influenced by the prediction of perturbation, the initial stance configuration, and physiological conditions like neurological diseases and ageing. As previously mentioned, the pattern of APAs is dependent on the prediction of perturbation which includes factors such gait speed (Caderby et al., 2014), gait direction (Inaba et al., 2020b), footwear and ground surface (Russo et al., 2021; Vieira et al., 2015). Specifically, the APAs characteristics exhibit a positive correlation to the magnitude of perturbation. In response to increased gait speed (i.e., an increase in perturbation) the magnitude of ML COP increases (Caderby et al., 2014), and the magnitude of ML COP decreases when the direction of gait initiation becomes more lateral, i.e., less lateral perturbations (Inaba et al., 2020b). To discuss the second factor, the initial stance, it is critical to understand changes in the base of support during gait initiation. Gait initiation signifies a transition from bilateral standing to single leg support and during this phase the base of support area decreases, which means the COP has to be transferred toward the stance leg. When individuals are asked to perform gait initiation from a wider stance, their ML COP travels further laterally and to compensate for the extra stance width (Rocchi et al., 2006). The last factor, physiological conditions can affect the capacity of the CNS to generate efficient APAs. Studies have demonstrated that for people with Parkinson's disease, the APAs generated are suboptimal (Bonora et al., 2017; Jacobs et al., 2009; Mancini et al., 2009; Maslivec et al., 2020), and for elderly population, the APAs produced are often incomplete and declined (Kimijanová, Bzdúšková, et al., 2021; Lu et al., 2017).

Gait initiation as a task involving multiple body segments and total body structural coordination requires a combination of both kinematic and kinetic measurements to provide the most comprehensive assessment. In investigating the same independent variable, study (Russo et al., 2021) measuring only force and COP data does not produce equally accurate and generalizable results as the one measuring both kinetic and kinematic data (Dessery et al., 2011; Yiou & Do, 2010). This emphasizes the need to implement kinematic measurements in assessing gait initiation.

Gait initiation and Kinematic

Kinematics of interest during gait initiation include joint specific variables like joint angle at a specific time point and changes of angles over a duration of time and stepping specific variables like first step width, step length and step speed (Caderby et al., 2014; Lee et al., 2019; Park et al., 2009; Zhao et al., 2021). The value in kinematic data is the accuracy and the ability to directly measure body mechanics. Through a pre-programmed model and inputs of anthropological parameters, researchers can also calculate not-directly measurable data like internal joint moments and the position of the center of mass (Bisseling & Hof, 2006; Dessery et al., 2011). Kinematic data is captured with motion capture system; it consists of multiple cameras that collect positional measurement of reflective markers affixed to important anatomical landmarks of the body. Those positional data will be processed in a software to calculate desired kinematic variables. The low margin of errors and the ability to directly measure joint angles have made motion capture system the gold standard in motion analysis (Higginson, 2009).

There are many factors that can affect body kinematics during step initiation, which includes vision (Kimijanová et al., 2021), injuries (Buckley et al., 2017; Chang et al., 2004; Fraser et al., 2019), aging, disease (Vallabhajosula et al., 2013) and limb preference (Dessery et al., 2011). When studying the effect of aging and Parkinsonism on the kinematics of multidirectional gait initiation, Vallabhajosula and his colleague (2013) found elderly took a smaller and slower first step and slower second step in comparison to the healthy young adults, and people with Parkinson's disease took a slower first step and longer time to initiate the second step compared to healthy age-controlled group. They concluded that aging would affect the speed of first step initiation, and Parkinsonism could result in rigidity and bradykinesia that may be associated with an increased risk of falls. However, they did not compare across different stepping direction; this aspect of the multidirectional GI still requires further investigation.

Gait Initiation and Obstacle Negotiation

Obstacle negotiation is a critical task in daily living. Proper execution of the task can prevent fall and decrease the risk of orthopedic injuries. An obstacle requires an individual to increase vertical and horizontal displacement of their legs, project their center of mass further, and elongate their step duration to clear the obstacle (Chien et al., 2018; Lowrey et al., 2007; Shin et al., 2015). Similar obstacle negotiation strategy can also be seen in the GI task (Yiou, Artico, et al., 2016; Yiou, Fourcade, et al., 2016). When an obstacle was presented, individuals shortened APA duration, increased ML COP displacement and center of mass velocity at heel off, and decreased AP COP displacement and center of mass velocity at heel off (Yiou, Fourcade, et al., 2016). Since the presence of an obstacle challenges the postural stability in the step execution phase and requires compensations from APA and stepping execution phases, larger ML COP displacement with prolonger APA duration and additional step width were produced to preserve lateral stability in GI with obstacle negotiation (Zettel et al., 2002). Additionally, the stability in the AP direction was primarily maintained by the increase in step distance (Zettel et al., 2002). However, these movement alterations were primarily observed in forward GI, the directional elements in the multidirectional GI could potentially interact with the postural control and movement kinematics of the obstacle negotiation. Therefore, there is a need for investigating the effect of obstacle negotiation in multidirectional GI to attain a more comprehensive understanding.

Limb Preference

It is important to discuss the definitions of limb preference and limb dominance here. Limb preference is the preferential use of a consistent limb in performing the selective tasks, and limb dominance is the objective measure of superior performance in motor task. Limb preference is evident in a range of daily tasks including both simple tasks like turning a doorknob, holding a cup of coffee and fine motor tasks like handwriting, sewing, and manipulating tools. From a motor learning standpoint, consistent use of a limb resembles a form of practice. Repetitions induces lateralization (bias to either right or left side) in strength (Fousekis et al., 2010; Hadzic et al., 2014), neuromuscular reflex (Furlong & Harrison, 2014), postural stability (Promsri et al., 2020; L. A. Teixeira et al., 2013), and motor skills (Castañer et al., 2018; Peters, 1988). However, this motor learning alone is not adequate to explain the origin of the limb preference. One prominent explanation of the source of limb preference is the dynamic dominance model (Sainburg, 2014), which postulates the limb preference in association with specific hemispheric laterizations that provide distinct and complementary advantages to the control of each arm (Mutha et al., 2012; Przybyla et al., 2013). In right-handed individuals, the left hemisphere specializes in the organization of movements that are mechanically efficient and accurate in predictable dynamic conditions, while the right hemisphere is specialized for impedance control mechanisms that ensure positional and velocity stabilization in unpredictable events and conditions. In other words, for right-handed individuals performing voluntary motor tasks, the right arm dominates in control while the left arm provides stability.

This model has been tested in a target-reaching task comparing the movement trajectories between preferred and nonpreferred hands (Mutha et al., 2013). The task composed of two phases, the learning phase and the probing phase. In the learning phase, participants performed 40 trial of the single trace, uncorrected, rapid motion using an index-finger-controlled cursor on the screen from a preset starting position to the target which is suddenly appeared as a cue for initiating movement. After 40 trials of learning, the experiment entered the probing phase. During the probing phase, the cursor was covertly displaced from the index finger, so that for each trial, although the screen was still showing the same starting position, the arm configurations were different. Through comparing the movement trajectory between learning phase and probing phase, Mutha et al. found that the preferred arm largely maintained the direction and straightness of its trajectory, while the nonpreferred arm tended to deviate towards the previously learned target position. This limb specific motor control bias is consistent with the hemispheric specialization in the dynamic dominance model.

In lower extremity, the dynamic dominance model was tested in a foot pedal reaching task. In the study, Marcori et al. (2020) deigned two experiments; one, the participant performed the aiming task with support, which means the reaching motion is in isolation of another leg, and two, the task was carried out while standing on the other leg. The results revealed an increased stance stability when the participants are supported on the left leg while performing the aiming task with the contralateral foot and no difference in task performance when each leg is reaching in isolation. This finding is aligned with the dynamic dominance model and highlights the potential motor asymmetry resulted from the hemispheric specialization. However, when investigating footedness in a variety of the motor tasks, the agreement between functionality and preference seems to be more task- and individual-specific.

Gait Initiation and Leg Dominance

Frequently in lower extremity motor tasks, one leg provides postural support while the other leg performs the mobilizing task. This movement coordination formulates a mobility-stability paradigm. Peters (1988) proposed the foot that is used for mobilizing tasks as the dominant leg, and the stabilizing leg is the non-dominant leg. When kicking a soccer ball, for example, one leg positions the body near the ball and supporting all the body weight (non-dominant leg) while the other leg initiates the dynamic swing movement and executes the kicking motion (dominant leg). If the mobility-stability paradigm is repetitively performed, the mobilizing and stabilizing features of each limb will be reinforced, which is shown in soccer players as the enhanced standing balance in stabilizing leg and improved soccer specific mobilizing skills in mobilizing leg (Teixeira & Teixeira, 2008). On the other hand, if individuals do not practice tasks emphasizing the mobility and stability element in each leg, the objective measures on postural stability and mobilizing performance do not correlate with the limb preference and differ between legs (Barone et al., 2011; Matsuda et al., 2008). Frequently, researchers determine leg dominance through self-report questionnaire surveying individuals' foot preference in tasks that are either mobility or stability focus (Ipek et al., 2021; van Melick et al., 2017; Yang et al., 2017). Considering the practical elements, footedness has become a popular topic for its value in understanding hemispheric lateralization and body asymmetry in the context of sports and rehabilitations.

Gait, as a fundamental locomotor skill for daily life and sports, assigns the stance leg to support the body weight and the swing leg for orienting the direction of the walk (Hase & Stein, 1999). The initiation of gait requires stance leg to accept and control the majority of the weight while the swing leg perform the locomotion (Park et al., 2009), which also fits in the mobility-stability paradigm. Therefore, it is reasonable to hypothesize that the footedness will affect gait initiation. According to the study by Yiou & Do (2010) in examining the gait initiation between preferred and nonpreferred leg, they found that the preferred limb exhibited a longer APAs phase and greater APAs magnitudes. Dessery et al. (2011) also found greater mediolateral impulse and smaller lateral center of mass displacement and step width from the nonpreferred leg start. Those unique characteristics provide insight to footedness in forward gait initiation but may not generalize to multidirectional gait initiation due to task specificity of motor control explained previously (under *Dynamical (Ecological) systems theory* section). Further investigation of the postural control and stepping kinematics might be needed.

Chapter 3: Method

Participants

Sixteen healthy young participants (seven males and nine females) were recruited for the study. Participants had to satisfy the following inclusion criteria: (1) 18-35 years of age; (2) no history and current diagnosis of clinical conditions that could impair gait (e.g., stroke, amputation and movement disorders like Parkinsonism, cerebral palsy, osteoarthritis); (3) do not currently take medications that can affect movement, balance, and coordination; (4) free from lower extremity surgery and injuries in the past one year. The data for two individuals were excluded due to irreversible marker occlusion and technical difficulties with the force plate. A statistical description of the participants' demographics is presented in table 3.1.

Table 3.1

Characteristics of the Participants

Sample Characteristics	n	%	M	SD
Gender				
Male	7	50		
Female	7	50		
Leg Preference				
Right	14	100		
Left	0	0		
Age			22.4	2.4
Height(cm)			170.7	11.75
Weight(kg)			69.3	11.96
Physical Activity				
Volume (min/week)			357.9	203.88
Intensity (Borg scale)			13.8	1.81

Note. Demographic description of the included participants. The statistical information presented contains the frequency (n), mean (M), and standard deviation (SD).

Participants were recruited through words of mouth. During recruitments, subjects were informed that the participation was completely voluntary and withdrawal from the study could occur at any time without penalty. The informed consent was obtained from all participants. No incentive was provided. The study procedures were approved by the Institutional Review Board of Texas Christian University.

Instruments

Age, height, weight, gender, and physical exercise volume were collected through a self-reported demographic survey (see Appendix A). Leg preference was surveyed through the Waterloo Footedness Questionnaire, and the preferred side was determined by the majority of the response (see Appendix B; van Melick et al., 2017). A strain-gauge force plate (464mm x 508mm, AMTI OR6-7, Advanced Mechanical Technology, Inc., Watertown, MA) embedded and leveled to the floor was used to capture COP and APA characteristics.

Kinematic data were recorded using an eight-camera motion capture system (Miqus M3, Qualisys AB, Göteborg, Sweden) with a frame rate of 250 frames per second. Calibration was performed according to the manufacture guideline with a standardized calibration wand (300.2mm in width) and a coordinate kit positioned on the force plate marking the zero-zero coordinate. To ensure the capture zone covered enough space for multidirectional GI, a 60-second calibration period was implemented. Calibration was performed prior to the participant's arrival. Both motion capture data and the force plate data were recorded in Qualisys Track Manager (QTM; Qualisys AB, Göteborg, Sweden).

