Foot clearance in young and older adults when negotiating an obstacle.

Sirirat Tohpreecha

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School of Sport, Rehabilitation and Exercise Sciences

University of Essex

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Dedication

To my dad, mom, and two younger brothers for their empowerment and deep love.

To the Faculty of Medicine at Prince of Songkla University for their sponsorship.

To my colleagues and the friendship trust,

their love and support make everything possible
Thank you for the inspiration.

Abstract

Background: Stepping over obstacles when walking is a common placing the foot close to the obstacle.

Objective Thesis aim was to determine when crossing an obstacle if: a) the repeatability of foot clearance parameters; b) foot clearance parameters were symmetrical; c) there were a difference in foot clearance parameters for different height obstacles and when performing a dual task; d) if there were a difference between sexes; and e) older adults stepped over an obstacle differently compared to younger adults.

Methodology: 20 healthy young adults and 10 healthy older adults performed four walking tasks (LOW/HIGH obstacles and HIGH/LOW Dual Task) at their chosen speed. The dual task involved holding a glass of water while walking. Markers were placed on the feet to aid identification of foot clearance parameters (toe height, heel height, and step distance away and in front of the obstacle).

Results: For aim a) moderate to excellent reliability for all foot clearance parameters; b) Most foot clearance measurements were symmetrical; c) foot clearance parameter were impacted by the height of the obstacle and the inclusion of a dual task; d) sex differences were broadly removed once normalized to height; e) older adults showed significantly closer step distance from obstacles for both leading and trailing limbs and a higher toe clearance for the trailing, compared to young adults.

Conclusion: Foot clearance parameters (discrete points) were repeatable and symmetrical, but further work should focus on the foot trajectory. When normalised to height there were no sex differences – an approach not commonly adopted in related literature. Older adults potentially reduced toe-tripping with the different foot placement but this may increase chance of a stumble with the heel after crossing the obstacle. Further work should develop a consistent obstacle clearance protocol to allow comparisons across studies.

Keywords: foot clearance, toe clearance, younger adults, older adults, stepping over, crossing over

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List of symbols and abbreviations

A	Step distance in front of box (cm) of leading limb
ANOVA	Analysis of Variance
ART	Available response time
ASIS	Anterior superior iliac spine
B	Step distance in front of box (cm) of trailing limb
C	Step distance away from box (cm) of leading limb
COM	The center of mass
D	Step distance away from box (cm) of trailing limb
Diff	The mean difference between two sessions
DT	Dual tasks
ES	Effect size
FC	Foot clearance
g	The acceleration due to gravity (9·81 m. s^{-2})
GA	Gait asymmetry
H1A	Toe height above front of box (cm) of leading limb
H3C	Heel height above back of box (cm) of leading limb
H3D	Heel height above back of box (cm) of trailing limb
HEEL_HEIGHT	Heel height above back box
HIB	Toe height above front of box (cm) of trailing limb
HIGH	The task involves stepping over an obstacle at a high box (20 cm) height.
HIGHT-DT	The task involves stepping over an obstacle at a high box (20 cm) while holding a glass of water without spilling it.

ICC	Intraclass correlation coefficients
l	Length (or height)
l_0	Leg length
L	Left
LOW	The task involves stepping over an obstacle at a low box (15 cm) height.
LOW_DT	The task involves stepping over an obstacle at a low box (15 cm) while holding a glass of water without spilling it.
L_LD_A_SOV	Left leading limb of step distance in front of box (cm)
L_LD_D_SOV	Left leading limb of step distance away from box (cm)
L_LD_H1A_SOV	Left leading limb of toe height above front of box (cm)
L_LD_H3C_SOV	Left leading limb of heel height above back of box (cm)
L_TL_B_SOV	Left trailing limb of step distance in front of box (cm)
L_TL_D_SOV	Left trailing limb of step distance away from box (cm)
L_TL_H3D_SOV	Left trailing limb of heel height above back of box (cm)
L_TL_HIB_SOV	Left trailing limb of toe height above front of box (cm)
LD	Leading Limb
LHC	Leading heel clearance
LTC	Leading toe clearance
LTL	Left trailing limb
MDC	Minimal detectable change
MFC	Minimum foot clearance
MTC	Minimum toe clearance
O_A	Older adult

R	Right
RI	Symmetry ratio or ratio index
R_LD_A_SOV	Right leading limb of step distance in front of box (cm)
R_LD_C_SOV	Right leading limb of step distance away from box (cm)
R_LD_H1A_SOV	Right leading limb of toe height above front of box (cm)
R_LD_H3C_SOV	Right leading limb of heel height above back of box (cm)
R_TL_B_SOV	Right trailing limb of step distance in front of box (cm)
R_TL_D_SOV	Right trailing limb of step distance away from box (cm)
R_TL_H1B_SOV	Right trailing limb of toe height above front of box (cm)
R_TL_H3D_SOV	Right trailing limb of heel height above back of box (cm)
RLL	Right leading limb
SA	Symmetry angle
SD	Standard deviation
SDDiff	The standard deviation of Diff
SEM	Standard Error of Measurement
SI	Symmetry index
SOV	Stepping over
SPSS	Statistical Package for the Social Sciences
STEP_AWAY	Step distance away from box
STEP_FRONT	Step distance in front of box
THL	Trailing heel clearance
TL	Trailing Limb
TOE_HEIGHT	Toe height above front box

TTC	Trailing trail clearance
v	walking velocity
VR	Virtual reality
Y_A	Younger adult

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Chapter I: General Introduction

Navigating around an obstruction while walking might be a difficult undertaking. It can lead to tripping, particularly among older people. Studies have indicated that tripping while walking is the cause of over half of all occurrences involving elderly adults (Deandrea, 2010; Rubenstein, 2006; Winter et al., 1990). The aim of these experiments was to assess whether older individuals stepped over an obstacle differently (based on obstacle clearance criteria) compared to younger adults. Individuals of different age groups can attribute this phenomenon to differences in their gait patterns. This study included obstacle clearance variables, such as the distance between the step and the obstacle, the height of the toe over the front of the obstacle, the height of the heel above the rear of the obstacle, and the distance between the step and the obstacle, and comprised of four tasks: stepping over a 15 cm obstacle, stepping over a 20 cm high obstacle, stepping over a 15 cm low obstacle with an additional task (holding a glass of water), and stepping over a 20 cm high obstacle with an additional task. The study design initially prioritized systematic reviews, followed by 4 experimental studies looking the reliability, symmetry, gender differences and age differences of obstacle clearance.

Introduction

This chapter provides a concise overview of the attributes of movement and techniques for assessing changes in the gait pattern in older individuals. The initial phase of the study involves examining the fundamental gait cycle, encompassing its definition and the measurement of other associated parameters. Another crucial factor to consider is the changes in walking and gait patterns that arise due to the process of aging. This involves closely studying and evaluating the body movement. Before engaging in physical exercise, it is advisable to consider different approaches to analyzing one's walking pattern. These approaches may involve the examination of kinematic data and the utilization of minimum foot clearance (MFC) as an analytical methodology. This work investigates the creation and application of a biomechanical model, as well as the evaluation of the probability of falling. The separate chapters of this thesis provide more in-depth evaluations of gait or functional movement, specifically concentrating on activities such as clearing an obstacle while walking. The last portion of the chapter provides a thorough overview of the fundamental matters and arguments presented in the thesis.

1.1 Background

Falls are considered behavioral indications of instability among older adults (Deandrea, 2010; Shumway-Cook and Wolcott, 2011). The World Health Organization (2016) categorizes older adults into three distinct groups: persons between the ages of 60 and 74, those with an average age ranging from 75 to 90 years, and individuals aged 90 years and above. Previous studies have indicated that falls are the most common cause of injury (Overstall et al., 1977). Accounting for nearly 60% of unintentional injuries and ranking as one of the main factors leading to accidental mortality in the population aged 65 and above (Rubenstein, 2006; Mills et al., 2008). Although fifty percent of falls occur while walking, the most common cause of falls is stepping on an obstacle (Overstall et al., 1977).

Researchers have conducted extensive research on the effects of walking on the aging process, including its potential to reduce the likelihood of falls. Several studies have shown the impact of age on walking ability (Hagoort et al., 2023; Aboutorabi et al., 2016; Kosse et al., 2016; Terrier and Reynard, 2015; Kobsar et al., 2014). Compared to young adults, older individuals displayed shorter and wider steps, longer step times, and increased variability in both step lengths and timings. Studies (Hagoort et al., 2023; Kosse et al., 2016; Aboutorabi et al., 2016; Kobsar et al., 2014) found the act of walking along a straight hallway path to be highly restrictive, with limited options to alter step patterns. The results indicate that the relationship between age and walking circumstances has a notable influence on movement, specifically in regards to stability, variability, time, and frequency domains (Deandrea, 2010). Severe walking limitations seem to intensify the aging-related differences in movement patterns (Hagoort et al., 2023).

Walking across an obstacle might be a challenging task. Studies suggest that stumbling when walking is responsible for about 50% of all incidents among the elderly (Rubenstein, 2006; Winter et al., 1990). Common barriers can vary in size, ranging from a few millimeters (mm) to over 150 mm, such as a stair step. Inside, you may encounter barriers at the entrance or the boundaries of the bathtub, while outside impediments can include uneven pavement, regular curves, or parking blocks. Stepping is the action of elevating two limbs alternatively to clear the floor while navigating through different surfaces in daily activities. The leg responsible for lifting the first leg when crossing an obstruction is known as the lead limb, which is then followed by the trailing limb that lacks visual input. Research has indicated (Chen et al., 1996) that older people often need to spend more time observing their surroundings, adjusting their walking style to avoid impediments, and using strategic methods when walking cautiously and overcoming barriers (Maki and McIlroy, 1996; Patla and Shumway-Cook, 1999).

Foot clearance is defined as the vertical distance between the foot's lowest point (usually the heel) and the ground during the swing phase of walking (Winter, 1992). It is a crucial aspect of human locomotion, ensuring that the foot successfully navigates over obstacles and uneven surfaces to avoid tripping or stumbling. Insufficient foot clearance can increase the risk of falls, especially in individuals with mobility impairments or neurological conditions.

To reduce the risk of falling, researchers have studied how age affects foot clearance. Chen et al. (1991) and Lowrey et al. (2007) have discovered that age does not exert a substantial influence on lead limb toe clearance. In terms of lead limb toe clearance, previous study revealed a notable correlation between age and obstacle height (Lu et al., 2006). The results showed that older people had a notable rise in toe clearance as the height of the obstacle increased, while younger adults did not see a similar impact on their toe clearance (Lu et al., 2006). Regarding more substantial difficulties, older persons exhibited greater degrees of lead limb toe clearance in comparison to younger individuals. McFadyen and Prince (2002) conducted a separate study that revealed that elderly individuals reduced the distance between their lead limb and the ground during walking. Three investigations conducted by McFadyen and Prince (2002), Lu et al. (2006), and Draganich and Kuo (2004) concluded that age does not have a significant effect on trailing limb clearance. The observed variances can be attributable to discrepancies in experimental methods and the procedures used to quantify obstacle encounters and foot clearance.

The height of the obstacle is a crucial determinant for effectively overcoming the floor. To reduce the risk of humans tripping or stumbling, it is necessary to increase the clearance when taller higher barriers are present. Scientists have conducted a thorough study of the impact of obstacle height on foot clearance, a topic that has sparked much controversy (Chen et al., 1991). The measured foot clearance when stepping over obstacles of different heights (25, 51, and 152 mm) using the least effective marker among the heel, toe, and mid-foot markers study (Chen et al., 1991). Likewise, researchers noted a substantial rise in the distance between the foot and the ground as the height of the obstruction increased. A separate study presented additional proof of the discrepancy in the primary method of regulating the final outcome between younger and older individuals (Lu et al., 2006). This study by Lu et al. (2006) showed that height had a distinct impact on both leading toe clearance and leading heel-obstacle distance. Irrespective of the height of the obstacle, the younger group consistently showed a higher clearance of the leading toe and a greater gap between the leading heel and the obstruction. On the other hand, the older group had to progressively raise the clearance of the leading toe and decrease the distance between the leading heel and the obstacle in a straight line as the height of the obstacle increased (Lu et al., 2006). The older group's height-affected trajectory suggests the establishment of a broader safety margin (Lu et al., 2006). The reduced ability of older individuals to respond to unexpected falls can likely explain this phenomenon (Lu et al., 2006). Furthermore, Lu et al. (2006) found that an increase in the distance between the leading toe and the ground would necessitate a proportional increase in the muscular exertion on the leg during the swinging motion. Certain conditions, such as age-related muscle weakening, may prevent older individuals from regaining their balance after tripping over a barrier and increase their risk of falling (Lu et al., 2006).