A 15-segment biomechanical model was built for this study. It contained 41 reflective markers placed on the following anatomical landmarks (from the feet to the head): 1st and 5th metatarsophalangeal joints (4), medial and lateral malleolus (4), calcaneus (2), shank (2), medial and lateral femoral epicondyle (4), mid-thigh (2), ASIS (2), PSIS (2), L4L5 joint (1), C7 (1), jugular notch (1), AC joints (2), medial and lateral humeral epicondyle (4), styloid process of radius and ulna (4), mid-3rd metacarpal bone (2), and four corner of the head (4).

To minimize the influence of pre-stepping positions, a black circular visual target (1 inch in diameter) was placed 4.5 m away from the force plate and at the eye level of the participant. In condition with the presence of an obstacle, a 15 cm height and 40-cm wide hurdle was placed 10-cm from the edge of the force plate and in line with the stepping direction.

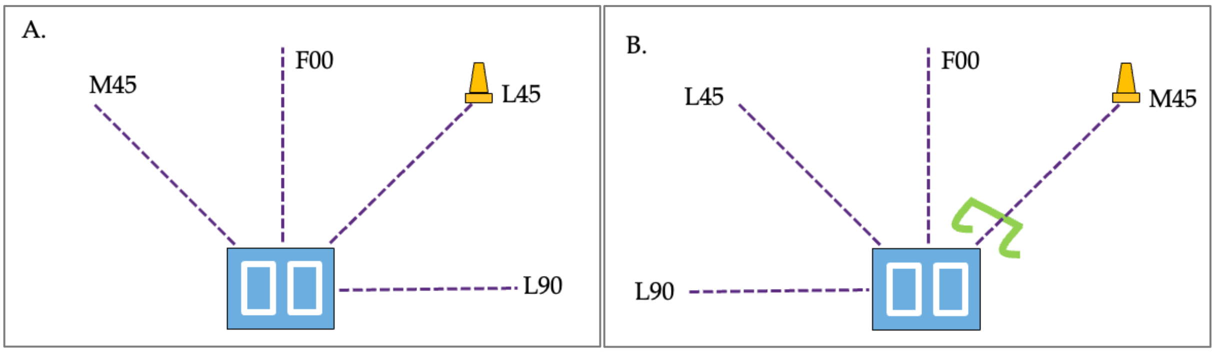
Experimental procedures

When the participant arrived at the testing site, the researcher delivered a general explanation of the study purpose, benefit, and risk as well as the consent form. After agreeing on the informed consent, the participant would complete the demographic survey and the Waterloo footedness questionnaire. The principal investigator was always present during the consent process to answer any questions and concerns. Once all the documents were completed, the participant would remove shoes and socks and change to appropriate clothes for reflective markers placement. To minimize marker placement errors, the same researcher placed markers for all participants, and the initial feet width was marked with masking tapes on the force plate. The initial stance was determined by the participant as the most comfortable stance for GI. An unrestricted familiarization period was provided, and the participant was encouraged to walk toward all directions.

A 15-centermeter tall bright orange cone was placed on the floor 3-meters away from the force plate to indicate the stepping direction for the trial. There were four walking directions (See figure 3.1): forward (F00), lateral (L90), 45° toward the midline (M45), and 45° away from the midline (L45). For each condition, the participant performed five trials with approximately 15 seconds between trials. All experimental conditions were randomized, and a minimal of oneminute recovery was assigned between conditions. No participant reported fatigue during data collection.

Figure 3.1

Demonstration of the experimental set up



Note. Experimental set up for the right leg stepping to the lateral 45 direction in the absence of obstacle (A). Bottom figure (B) demonstrates the set up for the left leg stepping to the medial 45 direction in the presence of obstacle. Feet position was marked by tapes on the force plate. The walking direction for the trial is indicated by the orange cone. F00: forward, L90: lateral, M45: 45° toward medial direction, L45: 45° toward lateral direction.

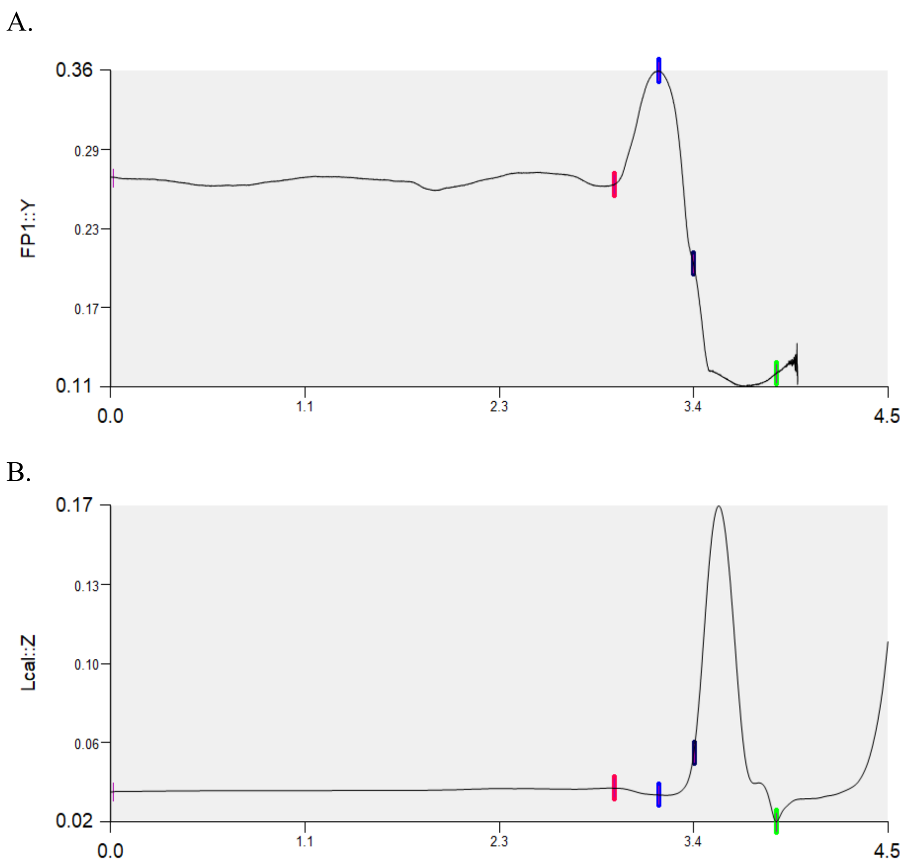
In the beginning of the trial, the participant stood relaxed with arms alongside the trunk and gaze focusing on the visual target. The researcher would remind the participant of the stepping direction and the stepping leg. Once the participant expressed confirmation and remained still, the research would call out "ready!" to indicate the start of recording. After 2 seconds of baseline standing, the researcher would call out "go!" to inform the participant to walk toward the direction of the cone. The participant was instructed to execute the most natural movement, and they could move at any time after the "go" cue. Most of the participants stepped right after the “go” cue; only one participant paused before action. When the participant reached the cone, the researcher would stop recording and signal the participant to return to the force plate in preparation for the next trial.

Data Processing

A semiautomatic marker identification process was performed. Initial identification was done by a pre-built automatic identification of markers model, then all markers went through manually inspection for any misidentification. The beginning 0.5 second was cropped and the data after the heel strike of the initial stance leg were removed. Gaps in the trajectories were filled with a polynomial trajectory filling tool and a relative position trajectory filling tool. Both tools were provided by the QTM software. Complete motion capture data along with force plate data were exported to the Visual 3D (V3D; v.7, C-Motion Inc., Boyds, Maryland, USA) for model building and kinematic variables computations. A two-second static standing trial extracted from the baseline standing phase was used to build the individualized model for each participant. Marker trajectory signals were lowpass filtered at 12hz (a fourth-order Butterworth). Then, four events were labeled: (1) APA onset, determined as the time where the mediolateral COP started to raise above the baseline, (2) APA max, the time where the mediolateral COP displacement reached the maximum value, (3) Heel off, the time when the vertical velocity of the calcaneus marker exceeded 0.1 m/s, (4) Heel strike, the time when the vertical displacement of the calcaneus marker reaches local minimum after the heel off event (see figure 3.2 for demonstration).

Figure 3.2

Mediolateral COP trajectory and vertical displacement of calcaneus marker



Note. A. the mediolateral COP trajectory. B. vertical displacement of the calcaneus marker. Four events are color-coded in the graph. Red: APA onset, defined as the onset of the raising portion of the mediolateral APA. Blue: APA max, the peak of the COP. Black: heel off, the point where the vertical velocity of the calcaneus marker exceeds 1.0 m/s. Green: heel strike, the local minimum point after the heel off event.

Anticipatory postural adjustment during GI was measured for its duration, magnitude, and velocity. The APA duration was the time between the events of APA onset and APA max, and APA magnitude was the COP displacement between these two events in both AP and ML directions. The average velocity of the APA was the ratio between APA magnitude and APA duration (Russo et al., 2021). Stepping kinematics were characterized by the step duration, step distance, step-width range, and step velocity. All stepping kinematic metrics were computed on the swing leg. The step duration was measured as the time between heel off to heel strike. Straight-line distance between heel off to heel strike was computed for the step distance. Step-width range indicated the variability while stepping; it was the difference between the maximum and minimum of the distance perpendicular to the path. The step velocity was the ratio between the distance travelled by the swing leg calcaneus marker and step duration.

Statistical Analysis

All statistical analyses were performed in SPSS software (Statistical Package for Social Sciences; International Business Machines, IBM). The mean of five trials for each dependent variable was compared using a repeated measure analysis of variance (RM-ANOVA) with directions (F00, L90, M45, L45), legs (left vs. right), and hurdle (presence vs. absence) as within factors. A significant result of the Mauchly's Test of Sphericity was corrected by Greenhouse-Geisser correction. For the variables that showed significance, Bonferroni pairwise-comparisons was performed to examine the effect of conditions. Level of significance was set to 0.05.

Chapter 4: Results

Temporal Variables

The results showed that both postural control and stepping variables were sensitive to the change in stepping direction. A significant direction-obstacle interaction effect was found for APA duration ($p < 0.001$, $\eta_p^2 = 0.743$) and step duration ($p < 0.001$, $\eta_p^2 = 0.666$). When stepping toward F00 without the obstacle, the APA duration was 0.291 ± 0.011 s, and the duration of the stepping was 0.529 ± 0.007 s. As the stepping direction shifting laterally, the APA duration shortened (L45: 0.197 ± 0.010 s, $p < 0.001$; L90: 0.163 ± 0.015 s, $p < 0.001$; table 4.1A), while the step duration remained relatively constant (L45: 0.524 ± 0.016 s, $p = 1.000$; L90: 0.514 ± 0.017 s, p=1.000; table 4.1B). In M45 direction, APA duration was longer than the F00 (M45: 0.371 ± 0.011 s, $p < 0.001$), yet the step duration stayed consistent with the F00 (0.548 ± 0.012 s, $p = 0.702$). As shown in figure 4.1A, the presence of the obstacle caused an increase in APA duration of F00 (0.314 ± 0.008 s, $p = 0.014$), L45 (0.272 ± 0.009 s, $p < 0.001$), L90 (0.273 ± 0.014 s, $p < 0.001$), but not M45 (0.372 ± 0.013s, $p = 0.882$). Regarding to the step duration, figure 4.1B shows that the presence of the obstacle increased the step duration in all directions (no obstacle: 0.529 ± 0.009s, obstacle: 0.812 ± 0.023 s, $p < 0.001$). When examine the effect of the stepping leg, significant main effect was found in APA duration ($p < 0.001$, $\eta_p^2 = 0.807$) and step duration ($p < 0.001$, $\eta_p^2 = 0.915$). More specifically, right leg GI contained longer APA duration (left: 0.262 ± 0.009 s, right: 0.301 ± 0.009 s, $p < 0.001$) and took significantly longer to complete the first step (left: 0.641 ± 0.015 s, right: 0.700 ± 0.016 s, $p < 0.001$).

Table 4. 1

Directional effect on A: APA duration and B: step durations

A.

Obstacle \ No Obstacle	**F00** 0.291 ± 0.011	**L45** 0.197 ± 0.010	**L90** 0.163 ± 0.015	**M45** 0.371 ± 0.011
F00 0.314 ± 0.008	<0.05 #	<0.001 ***	<0.001 ***	<0.001 ***
L45 0.272 ± 0.009	<0.05 *	<0.001 ###	<0.05 *	<0.001 ***
L90 0.273 ± 0.014	<0.05 *	NS	<0.001 ###	<0.001 ***
M45 0.372 ± 0.013	<0.001 ***	<0.001 ***	<0.001 ***	NS

B.

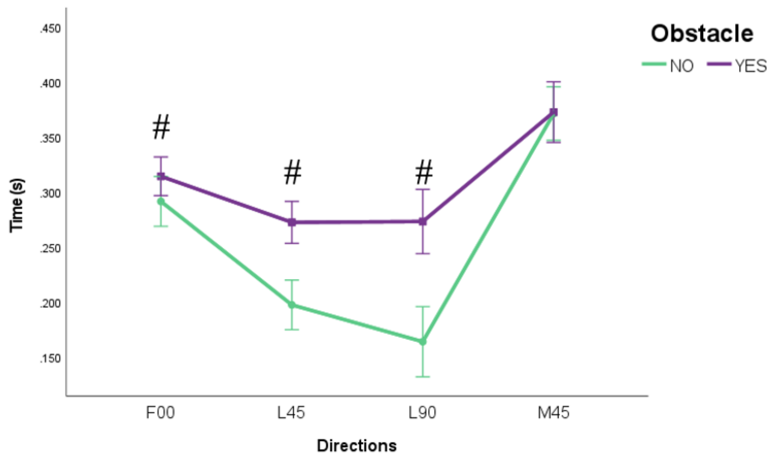
Obstacle \ No Obstacle	**F00** 0.529 ± 0.007	**L45** 0.524 ± 0.011	**L90** 0.514 ± 0.017	**M45** 0.548 ± 0.012
F00 0.781 ± 0.026	<0.001 ###	NS	NS	NS
L45 0.819 ± 0.023	NS	<0.001 ###	NS	NS
L90 0.876 ± 0.026	<0.001 ***	<0.01 **	<0.001 ###	NS
M45 0.773 ± 0.021	NS	<0.05 *	<0.001 ***	<0.001 ###

Note. The value under the bolded direction is mean ± standard error. The unit for durations is seconds. Direction effect: ***$p < 0.001$. ** $p < 0.01$. * $p < 0.05$. Obstacle effect: ### $p < 0.001$. ## $p < 0.01$. # $p<0.05$.

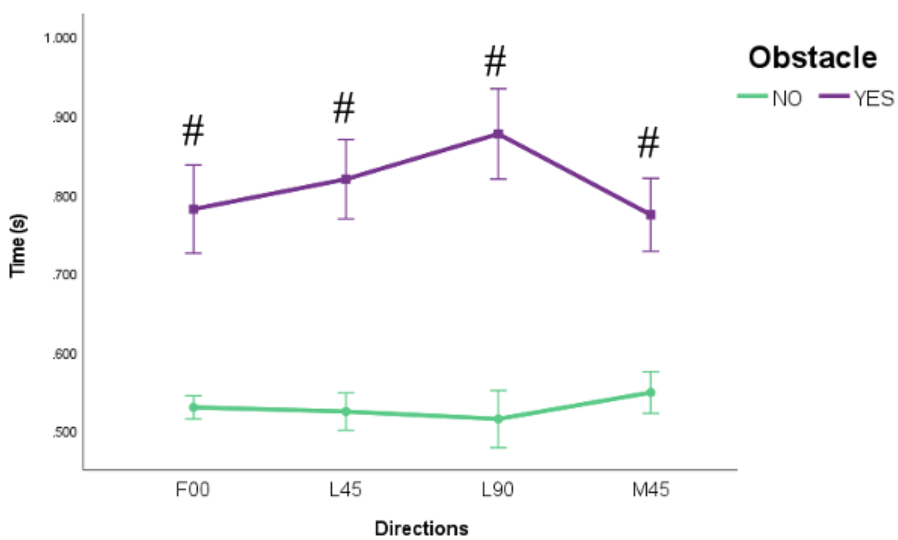
Figure 4. 1

Obstacle effect on A: APA durations and B: step durations

A.



B.



Note. The green line indicates the GI without the obstacle and the purple line indicates the GI with the obstacle. #: statistical significance of obstacle effect. Error bars indicate 95% confidence intervals.

Anticipatory Postural Control Variables

Significant direction-obstacle interaction effect was found in both ML and AP COP displacement (ML: $p < 0.001$, $\eta_p^2 = 0.628$; AP: $p < 0.001$, $\eta_p^2 = 0.496$). Similar to the APA duration, the ML COP displacement decreased as the stepping direction inclining laterally (F00: 0.055 ± 0.004 m; L45: 0.019 ± 0.003 m, $p < 0.001$; L90: 0.012 ± 0.002 m, $p < 0.001$; table 4.2A); however, when negotiating with the obstacle, the ML COP displacements of L45 and L90 showed similar values despite both smaller than the one in F00 (F00: 0.067 ± 0.004 m; L45: 0.040 ± 0.003 m, $p < 0.001$; L90: 0.037 ± 0.002 m, $p < 0.001$ against F00; table 4.2A). In the presence and the absence of the obstacle, the GI in M45 had the greatest ML COP displacement (0.086 ± 0.005 m, $p < 0.001$ versus all other directions). As detailed in table 4.2A, adding the obstacle increased the ML COP displacement for all directions ($p < 0.001$), except M45 (p = 0.134). In the AP direction, table 4.2B shows that the COP displacement was the greatest in F00 direction (0.043 ± 0.003 m), then M45 (0.033 ± 0.002 m), L45 (0.018 ± 0.001 m), and the least in L90 (0.004 ± 0.000 m). An additional obstacle lowered the AP COP displacement in F00 (0.032 ± 0.003 m, $p < 0.001$) and M45 (0.027 ± 0.003 m, $p < 0.001$), while the AP COP displacement showed a slight increase in L90 (0.007 ± 0.001 m, $p = 0.009$) and no change in L45 (0.017 ± 0.002 m, $p = 0.166$). The stepping leg had no significant effect on COP displacement in the APA phase in both directions.

The velocity of the COP movement during the APA phase displayed a distinct pattern from the magnitude metrics. In ML COP velocity, there were significant direction-obstacle interaction effect ($p < 0.001$, $\eta_p^2 = 0.472$) and direction-stepping leg interaction effect ($p = 0.004$, $\eta_p^2 = 0.289$), and similarly in AP COP velocity, there were significant direction-obstacle interaction effect ($p < 0.001$, $\eta_p^2 = 0.518$) and direction-stepping leg interaction effect ($p = 0.036$, $\eta_p^2 = 0.196$). Specifically, with an increase in the stepping laterality, the COP velocity showed a decreasing trend in both AP and ML axis. The ML COP velocity without the obstacle decreased from 0.154 ± 0.014 m/s in F00 to 0.105 ± 0.009 m/s in L45, and 0.023 ± 0.003 m/s in L90 and the ML COP velocity in M45 was the same as the L45 (p = 0.679; table 4.2C). In the presence of the obstacle, ML COP velocity decreased in F00, L45, and M45 (F00: 0.109 ± 0.010 m/s; L45: 0.066 ± 0.010 m/s; M45: 0.075 ± 0.012 m/s; figure 4.2C), but the one in L90 remained unaffected (0.028 ± 0.004 m/s, p = 0.354). Regarding to the AP COP velocity metrics in GI without obstacle, shown in table 4.2D, M45 exhibited the greatest velocity; followed by F00, L45 and L90 (M45: 0.237 ± 0.017 m/s; F00: 0.200 ± 0.017 m/s; L45: 0.090 ± 0.011 m/s; L90: 0.062 ± 0.012 m/s). The presence of the obstacle increased the AP COP velocity in F00, L45, and L90 (F00: 0.219 ± 0.014 m/s, p = 0.034; L45: 0.153 ± 0.014 m/s, p < 0.001; L90: 0.136 ± 0.013 m/s, p < 0.001) but not the AP COP velocity in M45 (0.246 ± 0.019 m/s, p = 0.266).

Table 4.2

Directional effect on A. ML COP displacement, B. AP COP displacement, C. ML COP velocity, D. AP COP velocity

A.

No Obstacle / Obstacle	**F00** 0.055 ± 0.004	**L45** 0.019 ± 0.003	**L90** 0.012 ± 0.002	**M45** 0.084 ± 0.005
F00 0.067 ± 0.004	<0.001 ###	<0.001 ***	<0.001 ***	<0.001 ***
L45 0.040 ± 0.003	<0.001 ***	<0.001 ###	<0.01 **	<0.001 ***
L90 0.037 ± 0.004	<0.001 ***	NS	<0.001 ###	<0.001 ***
M45 0.088 ± 0.006	<0.001 ***	<0.001 ***	<0.001 ***	NS

B.

No Obstacle / Obstacle	**F00** 0.043 ± 0.003	**L45** 0.019 ± 0.001	**L90** 0.004 ± 0.000	**M45** 0.033 ± 0.003
F00 0.032 ± 0.003	<0.001 ###	<0.001 ***	<0.001 ***	<0.01 **
L45 0.017 ± 0.002	<0.001 ***	NS	<0.001 ***	<0.01 **
L90 0.007 ± 0.001	<0.001 ***	<0.01 **	<0.01 ##	<0.001
M45 0.027 ± 0.002	<0.05 *	<0.001 ***	<0.001 ***	<0.01 ##

C.

No Obstacle / Obstacle	**F00** 0.154 ± 0.014	**L45** 0.105 ± 0.009	**L90** 0.023 ± 0.003	**M45** 0.092 ± 0.008
F00 0.109 ± 0.010	<0.001 ###	<0.01 **	<0.001 ***	<0.001 ***
L45 0.066 ± 0.010	<0.001 ***	<0.001 ###	<0.001 ***	NS
L90 0.023 ± 0.003	<0.001 ***	<0.01 **	NS	<0.001 ***
M45 0.092 ± 0.008	<0.001 ***	NS	<0.001 ***	<0.01 ##

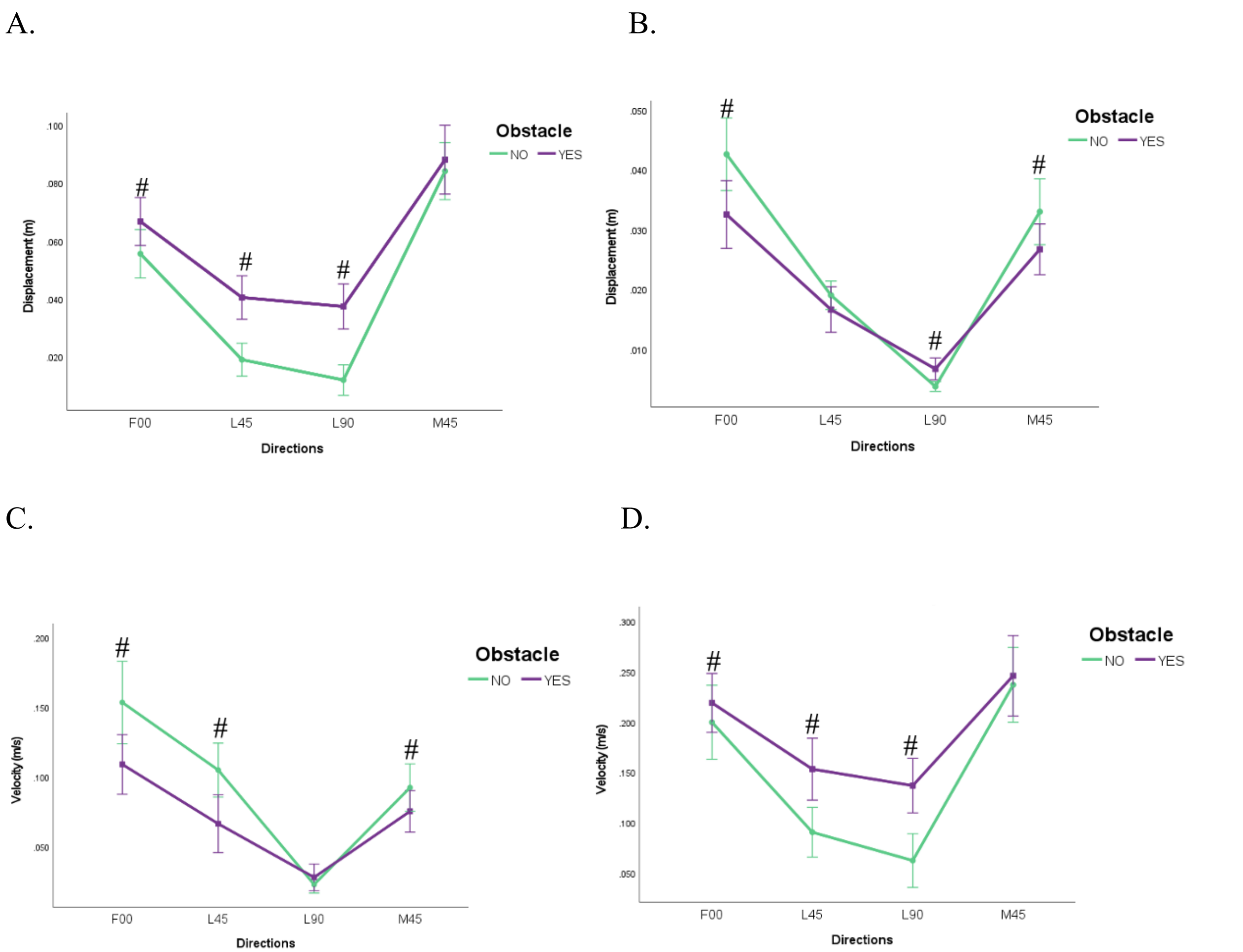
D.