The main objective of the introductory section is to present a comprehensive summary of the current body of literature on gait adaptation when traversing obstacles, with a specific emphasis on contrasting the characteristics of young and older individuals. To achieve these objectives, this study will analyze the terminology and fundamental principles relating to the gait cycle and its adaptation during obstacle traversal.

1.2 Aging

Three distinct classes exist for older adults. The first category comprises adults aged 60 to 74 years; the second group consists of individuals with an average age ranging from 75 to 90 years; and the third group includes those who are 90 years of age or older (Organisation, 2016). However, previous studies have suggested that the elements influencing the aging process can be classified as either major or secondary variables, such as intrinsic and extrinsic factors.(Shumway-Cook and Wolcott, 2011; Rowe and Kahn, 1997). Primary factors, also known as intrinsic causes, refer to the alterations in gene expression that occur across the lifespan and lead to a decline in neural function within a given system. On the contrary, an alternative viewpoint argues that several environmental factors, including nutrition, exercise, stress levels, and acquired disease, can potentially lead to detrimental effects on the system (Shumway-Cook and Wolcott, 2011).

Several factors significantly influence the typical alterations in postural control. The initial impairment is characterized by a reduced ability to quickly initiate muscular reactions as well as a decrease in the strength of responses (Shumway-Cook and Wolcott, 2011). As a result, this leads to a prolonged period that necessitates the establishment of equilibrium. Furthermore, the delayed response of the body to maintain balance leads to reduced stability during task performance (Shumway-Cook and Wolcott, 2011). Researchers have found that raising the legs reduces the sensory input required to sustain equilibrium. As a result, older people encounter difficulties maintaining their balance, resulting in excessive swaying or a loss of equilibrium (Shumway-Cook and Wolcott, 2011). Finally, trying to perform two tasks simultaneously leads to a deterioration in the physical ability to maintain posture, resulting in a loss of balance and falling. Shumway-Cook and Wolcott (2011) suggest that attention processing is essential for executing postural movements. This may result in diminished performance when attempting to simultaneously execute another operation. A study is undertaken using the dual-task paradigm to investigate the relationship between cognitive processing and motor performance. Engaging in many tasks while walking has been linked to an increased susceptibility to falling occurrences (Shin and An, 2014; Watson et al., 2010). Studies have shown that changes in walking pattern can occur before the development of cognitive problems. Watson et al. (2010) found a connection between executive function, memory, and gait speed and the decline of well-functioning elderly persons.

1.3. Fall

The decrease in physical activity in elderly individuals indicates a lack of regularity in their daily schedules. Both intrinsic physiological and musculoskeletal factors, as well as external environmental factors, influence this phenomenon (Deandrea, 2010; Shumway-Cook and Wolcott, 2011). Unintentional injuries are the leading cause of death in the elderly population, with falls accounting for nearly two-thirds of these fatalities. Various studies have consistently demonstrated that falls are the primary cause of injuries, accounting for more than 60% of unintentional injuries and ranking among the leading causes of accidental mortality among individuals aged 65 and above (Mills, Barrett, & Morrison, 2008; Rubenstein, 2006). According to Rubenstein (2006), numerous studies consistently demonstrate that movement plays a significant role in the prevalence of falls among elderly individuals. Furthermore, researchers have discovered various key indicators of falls in this particular population, encompassing sociodemographic traits, sensory capabilities, psychological elements, medical ailments, and medication consumption. Notable factors encompass vertigo, Parkinson's disease, acrophobia, dependence on mobility aids, and the administration of antiepileptic medications. According to Santhiranayakam et al. (2015), stumbling while walking is the primary cause of falls in elderly adults without any pre-existing health conditions (Santhiranayagam et al., 2015). A trip refers to the abrupt cessation of the forward movement of the swinging foot during walking, resulting from an external force.

The International Classification of Functioning, Disability, and Health (ICF) framework classifies mobility as one of the nine domains, which includes activity, participation, and body structure and function. The concept of mobility, commonly known as locomotion, comprises three fundamental elements (Shumway-Cook and Wolcott, 2011). Firstly, it refers to the ability to change the physical shape in accordance with a predetermined path. Progression, as defined by Shumway-Cook and Wolcott (2011), is the act or process of advancing or evolving. Postural control is the second essential requirement. Balance is the ability to maintain control over one's body posture with respect to the surrounding space, including factors such as orientation and stability. This refers to the capacity to maintain equilibrium while objects are not moving (steady-state balance), adjust to changes in the external environment (reactive balance), and predict and make adjustments for future changes (anticipatory balance control) (Shumway-Cook and Wolcott, 2011). Adaptability is the ability to adjust one's walking style in order to effectively meet different tasks and environmental demands.

1.4 Gait cycle

1.4.1 The definition of a gait cycle

There are two distinct segments to the gait cycle. The initial part of the gait cycle is known as the stance phase, during which a foot establishes contact with the ground. This phase includes two key components: weight acceptance and single-leg stance, which collectively account for 60% of the whole gait cycle. The swing phase, which comprises 40% of the cycle, refers to the period during which the limb is in motion and advancing. Moreover, the events occurring during the gait cycle consist of eight distinct events, including initial contact, loading response, midstance, terminal stance, pre-swing, starting swing, mid-swing, and terminal swing, as shown in Figure 1.1.

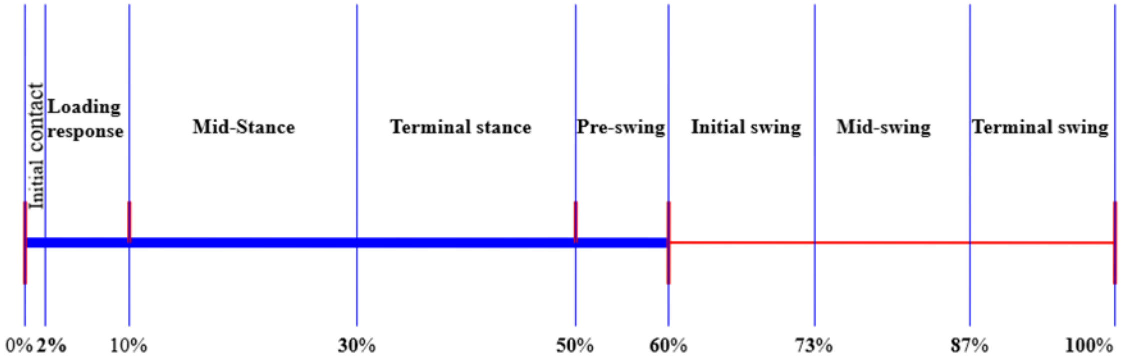

Figure 1. 1 The diagram demonstrates the 8 phases of the gait cycle

1.4.2 Gait in older adults

A gait cycle has two distinct phases (stance and swing). Each of these phases necessitates the implementation of distinct motor techniques (Winter, 1984). Since the focus of this PhD is foot-clearance over an obstacle, which occurs in swing, this section will focus on the swing phase. During the swing phase, the crucial event is the movement of the foot of the swinging limb from its previous position to the next, which forms the foundation for the forward movement of the body. Nevertheless, multiple events take place throughout the swing period (Winter, 1992). The swing leg achieves its motion through the coordination of a seven-segment kinematic chain, comprising the thigh, shank, and foot segments of both support limbs and the pelvis. Furthermore, the movement of the swinging limb resembles that of a compound pendulum. However, it is important to note that there is a force-driven damp oscillator, specifically muscular activity, that is necessary for the entire swing period. To guarantee that the toes do not touch the ground, the pre-tibia muscles contract concentrically, causing the ankle to flex upwards after the toes leave the ground. The hamstrings group in late swing results in a decrease in the forward-backward speed of the foot before the heel makes contact with the ground (Mills and Barrett, 2001)

Similarly, there are two crucial aspects to consider regarding the impact of age on the mechanics of the swing phase, particularly when it comes to falls: minimal toe clearance and heel contact. Minimal toe clearance refers to the distance between the toe and the ground, while heel contact occurs during the swing phase and the transition from swing to stance. Mills et al. (2001) state that slips or trips are the main reason for accidental injuries in the older adult population, particularly when walking. A trip is an occurrence in which an external force disrupts the movement of the leg that is swinging, creating a condition that increases the likelihood of slipping (Mills and Barrett, 2001). This phenomenon is particularly prevalent during the mid-swing phase. Moreover, the bulk of slides occur immediately after the heel makes contact with the ground.

The gait characteristics facing the environment have significant importance in predicting falls. Age-related variations in gait adaptation, for example, influence balance ability, leg muscle strength, sensory information, and cognitive aspects (Shumway-Cook and Woollacott, 2012). Older adults performed cognitive tasks at a slower pace than middle-aged and younger adults, according to a number of cross-sectional studies. Additionally, there was a distinction in gait velocity during dual-task walking. Shin & An (2014) observed a decline in proactive locomotor ability with age. Older individuals require more time to monitor their surroundings, modify their approach to avoid obstacles, and employ crossing strategies that involve a gradual approach and prolonged operation (Kim and Brunt, 2007; Galna et al., 2009).

Empirical studies have demonstrated the effectiveness of numerous biomechanical approaches in assessing gait. For example, there are gait characteristics encompassing spatial-temporal, kinematics, kinetics, and electromyography (EMG) parameters. Previous research has indicated that gait patterns in healthy older individuals exhibit certain characteristics, such as diminished gait velocity and cadence, shorter stride length, and shorter step length, in comparison to young adults (Begg et al., 2007). Enhanced durations of single- or double-limb support and diminished angular range of motion are additional factors contributing to the general deceleration in older individuals. However, compared to young adults (20–40 years), older people (above 55 years) exhibit gait adaptations, (Kovacs, 2005) such as a reduced walking pace. Elderly individuals may modify their gait patterns to reduce the risk of falling.

1.5 Stepping over an obstacle

Stepping over an obstacle is a challenging task in everyday life. It is made up of intrinsic and external factors related to the individual and their surroundings (Galna et al., 2009; Pan et al., 2016). Intrinsic characteristics include musculoskeletal components, reaction speed, changes in balance and gait, and cognitive features such as executive function, attention, and visual-spatial abilities (Chen et al., 1994; Galna et al., 2009; Chen et al., 1991). The extrinsic factor encompasses environmental attributes, including both anticipated and unanticipated (Galna et al., 2009). Due to a combination of these intrinsic and extrinsic factors, stumbling while crossing obstacles is presumably among the most prevalent causes of falls among the elderly. Subsequently, two lower extremities—the leading and trailing limbs—lift in an alternating motion in order to clear the floor. The primary limb is the lower extremity that initiates the gait cycle and traverses an impediment, whereas the secondary limb is the lower extremity that succeeds the first limb and passes an impediment. To effectively clear obstacles, it is imperative to ensure appropriate synchronization and movement of the leading leg. Previous studies have indicated that in order to maintain enough toe clearance, the leading limb relies on visual information acquired at least two steps before encountering an obstruction (Timmis and Buckley, 2012). The trailing limb relies on proprioceptive feedback from the leading limb due to the absence of visual information (Mohagheghi et al., 2004; Draganich and Kuo, 2004).

1.6 Foot Clearance (FC)

Foot clearance during walking, which includes both the toe and heel, is the minimum vertical distance that occurs between the foot and the ground while the swing is in its mid-swing phase (Winter, 1992). The toe or foot clearance for obstacle traversing and other locomotion tasks varies considerably, ranging from 6.8 to 18 centimeters (Lowrey et al., 2007; Lu et al., 2006; Draganich and Kuo, 2004; Berg and Blasi, 2000; Sparrow et al., 1996; Austin et al., 1999). Aging influences swing phase mechanics at two critical junctures, as observed from a fall perspective (Mills and Barrett, 2001). There are two important factors to consider in the context of human locomotion. The first factor is known as minimal toe clearance (MTC), which refers to the smallest distance between the toe and the ground during the gait cycle. The second factor is heel contact, which occurs during the swing portion of the gait cycle and the subsequent transition from swing to stance. Furthermore, van Hedel et al. (2005) observed that MTC occurs when the toe positions itself in front of the foot, distanced from the base of support, aligning with the direction of limb advancement, thereby increasing the likelihood of a fall (van Hedel et al., 2005).