No Obstacle / Obstacle	**F00** 0.200 ± 0.017	**L45** 0.090 ± 0.011	**L90** 0.062 ± 0.012	**M45** 0.237 ± 0.017
F00 0.219 ± 0.014	<0.05 #	<0.001 ***	<0.001 ***	<0.05 *
L45 0.153 ± 0.014	<0.001 ***	<0.001 ###	<0.05 *	<0.001 ***
L90 0.136 ± 0.013	<0.001 ***	NS	<0.001 ###	<0.001 ***
M45 0.246 ± 0.019	NS	<0.001 ***	<0.001 ***	NS

Note. Note. The value under the bolded direction is mean ± standard error. The unit for displacements is meters, and the unit for the velocity is meters per second. Direction effect : ***$p < 0.001$. ** $p < 0.01$. * $p < 0.05$. Obstacle effect : ### $p < 0.001$. ## $p < 0.01$. # $p<0.05$.

Figure 4.2

Obstacle effect on A: ML COP displacement, B: AP COP displacement, C: ML COP velocity and D: AP COP velocity.



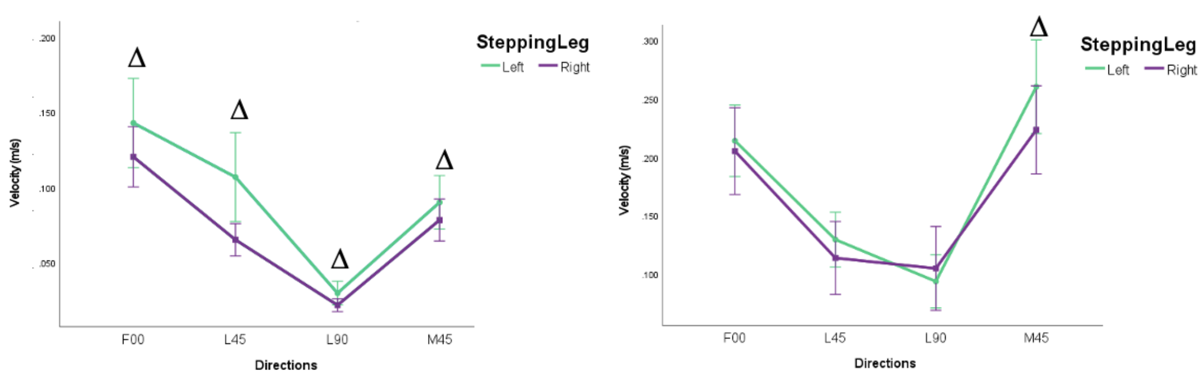
Note. The green line indicates the GI without the obstacle and the purple line indicates the GI with the obstacle. #: statistical significance of obstacle effect. Error bars indicate 95% confidence intervals.

Moreover, there was a significant direction-stepping leg interaction effect in both ML COP velocity ($p = 0.004$, $\eta_p^2 = 0.289$) and AP COP velocity ($p = 0.036$, $\eta_p^2 = 0.195$). In the ML direction, the faster COP velocity was found in left-leg GI toward all directions (F00: L: 0.143 ± 0.014 m/s, R: 0.120 ± 0.009 m/s, $p = 0.009$; L45: L: 0.107 ± 0.014 m/s, R: 0.065 ± 0.005 m/s, $p = 0.003$; L90: L: 0.029 ± 0.004 m/s, R: 0.021 ± 0.002 m/s, $p = 0.013$; M45: L: 0.090 ± 0.008 m/s, R: 0.078 ± 0.006 m/s, $p = 0.029$; figure 4.3A). While in the AP direction, higher COP velocity only found in the left-leg GI toward M45 (L: 0.260 ± 0.019 m/s, R: 0.223 ± 0.017 m/s, $p = 0.001$; figure 4.3B). It is noteworthy that although ML and AP COP velocity displayed different pattern of change in each direction under the effect of the stepping leg, the stepping direction that showed changes all indicated a higher velocity on the left-leg GI.

Figure 4.3

Stepping leg effect on A: ML COP velocity and B: AP COP velocity

A. B.



Note. The green line indicates the GI without the left leg (non-dominant leg) and the purple line indicates the GI with the right leg (dominant leg). Δ: statistical significance of leg dominance effect. Error bars indicate 95% confidence intervals.

Stepping Characteristics

In the step execution phase, the stepping characteristic also presented some interesting findings. There was a significant direction-obstacle effect in the step distance ($p < 0.001$, $\eta_p^2 =$

0.417). The post hoc test results in table 4.3A showed that the M45 had the greatest step distance (without obstacle: 0.698 ± 0.016 m; obstacle: 0.786 ± 0.019 m), and the step distance decreased as the stepping direction moved laterally toward L90 (without obstacle: F00: 0.601 ± 0.018 m, L45: 0.438 ± 0.012 m, L90: 0.300 ± 0.014 m; with obstacle: F00: 0.696 ± 0.013 m, L45: 0.579 ± 0.010 m, L90:0.435 ± 0.011 m). An illustration in the figure 4.4A shows a uniform increase in step distance toward all direction under the presence of the obstacle. No leg difference was observed in both the step distance and step path distance.

Furthermore, as displayed in table 4.3B, the same trend where the magnitude decreased as the laterality increased from M45 to L90 could be also found in the step velocity. This trend persisted in the presence of the obstacle, and the obstacle increased step velocity significantly in all stepping directions, which can be observed in figure 4.4B. There was a significant main effect of the stepping leg where the left leg (1.325 ± 0.037 m/s) was stepping significantly faster than the right leg (1.228 ± 0.034 m/s, $p < 0.001$). Step width range, a variability measurement, in no obstacle stepping did not differentiate between directions except in the L90 where the metric magnitude was significantly higher than the rest of the directions (L90: 0.270 ± 0.009 m; F00: 0.200 ± 0.011 m, $p = 0.001$; L45: 0.219 ± 0.009 m, $p = 0.002$; M45: 0.223 ± 0.010 m, $p = 0.003$; table 4.3C). The presence of the obstacle did not alter this pattern, yet it magnified the magnitude of the step width range in each direction (L90: 0.776 ± 0.066 m; F00: 0.471 ± 0.025 m, $p < 0.001$; L45: 0.500 ± 0.032 m, $p < 0.001$; M45: 0.483 ± 0.031 m, $p = 0.001$; figure 4.4C). No leg effect was observed in these two variables.

Table 4.3

Directional effect on A: step distance, B: step velocity, C: step width range.

A.

Obstacle \ No Obstacle	**F00** 0.601 ± 0.018	**L45** 0.438 ± 0.012	**L90** 0.300 ± 0.014	**M45** 0.698 ± 0.016
F00 0.696 ± 0.013	<0.001 ###	<0.001 ***	<0.001 ***	<0.001 ***
L45 0.579 ± 0.010	<0.001 ***	<0.001 ###	<0.001 ***	<0.001 ***
L90 0.435 ± 0.011	<0.001 ***	<0.001 ***	<0.001 ###	<0.001 ***
M45 0.786 ± 0.019	<0.001 ***	<0.001 ***	<0.001 ***	<0.001 ###

B.

Obstacle \ No Obstacle	**F00** 1.301 ± 0.045	**L45** 1.000 ± 0.028	**L90** 0.737 ± 0.028	**M45** 1.479 ± 0.051
F00 1.489 ± 0.044	<0.001 ###	<0.001 ***	<0.001 ***	<0.001 ***
L45 1.359 ± 0.033	<0.001 ***	<0.001 ###	<0.001 ***	<0.001 ***
L90 1.254 ± 0.041	<0.001 ***	<0.001 ***	<0.001 ###	<0.001 ***
M45 1.596 ± 0.045	<0.01 **	<0.001 ***	<0.001 ***	<0.01 ##

C.

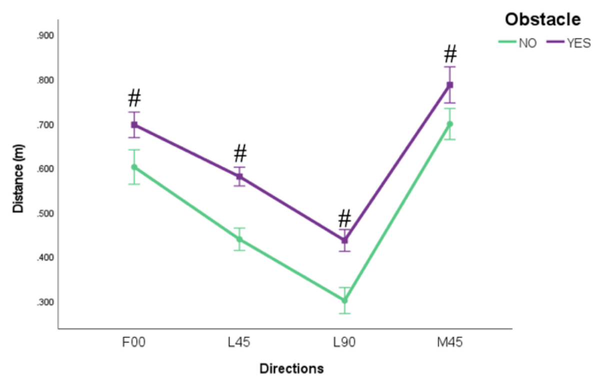
No Obstacle / Obstacle	**F00** 0.200 ± 0.011	**L45** 0.219 ± 0.009	**L90** 0.270 ± 0.009	**M45** 0.223 ± 0.010
F00 0.471 ± 0.025	<0.001 ###	NS	<0.01 **	NS
L45 0.500 ± 0.032	NS	<0.001 ###	<0.01 **	NS
L90 0.776 ± 0.066	<0.001 ***	<0.001 ***	<0.001 ###	<0.01 **
M45 0.483 ± 0.031	NS	NS	<0.01 **	<0.001 ###

Note. The value under the bolded direction is mean ± standard error. The unit for step distance and step width range is meters, and the unit for step velocity is meters per second. Direction effect : ***$p < 0.001$. ** $p < 0.01$. * $p < 0.05$. Obstacle effect : ### $p < 0.001$. ## $p < 0.01$. # $p<0.05$.

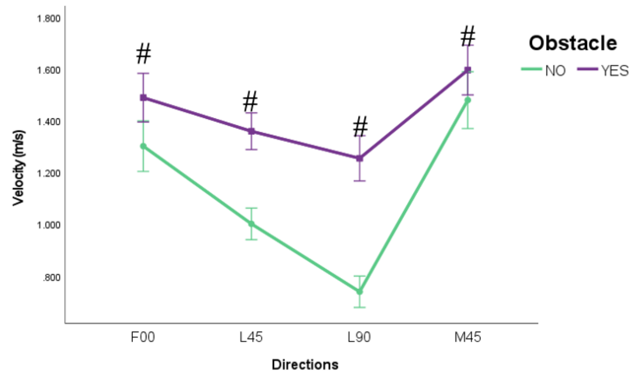
Figure 4.4

Obstacle effect on A: step distance, B: step velocity and C: step width range.

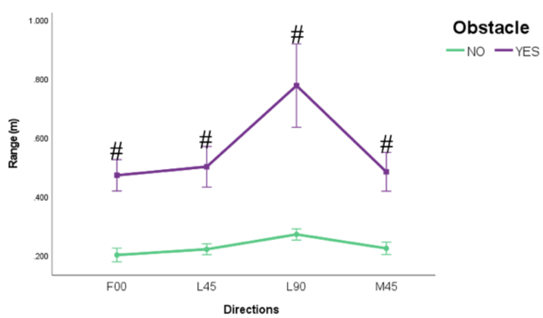
A.



B.



C.



Note. The green line indicates the GI without the obstacle and the purple line indicates the GI with the obstacle. #: statistical significance of obstacle effect. Error bars indicate 95% confidence intervals.

Chapter 5: Discussion

The ability to perform and adapt GI under various environmental constraints is critical to an individual's quality of living. To our knowledge, this is the first study investigating how stepping leg, stepping direction, and obstacle negotiation affect anticipatory postural control and stepping kinematics in GI. In the current study, individuals performed GI toward four directions ranging from medial 45 degrees to lateral 90 degrees with right and left legs, and in the presence or absence of an obstacle. Overall, the results showed that both COP and stepping kinematics were influenced by stepping direction, obstacle, and the GI leg.

Stepping Directions and Postural Control Characteristic

Previous evidence has established that the APA activities in AP and ML directions contribute differently to a forward GI, where the AP COP displacement provides a mechanical advantage for forward propulsion, and the ML COP displacement promotes lateral center of mass shift to unload the swing leg (Yiou et al., 2017). Aruin (2002) had reviewed the effect of movement direction and magnitude on the APA in voluntary movements. Lately, Inaba et al. (2020) evaluated the adaptability of APA in a multidirectional stepping task and found a decreasing trend of AP and ML APA activities (quantified as COP displacements) when the stepping direction shifted laterally. The pattern of change from this study (see table 4.2 A B and figure 4.2 A B) agreed with the finding from the Inaba's group (2020). Previous evidence showed that in the APA phase, the AP COP displacement was associated with the torque generation of the ankle plantar flexors which provided forward acceleration in GI (Park et al., 2009). As the stepping directions shifted toward L45 and L90, the demand for forward propulsion decreased resulting in a reduction of AP COP displacement. In the ML direction, a decreased COP displacement might be related to the change in stepping technique. When performing GI toward L45 and L90, at the instance when the swing leg was lifted off the ground, the falling caused by the center of gravity outside the stance leg base of support became in line with the direction of stepping which contributed to the lateral propulsion. Commonly in forward GI, individuals use a weight shifting technique to move the center of mass over the stance leg and lift the swing leg, yet with lateral stepping the stance leg is pivoted to propel the center of mass laterally (Patla et al., 1993). Mechanically, this technique allows for the execution of lateral stepping without completely moving the center of gravity over the stance leg while still maintaining postural stability and providing a fulcrum for lateral GI (Yiou et al., 2012). In another words, the pivoting technique associated with lateral GI transfers the postural perturbation to a mechanical leverage that facilitates lateral movement. Although this technique has been documented in lateral stepping (Patla et al., 1993) and in the current study of lateral GI, future analysis of movement kinematics will be required to confirm the use of this technique.

Furthermore, the investigation of voluntary medial GI in healthy young adults was a novel addition to the current literature. During the process of M45 GI, individuals moved their swing leg further and across the body before heel strike, which resulted in substantial ML postural perturbations. These perturbations were counteracted by a greater ML COP displacement in APA phase, as shown by a larger ML COP displacement in comparison to forward GI. In the AP direction, since the center of mass acceleration of the M45 GI was not executed directly forward but toward medial 45 degrees, the COP displacement in AP direction, that was associated with the forward propulsive force (Yiou et al., 2017), was reduced. These anticipatory postural control findings in M45 GI offer an insight to the GI strategy for individuals with high risk of fall or balance impairments. Since stepping with different legs toward M45 and L45 can lead to the same moving direction, for example, stepping with right leg toward M45 and left leg toward L45 (see figure 3.1), the selection of the movement strategy becomes critical. Stepping toward M45 elicited significant longer APA duration and greater COP displacements in both AP and ML directions than toward L45. Previous studies on the scaling of APA in upper body movements have positively associated the magnitude of APA with the predicted disturbance and the stability condition of the body (Toussaint et al., 1998; Yiou et al., 2009). Current study supports that the M45 GI will impose a larger postural perturbation and represented a less stable movement strategy for GI than L45 with the opposite leg when stepping toward the same direction. Overall, individuals with postural impairments are recommended to avoid medial cross-body GI to prevent falls from inability to compensate for large postural perturbations.

In the APA phase, additional to the magnitude and duration metrics, the COP velocity can provide insights into the postural control strategies related to GI. Reductions in COP velocities in forward GI have been found in groups with various clinical conditions, such as individuals with obesity (Cau et al., 2014), people following an acute concussion (Buckley et al., 2020), people with Parkinson's Disease, and elderly population with postural instability (Hass et al., 2008). In the current study, since all participants were healthy and performed multidirectional GI in a self-selected pace, the most likely explanation to the reductions in COP velocity were the lateral shift in stepping directions. Generally, decreasing trends are seen in both AP and ML COP velocity with the slowest velocities of both AP and ML directions in L90 and the greatest velocities in either M45 or F00. A similar pattern exists in the duration and magnitude metrics of the APA; for instance, in GI without the obstacle, the ML COP velocity to L90 is 15% of the one in F00, and the COP displacement is 20% of the ones in F00. These patterns might be related to the fact that the COP movement in the APA phase must be slowed down when reaching the APA peak to accelerate away from the swing leg to unload it. Previous evidence has demonstrated importance of force generation and force control in the organization of GI APA which includes the COP displacement and COP velocity (Khanmohammadi et al., 2016; Yiou et al., 2011, 2012). Therefore, proper control of the neuromuscular system is critical in directional adaptations of the multidirectional GI, and populations with reduced COP velocity in GI are likely to benefit from enhancing neuromuscular capacity.

Stepping directions and step characteristics

The stepping motions of GI without the obstacle were directional specific. The step distance and step velocity all decreased with the lateral shift of the stepping direction, while the step duration remained constant in all directions. In another word, the time it took to complete the first step of GI was independent of the change in stepping direction. Considering the high degree of changes in step distance and step velocity, this finding was not expected, and the reason for such insensitivity was unknown. According to Krasovsky & Levin (2010), temporal measures, such as discrete relative phase and continuous relative phase measurements, are a meaningful tool for gait coordination assessment. Although step duration was the simplest form of the temporal measure, it still provides a clue for the future research in evaluating gait coordination under directional constraints.

In previous works, shortened step distance and slowed step velocity in GI had been correlated with aging (Muir et al., 2014), risk of fall in elderly (Mbourou et al., 2003), and encountering a situation that might impose a threat to the integrity of posture, for example, a slippery floor (Espy et al., 2010), but the reductions seen in this study might be contributed by the change in stepping techniques (Patla et al., 1993). As mentioned before, the lateral GI utilized a pivoting technique that required the stance leg to pivot to propel the center of mass in the direction of stepping. This technique, in comparison to the weight shift and unloading technique in the F00 GI, resulted in smaller COP displacements and reduced acceleration of the center of mass toward the stepping direction. The reduction in the center of mass acceleration in combination with the limited range of rotational motion in the hip (Cheatham et al., 2017) could result in a shortened step length and decreased step velocity. Due to individualized mobility capacities and movement strategies, movement practitioners should be familiar with the effect of this pivoting technique seen in the lateral GI, so that individuals underwent rehabilitation programs can be more functional and be less restricted in daily tasks.

The movement variability, which was quantified by step width range, was constant in all stepping directions, except in L90. When GI occurred toward L90, individuals showed significantly higher variability in their step trajectories. According to the dynamical systems theory which proposes that the movement variability is a searching strategy where the individual looks for the most stable movement solution (Stergiou & Decker, 2011), the observed increase in variability might relate to the novel lateral stepping technique. Since this novel technique is not a dominating gait pattern of daily life and sports (Glaister et al., 2007; Taylor et al., 2017), its performance accompanies with an active optimizing searching process, which is shown as an increased movement variability. Although learning effect can occur after practices, the formation of a stable movement solution normally takes weeks or even years (Bergmann et al., 2021; Ericsson et al., 1993). The short familiarization period before the data collection was not adequate. Nevertheless, it was uncertain whether this increased variability negatively affect the performance among healthy young adults because all participants successfully executed the lateral GI; future investigations on the variability of lateral GI among different population were recommended to provide insights for fall prevention among elderly and individuals with clinical conditions.

The obstacle negotiation on postural control and stepping kinematics

The act of obstacle negotiation during gait results in an elevated step height, increased step duration, and further projection of the center of mass (Chien et al., 2018; Lowrey et al., 2007; Shin et al., 2015). These characteristics were also observed in the GI with an obstacle.

Yiou, Fourcade, et al. (2016) documented the scaling of the anticipatory COP displacements in response to an obstacle negotiation. In their forward GI experiment, the ML center of mass displacement increased, while the AP center of mass displacement decreased with the presence of the obstacle (Yiou, Fourcade, et al., 2016). These changes were also observed in the current study. Since clearing the obstacle required a longer step duration and a larger step height meaning greater postural perturbations, the APA whose primary functions were to counteract the postural perturbations in the stepping phase were also up scaled. Additionally, the participants in the current study demonstrated an increased APA duration in the presence of the obstacle which contrasted the previous work (Yiou, Fourcade, et al., 2016). This discrepancy, potentially, could be related to the statistical analysis method used by Yiou, Fourcade, et al. (2016) where the APA duration from self-initiated GI was combined with the APA duration from time-pressured GI to assess the effect of obstacle. The results from current study supplement the effect of an obstacle in self-initiated GI alone, which is that an additional obstacle actually increased the APA duration.

When examining the effect of the obstacle in non-forward stepping directions, the change in postural control and stepping kinematics were not consistent across all directions. The M45 was not changed by the presence of the obstacle for APA duration and ML COP displacement metrics, and the AP COP displacement in L45 was not affected by the presence of the obstacle. When examining COP velocity responses to the presence of the obstacle, the ML COP velocity decreased in all directions, except L90, and the AP COP velocity increased in all directions but M45. The specific reason for these non-responding directions was unclear. Since the APA generated is based on previous experience and learning (Kanekar & Aruin, 2015), it is possible that the APAs generated in these specific non-responding directions under the obstacle condition are novel and inaccurate, which are then compensated in the step execution phase.

The obstacle increased all stepping metrics including the duration, distance, velocity, and variability, and these changes were observed in all stepping directions. The increases in the stepping metrics were related to the obstacle clearing technique, which had been documented by previous studies (Chien et al., 2018; Lowrey et al., 2007; Shin et al., 2015; Yiou, Artico, et al., 2016), yet the increased variability with obstacle negotiation during GI was novel. Because gait variability is associated with supraspinal control (Lo et al., 2017), walking on an uneven surface or simultaneously performing a cognitive or manual task, that requires actively involvement of the functional brain network, will inevitably increase gait variability (Nohelova et al., 2021). In this study, the obstacle negotiation was a secondary task that demanded the supraspinal control, which in turn, caused a universal increase in movement variability during the multidirectional GI. Although the use of range in step width to quantify step variability is a generalized method, the information provided by this metric still cannot be overlooked.

The stepping leg and multidirectional GI

When the participants were stepping with the dominant leg, APA duration was increased, while no change in APA magnitudes between legs were found. The effect of leg dominance in anticipatory postural control during GI was reported by Yiou and Do (2010) where an increased APA duration and higher center of gravity (the ratio between the ground reaction force and subject's mass) displacement and velocity were found in dominant leg GI. The current study further demonstrated this pattern of change in APA duration of GI toward multiple directions. Additionally, ML COP velocity in non-dominant leg stepping was larger in all stepping directions, while the AP COP velocity only significantly differed in M45 direction where the non-dominant leg was faster. Stepping with the dominant leg also showed significantly longer duration in the step execution phase, which was consistent with the previous evidence (Dessery et al., 2011). According to the dynamic dominance theory, the right limb is specialized in dynamic control task while the left limb is impedance control focused Bot. Although a previous investigation in a lower limb aiming task did not exhibit leg specialization because of the bilateral nature of the lower limb movements (Marcori et al., 2020b), the asymmetrical findings in this study might showed the otherwise. Since all the participants were right foot dominant, when stepping with the dominant leg (right leg), the non-dominant leg (the left leg) was supporting on the ground for a longer period, which corresponds to the better stability control on the left leg finding in the study by Marcori et al. (2020). Clearly, this aspect alone is not adequate for making a conclusion; further investigation with more tasks and individuals with different leg dominance might be needed.

Limitations

One limitation of the current study concerns the sample of subjects. Our experiment only included right-footed college-age individuals. Although there was not an inclusion criteria about lower limb preference, the left-footed and mixed-footed individuals were too few to recruit. It is necessary to verify the findings in individuals with different lower limb preference to generalize the findings. All participants were physically active with more than 300 minutes exercise volume per week and in normal weight range. We cannot speculate if similar movement adaptations to be observed in overweight population or individuals with sedentary lifestyle.

Conclusion

The current study demonstrated that during GI, the anticipatory postural control was modulated to the perceived magnitude of postural perturbations associated with multidirectional elements, obstacle negotiation, and leg preference, while the adaptability of the stepping motion was related to the demands of the GI condition. When performing GI under unfamiliar constraints, movement variability increased and APA accuracy decreased, but these alterations did not affect the completion of GI in healthy young adults. In lateral GI, an emergent pivoting technique was utilized to transform the lateral postural perturbation in weight shift to a mechanical advantage that allowed lateral propulsion. In the presence of the obstacle, mediolateral APA were magnified to satisfy the demand of obstacle negotiation, and the stepping kinematic variables were up scaled to overcome the obstacle. Stepping with dominant leg was slower and possessed a longer APA phase and step execution phase. These findings emphasize the adaptability of GI respect to various constraints and provide movement alteration patterns for clinical practitioners and researchers.