The study of obstacle crossing uses a variety of variables involved in toe clearance. Prior research operationalized the concept of toe clearance as the minimal vertical distance between the highest point of an obstacle and the lowest position of the toe as it traversed toward the midpoint of the obstacle (Chen et al., 1991). Studies have indicated that toe clearance is commonly defined as the vertical separation between the apex of the big toe and the critical edge of the obstacle during the crossing motion (Soma et al., 2010). Therefore, we conducted the measurement of toe clearance at the moment when we elevated the foot to a position above the front and rear of the obstruction. These findings indicate the need for further clarification of the concept of foot clearance, as variations in its definition could potentially impact the outcomes of the study.

1.7 Lower limb movement while negotiating obstacle

Stepping is the action of raising and lowering two limbs in an alternating manner to elevate them above the ground. When crossing over an obstacle, the lead limb lifts the first leg, followed by the trailing limb. The trailing limb lacks visual input (Patla, 1997; Patla et al., 1996). However, it is crucial to execute suitable limb movements when navigating obstacles in order to prevent tripping. Multiple studies have indicated that the notion of toe and heel clearance is an important factor in several domains, specifically in design and biomechanics (Lu et al., 2006; Austin et al., 1999; Muir et al., 2015). The term "gap" or "distance" refers to the spatial separation between the toe and heel of an object or person. The displacement of the swing limb during locomotion over an obstructing object indicates the necessity to prioritize safety (Austin et al., 1999).

Austin et al. (1999) defined the crucial height as a specific transition point where clearance distances change direction. The clearance distances exhibit linear growth at first, but after they reach the crucial interference point where this plateaus or begins to decrease in a linear manner

(Austin et al., 1999). The second phenomenon pertains to the onset of a transitional phase that occurs following a period of growing gaps between the clearance of the toe and heel (Austin et al., 1999).

The impact of obstacle height on leading toe clearance and leading heel-obstacle distance further demonstrated the differences in the leading end-point control approach between young and older adults. The younger adults showed consistent leading toe clearance and leading heel-obstacle distance, regardless of the height of the obstacle (Lu et al., 2006). In contrast, the older adults had a linear rise in leading toe clearance and a linear decrease in leading heel-obstacle distance as the obstacle height increased (Lu et al., 2006). This strategy appeared to be in accordance with the first concept discussed by Austin et al., (1999). Likewise, the height-influenced observed trajectory in the older group suggests the implementation of a greater safety margin. Lu et al. (2006) likely intended this adjustment to offset the decline in older individuals' capacity to effectively recover from unforeseen tripping incidents due to age-related physical deterioration. Additionally, a change in leading toe clearance necessitates a corresponding rise in muscular exertion on the swing limb (Lu et al., 2006). If age-related muscular debility fails to meet these requirements, for example, older individuals may struggle to recover from stumbling over the obstacle, thereby increasing the risk of falls (Lu et al., 2006).

The lack of visual cues as the following limb moves, in contrast to the leading limb, enhances the variability in controlling the trajectory of the toe. (Patla, 1997; Patla et al., 1996). Likewise, the impact of ipsilateral limb crossing on the risk of falling in older individuals remains uncertain, as the alteration in mechanical loads on the leading and trailing limbs while the body is supported is not well understood (Lu et al., 2006). During the stance phase of gait, when the front limb advances forward and the back limb remains stationary, the center of mass (COM) moves away from the base of support, which is represented by the back foot. Consequently, this displacement may cause challenges in reestablishing balance following episodes of tripping or stumbling. Conversely, the center of mass (COM) showed a path directed towards the foot that was supporting the body's weight when moving over the leg that was behind decreasing the probability of instability in the supporting leg (Lu et al., 2006). Thus, if the trailing leg is responsible for a trip or stumble, the process of recovering from it may be simpler compared to when the leading limb is to blame (Lu et al., 2006).

Joint Kinematics and obstacle clearance

Previous research on obstacle-crossing has mostly examined the joint angles of the swing limb (Patla and Rietdyk, 1993; McFadyen et al., 1993; McFadyen and Carnahan, 1997; Chou and Draganich, 1997; Lu et al., 2006; Kovacs, 2005; Sparrow et al., 1996; Chen et al., 1991; McKenzie and Brown, 2004). Likewise, when the leading toe was above the obstacle, the older group employed a swing hip flexion strategy to get the intended foot clearance, whereas the younger group consistently employed a swing ankle eversion strategy for all heights (Lu et al., 2006). In the 10% condition, the older group had more hip crossing flexion, adduction, and ankle crossing dorsiflexion of the trailing stance limb than the younger group. This was done to help them adjust to changes in the swing limb. Elderly individuals frequently exhibit a flexed trailing stance limb position, characterized by a lowered position of the leading toe and enhanced stability (Lu et al., 2006; Austin et al., 1999). Similarly, a greater crossing flexion at the leading hip contributes to elevating the position of the leading toe. The utilization of two distinct limb positioning techniques yielded consistent leading toe clearance across both age groups in the 10% condition. Both groups demonstrated similar crossing angular displacements of the trailing stance limb when faced with higher obstacles. However, older individuals demonstrated more flexion of the leading hips in order to attain greater toe clearance. The hip joint, which is the closest joint to the lower limb, provided a more effective method of raising the swing toe compared to the ankle joint in the older demographic. Nevertheless, larger hip flexor forces were necessary to elevate the entire limb. Insufficient strength in the hip flexors may lead to a limited ability to enhance hip flexion, thus indicating an increased susceptibility to falls (Lu et al., 2006).

Additionally, the kinematics of the lower limb joint during the crossing of the trailing limb differed significantly from those observed during the crossing of the leading limb (Lu et al., 2006). Previous study has reported that older adults had lesser hip, knee, and ankle flexion when stepping over an obstacle compared to young adults, particularly at higher obstacles (Lu et al., 2006). However, it is worth noting that the trailing toe clearances of the older group were not statistically different from those of the younger group (Lu et al., 2006. There is a hypothesis (Lu et al., 2006 that the increases in hip flexion observed in the older group were not influenced by the trajectory of the trailing toe but rather by the anterior movement of the upper body. This anterior movement aimed to bring the center of mass (COM) closer to the foot in the leading posture, thereby aiding in the maintenance of body stability (Lu et al., 2006).

Thirdly, the objective was to investigate the impact of advancing age on the utilization of these strategies. The rationale of the former study reveals that older individuals often exhibit slower gait speed and shorter step length when faced with fixed, visible obstacles (Lowrey et al., 2007; Di Fabio et al., 2004; Chen et al., 1991). People commonly understand the adaptations in this issue as cautious walking strategies, but the reduced stride length increases the likelihood of encountering difficulties (Barbieri et al., 2014; Lowrey et al., 2007; Chen et al., 1991). As individuals age, the steady decrease in step length in both level gait (Muir et al., 2014) and obstructed gait (Barbieri et al., 2014) likely contributes to the worsening of contact risk. Individuals over 80 years old face an increased risk of falling due to a progressively shorter step duration compared to those aged 65–79 years. The results indicate that the lead limb trajectory of older adults follows a rectangular shape, with the foot initially raised vertically to reach its maximum height, then moving forward to successfully navigate the obstacle. Furthermore, compared to their younger counterparts, older individuals showed a more significant decrease in gait speed and a greater degree of overshoot. The overshoot was the maximum anterior-posterior toe position during swing minus the anterior-posterior toe position at landing.

1.8 Age and foot clearance when stepping over an obstacle

The impact of age on foot clearance during obstacle traversal is believed to decrease the likelihood of tripping or falling. Research (Lu et al., 2006) has indicated that older adults exhibit heightened toe-obstacle clearance when crossing obstacles, likely as a means to mitigate the likelihood of tripping. This is because a greater clearance between the foot and the obstruction reduces the chances of the foot making contact with the obstacle (Lu et al., 2006). Compared to the younger individuals, the older adults employed several crossing-over methods, such as reducing their stride length, decreasing their crossing speed, and minimizing the space between the obstruction and their heel strike (Chen et al., 1991). The older individuals who successfully navigated obstacles exhibited distinct end-point control in comparison to the younger individuals. Lu et al. (2006) demonstrated that elderly individuals exhibited greater leading toe-obstacle clearance and trailing toe-obstacle distance but had reduced leading heel-obstacle distance.

Elderly individuals exhibited a notably more cautious (Chen et al., 1991) approach while navigating obstacles, characterized by reduced crossing speed, shorter stride length, and a smaller gap between the obstacle and the heel strike. However, there were no discernible age-related disparities in walking without obstacles. Furthermore, the elderly individuals successfully traversed the obstacle, resulting in a 10% advancement in their obstacle-crossing stride.

1.8.1 The obstacle height and foot clearance when stepping over an obstacle

Potentially influencing the obstacle height is the foot clearance required to prevent tripping. We have used foot (or foot-obstacle) clearance as an important kinematic index to evaluate the strategies used when crossing obstacles of varying heights. The effects of obstacle height on foot clearance have been the subject of extensive research and have presented significant controversy. For the leading limb, Chen et al. (1991) used the lowest of the heel, toe, and mid-foot markers to calculate the foot clearance when stepping over obstacles of three different heights (25, 51, and 152mm). They found that in 82% of the trials, the leading heel was the lowest, and that foot clearance increased significantly with increasing obstacle height. Sparrow et al. (1996) proposed that subject size differences could lead to potential errors in clearance calculations, necessitating the adjustment of obstacles based on leg lengths for each subject. They studied the effects of obstacle height (10, 25, and 40% leg length) on foot clearance using the heel marker and found that obstacle height did not affect foot clearance. Patla et al. (1996) used the toe marker to calculate the foot clearance when crossing obstacles with three heights (67, 134, and 268mm). No significant difference was found between the clearances in the 67 mm and 134 mm obstacles, but the clearance for the 268mm obstacle was higher than that for the lower obstacles. Austin et al. (1999) used both toe and heel markers to calculate the foot clearance when crossing obstacles of three heights (31, 76, and 126mm) and found that both lead toe and heel clearances increased with obstacle height except for 76 and 126mm obstacles. Lu et al. (2009) used both toe and heel markers to calculate the foot clearance when crossing an obstacle (2 cm). Likewise, the comparisons of the older and younger groups indicated that the older group had shorter leading heel obstacle distances and longer trailing toe obstacle distances across all heights. Other studies have used a percentage of leg length to determine the obstacle height such as 20% and 30 % of leg length (Lu et al., 2006). Previous research has employed a proportion of leg length, specifically 20% and 30% of leg length, to ascertain the height of the obstruction (Lu et al., 2006). For instance, when assessing foot clearance in research, the percentage of leg length as the obstacle height establishes a consistent relative height for each participant.

The studies described so far have been relatively simple - approach obstacle-stepover-depart. Yet there have been different types of obstacle related studies. A few examples are Lowrey et al. (2009) who used both toe and heel markers to calculate the foot clearance when crossing stepping over one or two obstacles scaled to their lower leg length. This demonstrated foot clearance when stepping over multiple obstacles in young and older adults (Lowrey et al., 2007). When stepping with multiple obstacles, age did not have an effect on lead and trail clearance (Lowrey et al., 2007). Muir (2015) used both toe and heel markers to calculate foot clearance when crossing obstacles with three heights (1, 10, and 20 cm) while wearing goggles that obstructed the lower visual field in young and older adults (Muir et al., 2015). The results showed that the distance between the lead heel and the obstacle was shorter than the distance between the toe and the obstacle. Maidan et al. (2018) used both toe and heel markers to calculate the foot clearance when crossing obstacles with two heights. Maidan et al. (2018) used both toe and heel markers to calculate the foot clearance when crossing obstacles of 25- and 75-mm anticipated and unanticipated heights in both young and older adults. The results mentioned above indicate that older people tend to position their leading foot closer to the obstacles following landing, in contrast to young adults (Maidan et al., 2018). With an increase in obstacle height, the previous pattern became more apparent. There was a positive correlation between the distance of the leading foot after the obstacle and the clearance of the trailing foot, as well as motor, cognitive, and functional abilities. Greater distance of the leading foot after the obstacle and enhanced clearance of the trailing foot were associated with higher levels of these abilities.