Reference

Aboutorabi, A., Arazpour, M., Bahramizadeh, M., Hutchins, S. W., & Fadayevatan, R. (2015). The effect of aging on gait parameters in able-bodied older subjects: a literature review. *Aging Clinical and Experimental Research 2015 28:3*, *28*(3), 393–405. https://doi.org/10.1007/S40520-015-0420-6

Ahl, L. E., Johansson, E., Granat, T., & Carlberg, E. B. (2005). Functional therapy for children with cerebral palsy: an ecological approach. *Developmental Medicine and Child Neurology*, *47*(9), 613–619. https://doi.org/10.1017/S0012162205001210

Aruin, A. (2002). The organization of anticipatory postural adjustments. *Journal of Automatic Control*, *12*(1), 31–37. https://doi.org/10.2298/JAC0201031A

Aruin, A. S., Forrest, W. R., & Latash, M. L. (1998). Anticipatory postural adjustments in conditions of postural instability. *Electroencephalography and Clinical Neurophysiology/Electromyography and Motor Control*, *109*(4), 350–359. https://doi.org/10.1016/S0924-980X(98)00029-0

Aruin, A. S., & Latash, M. L. (1995). The role of motor action in anticipatory postural adjustments studied with self-induced and externally triggered perturbations. *Experimental Brain Research*, *106*(2), 291–300. https://doi.org/10.1007/BF00241125

Aruin, A. S., Ota, T., & Latash, M. L. (2001). Anticipatory postural adjustments associated with lateral and rotational perturbations during standing. *Journal of Electromyography and Kinesiology*, *11*(1), 39–51. https://doi.org/10.1016/S1050-6411(00)00034-1

Bagesteiro, L. B., & Sainburg, R. L. (2002). Handedness: Dominant arm advantages in control of limb dynamics. *Journal of Neurophysiology*, *88*(5), 2408–2421. https://doi.org/10.1152/JN.00901.2001

Barone, R., Macaluso, F., Traina, M., Leonardi, V., Farina, F., & Felice, V. di. (2011). Soccer players have a better standing balance in nondominant one-legged stance. *Open Access Journal of Sports Medicine*, *2*, 1. https://doi.org/10.2147/OAJSM.S12593

Beckers, L. W. M. E., Geijen, M. M. E., Kleijnen, J., Rameckers, E. A. A., Schnackers, M. L. A. P., Smeets, R. J. E. M., & Janssen-Potten, Y. J. M. (2020). Feasibility and effectiveness of home-based therapy programmes for children with cerebral palsy: a systematic review. *BMJ Open*, *10*(10). https://doi.org/10.1136/BMJOPEN-2019-035454

Belenkii, V. E., Gurfinkel, V. S., & Paltsev, E. I. (1967). On the control elements of voluntary movements. *Biofizika*, *12*(1), 135–141.

Berg, W. P., & Strang, A. J. (2012). The role of electromyography (EMG) in the study of anticipatory postural adjustments. *Applications of EMG in Clinical and Sports Medicine*. https://doi.org/10.5772/25388

Bergmann, F., Gray, R., Wachsmuth, S., & Höner, O. (2021). Perceptual-motor and perceptual-cognitive skill acquisition in soccer: A systematic review on the influence of practice design and coaching behavior. *Frontiers in Psychology*, *12*. https://doi.org/10.3389/fpsyg.2021.772201

Bisseling, R. W., & Hof, A. L. (2006). Handling of impact forces in inverse dynamics. *Journal of Biomechanics*, *39*(13), 2438–2444. https://doi.org/10.1016/J.JBIOMECH.2005.07.021

Bonora, G., Mancini, M., Carpinella, I., Chiari, L., Horak, F. B., & Ferrarin, M. (2017). Gait initiation is impaired in subjects with Parkinson's disease in the OFF state: Evidence from the analysis of the anticipatory postural adjustments through wearable inertial sensors. *Gait & Posture*, *51*, 218–221. https://doi.org/10.1016/J.GAITPOST.2016.10.017

Brenière, Y., & Do, M. C. (1991). Control of Gait Initiation. *Journal of Motor Behavior*, *23*(4), 235–240. https://doi.org/10.1080/00222895.1991.9942034

Buckley, T. A., Munkasy, B. A., Krazeise, D. A., Oldham, J. R., Evans, K. M., & Clouse, B. (2020). Differential effects of acute and multiple concussions on gait initiation performance. *Archives of Physical Medicine and Rehabilitation*, *101*(8), 1347–1354. https://doi.org/10.1016/J.APMR.2020.03.018

Buckley, T. A., Oldham, J. R., Munkasy, B. A., & Evans, K. M. (2017). Decreased anticipatory postural adjustments during gait initiation acutely post-concussion. *Archives of Physical Medicine and Rehabilitation*, *98*(10), 1962. https://doi.org/10.1016/J.APMR.2017.05.002

Caderby, T., Yiou, E., Peyrot, N., Begon, M., & Dalleau, G. (2014). Influence of gait speed on the control of mediolateral dynamic stability during gait initiation. *Journal of Biomechanics*, *47*(2), 417–423. https://doi.org/10.1016/J.JBIOMECH.2013.11.011

Callisaya, M. L., Blizzard, L., Martin, K., & Srikanth, V. K. (2016). Gait initiation time is associated with the risk of multiple falls-A population-based study. *Gait & Posture*, *49*, 19–24. https://doi.org/10.1016/J.GAITPOST.2016.06.006

Cameron, M. H., & Wagner, J. M. (2011). Gait abnormalities in multiple sclerosis: Pathogenesis, evaluation, and advances in treatment. *Current Neurology and Neuroscience Reports 2011 11:5*, *11*(5), 507–515. https://doi.org/10.1007/S11910-011-0214-Y

Cano-de-la-Cuerda, R., Molero-Sánchez, A., Carratalá-Tejada, M., Alguacil-Diego, I. M., Molina-Rueda, F., Miangolarra-Page, J. C., & Torricelli, D. (2015). Theories and control models and motor learning: Clinical applications in neurorehabilitation. *Neurología (English Edition)*, *30*(1), 32–41. https://doi.org/10.1016/J.NRLENG.2011.12.012

Castañer, M., Andueza, J., Hileno, R., Puigarnau, S., Prat, Q., & Camerino, O. (2018). Profiles of motor laterality in young athletes' performance of complex movements: Merging the MOTORLAT and PATHoops tools. *Frontiers in Psychology*, *9*(JUN), 916. https://doi.org/10.3389/FPSYG.2018.00916

Cau, N., Cimolin, V., Galli, M., Precilios, H., Tacchini, E., Santovito, C., & Capodaglio, P. (2014). Center of pressure displacements during gait initiation in individuals with obesity. *Journal of NeuroEngineering and Rehabilitation*, *11*(1), 1–8. https://doi.org/10.1186/1743-0003-11-82

Chang, H. A., Chuang, T. Y., Lee, S. J., Liao, S. F., Lee, H. C., Shih, Y. H., & Cheng, H. (2004). Temporal differences in relative phasing of gait initiation and first step length in patients with cervical and lumbosacral spinal cord injuries. *Spinal Cord 2004 42:5*, *42*(5), 281–289. https://doi.org/10.1038/sj.sc.3101587

Cheatham, S., Hanney, W. J., & Kolber, M. J. (2017). Hip range of motion in recreational weight training participants: A descriptive report. *International Journal of Sports Physical Therapy*, *12*(5), 764–773.

Chen, B., Liu, P., Xiao, F., Liu, Z., & Wang, Y. (2021). Review of the upright balance assessment based on the force plate. *International Journal of Environmental Research and Public Health 2021, Vol. 18, Page 2696*, *18*(5), 2696. https://doi.org/10.3390/IJERPH18052696

Chien, J. H., Post, J., & Siu, K.-C. (2018). Effects of aging on the obstacle negotiation strategy while stepping over multiple obstacles. *Scientific Reports*, *8*(1), 8576. https://doi.org/10.1038/s41598-018-26807-5

Clark, M. E., McEwan, K., & Christie, C. J. (2018). The effectiveness of constraints-led training on skill development in interceptive sports: A systematic review: *International Journal of Sports Science & Coaching*, *14*(2), 229–240. https://doi.org/10.1177/1747954118812461

Dessery, Y., Barbier, F., Gillet, C., & Corbeil, P. (2011). Does lower limb preference influence gait initiation? *Gait & Posture*, *33*(4), 550–555. https://doi.org/10.1016/j.gaitpost.2011.01.008

Ericsson, K. A., Krampe, R. T., & Tesch-Römer, C. (1993). The role of deliberate practice in the acquisition of expert performance. *Psychological Review*, *100*(3), 363–406. https://doi.org/10.1037/0033-295X.100.3.363

Espy, D. D., Yang, F., Bhatt, T., & Pai, Y.-C. (2010). Independent influence of gait speed and step length on stability and fall risk. *Gait & Posture*, *32*(3), 378–382. https://doi.org/10.1016/j.gaitpost.2010.06.013

Fajen, B. R., Riley, M. A., & Turvey, M. T. (2008). Information, affordances, and the control of action in sport. *International Journal of Sport Psychology*, *40*(1), 79–107.

Fousekis, K., Tsepis, E., & Vagenas, G. (2010). Lower limb strength in professional soccer players: Profile, asymmetry, and training age. *Journal of Sports Science & Medicine*, *9*(3), 364.

Fraser, J. J., Hart, J. M., Saliba, S. F., Park, J. S., Tumperi, M., & Hertel, J. (2019). Multisegmented ankle-foot kinematics during gait initiation in ankle sprains and chronic ankle instability. *Clinical Biomechanics*, *68*, 80–88. https://doi.org/10.1016/J.CLINBIOMECH.2019.05.017

Furlong, L. A. M., & Harrison, A. J. (2014). Differences in plantarflexor function during a stretch-shortening cycle task due to limb preference. *Laterality*, *20*(2), 128–140. https://doi.org/10.1080/1357650X.2014.921688

Gioia, G. A., & Isquith, P. K. (2011). Ecological assessment of executive function in traumatic brain injury. *Developmental Neuropsychology*, *25*(1–2), 135–158. https://doi.org/10.1080/87565641.2004.9651925

Glaister, B. C., Bernatz, G. C., Klute, G. K., & Orendurff, M. S. (2007). Video task analysis of turning during activities of daily living. *Gait & Posture*, *25*(2), 289–294. https://doi.org/10.1016/J.GAITPOST.2006.04.003

Gray, R. (2018). Comparing cueing and constraints interventions for increasing launch angle in baseball batting. *Sport, Exercise, and Performance Psychology*, *7*(3), 318–332. https://doi.org/10.1037/SPY0000131

Hadzic, V., Sattler, T., Veselko, M., Markovic, G., & Dervisevic, E. (2014). Strength asymmetry of the shoulders in elite volleyball players. *Journal of Athletic Training*, *49*(3), 338–344. https://doi.org/10.4085/1062-6050-49.2.05

Hall, L. M., Brauer, S., Horak, F., & Hodges, P. W. (2010). Adaptive changes in anticipatory postural adjustments with novel and familiar postural supports. *Journal of Neurophysiology*, *103*(2), 968–976. https://doi.org/10.1152/JN.00479.2009

Hallemans, A., Ortibus, E., Meire, F., & Aerts, P. (2010). Low vision affects dynamic stability of gait. *Gait & Posture*, *32*(4), 547–551. https://doi.org/10.1016/J.GAITPOST.2010.07.018

Hase, K., & Stein, R. B. (1999). Turning strategies during human walking. *Journal of Neurophysiology*, *81*(6), 2914–2922. https://doi.org/10.1152/JN.1999.81.6.2914

Hass, C. J., Waddell, D. E., Wolf, S. L., Juncos, J. L., & Gregor, R. J. (2008). Gait initiation in older adults with postural instability. *Clinical Biomechanics*, *23*(6), 743–753. https://doi.org/10.1016/J.CLINBIOMECH.2008.02.012

Herbort, O., & Butz, M. v. (2010). Planning and control of hand orientation in grasping movements. *Experimental Brain Research*, *202*(4), 867–878. https://doi.org/10.1007/S00221-010-2191-9

Higginson, B. K. (2009). Methods of running gait analysis. *Current Sports Medicine Reports*, *8*(3), 136–141. https://doi.org/10.1249/JSR.0B013E3181A6187A

Hof, A. L., Gazendam, M. G. J., & Sinke, W. E. (2005). The condition for dynamic stability. *Journal of Biomechanics*, *38*(1), 1–8. https://doi.org/10.1016/j.jbiomech.2004.03.025

Honeine, J. L., Schieppati, M., Crisafulli, O., & Do, M. C. (2016). The neuro-mechanical processes that underlie goal-directed medio-lateral APA during gait initiation. *Frontiers in Human Neuroscience*, *10*(AUG2016), 445. https://doi.org/10.3389/FNHUM.2016.00445

Inaba, Y., Suzuki, T., Yoshioka, S., & Fukashiro, S. (2020). Directional control mechanisms in multidirectional step initiating tasks. *Frontiers in Human Neuroscience*, *14*, 178. https://doi.org/10.3389/FNHUM.2020.00178

Ipek, F., Doğan, M., Yildiz Kabak, V., Atasavun Uysal, S., & Düger, T. (2021). Cross-cultural adaptation, validity and reliability of Turkish version of the Waterloo Handedness and

Footedness Questionnaire-Revised. *Laterality*, *26*(6), 624–644. https://doi.org/10.1080/1357650X.2021.1882479