1.9 Dual-task walking

Dual-task walking is defined as the ability to perform two tasks simultaneously. For example, they are walking and carrying groceries at the same time. It entails coordinating motor, cognitive, and attentional resources to successfully complete both tasks without compromising gait stability or performance (Shumway-Cook and Wolcott, 2011). Likewise, dual-task paradigms, also known as cognitive-motor interference, occur when individuals must simultaneously perform both cognitive and motor tasks, such as walking while performing a cognitive task (McIsaac et al., 2015; Shumway-Cook and Wolcott, 2011). When individuals engage in walking while simultaneously encountering obstacles, they divide their attention between cognitive processes and motor control, resulting in interference between their cognitive and motor abilities (Shumway-Cook and Wolcott, 2011). This interference can affect various aspects of gait instability (Shumway-Cook and Wolcott, 2011). Additionally, older adults often experience age-related declines in cognitive functions such as attention, working memory, and executive function (Shumway-Cook and Wolcott, 2011). The cognitive changes can impact their ability to effectively allocate attention while walking with dual activities, potentially compromising their stability and ability to navigate hazards (Shumway-Cook and Wolcott, 2011). Understanding the influence of cognitive load on the ability of older adults to lift their feet is crucial for creating successful strategies to prevent falls and aid in rehabilitation (Montero-Odasso et al., 2012).

In this current research, a dual task was used, which involved motor skills similar to walking, such as holding a glass of water without spilling. This task has low novelty and high complexity (McIsaac et al., 2015). It has less cognitive load (Hall et al., 2011), divided attention (Hall et al., 2011), motor control and coordination (Hunter et al., 2018), and prioritization of task (Hall et al., 2011) than counting backwards task. Additionally, engaging in a secondary motor task, such as maintaining a grip on a glass of water, necessitates greater motor control and coordination (Hunter et al., 2018). This can disturb the typical walking pattern and require adaptations to maintain equilibrium and avoid falls.

1.10 The range of dual tasks that have been used in the walking gait

Dual-task paradigms examine how individuals execute a secondary task while walking, showing cognitive-motor interference and gait modifications due to split attention.

1.10.1 Cognitive dual tasks

Cognitive dual-tasking walking describes the concurrent execution of a physical task (i.e. walking), specifically ambulation, alongside a cognitive task demanding mental exertion. This framework is extensively employed to evaluate motor-cognitive interference and comprehend the competition brain's allocation of shared resources between motor control and cognitive processing (Smith et al., 2016).

Dual-task walking research has utilized various cognitive tasks, each addressing distinct cognitive domains. Researchers commonly employ mental arithmetic activities, like serial subtraction (e.g., repeatedly subtracting 7 from 100), to evaluate working memory and sustained attention. Verbal fluency exercises, including naming animals or producing words that commence with a particular letter, activate executive functions and language processing. Memory tasks, which require the recollection and verbalization of sequences of numbers or words, assess working memory and attentional skills. Reaction activities, including responses to auditory or visual stimuli, assess sensorimotor integration and response time. Decision-making tasks, such as the Stroop test, necessitate executive processes like inhibition and cognitive flexibility (Smith et al., 2016; Beauchet et al., 2005).

A meta-analysis found that the mean walking speed under single-task conditions was 1.21 m/s, but with the addition of a dual task, it was significantly reduced to 1.02 m/s (Smith et al., 2016). The review looked at two types of dual tasks: mental tracking and verbal fluency. However, it didn't look at the effects of tasks with different levels of difficulty or how a dual task changed other aspects of a person's spatial and temporal gait (Smith et al., 2016).

Cognitive dual-task walking is therapeutically important, as it helps identify those at risk of falls or cognitive decline, particularly among the elderly and those with neurological conditions (Shumway-Cook and Wolcott, 2011). In dual-task scenarios, older adults often exhibit increased costs compared to younger individuals, marked by reduced walking speeds, heightened gait variability, and compromised postural stability (Shumway-Cook and Wolcott, 2011). This may pertain to older adults who ambulate slowly under single-task conditions and are aware of their fall risk; modifying stride length to adopt shorter steps may offer some protection against falls, as shorter steps improve stability and align the center of mass closer to the moving base of support.

Cognitive dual-task tests are important for learning how the brain works and creating ways to help people move around more easily and lower their risk of falling (Montero-Odasso et al., 2012).

1.10.2. Motor Dual Tasks

Walking motor tasks typically require upper-limb coordination or balance control, often imposing a physical load or demanding hand-eye synchronization. Here are some examples of these tasks:

1.10.2.1 Carrying an Object

Walking while holding an object, such as a tray containing a cup of water, can result in a decrease in postural control and an increase in sway (Kelly et al., 2008). Previous study indicates that carrying activities can expose age-related alterations in motor control, with younger persons often exhibiting a lesser effect on gait stability compared to older ones (Kelly et al., 2008).

1.10.2.2 Manual Dexterity Tasks

Tasks that require hand movements, such as manipulating small objects, frequently activate motor control and executive functions, altering spatial-temporal gait characteristics and reducing walking speed (Verghese et al., 2007).

1.10.3 Combination Cognitive-Motor Dual Tasks

The integration of cognitive and movement components can establish a demanding dual-task paradigm, particularly for individuals with cognitive or motor impairments, for example;

1.10.3.1 Texting or Utilizing a Smartphone While Walking

Engaging in texting or reading messages on a smartphone while walking necessitates cognitive focus and manual skill, adversely affecting gait characteristics such as diminished speed and heightened variability (Schabrun et al., 2014).

Kao et al. (2015) examine the effects of mobile phone usage on walking stability in healthy people, emphasizing the dual-task interference resulting from divided cognitive attention between ambulation and cell phone activities. The key finding was increased gait variability, which is a common indicator of diminished gait stability. This suggests that the increased cognitive load from mobile phone usage disrupts motor control during ambulation, leading to less uniform step patterns. Participants displayed reduced walking speed and shorter step lengths when using their cell phones, employing a more caution gait when attention is divided.

Agreeing with Lamberg and Muratori (2012) who also showed that cell phone usage can alter walking speed, step length, and gait patterns. Moreover, an increase in step width variability was observed, which suggests compensatory modifications for balance by expanding the base of support (Lamberg and Muratori ,2012). Task-specific discrepancies were seen, with texting causing more significant disturbances in stability compared to talking, possibly due to texting's demand for visual attention and cognitive concentration, whereas talking predominantly necessitates auditory processing. Researchers found that using cell phones made even healthy young adults' walking less stable (Kao et al., 2015). This suggests that the effects of multitasking with a phone are widespread enough to affect healthy, stable individuals, potentially impacting larger groups of people who may be more easily distracted (Kao et al., 2015).

The study by Kao et al. (2015) emphasizes the risks of cell phone usage while walking, indicating that even healthy persons may have gait instability. This has significant consequences for safety, particularly in urban environments where distracted walking heightens the likelihood of accidents or falls. The research advocates for dual-task training in rehabilitation, especially for individuals more susceptible to instability, to enhance balance and safety in multitasking settings.

When texting while walking, the downward head attitude, which diverts attention from the walking environment, thus restricting awareness of obstacles and alterations in the walking surface may increase the risk of trips or falls and affect postural stability.

1.10.3.2 Listening and Responding Tasks

Activities in which individuals walk while responding to questions or making decisions exhibit cognitive-motor interference, resulting in decreased walking speed and compromised stability, especially among older persons (Plummer et al., 2015).

However, the study by Schäfer and Schumacher (2014) investigates the interaction between cognitive and motor functions in healthy older individuals, especially during dual-task activities. The results revealed that cognitive-motor interference is more widespread in older adults, leading to diminished cognitive task performance or reduced gait rates. They prioritize motor tasks over cognitive processes to ensure stability and reduce fall risks. The complexity of tasks is essential since more complex dual tasks may lead to increased cognitive-motor interference. The authors suggest that programs designed to improve cognitive and motor skills may benefit healthy older adults, including dual-task training and physical activities like dance or Tai Chi. These techniques can improve flexibility and reduce interference in elderly individuals

1.10.4 New Directions for Dual-Task Research

1.10.4.1 Virtual Reality (VR) Dual Tasks

Virtual reality settings can replicate complex tasks demanding both cognitive and motor reactions, such as navigating a virtual city while executing arithmetic operations. Virtual reality tasks offer immersive experiences that can replicate real-world scenarios, providing a controlled environment in which to observe adaptive gait behaviors (Howe et al., 2017).

1.10.4.2 Emotional Distraction Tasks

A number of studies employ emotional stimuli, such as listening to emotionally charged words, to investigate the impact of emotional processing on gait. Studies indicate that emotional distraction might elevate gait variability and diminish speed (Young et al., 2020).

1.11 Limb symmetry

Symmetrical gait refers to a walking pattern where the movements of the left and right sides of the body closely resemble each other or are mirror pictures of each other (Sadeghi et al., 2000; Viteckova et al., 2018). A symmetrical gait pattern is characterized by the coordinated motion of both legs, where step lengths, timing, and force distribution are equal (Viteckova et al., 2018; Sadeghi et al., 2000). Asymmetrical gait, in the context of walking, refers to a pattern where there are differences or irregularities in the movements of the left and right sides of the body (Viteckova et al., 2018; Sadeghi et al., 2000). Various manifestations of an unbalanced walking pattern may indicate the existence of underlying issues pertaining to the musculoskeletal system, nervous system, or overall physiological functioning. Gait symmetry is often determined based on a discrete measure i.e. step length and arbitrary deemed asymmetrical if the difference is >10%. In this thesis I wanted to establish if the foot clearance parameters were symmetrical when clearing an obstacle.

1.11 Reliability

Reliability is a metric used to assess the dependability or consistency of something. Consistency ensures stable and reliable outcomes, regardless of the frequency or repetition of using a particular technique to test the same thing. It guarantees the assurance, uniformity, and steadfastness of measures (Portney and Watkins, 2000). There exist three primary categories of reliability. Inter-rater reliability refers to the consistency of assessments performed by multiple raters using the same evaluation tool (Portney and Watkins, 2000). The acquired assessments should be consistent with each other, showing that the evaluation tool is credible. Intra-rater reliability refers to the degree of consistency in measures conducted by the same evaluator under identical settings (Portney and Watkins, 2000). In this scenario, a single assessor takes measurements on two separate occasions. If the findings are consistently the same on both instances, then the reliability is strong (Portney and Watkins, 2000). Thirdly, test-retest reliability assesses the consistency of measurements by administering the same instrument to the same group on two separate occasions, with an appropriate time gap between the tests (Portney and Watkins, 2000).

Test-retest reliability has been shown in walking to assess the consistency of measurements by administering the same instrument or testing the same participants over at least 2 sessions with an appropriate time gap between the tests (Portney and Watkins, 2000). The reliability of walking evaluations may vary depending on the specific characteristics being assessed, such as kinematic and kinetics data (Meldrum et al., 2014). The study (Meldrum et al., 2014) evaluated the test-retest reliability of three-dimensional gait analysis, which focused on spatial-temporal properties. For instance, the study examined the frequency, length, speed, duration, and width of steps. The results indicate that the intraclass correlation coefficients (ICC) were equal to or more than 0.90, demonstrating a high level of agreement. In addition, the standard error of measurement (SEM) was low, and the least detectable change (MDC) was modest. In general, the range of joint movement throughout the walking cycle was more uniform compared to the lowest or maximum values. Additionally, movement in the sagittal plane exhibited greater interclass correlation coefficients (ICCs). Concerning kinematic data, the majority of parameters displayed a remarkably low standard error of measurement (5˚). The measurements made in the transverse plane demonstrated low dependability, as shown by the lowest intraclass correlation coefficients (ICCs). The intra-class correlation coefficients (ICCs) for the kinetic data varied between 0.51 and 0.81 (Meldrum et al., 2014). Ensuring test-retest reliability is crucial to ensuring that walking assessments produce consistent and dependable results over numerous sessions.

1.12 Summary

Stepping over an obstacle is a frequently performed movement that requires complex biomechanical processes. When analyzing the biomechanics of stepping over an obstacle, it is critical to consider a variety of important factors. The methodology and strategic structure are the initial essential components. When faced with an obstacle, it is necessary to evaluate its dimensions, including its height, width, and distance, in order to determine the most effective method for overcoming it. This requires the utilization of visual perception, spatial awareness, and motor planning to synchronize the movements. However, stepping is the action of raising and lowering two limbs in an alternating manner to elevate them above the ground. When crossing over an obstacle, the lead limb lifts the first leg, followed by the trailing limb. The trailing limb lacks visual input (Patla et al., 1996; Patla, 1997).

Dual-task walking is a reflection of the complex relationship between motor and cognitive processes that are involved in everyday mobility. Gaining insight into the mechanics of dual-task walking can provide valuable information for developing interventions that aim to enhance mobility and minimize the likelihood of falls, especially among older persons and individuals with medical conditions.

Falls pose a significant risk for elderly individuals, frequently associated with inadequate foot clearance while ambulating (Winter, 1991; Muir et al., 2013). Researchers have looked into general gait metrics and fall risks in older people, but they still do not fully understand how the specific foot clearance parameters of young and older people differ when they have to negotiate obstacles (Heijnen et al., 2014). This is crucial, as inadequate obstacle negotiation frequently leads to falls, particularly in settings with irregular surfaces or unforeseen impediments. Investigating this could provide insights into age-related gait adaptations and help develop preventive interventions that enhance stability and mobility in older adults.

Consistency in foot clearance measurements is fundamental for reliable gait assessment and research reproducibility. Young adults typically demonstrate high stability and control, but it remains uncertain how their foot clearance parameters might vary with obstacle height (Patla et al., 1996; Begg et al., 2007). Exploring this can provide reference data to evaluate how well younger populations maintain consistent movement patterns, potentially setting a baseline for identifying deviations in populations with gait impairments.

Gait symmetry correlates with efficient and steady movement, but asymmetry may signify possible imbalance or injury risk (Sadeghi et al., 2000; Patterson et al., 2010). Despite much study on symmetry in linear walking, the degree of symmetry in obstacle negotiating across different walking tasks remains poorly understood. Comprehending this can elucidate how task complexity may influence gait symmetry, which is crucial for formulating rehabilitation programs intended to restore or preserve symmetrical movement.

Male and female frequently have different movement patterns attributable to physiological variations like leg length, muscle mass, and joint flexibility (Ko et al., 2010; Kerrigan et al., 1998). However, our understanding of these the impact of inequities on foot clearance, particularly during obstacle navigation, is inadequate. Looking into differences between male and female in how much space they need to clear their feet could lead to the creation of gender-specific therapies, training plans, or assistive equipment that fits the needs of each group. This would make it safer for individuals of all backgrounds to move around.

Older individuals may demonstrate diminished motor control and balance, especially during intricate walking activities that require obstacle navigation (Cham & Redfern, 2002; Galna et al., 2013). The impact of employment difficulties on foot clearance varies between young and elderly people and remains ambiguous. Comprehending these distinctions is essential for devising therapies that address certain age-related deficiencies, hence mitigating fall risk in older persons through targeted training on intricate walking tasks.

In summary, there is a lack of research on foot clearance measurements in adults, with only a few studies discussing reliability, gait symmetry, gender variations, or specific characteristics of obstacle. However, these inquiries highlight significant deficiencies in our comprehension of foot clearance across the variety of groups and situations, with implications for safety, injury prevention, and customized therapeutic strategies.

Research Questions

1: What is the gap in research involved foot clearance parameters when stepping over an obstacle in young and older adults?

2: In young adults, how consistent are foot clearance measures when negotiating obstacles of different heights?

3: What is the level of symmetry in foot clearance when stepping over an obstacle with four walking tasks?

4: Are there any foot clearance parameters when stepping over obstacles that differ between genders?

5: Are there differences in foot clearance parameters between young and older people while stepping over an obstacle with four walking tasks?

Aims of study

Chapter IV: Repeatability in young adults

The purpose of this thesis was to:

1) assess the consistency and reliability of foot clearance measurements during the performance of obstacle negotiation tasks.

Chapter V: Gait symmetry in young adults

1) to a) establish if foot clearance parameters are symmetrical when stepping over an obstacle and b) compare four commonly used gait symmetry indices, namely, symmetry ratio (RI), symmetry index (SI), gait symmetry (GA) and symmetry angle (SA).

Chapter VI: Gender difference in young adults

1a) compare foot clearance parameters when stepping over different an obstacle of different height or when performing a different task, and 1 b) comparing obstacle clearance between males and female participants both pre and post normalization to stature.

Chapter VII: Stepping over an obstacle in young and older adults

1) establish if older adults negotiated an obstacle differently – under single and dual task conditions - (based on obstacle clearance parameters) compared to younger adults. It was possible that this would be the case due to differences in walking gait between older and younger adults.

Hypothesis

Chapter IV: Repeatability in young adults

1 There will be a high level of consistency in foot clearance measurements in young adults during obstacle negotiation tasks that exhibits repeatability over several trials.

Chapter V: Gait symmetry in young adults

1 Foot clearance parameters will not be asymmetrical when stepping over an obstacle.

Chapter VI: Gender difference in young adults

1 There will be significant difference in foot clearance and spatial temporal parameters whilst stepping over an obstacle based on obstacle height (two obstacle heights: 15 cm. and 20 cm.).

2 There will be significant difference in foot clearance and spatial temporal parameters whilst stepping over an obstacle based on two task demands (with and without holding a glass of water).

3 There will be significant difference in foot clearance and spatial temporal parameters whilst stepping over an obstacle based on gender.

Chapter VII: Stepping over an obstacle in young and older adults

1. There will be significant difference in foot clearance parameters whilst stepping over an obstacle based on obstacle height (two obstacle heights: 15 cm. and 20 cm.).
2. There will be significant difference in foot clearance parameters whilst stepping over an obstacle based on two task demands (with and without holding a glass of water).
3. There will be significant difference in foot clearance parameters whilst stepping over an obstacle between healthy young and older adults

Chapter II: Obstacle height and an additional task on foot clearance in young and older adults whilst stepping over an obstacle: A systematic review

Abstract

Background: Stepping over an obstacle is a commonly seen locomotor activity that has been associated with an increased risk of falling. We hypothesize that the primary cause of stumbling when navigating obstacles is the interaction between internal and exterior factors within the human body.

This systematic review aims to address these critical gaps by comparing foot clearance during obstacle negotiation under varying task complexities and conditions in younger and older adults

Methodology: This study used search criteria related to overcoming obstacles in the title, abstract, or keywords. This initially yielded a total of 520 publications, from which we subsequently selected ten for review.

Results: Obstacle height and additional tasks significantly influence foot clearance in older adults and young individuals. Older adults exhibit a reduced approach speed, a shorter heel-to-heel crossing step length, and an increased leading toe clearance. However, leg lengths of 20% and 30% reduced the toe clearance over obstacles. Obstacle height is a significant factor in foot clearance, with greater obstacles requiring increased clearance to mitigate the risk of tripping or stumbling. The study also highlights the importance of understanding the factors influencing foot clearance and stepping over obstacles in both young and older adults. Dual-task walking, which involves performing two tasks simultaneously while walking, does not significantly impact toe clearance but does decrease heel-obstacle distance. Understanding these factors is crucial for

designing safe spaces, improving fall prevention, and facilitating secure obstacle navigation and accident prevention.

Conclusions: In conclusion, the interaction between age and obstacle height on foot clearance may be a complicated combination of biomechanical factors, adaptability, and individual variability. Understanding how people deal with the difficulties of dual-task walking provides insights into the complexity of daily life and human cognition.

Keywords: foot clearance, toe clearance, younger adults, older adults, stepping over, crossing over

2.1 Introduction

Falls provide a primary cause of injury and diminished quality of life in elderly individuals, with insufficient foot clearance during ambulation identified as a significant contributing factor (Winter, 1991; Muir et al., 2013). Efficient obstacle navigation, a frequent daily problem, demands accurate foot clearance to prevent tripping or excessive energy consumption. However, our understanding of the precise foot clearance measures for navigating obstacles of varying heights in younger adults, particularly in dual-task scenarios, remains inadequate (Heijnen et al., 2014).

Current research has thoroughly examined overall gait measurements and fall risks in older populations; nevertheless, significant gaps remain in comprehending how age-related alterations in biomechanics and motor control affect foot clearance during complex activities. Inadequate obstacle navigation is a common contributor to falls, particularly in settings with irregular surfaces or unexpected obstacles. Comprehending foot clearance dynamics among various age groups is essential for recognizing age-specific compensating methods and mobility difficulties (Patla et al., 1996; Begg et al., 2007).

The impact of task complexity on gait symmetry and stability during obstacle negotiation has been inadequately explored. Although gait symmetry is acknowledged as an indicator of effective and stable mobility, the manner in which this symmetry alters in reaction to differing barrier heights or dual-task scenarios remains ambiguous (Sadeghi et al., 2000; Patterson et al., 2010). Such insights are crucial for formulating rehabilitation regimens intended to restore symmetrical and efficient movement patterns.

Men and women differ physiologically in terms of leg length, muscle mass, and joint flexibility, which may influence foot clearance. However, research on how these differences affect obstacle negotiating is still insufficient (Ko et al., 2011; Kerrigan et al., 1998). Examining these differences can guide the creation of gender-specific therapies, assistive technologies, or training programs. Older persons frequently exhibit diminished motor control and balance, especially while engaging in dual-task walking. The complexity of concurrently managing cognitive and physical demands may further impede their capacity to sustain sufficient foot clearance (Cham & Redfern, 2002; Galna et al., 2013). Comprehending the differential effects of dual-task situations on younger and older persons may inform the development of therapies customized to age-specific requirements. This systematic review aims to address these critical gaps by comparing foot clearance during obstacle negotiation under varying task complexities and conditions in younger and older adults. By synthesizing existing evidence, the review seeks to advance our understanding of age-related gait adaptations and inform interventions that enhance mobility and reduce fall risk in older populations.

2.2 Methods

2.2.1 Eligibility criteria.

The research aims to assess foot clearance and obstacle negotiation tasks in young adults aged 18–35 and elderly adults aged 60 and above, concentrating on healthy individuals without significant impairments. The investigations included evaluations of single-task and dual-task conditions, comparisons between younger and older individuals, and variations in obstacle heights or leg lengths. The principal outcomes are toe clearance, heel clearance, and minimum foot clearance over obstacles. The study design encompasses a cross-sectional study. However, the study excluded individuals with previous lower limb surgeries, balance impairments, or mobility restrictions not associated with age. The emphasis was on non-stepping tasks and therapies, without contrasting young and older persons or single-task versus dual-task walking. The results lacked relevance and specificity, and the study design encompassed reviews, meta-analyses, conference abstracts, commentaries, and publications in languages other than English.

2.2.2 Search strategy

The search strategy was applied to identify all articles involving crossing over or stepping over between younger and older adults. In December 2021, we searched five online databases, including CINAHL (EBSCO host) (1985-December 2021, PubMed (1985-December 2021), Medline-complete (1985-December 2021), Medline with full text (1985-December 2021) and Cochrane (1985-December 2021)

A search using MESH terms and free text words was conducted using the search terms related to “crossing over," "obstacle," and “older adults." In terms of keywords, there are several free text words that use the search terms related to “walking” or “crossing over” or "stepping over" AND “toe clearance" or "foot clearance” AND "obstacle” AND “elderly” or “elderly adults” or “aged” or “older” or “elder” or “geriatric” or “elderly people” or “old people” or “senior” or "aging.”

2.2.3 Study records

2.2.3.1 Data management

The initial phase of the project involved amalgamating all primary articles sourced from electronic databases. Reviewers excluded articles that did not pertain to the subject of crossing over or stepping over an obstacle during the initial stage of title and abstract screening. We evaluated the abstracts that remained after the initial screening process using the predetermined criteria for inclusion and exclusion. We conducted a thorough examination of all available articles in cases where there was insufficient information to make a decision regarding the inclusion of the article.

2.2.3.2 Selection process

The extracted data included a description of demographic participants and key outcomes such as age, sex, sample size, obstacle height, walking speed, method of measuring MFC, time constraint, footwear, and task.

2.2.3.3 Data collection

Articles included in this review compare younger and older adults. Various variables were analyzed, such as age, methodology, and outcomes. The term quality assessment is defined as its capacity to avoid potential bias and generate results that are generalized. The quality dimension involved both internal and external validity. Internal validity is defined as the measurement's accuracy. Other outcomes are generalized to the population of interest. However, a quality appraisal tool is an important process in systematic reviews. This study used a tool developed by Law (Law and MacDermid, 2008). Galna et al. used a tool to appraise each study. Before using the appraisal tool, Galna et al. used PRISMA to guide the search and selection of papers. Galna et al. scored the quality appraisal tool on a scale of one. A score of zero indicates low quality, and one indicates high-quality research as well.