Ivanenko, Y., & Gurfinkel, V. S. (2018). Human postural control. *Frontiers in Neuroscience*, *12*(MAR), 171. https://doi.org/10.3389/FNINS.2018.00171

Jacobs, J. v., Nutt, J. G., Carlson-Kuhta, P., Stephens, M., & Horak, F. B. (2009). Knee trembling during freezing of gait represents multiple anticipatory postural adjustments. *Experimental Neurology*, *215*(2), 334–341. https://doi.org/10.1016/J.EXPNEUROL.2008.10.019

Kaewmanee, T., Liang, H., & Aruin, A. S. (2020). Effect of predictability of the magnitude of a perturbation on anticipatory and compensatory postural adjustments. *Experimental Brain Research 2020 238:10*, *238*(10), 2207–2219. https://doi.org/10.1007/S00221-020-05883-Y

Kanekar, N., & Aruin, A. S. (2015). Improvement of anticipatory postural adjustments for balance control: Effect of a single training session. *Journal of Electromyography and Kinesiology*, *25*(2), 400–405. https://doi.org/10.1016/J.JELEKIN.2014.11.002

Khanmohammadi, R., Talebian, S., Hadian, M. R., Olyaei, G., & Bagheri, H. (2016). Characteristic muscle activity patterns during gait initiation in the healthy younger and older adults. *Gait & Posture*, *43*, 148–153. https://doi.org/10.1016/J.GAITPOST.2015.09.014

Kimijanová, J., Bzdúšková, D., Hirjaková, Z., & Hlavačka, F. (2021). Age-related changes of the anticipatory postural adjustments during gait initiation preceded by vibration of lower leg muscles. *Frontiers in Human Neuroscience*, *15*. https://doi.org/10.3389/FNHUM.2021.771446

Kimijanová, J., Hirjaková, Z., Bzdúšková, D., & Hlavačka, F. (2021). Influence of vision on gait initiation and first step kinematics in young and older adults. *Physiological Research*, *70*(S3), S409–S417. https://doi.org/10.33549/PHYSIOLRES.934813

King, A. C., & Wang, Z. (2017). Asymmetrical stabilization and mobilization exploited during static single leg stance and goal directed kicking. *Human Movement Science*, *54*, 182–190. https://doi.org/10.1016/j.humov.2017.05.004

Knox, M. F., Chipchase, L. S., Schabrun, S. M., & Marshall, P. W. M. (2016). Anticipatory and compensatory postural adjustments in people with low back pain: A protocol for a systematic review and meta-analysis. *Systematic Reviews*, *5*(1), 1–5. https://doi.org/10.1016/j.spinee.2018.06.008

Krasovsky, T., & Levin, M. F. (2010). Review: Toward a better understanding of coordination in healthy and poststroke gait. *Neurorehabilitation and Neural Repair*, *24*(3), 213–224. https://doi.org/10.1177/1545968309348509

Krishnan, V., Latash, M. L., & Aruin, A. S. (2012). Early and late components of feed-forward postural adjustments to predictable perturbations. *Clinical Neurophysiology*, *123*(5), 1016–1026. https://doi.org/10.1016/J.CLINPH.2011.09.014

Lee, Y. J., Liang, J. N., Chen, B., & Aruin, A. S. (2019). Characteristics of medial-lateral postural control while exposed to the external perturbation in step initiation. *Scientific Reports 2019 9:1*, *9*(1), 1–10. https://doi.org/10.1038/s41598-019-53379-9

Lo, O.-Y., Halko, M. A., Zhou, J., Harrison, R., Lipsitz, L. A., & Manor, B. (2017). Gait speed and gait variability are associated with different functional brain networks. *Frontiers in Aging Neuroscience*, *9*. https://doi.org/10.3389/fnagi.2017.00390

Lowrey, C. R., Watson, A., & Vallis, L. A. (2007). Age-related changes in avoidance strategies when negotiating single and multiple obstacles. *Experimental Brain Research*, *182*(3), 289–299. https://doi.org/10.1007/s00221-007-0986-0

Lu, C., Amundsen Huffmaster, S. L., Harvey, J. C., & MacKinnon, C. D. (2017). Anticipatory postural adjustment patterns during gait initiation across the adult lifespan. *Gait & Posture*, *57*, 182. https://doi.org/10.1016/J.GAITPOST.2017.06.010

Mancini, M., Zampieri, C., Carlson-Kuhta, P., Chiari, L., & Horak, F. B. (2009). Anticipatory postural adjustments prior to step initiation are hypometric in untreated Parkinson's disease: An accelerometer-based approach. *European Journal of Neurology : The Official Journal of the European Federation of Neurological Societies*, *16*(9), 1028. https://doi.org/10.1111/J.1468-1331.2009.02641.X

Marcori, A. J., Teixeira, L. A., Dascal, J. B., & Okazaki, V. H. A. (2020a). Are the predictions of the dynamic dominance model of laterality applicable to the lower limbs? *Human Movement Science*, *73*, 102684. https://doi.org/10.1016/J.HUMOV.2020.102684

Marcori, A. J., Teixeira, L. A., Dascal, J. B., & Okazaki, V. H. A. (2020b). Are the predictions of the dynamic dominance model of laterality applicable to the lower limbs? *Human Movement Science*, *73*. https://doi.org/10.1016/j.humov.2020.102684

Mariani, B., Hoskovec, C., Rochat, S., Büla, C., Penders, J., & Aminian, K. (2010). 3D gait assessment in young and elderly subjects using foot-worn inertial sensors. *Journal of Biomechanics*, *43*(15), 2999–3006. https://doi.org/10.1016/J.JBIOMECH.2010.07.003

Mark Latash. (2012). *Fundamentals of Motor Control*. Academic Press.

Maslivec, A., Fielding, A., Wilson, M., Norris, M., & Young, W. (2020). 'Recoupling' the attentional and motor control of preparatory postural adjustments to overcome freezing of gait in Parkinson's. *Journal of NeuroEngineering and Rehabilitation*, *17*(1), 1–13. https://doi.org/10.1186/S12984-020-00776-1/TABLES/2

Massion, J. (1994). Postural control system. *Current Opinion in Neurobiology*, *4*, 877–887.

Matsuda, S., Demura, S., & Uchiyama, M. (2008). Centre of pressure sway characteristics during static one-legged stance of athletes from different sports. *Journal of Sports Sciences*, *26*(7), 775–779. https://doi.org/10.1080/02640410701824099

Mbourou, G. A., Lajoie, Y., & Teasdale, N. (2003). Step length variability at gait initiation in elderly fallers and non-fallers, and young adults. *Gerontology*, *49*(1), 21–26. https://doi.org/10.1159/000066506

Meeuwisse, W. H. (1994). Assessing causation in sport injury a multifactorial model. *Clinical Journal of Sport Medicine*, *4*(3), 166–170.

Menz, H. B., Auhl, M., & Munteanu, S. E. (2017). Effects of indoor footwear on balance and gait patterns in community-dwelling older women. *Gerontology*, *63*(2), 129–136. https://doi.org/10.1159/000448892

Meyns, P., Bruijn, S. M., & Duysens, J. (2013). The how and why of arm swing during human walking. *Gait & Posture*, *38*(4), 555–562. https://doi.org/10.1016/J.GAITPOST.2013.02.006

Mornieux, G., Gehring, D., Fürst, P., & Gollhofer, A. (2014). Anticipatory postural adjustments during cutting manoeuvres in football and their consequences for knee injury risk. *Journal of Sports Sciences*, *32*(13), 1255–1262. https://doi.org/10.1080/02640414.2013.876508

Moy, B., Renshaw, I., & Pavey, T. (2020). Impact of the constraints-led approach on students' motor performance. *Journal of Physical Education and Sport*, *20*(6), 3345–3353. https://doi.org/10.7752/JPES.2020.06453

Muir, B. C., Rietdyk, S., & Haddad, J. M. (2014). Gait initiation: The first four steps in adults aged 20–25 years, 65–79 years, and 80–91 years. *Gait & Posture*, *39*(1), 490–494. https://doi.org/10.1016/j.gaitpost.2013.08.037

Mutha, P. K., Haaland, K. Y., & Sainburg, R. L. (2012). The effects of brain lateralization on motor control and adaptation. *Journal of Motor Behavior*, *44*(6), 455–469. https://doi.org/10.1080/00222895.2012.747482

Mutha, P. K., Haaland, K. Y., & Sainburg, R. L. (2013). Rethinking motor lateralization: specialized but complementary mechanisms for motor control of each arm. *PLOS ONE*, *8*(3), e58582. https://doi.org/10.1371/JOURNAL.PONE.0058582

Nam, H.-S., Kim, J.-H., & Lim, Y.-J. (2017). The effect of the base of support on anticipatory postural adjustment and postural stability. *The Journal of Korean Physical Therapy*, *29*(3), 135–141. https://doi.org/10.18857/JKPT.2017.29.3.135

Newell, K. M. (1986). Constraints on the development of coordination. *Motor Development in Children: Aspects of Coordination and Control*, 341–360. https://doi.org/10.1007/978-94-009-4460-2_19

Nohelova, D., Bizovska, L., Vuillerme, N., & Svoboda, Z. (2021). Gait variability and complexity during single and dual-task walking on different surfaces in outdoor environment. *Sensors*, *21*(14), 4792. https://doi.org/10.3390/s21144792

Nonnekes, J., Růžička, E., Nieuwboer, A., Hallett, M., Fasano, A., & Bloem, B. R. (2019). Compensation strategies for gait impairments in Parkinson disease: A review. *JAMA Neurology*, *76*(6), 718–725. https://doi.org/10.1001/JAMANEUROL.2019.0033

Nutt, J. G., Bloem, B. R., Giladi, N., Hallett, M., Horak, F. B., & Nieuwboer, A. (2011). Freezing of gait: moving forward on a mysterious clinical phenomenon. *The Lancet. Neurology*, *10*(8), 734. https://doi.org/10.1016/S1474-4422(11)70143-0

Park, S., Choi, H., Ryu, K., Kim, S., & Kim, Y. (2009). Kinematics, kinetics and muscle activities of the lower extremity during the first four steps from gait initiation to the steady-state walking. *Journal of Mechanical Science and Technology*, *23*(1), 204–211. https://doi.org/10.1007/S12206-008-0812-Z

Passos, P., Araújo, D., Davids, K., & Shuttleworth, R. (2008). Manipulating constraints to train decision making in Rugby Union. *International Journal of Sports Science & Coaching*, *3*(1), 125–140. https://doi.org/10.1260/174795408784089432

Patla, A. E., Frank, J. S., Winter, D. A., Rietdyk, S., Prentice, S., & Prasad, S. (1993). Age-related changes in balance control system: Initiation of stepping. *Clinical Biomechanics*, *8*(4), 179–184. https://doi.org/10.1016/0268-0033(93)90012-7

Peters, M. (1988). Footedness: Asymmetries in foot preference and skill and neuropsychological assessment of foot movement. *Psychological Bulletin*, *103*(2), 179–192. https://doi.org/10.1037/0033-2909.103.2.179

Promsri, A., Haid, T., Werner, I., & Federolf, P. (2020). Leg dominance effects on postural control when performing challenging balance exercises. *Brain Sciences*, *10*(3). https://doi.org/10.3390/BRAINSCI10030128

Przybyla, A., Coelho, C. J., Akpinar, S., Kirazci, S., & Sainburg, R. L. (2013). Sensorimotor performance asymmetries predict hand selection. *Neuroscience*, *228*, 349. https://doi.org/10.1016/J.NEUROSCIENCE.2012.10.046

Rocchi, L., Chiari, L., Mancini, M., Carlson-Kuhta, P., Gross, A., & Horak, F. B. (2006). Step initiation in Parkinson's disease: Influence of initial stance conditions. *Neuroscience Letters*, *406*(1–2), 128–132. https://doi.org/10.1016/J.NEULET.2006.07.027

Roller, M. L., Lazaro, R. T., Byl, N. N., & Umphred, D. A. (2013). Contemporary issues and theories of motor control, motor learning, and neuroplasticity. *Neurological Rehabilitation*, 69–98. https://doi.org/10.1016/B978-0-323-07586-2.00013-3

Russo, Y., Marinkovic, D., Obradovic, B., & Vannozzi, G. (2021). Characterization of anticipatory postural adjustments in lateral stepping: Impact of footwear and lower limb preference. *Sensors*, *21*(24), 8244. https://doi.org/10.3390/s21248244

Sadeghi, H., Allard, P., Prince, F., & Labelle, H. (2000). Symmetry and limb dominance in able-bodied gait: A review. *Gait & Posture*, *12*(1), 34–45. https://doi.org/10.1016/S0966-6362(00)00070-9

Sainburg, R. L. (2014). Convergent models of handedness and brain lateralization. *Frontiers in Psychology*, *5*(SEP), 1092. https://doi.org/10.3389/FPSYG.2014.01092