2.3 Results

2.3.1 Yield

The present reviews identified a total of 520 studies. The publication of search strategies and inclusion criteria encompassed the years 1985 through 2021. A total of 250 items were deemed ineligible based on their evaluation against the specified criteria. We conducted a total of fifty-two investigations to study the phenomenon of crossing over an obstacle, focusing specifically on kinetic and kinematic analyses. Several articles featured individuals suffering from various conditions such as low back discomfort, neurovascular disease, and osteoarthritis. A total of twenty articles were deemed to be implicated, and comprehensive manual scripts of these were taken into consideration. The study included ten publications that met the established criteria after a thorough review (Figure 2.1).

2.3.2 Quality of assessment

Table 2.1 summarizes and displays the quality assessment results for each article. All of the studies got a maximum score of one for all of the following: answering questions about the participants, recruitment and sampling methods, outcome details, methodology details that answered their questions, discussion of the study's results, reliability of the methodology, key findings that supported the results, key findings that were logically interpreted and supported by references, and clinical implications that were stated. On fourteen questions, the total average score was approximately eighty percent.

However, there was a full score in the items that involved research aims, key outcome variables, research questions that were adequately answered in the discussion, key findings that supported the results, and key findings that were logically interpreted and supported by references. Next, a score closer to ninety percent was in the items of participant detailed items, inclusion and exclusion criteria detailed items, and methodology able to answer the question item, whereas the score of adequate methodologies to repeat the study item was approximately eighty percent. Additionally, the items describing the recruitment and sampling methods and the controlled covariates received scores ranging from sixty to seventy percent. Finally, the item on clinical implications received a score of forty percent. In addition, there was a lack of reliability in the methodology stated for all the studies in this review.

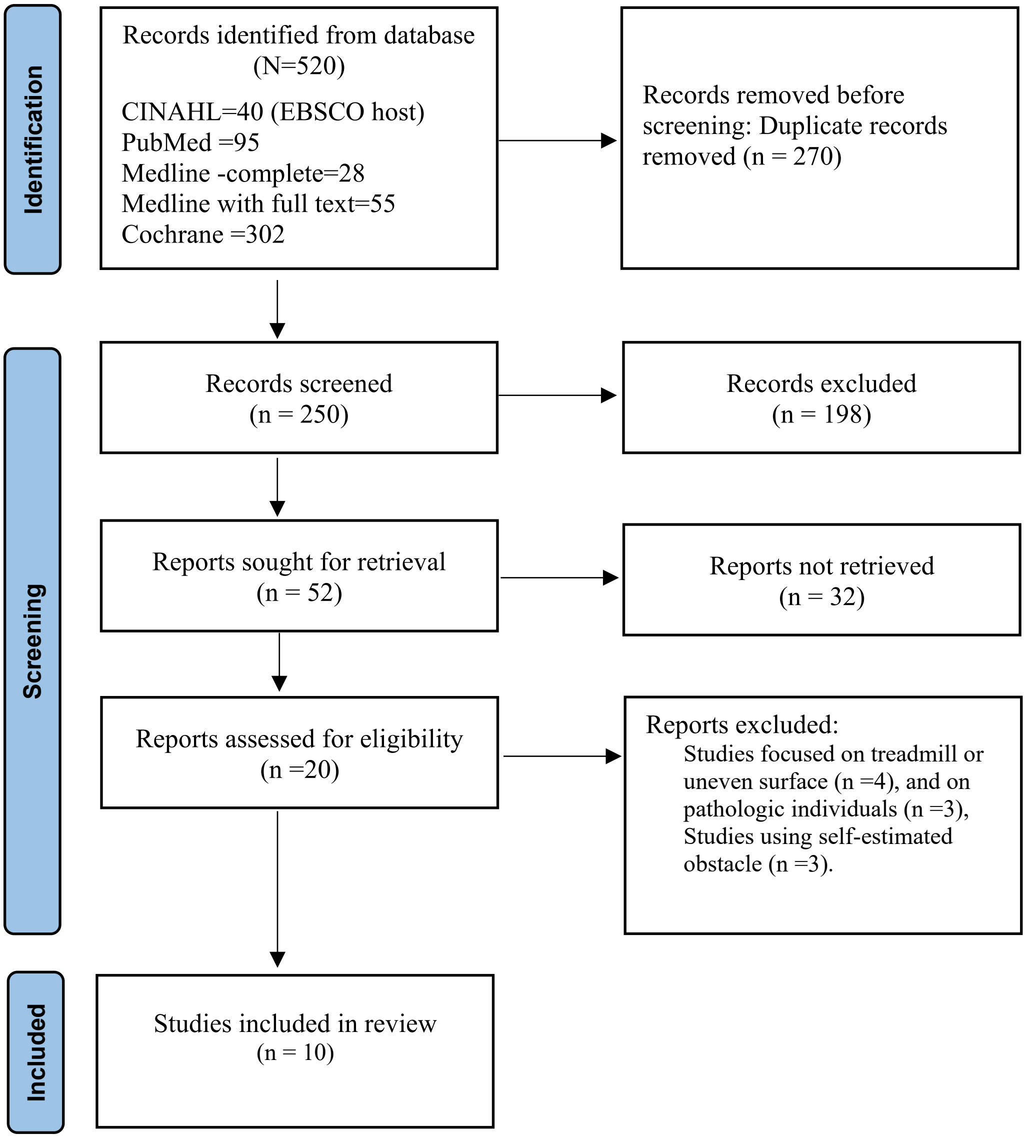

Figure 2. 1 Diagram of identification study

Table 2. 1 The quality appraisal results

Question	Scoring criteria	L Maindan 2018	Kunimune and Okada, 2017	Muir 2015	Shin et al., 2015	Soma et al., 2010	Harley et al., 2009	Lowrey et al 2007	Lu et al., 2006	Di Fabio et al, 2004	Chen et al., 1991	Average
1 Research aim or question clearly stated	1=yes; 0.5=yes but lacking detail or clarify; 0= no	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
2 Participants detailed	Number	1	1	1	1	1	1	1	1	1	1	1
	Age	1	1	1	1	1	1	1	1	1	1	1
	Sex	1	1	1	1	1	0	1	0	1	1	0.8
	Height or Leg length	1	1	1	1	1	0	1	1	1	1	0.9
	Weight	0	1	1	1	1	0	1	1	0	1	0.7
	Sub-total	**0.8**	**1**	**1**	**1**	**1**	**0.4**	**1**	**0.8**	**0.8**	**1**	**0.88**
3 Recruitment and sampling method described	1=yes; 0.5=yes but lacking detail or clarify; 0= no	**1**	**1**	**1**	**1**	**0.5**	**0**	**1**	**0**	**0.5**	**0.5**	**0.65**
4. Inclusion and exclusion criteria detailed	1=yes; 0.5=yes but lacking detail or clarify; 0= no	**1**	**1**	**1**	**1**	**0.5**	**1**	**1**	**0.5**	**1**	**1**	**0.9**
5 Controlled covariates	Height	0	1	1	1	1	0	1	1	1	0	0.7
	walking speed/cadence	1	0	1	0	1	1	0	0	1	1	0.6
	Age	1	1	1	1	1	1	1	1	1	1	1
	Gender	0	1	0	1	1	0	0	0	1	1	0.5
	Limb Asymmetry	0	1	0	1	1	0	1	1	1	1	0.7
	dual task /an additional task	1	1	1	0	1	1	0	0	1	0	0.6
	Sub-total	**0.4**	**0.7**	**0.6**	**0.6**	**0.9**	**0.4**	**0.4**	**0.4**	**1**	**0.6**	**0.6**
6 Key outcome variables clearly described	1=yes; 0.5=yes but lacking detail or clarify; 0= no	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
7 Adequate methodologies to repeat study	Participant sampling	0	0	0	0	0	0	0	0	0	0	0
	Equipment	1	1	1	1	1	1	1	1	1	1	1
	Procedure	1	1	1	1	1	1	1	1	1	1	1
	Data processing	1	1	1	1	1	1	1	1	1	1	1
	statistics analysis	1	1	1	1	1	1	1	1	1	1	1
	Sub-total	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**
8 Methodology able to answer the question	Participant sampling	1	1	1	1	1	1	1	1	1	1	1
	Equipment	1	1	1	1	1	1	1	1	1	1	1
	Procedure	1	1	1	1	1	1	1	1	1	0	0.9
	Data processing	1	1	1	1	1	1	1	1	1	1	1
	Statistics analysis	1	1	1	1	1	1	1	0	1	0	0.8
	Sub-total	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**0.8**	**1**	**0.6**	**0.9**
9 Reliability of methodology started	1= yes, 0= no	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
10 Internal validities of the method started	1= yes, 0= no	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
11 Research questions answered adequately in discussion	1= yes, 0= no	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
12 Key findings supported the results	1= yes, 0= no	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
13 Key findings logically interpreted and supported by references	1= yes, 0= no	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
14 Clinical implications stated	1=yes; 0.5=yes but lacking detail or clarify; 0= no	**1**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0.4**
Average		**0.8**	**0.9**	**0.8**	**0.8**	**0.8**	**0.6**	**0.8**	**0.7**	**0.8**	**0.8**	**0.8**

Table 2. 2 Summary of characteristic data from ten studies.

	Studies	Study design	sample size (Y_A=young adult, O_A=older adult	Gender:	Age (Yrs.), (mean (SD))	Protocol	Single or multi-obstacle	A second task or an additional task	obstacle height; D=depth (cm), W= width (cm), H=heights(cm)	Walking speed	Footwear	Method for measuring MFC	Statistical tests
1	I. Maidan et.al 2018	Cross-sectional study	Y_A=20, O_A=20 (50% woman)	Mixed	Y_A=29.3(3.8) O_A= 77.7(3.4)	walked through an obstacle course while negotiating anticipated and unanticipated obstacles	Single obstacle	anticipated and unanticipated condition	D = 20 cm, W=60 cm, H = 2.5 cm and 7.5 cm	I) the infinite available time\II) an available time of 425 msec	shoes	Kinect cameras	Linear-mix models assessed changes between groups and conditions.
2	Kunimune and Okada, 2017	Cross-sectional study	Y_A=13, O_A=15	Female	Y_A = 21.5 (1.4), O_A = 68.5 (3.5)	Crossing over while wearing liquid crystal shutter goggles with three visual conditions; 1) full visibility, 2) occlusion at T- 2 steps, and 3) occlusion at T-1 step, where T refers to the time of obstacle crossing. Right foot is leading limb.	Single obstacle	visual condition	D = 5 cm, W=70 cm, H = 2.5 cm, 5 cm, and 10 cm	self-selected pace	Not stated	Pressure-sensing mat at heel contact, Single toe marker, Motion analysis software	Sample t-tests, A mixed-design analysis of variance model, Bonferroni correction, Paired t-test and Pearson's correlation coefficient
3	Muir, BC, 2015	Cross-sectional study	Y_A (20-25) =19, M/F=9/10; O_A (65-79) =11, M/F=3/8, O_A (80-91) =18, M/F=7/11	Mixed	Y_A (20-25) =22 (1.3); O_A (65-79) = 73.5 (4.0), O_A (80-91) =85.1(2.9)	stepping over a stationary while wearing goggles that obstructed the lower visual field	Single obstacle	wore the goggles	78 cm wide by 0.5 cm deep, composed of Masonite, painted flat black, and designed to tip if contacted. The obstacle height is 1, 10 and 20 cm	self-selected pace	Not stated	3D Optotrak system. Fifth metatarsal, posterior calcaneus, lateral malleolus, lateral femoral condyle, greater trochanter and glenohumeral axis	A two-way, linear mixed model ANOVA
4	Shin et al., 2015	Cross-sectional study	Y_A=9, O_A=16	Female	Y_A = 19.6(1.4), O_A = 73.7(4.4)	walk along 4 m walkway and step over the obstacle; 5 cm and 20 cm obstacle height	Single obstacles	no	D = 2 mm, W=45 cm, H = 5 cm, and 20 cm	as quickly as possible	Not stated	Single toe marker, 3D	Two-factor ANOVA with repeated measures on one factor
5	Soma et al., 2010	Cross-sectional study	Y_A=30, O_A=30	Female	Y_A= 26.0 (3.2), O_A = 69.0 (3.6)	Walk at comfortable speed, and stepping over. During walking, repetitive subtract 7 starting from 100, and answer our questions	Single obstacle	Solitary motor task	D = 15 cm, W= 80 cm, H = 2 cm	comfortable speed	Not stated	Single toe marker, 3D	A two-way, linear mixed model ANOVA