Saint-Maurice, P. F., Troiano, R. P., Bassett, D. R., Graubard, B. I., Carlson, S. A., Shiroma, E. J., Fulton, J. E., & Matthews, C. E. (2020). Association of daily step count and step intensity with mortality among US adults. *JAMA*, *323*(12), 1151–1160. https://doi.org/10.1001/JAMA.2020.1382

Saunders, J. A., & Knill, D. C. (2003). Humans use continuous visual feedback from the hand to control fast reaching movements. *Experimental Brain Research 2003 152:3*, *152*(3), 341–352. https://doi.org/10.1007/S00221-003-1525-2

Scheidt, R. A., Conditt, M. A., Secco, E. L., & Mussa-Ivaldi, F. A. (2005). Interaction of visual and proprioceptive feedback during adaptation of human reaching movements. *Journal of Neurophysiology*, *93*(6), 3200–3213. https://doi.org/10.1152/jn.00947.2004

Schlenstedt, C., Mancini, M., Nutt, J., Hiller, A. P., Maetzler, W., Deuschl, G., & Horak, F. (2018). Are hypometric anticipatory postural adjustments contributing to freezing of gait in Parkinson's disease? *Frontiers in Aging Neuroscience*, *10*, 36. https://doi.org/10.3389/FNAGI.2018.00036

Shin, S., Demura, S., Watanabe, T., Yabumoto, T., Lee, J.-H., Sakakibara, N., & Matsuoka, T. (2015). Age-related and obstacle height-related differences in movements while stepping over obstacles. *Journal of Physiological Anthropology*, *34*(1), 15. https://doi.org/10.1186/s40101-015-0052-8

Stergiou, N., & Decker, L. M. (2011). Human movement variability, nonlinear dynamics, and pathology: Is there a connection? *Human Movement Science*, *30*(5), 869–888. https://doi.org/10.1016/J.HUMOV.2011.06.002

Summers, J. J., & Anson, J. G. (2009). Current status of the motor program: Revisited. *Human Movement Science*, *28*(5), 566–577. https://doi.org/10.1016/J.HUMOV.2009.01.002

Taylor, J. B., Wright, A. A., Dischiavi, S. L., Townsend, M. A., & Marmon, A. R. (2017). Activity demands during multi-directional team sports: A systematic review. *Sports Medicine*, *47*(12), 2533–2551. https://doi.org/10.1007/S40279-017-0772-5

Teixeira, L. A., de Oliveira, D. L., Romano, R. G., & Correa, S. C. (2013). Leg preference and interlateral asymmetry of balance stability in soccer players. *Research Quarterly for Exercise and Sport*, *82*(1), 21–27. https://doi.org/10.1080/02701367.2011.10599718

Teixeira, M. C. T., & Teixeira, L. A. (2008). Leg preference and interlateral performance asymmetry in soccer player children. *Developmental Psychobiology*, *50*(8), 799–806. https://doi.org/10.1002/DEV.20322

Tesio, L., & Rota, V. (2019). The motion of body center of mass during walking: A review oriented to clinical applications. *Frontiers in Neurology*, *10*, 999. https://doi.org/10.3389/FNEUR.2019.00999

Toussaint, H. M., Michies, Y. M., Faber, M. N., Commissaris, D. A. C. M., & Van Dieën, J. H. (1998). Scaling anticipatory postural adjustments dependent on confidence of load estimation in a bi-manual whole-body lifting task. *Experimental Brain Research*, *120*(1), 85–94. https://doi.org/10.1007/S002210050380

Turvey, M. T., Fitch, H. L., & Tuller, B. (1982). *Human motor behavior: An introduction*. Lawrence Erlbaum Associates.

Uemura, K., Yamada, M., Nagai, K., & Ichihashi, N. (2011). Older adults at high risk of falling need more time for anticipatory postural adjustment in the precrossing phase of obstacle negotiation. *The Journals of Gerontology: Series A*, *66A*(8), 904–909. https://doi.org/10.1093/GERONA/GLR081

Vallabhajosula, S., Buckley, T. A., Tillman, M. D., & Hass, C. J. (2013). Age and Parkinson's disease related kinematic alterations during multi-directional gait initiation. *Gait & Posture*, *37*(2), 280–286. https://doi.org/10.1016/j.gaitpost.2012.07.018

van Melick, N., Meddeler, B. M., Hoogeboom, T. J., Nijhuis-van der Sanden, M. W. G., & van Cingel, R. E. H. (2017). How to determine leg dominance: The agreement between self-reported and observed performance in healthy adults. *PLoS ONE*, *12*(12). https://doi.org/10.1371/JOURNAL.PONE.0189876

Vieira, M. F., de Camargo Neves Sacco, I., da Silva Azevedo Nora, F. G., Rosenbaum, D., & Lobo Da Costa, P. H. (2015). Footwear and foam surface alter gait initiation of typical subjects. *PLOS ONE*, *10*(8), e0135821. https://doi.org/10.1371/JOURNAL.PONE.0135821

Warren, W. H. (1990). The perception-action coupling. *Sensory-Motor Organizations and Development in Infancy and Early Childhood*, 23–37. https://doi.org/10.1007/978-94-009-2071-2_2

Wentink, E. C., Beijen, S. I., Hermens, H. J., Rietman, J. S., & Veltink, P. H. (2013). Intention detection of gait initiation using EMG and kinematic data. *Gait & Posture*, *37*(2), 223–228. https://doi.org/10.1016/J.GAITPOST.2012.07.013

Wrisley, D. M., & Kumar, N. A. (2010). Functional gait assessment: Concurrent, discriminative, and predictive validity in community-dwelling older adults. *Physical Therapy*, *90*(5), 761–773. https://doi.org/10.2522/PTJ.20090069

Yang, N., Waddington, G., Adams, R., & Han, J. (2017). Translation, cultural adaption, and test–retest reliability of Chinese versions of the Edinburgh Handedness Inventory and Waterloo Footedness Questionnaire. *Laterality*, *23*(3), 255–273. https://doi.org/10.1080/1357650X.2017.1357728

Yiou, E., Artico, R., Teyssedre, C. A., Labaune, O., & Fourcade, P. (2016). Anticipatory postural control of stability during gait initiation over obstacles of different height and distance made under reaction-time and self-initiated instructions. *Frontiers in Human Neuroscience*, *10*. https://doi.org/10.3389/fnhum.2016.00449

Yiou, E., Caderby, T., Delafontaine, A., Fourcade, P., & Honeine, J.-L. (2017). Balance control during gait initiation: State-of-the-art and research perspectives. *World Journal of Orthopedics*, *8*(11), 815–828. https://doi.org/10.5312/wjo.v8.i11.815

Yiou, E., Caderby, T., & Hussein, T. (2012). Adaptability of anticipatory postural adjustments associated with voluntary movement. *World Journal of Orthopedics*, *3*(6), 75. https://doi.org/10.5312/WJO.V3.I6.75

Yiou, E., Ditcharles, S., & Le Bozec, S. (2011). Biomechanical reorganisation of stepping initiation during acute dorsiflexor fatigue. *Journal of Electromyography and Kinesiology*, *21*(5), 727–733. https://doi.org/10.1016/J.JELEKIN.2011.04.008

Yiou, E., & Do, M. C. (2010). Control of mediolateral stability during rapid step initiation with preferred and non-preferred leg: Is it symmetrical? *Gait & Posture*, *32*(1), 145–147. https://doi.org/10.1016/J.GAITPOST.2010.03.018

Yiou, E., Fourcade, P., Artico, R., & Caderby, T. (2016). Influence of temporal pressure constraint on the biomechanical organization of gait initiation made with or without an obstacle to clear. *Experimental Brain Research*, *234*(6), 1363–1375. https://doi.org/10.1007/S00221-015-4319-4

Yiou, E., Mezaour, M., & Le Bozec, S. (2009). Anticipatory postural adjustments and focal performance during bilateral forward-reach task under different stance conditions. *Motor Control*, *13*(2), 142–160. https://doi.org/10.1123/MCJ.13.2.142

Zettel, J. L., McIlroy, W. E., & Maki, B. E. (2002). Can stabilizing features of rapid triggered stepping reactions be modulated to meet environmental constraints? *Experimental Brain Research*, *145*(3), 297–308. https://doi.org/10.1007/s00221-002-1083-z

Zhao, G., Grimmer, M., & Seyfarth, A. (2021). The mechanisms and mechanical energy of human gait initiation from the lower-limb joint level perspective. *Scientific Reports 2021 11:1*, *11*(1), 1–12. https://doi.org/10.1038/s41598-021-01694-5

Appendix A

Demographic Survey

Participant ID Number: ______________

Today's date: ______/______/______ Date of birth: ______/______/______

Sex: Male Female

Height (inches): _________________ Weight (lbs): _____________

Level of physical activity:

Days per week exercising - __________

Average length of each exercise session - __________

Average exercise intensity (Borg scale 6-20) - __________

Are you currently experiencing an clinical condition that could impair your movement?

YES NO

Are you currently taking medications that could impair your movement and coordination?

YES NO

Have you had a lower extremity injury within the past year?

YES NO

Have you had a surgery in either lower extremity within the last 1 year?

YES NO

Appendix B

Waterloo Footedness Questionnaire—Revised

Instructions: Answer each of the following questions as best you can. If you always use one foot to perform the described activity, circle **Ra** or **La** (for **right always** or **left always**). If you **usually** use one foot, circle **Ru** or **Lu**, as appropriate. If you use **both** feet **equally often**, circle **Eq**.

Please do not simply circle one answer for all questions, but imagine yourself performing each activity in turn, and then mark the appropriate answer. If necessary, stop and pantomime the activity.

1	Which foot would you use to kick a stationary ball at a target straight in front of you?	La	Lu	Eq	Ru	Ra
2	If you had to stand on one foot, which foot would it be?	La	Lu	Eq	Ru	Ra
3	Which fool would you use to smooth sand at the beach?	La	Lu	Eq	Ru	Ra
4	If you had to step up onto a chair. which foot would you place on the chair first?	La	Lu	Eq	Ru	Ra
5	Which foot would you use to stomp on a fast-moving bug?	La	Lu	Eq	Ru	Ra
6	If you were to balance on or foot on a railway track, which foot would you use?	La	Lu	Eq	Ru	Ra
7	If you wanted to pick up a marble with your toes, which foot would you use?	La	Lu	Eq	Ru	Ra
8	If you had to hop on one foot, which foot would you use?	La	Lu	Eq	Ru	Ra
9	Which foot would you use to help push a shovel into the ground?	La	Lu	Eq	Ru	Ra
10	During relaxed standing, people initially put most of their weight on one foot, leaving the other leg slightly bent. Which foot do you put most of your weight on first	La	Lu	Eq	Ru	Ra
11	Is there any reason (i.e, injury) why you have changed your foot preference for any of the above activities?	YES	NO	(circle one)		
12	Have you ever been given special training or encouragement to use a particular foot for certain activities?	YES	NO	(circle one)		
13	If you have answered YES for either question 11 or 12, please explain:					

Abstract

Background: Understanding the anticipatory postural adjustments (APA) and stepping characteristics associated with gait initiation (GI) has enhanced the approaches used for gait rehabilitation, the design of adaptive devices, and the development of fall prevention programs. However, previous studies have primarily concentrated on forward GI. Therefore, the movement characteristics of multidirectional GI, which is common in daily activities and sports, remain unknown. **Purpose**: This study aimed to investigate the APA parameters and stepping kinematics of healthy young adults when performing multidirectional GI with the effect of an obstacle (presence versus absence) and stepping leg (right versus left). **Methods**: Fourteen right-leg dominant young adults (Female: N = 7; age: 22.4 ± 2.4) performed five trials of GI at their comfortable pace. Experimental conditions included legs, obstacle (a 15cm-height hurdle), and directions (forward: F00, lateral: L90, medial 45 degrees: M45, lateral 45 degrees: L45). Repeated Measure ANOVAs (directions, obstacle, legs as within factors) with Bonferroni post hoc were used to assess the statistical significance. **Results**: APA duration and mediolateral (ML), anteroposterior(AP) COP displacement decreased as the stepping direction shifted laterally from F00 to L90. Similar pattern of change was observed in the COP velocity metrics. Step distance decreased as the laterality increased from M45 to L90, yet the step durations remained consistent throughout directions in GI without an obstacle. Step variability was the greatest in L90. The presence of an obstacle significantly increased ML COP displacement, step distance, step duration, step velocity, and step variability. On average, the dominant leg stepping had longer APA duration and step duration, while the ML COP velocity in the APA phase were slower in all stepping directions. **Significance**: These findings demonstrate the unique characters of multidirectional GI and provide clinical relevance to the improvement of the movement versatility of gait rehabilitation programs for individuals recovering from lower limb impairments.