	Studies	Study design	sample size (Y_A=young adult, O_A=older adult	Gender:	Age (Yrs.), (mean (SD))	Protocol	Single or multi-obstacle	A second task or an additional task	obstacle height; D=depth (cm), W= width (cm), H=heights(cm)	Walking speed	Footwear	Method for measuring MFC	Statistical tests
6	Harley et al., 2009	Cross-sectional study	Y_A=21, O_A=25	not stated	Y_A= 20.23 (2.49), O_A (60-69) = 64.77 (3.23), O_A (70-79) = 74.00 (3.23),	Walk and crossing over concurrent with and without verbal fluency, walk without obstacle’	Multi-obstacles	cognitive Interference; verbal fluency	**Small**; D = 25 mm, W=76 mm, H = 300 mm, **Large;** D = 152 mm, W=76 mm, H = 300 mm,	briskly	Not stated	Single toe marker, 3D	A repeated-measures ANOVA
7	Lowrey et al 2007	Cross-sectional study	Y_A=8 (Male=4, Female =4), O_A=8	Mixed	Y_A males =23.8 (2.4), Y_A females = 22.5 (2.4); O_A males =75.8 (4.2), O_A females, = 76.5 (5.0)	Walk along 5 m and stepping over one or two obstacles	Multi-obstacles	no	adjusted 45% of lower leg length (a 2.5 cm & 5 cm piece of wood that spanned the width of the GAITRite carpet)	self-selected pace	shoes	Single toe marker, 3D	A multivariate analysis of variance (MANOVA)
8	Lu et al., 2006	Cross-sectional study	Y_A=15, O_A=15	not stated	Y_A= 23.0 (3), O_A = 72.0 (6)	Walk along 8 m and crossed a height-adjustable obstacle	Single obstacle	no	heights of 20% and 30% of leg length a 1.5 m long aluminum tube with a diameter of 1.5 cm placed across a metal frame	self-selected pace	not stated	Single toe marker, 3D	RMANCOVA
9	Di Fabio et al, 2004	Cross-sectional study	Y_A=15 ((Male=4, Female =11), O_A=18 (Male=4, Female =14),	Mixed	Y_A= 23.0 (1), O_A = 84.0 (5)	Walk along a 3 m walkway while stepped over each three foam obstacles.	Single obstacle	audio and visual condition	D = 21 cm, W=51 cm, H = 7.6 cm, 12.7 cm, and 23 cm	self-selected pace	not stated	Single toe marker, 3D	One-way ANOVA, Two-way ANOVA
10	Chen et al., 1991	Cross-sectional study	Y_A=24, O_A=24	Mixed	Y_A Female= 21.7 (2.1), Y_A Male = 21.5 (2.0), O_A Female = 71.2 (6.5), O_A Male = 71.3 (4.5)	Walk along a 3 m walkway and then stepping over the obstacle in their usual manner, continuing at least 2 m past before stepping	Single obstacle	no	D = 25 mm, W=450 mm, H = 25, 51, and 152 mm	comfortable speed	shoes	optoelectronic system	One-way ANOVA

2.3.3 Sample characteristics

Table 2.2 provides a comprehensive summary of the participant characteristics as reported in each respective publication. The review encompassed papers that reported a mean age range of 65 to 84 years for older persons and 19 to 26 years for younger adults. The sample for three studies exclusively comprised female participants (Kunimune and Okada, 2017; Shin et al., 2015; Soma et al., 2010), whereas the remaining five studies included participants of both genders (Maidan et al., 2018; Muir et al., 2015). Studies by Lowrey et al. (2007), Di Fabio et al. (2004), and Chen et al. (1991) have also included participants of both genders. The two studies did not provide any information regarding the gender of the subjects (Harley et al., 2009; Lu et al., 2006).

2.3.4 The obstacle heights.

Two aspects comprised the heights of the obstacles. All articles consistently described the obstacle's height as ranging from 2 to 30 centimeters. Seven articles used an obstacle height that was more than nineteen centimeters, whereas four articles used a depth dimension of 20 cm (Maidan et al., 2018), 15 cm (Soma et al., 2010), 15.2 cm (Harley et al., 2009), and 21 cm (Di Fabio et al., 2004), respectively. Another challenge was adapting to the participants' different leg lengths. The measurements corresponded to 20%, 30%, and 45% of the length of the leg. In two articles, obstacle height was used to account for participant leg length percentages. According to Lu et al., 2006, and Lowrey et al., 2007, Table 2.2 illustrates this.

Nine studies used obstacles in the form of squares, as shown in Table 2.2. The materials used for its construction include wood (Lowrey et al., 2007; Soma et al., 2010), Masonite painted flat black (Muir et al., 2015), aluminum tube (Lu et al., 2006), translucent acrylic plate (Shin et al., 2015), foam obstacles (Di Fabio et al., 2004), and a firm dark surface (Chen et al., 1991). Only two articles did not state the material, whereas there was a study that used the unique computerized obstacle course in the ascending part of the elliptic path (Maidan et al., 2018), as shown in Table 2.2.

2.3.5 An additional task: Single or dual task walking

There were two dual-task walking studies in this review. One was a cognitive task (counting backward). The other was a dual-task (obstacle crossing with a verbal task) condition (Harley et al., 2009). However, others used a cue that involved system requirements for postural control as an additional condition, leading to increased complexity in stepping (Shumway-Cook and Woollacott, 2017). There were four articles that focused on visual conditions, one that combined visual and audit conditions, and another that addressed multiple obstacle conditions. In addition, there were three articles for single-task walking (obstacle crossing only), as shown in Table 2.2.

2.3.6 Walking speed and shoe

A total of seven articles employed either self-selected speed or natural speed as their chosen methodology. Two experiments were conducted with vigorous walking. The investigation used a 425-millisecond time interval that was easily accessible. However, three articles documented the act of wearing shoes, whereas the remaining seven articles did not provide any information addressing footwear, as indicated in Table 2.2.

2.3.7 Markers in use and the measuring foot clearance

Five research articles employed toe and heel markers to measure foot clearance distance during the process of stepping over the obstacle. The last five items exclusively employed toe markers, as shown in Table 2.2.

Table 2. 3 Summary of outcomes of the eligible studies

Studies	**Side of leading limb**	**Outcome measures**	**Results** **Effect size /Statistic finding** **Mean (SD)**	**Key findings**	**Recommendation for further study**
I. Maidan et.al 2018	not stated	(1) distance of trailing foot before the obstacles, (2) distance of the leading foot after the obstacles, (3) clearance of the leading foot above the obstacles, and 4) clearance of the trailing foot above the obstacles.	The study found that older adults tend to position their leading foot closer to obstacles after landing, a significant difference from young adults. This pattern is reinforced by height obstacles, as indicated by the significant interaction between group and height factors. Additionally, older adults showed a significantly lower level of clearance over obstacles compared to young adults.	The study indicates age-related changes in obstacle crossing strategies, influenced by obstacle characteristics. It suggests functional exercise should incorporate obstacle negotiation training, with variable height and response times,	Further research is needed to understand motor and cognitive ability.
Kunimune and Okada, 2017	Right	The variables of interest in this study include the toe clearance of the leading limb (LTC), the clearance of the trailing limb (TTC), step length, step width, walking speed, and crossing over time for the lead limb (indicating the limb that crosses over an obstacle). Additionally, the trail foot location will be determined using motion software. Timed Up &go test (TUG), Sit to Stand (SIS)	The study found that younger adults had higher physical function levels in the Timed Up and Go (TUG) and Sit-to-Stand (STS) tests compared to older adults. Age and visual condition significantly influenced both LTC and TTC, with stronger effects in older adults. The total task completion time was higher in the occlusion T-2 step condition compared to full visibility. Obstacle height significantly impacted TTC, with 2.5 cm heights having a higher impact. Long-term care and total transit time were significantly associated. Step width was also observed to be higher in older adult condition compared to full vision.	Age does not significantly impact visuomotor control for crossing obstacles. Older adults with may rely more on visual cues for stability and require wider step widths when obstacles have limited view.	Further research may focus on gender differences in visual information usage during obstacle crossing and eye movement in older adults with previous falls and high fall risk, focusing on the impact of different obstacles' postural threat.
Muir, BC, 2015	Lead limb = (first foot to cross obstacle) and trail (second foot)	The variables of interest in this study include the horizontal distance between the trail toes, the lead distance, the minimum clearance of the trail foot, the width of the step, and the variability in step length. The variability of each metric was determined by calculating the standard deviation of the six trials conducted for each obstacle condition.	Obstacle contact was recorded in 17 out of 840 trials, with a 2% occurrence rate across all age groups. The Modified Functional Reach Test showed that the distance between the lead heel and the obstacle was smaller than the distance between the toe and the obstruction in 78%, 89%, and 85% of trials on individuals aged 20-25 years, 65-79 years, and 80-91 years, respectively. The trailing foot and toe were closer to the obstacle compared to the heel. Older individuals experienced a more significant reduction in gait speed and higher overshoot. Effect size of Lead HHD (cm) at 3 obstacle height: 1 cm =4.8; 10 cm=6.8; 20 cm =7.7 Effect size of Lead HTD (cm) at 3 obstacle height: 1 cm =2.3; 10 cm=2.7; 20 cm =3.7 Effect size of Lead MFC (cm) at 3 obstacle height: 1 cm =0.2 ; 10 cm=1.5; 20 cm =0.4	The kinematics of leading and trailing limb trajectories include consistently placing the trail foot ahead of the obstacle, raising the lead toe vertically to prevent impact, and stretching beyond the landing position (lead overshoot) to achieve a shorter step length. As individuals age, the inclination of the head decreases, indicating a gradual change in limb trajectories.	Further research may examine how the rectangular ratio is affected by the postural threat imposed by obstacles of different shapes and properties.

Y_A=young adult, O_A= older adult, Toe clearance of leading limb (LTC), Toe clearance of Trailing limb (TTC), COG = Center of gravity, TRT = Trip risk integral, Timed Up &go test (TUG), Sit to Stand (SIS)

Studies	Side of leading limb	Outcome measures	Results Effect size /Statistic finding	Key findings	Recommendation for further study
Shin et al., 2015	not stated	The distance between the ground and toe, heel, knee, COG, shoulder, and waist; the angle of hip flexion/ extension, hip abduction/ adduction, knee flexion/ extension, ankle dorsiflexion/ plantarflexion, trunk flexion/ extension and trunk rotation in the initial contact and swing instants of LL and TL	The research indicated that older women exhibited reduced toe height and increased trunk rotation when preparing to step over a 20-cm obstacle, in contrast to younger women. The leading lower limb exhibited enhanced ankle dorsiflexion and hip adduction, whereas the trailing lower limbs demonstrated augmented ankle dorsiflexion, knee flexion, hip flexion, and foot inversion to circumvent contact with the obstruction. This pattern is indicative of elderly adults with diminished lower limb strength.	The study indicates that elderly women frequently flex their trunk forward and incline their upper body during trailing limb swings, likely attributable to inadequate lower-limb strength; nonetheless, this posture heightens the risk of falls or balance loss.	The current understanding of the trailing limb movement pattern, which involves increased ankle dorsiflexion, knee flexion, hip flexion, and foot inversion in elderly individuals who struggle to lift their lower limbs, indicates a decrease in lower-limb strength.
Soma et al., 2010	not stated	Gait speed, step length, cadence, lead clearance, Trail clearance, Toe--obstacle distance, Heel obstacle distance	The study demonstrates substantial impacts of gait speeds, step length, cadence, leading and trailing toe clearance, and heel-obstacle distance on both age and gait factors, in addition to cadence and age factors. However, the effect size of a single task of lead clearance (cm), trail clearance (cm), toe-obstacle distance (cm), and heel obstacle distance (cm) were 0.9, 0.2, 0.4, and 0.9, respectively, whereas the effect size of the dual task for the same variables was 1.2, 0.7, 0, and 0.9, respectively	The motor and cognitive tasks used in this study only affected the heel-obstacle distance when the subjects stepped over the obstacle.	Further research may be necessary to investigate the level of cognitive influence on motion.
Harley et al., 2009	not stated	Trail-toe distance, Lead-heel distance, Trail-toe clearance, Lead-toe clearance, step velocity	The study found that individuals aged 20-29 and 60-69 tend to approach obstacles closer before crossing them, resulting in increased vertical toe clearance and decreased gait variability. However, verbal production slightly declined during dual-task performance. Similarly, those aged 70-79 showed similar dual-task stepping methods during the pre-crossing phase, but decreased vertical clearance and increased variability in distance between obstacles and heels during traversal. No significant changes were observed in speech production during the sessions. However, the effect size of single task of Lead-heel distance (cm), Trail-toe distance (cm), Lead-Toe-clearance (cm), and Trail-toe clearance (cm) was 7.3,0.9, 1, and 1.1, respectively, whereas the effect size of the dual task at the same variables was 6.7,2.2,0.8, and 1, respectively.	The 20-29 and 60-69 age groups exhibited enhanced vertical toe-obstacle clearance and diminished gait variability in dual-task trials, whereas the 70-79 age group displayed decreased clearance and heightened variability during crossing.	Further research is necessary to understand the intricate connection between obstacle crossing, advanced age, and attentional demands in both young and older adults, using reliable interventions.
Lowrey et al 2007	free to choose the crossing limb for each trial	Lead and trail toe clearance values, take-off and landing distance, step time, length, width and velocity, and three-dimensional trunk angles.	The research indicated that both older and younger persons effectively accomplished obstacle avoidance tasks, with no significant discrepancies in take-off distances. Older persons mitigated obstacles by decreasing stride velocity and positioned themselves nearer to the trailing edge. Both young and older persons exhibited comparable trunk mobility; however, older adults employed shorter step lengths and narrower step widths, resulting in a more constrained base of support. The elderly individuals shortened their landing lengths to alleviate risks and exhibited comparable trunk movement despite a constrained base of support, presumably heightening their susceptibility to tripping or instability. The effect size of the lead foot heel distance (cm) when adjusted 45% of lower leg length was 1.8	Both older and younger adults successfully navigate obstacles with similar foot clearances and take-of-view distances. Older adults use a cautious crossing strategy with reduced step velocity, but shortened landing distances may increase risk of tripping or imbalance. Both age groups use similar trunk roll and pitch motions, but older adults use a narrower base of support, potentially increasing the risk of imbalance during obstacle avoidance.	Future research should compare visual and locomotor responses of older and younger adults when stepping over fixed height obstacles, considering environmental factors and potential adjustments to step lengths and foot clearances, as not all obstacles are scaled according to leg length and step length.

Y_A=young adult, O_A= older adult, Toe clearance of leading limb (LLC), Toe clearance of Trailing limb (TLC), COG = Center of gravity, TRT = Trip risk integral, Timed Up &go test (TUG), Sit to Stand (SIS)

Studies	Side of leading limb	Outcome measures	Results Effect size /Statistic finding	Key findings	Recommendation for further study
Lu et al., 2006	Not stated	Foot-obstacle distances, step length and foot clearances	The study found that older individuals showed an increase in leading toe clearance with increased obstacle height, modifying fewer joint angular components compared to younger individuals. However, no significant disparity was observed during trailing limb crossing, despite a distinct joint kinematic pattern in the older group. The effect size of the leading heel-obstacle distance at 10%, 20%, and 30% leg length was 0.4, 1.1, and 1.1, respectively. The effect size of the trailing toe-obstacle distance at 10%, 20%, and 30% leg length was 1.1, 1.2, and 0.9, respectively.	Older individuals tend to be cautious when navigating obstacles, leading to a decline in physical capabilities associated with aging.	Understanding kinematic control in stepping over obstacles can serve as a foundation for future research on the elderly population.
Di Fabio et al, 2004	The lead foot was defined as the first foot over the obstacles: the lag foot was	Foot distance and velocity using reflective markers	Older, low-risk participants showed smaller vertical foot lift asymmetries, while high-risk subjects made more frequent contact with obstacles. Younger, low-risk older individuals also showed foot lift symmetry.	Th study found a significant difference in foot clearance during obstacle negotiation among elderly individuals at high risk, possibly due to hip extension constraints and executive cognitive function impairments.	Further research may investigate the impact of cognitive loads on the kinematics of stepping movements.
Chen et al., 1991	not stated	Speed, Toe and Heel distance, step length, step width, foot clearance, Range of motion; hip, knee and ankle	The study found that age did not affect minimum swing foot clearance over obstacles, with a mean of 64 mm for 25 mm obstacles. However, old adults exhibited a more conservative strategy when crossing obstacles, with slower speed, shorter step length, and shorter obstacle-heel strike distance. Despite avoiding tripping, 4/24 healthy old adults stepped on an obstacle, indicating an increased risk for obstacle contact with age. The effect size of the foot clearance at the 25 mm obstacle height between young and older adults: Male toe distance (cm) = 0.3; Male heel distance (cm) = 0.2; Male foot clearance (cm) = 0.4; Female toe distance (cm) = 0.6 Female heel distance (cm) =1.4; Female foot clearance (cm) = 0.1	Old adults use a more cautious approach to crossing obstacles, avoiding toe contact but increasing the risk of stepping on obstacles, as demonstrated by 4/24 of them.	The results of this study may have been influenced by factors such as the pelvic harness, reduced stride width in older adults, and the approach speed. The early start of trials may have allowed participants to adjust and gain confidence. The elderly may be at a reduced risk of tripping or falling, potentially underestimating age-related differences in the results

Y_A=young adult, O_A= older adult, Toe clearance of leading limb (LTC), Toe clearance of Trailing limb (TTC), COG = Center of gravity, TRT = Trip risk integral, Timed Up &go test (TUG), Sit to Stand (SIS)

2.3.8 Outcomes variables

Ten articles observed a diverse range of outcome variables. The outcome measures included the distance of the trailing toe before the obstacles, the distance of the leading heel after the obstacles, the clearance of the leading foot above the obstacles, and the clearance of the trailing foot above the obstacles. Various studies (Maidan et al., 2018; Muir et al., 2015; Soma et al., 2010; Harley et al., 2009; Lowrey et al., 2007; Lu et al., 2006; Chen et al., 1991; Shin et al., 2015) assessed these measures. The following studies have investigated different aspects of gait parameters: (5) toe clearance of the leading limb (LTC) (Kunimune and Okada, 2017; Muir et al., 2015; Soma et al., 2010; Di Fabio et al., 2004), (6) the clearance of the trailing limb (TTC) (Kunimune and Okada, 2017; Muir et al., 2015; Soma et al., 2010; Di Fabio et al., 2004), (7) step length (Kunimune and Okada, 2017; Soma et al., 2010; Lowrey et al., 2007; Lu et al., 2006; Chen et al., 1991), (8) step width (Muir et al., 2015; Lowrey et al., 2007), (9) cadence (Soma et al., 2010; Chen et al., 1991), (10) walking speed and crossing over time for the lead limb (Kunimune and Okada, 2017; Soma et al., 2010; Lowrey et al., 2007), (11) angular kinematics of lower extremity such as hip flexion (Muir et al., 2015; Shin et al., 2015; Chen et al., 1991), (12) timed Up &go test (TUG) (Kunimune and Okada, 2017; Di Fabio et al., 2004), (13) sit to stand (SIS) (Kunimune and Okada, 2017), and (14) center of gravity (COG) (Shin et al., 2015).

2.3.9 Foot clearance during single-task stepping with a different height in young and older adults

Three articles reported foot clearance during single-task stepping with a different height in young and older adults (Chen et al., 1991; Lu et al., 2006). Lead and trail clearance had no effect on age when negotiating obstacles of three distinct heights (25, 51, and 152 mm) at free speed (Chen et al., 1991). The older adults employed the following crossing-over strategies: a reduced step length, a slower crossing speed, and a shorter obstacle-heel strike distance when compared to younger adults. According to Lu et al. (2006), as the obstacle height increased, the elder group showed a noticeable increase in leading toe clearance. In contrast to young adults, this increase required a reduced number of adjustments to joint angular components. During the trailing limb crossing, there was no statistically significant difference in trailing toe clearance between the old and young groups. However, the elder group exhibited a different joint kinematic pattern. Older adults were inclined to adopting a more careful strategy while negotiating obstacles, leading to a decrease in physical capacities linked to the aging process (Lu et al., 2006). Finally, the persons under observation indicated that older adults used a strategy of minimizing landing lengths to mitigate potential hazards. Table 2.3 demonstrates that, despite maintaining a restricted base of support (BOS), participants exhibited comparable degrees of trunk motion, which increased their susceptibility to tripping or experiencing instability while traversing obstacles.

2.3.10 Foot clearance during dual-task stepping with a different height in young and older adults

Two articles reported strategies for foot clearance during dual-task stepping with different heights in young and older adults (Soma et al., 2010; Harley et al., 2009). The concept of dual-tasking refers to the cognitive ability to perform two tasks simultaneously. Participants within the age ranges of 20 to 29 and 60 to 69 demonstrated a tendency to approach obstacles at a shorter distance before crossing them during the experimental trials (Harley et al., 2009). Furthermore, these subjects showed a decrease in vertical toe clearance and a reduction in gait variability. Both groups exhibited a slight decrease in verbal production while performing dual tasks (Harley et al., 2009).

In addition, the age groups ranging from 70 to 79 years old demonstrated similar dual-task stepping strategies in the pre-crossing phase (Harley et al., 2009). However, throughout the traversal, it demonstrated a decreased vertical clearance with respect to obstacles and an increased variability in the distance between objects and the heel. Table 2.3 shows that there were no significant changes in speech production across the different sessions (Harley et al., 2009).

In young and older adults, Soma et al. (2010) reported foot clearance during dual-task stepping. One was a dual task, consisting of a motor task and a concurrent cognitive task. The other was a solitary motor task. The motor task was stepping over an obstacle with a comfortable gait (Soma et al., 2010). The cognitive task was a 7-series task (Soma et al., 2010). As shown in Table 2.3, this result demonstrated that dual tasks did not influence toe clearance; instead, the heel obstacle distance decreased (Soma et al., 2010).

2.3.11 Foot clearance during stepping with multiple obstacles in young and older adults

An article reported foot clearance in young and older adults when stepping with multiple obstacles. When stepping over multiple obstacles, age had no effect on lead and trail clearance (Lowrey et al., 2007). A study reported that both age groups demonstrated successful performance in completing the obstacle avoidance task, and the introduction of a second obstacle did not impact the clearance strategies employed by either the older adults or the younger adults (Lowrey et al., 2007). Also, the identified older adults successfully addressed the obstacles by decreasing their stride pace and positioning themselves closer to the trailing edge (Lowrey et al., 2007). Table 2.3 shows that there were no significant differences in take-off distances among the three age groups.

The older adults demonstrated comparable amounts of trunk mobility to the younger adults when maneuvering the obstacle. However, older adults achieved this by employing shorter step lengths and smaller step widths as compared to younger adults, resulting in a more constrained base of support (Lowrey et al., 2007). The participant demonstrated a decline in velocity during the crossing phase, suggesting a conscious adaptation towards a more responsible approach to crossing (Lowrey et al., 2007), as shown in Table 2.3.

2.3.12 Foot clearance during stepping with visual and /or audio condition in young and older adults

Four articles reported strategies for foot clearance when stepping with visual and/or audio conditions in young and older adults (Maidan et al., 2018; Kunimune and Okada, 2017; Muir et al., 2015; Di Fabio et al., 2004). The first study examined the relationship between the distance of the leading foot and the clearance of the trailing foot following the crossing of obstacles and the corresponding motor, cognitive, and functional capacities (Maidan et al., 2018). The methodology involved walking through an obstacle course while negotiating both anticipated and unanticipated obstacles. The results of the study indicate that older adults had a tendency to position their leading foot in closer proximity to the obstacle after landing, in contrast to young adults (Maidan et al., 2018), as shown in Table 2.3.

Next, the researchers looked at how far the leading limb's toe cleared (LTC) and the trailing limb's toe cleared (TTC) when people stepped over obstacles while wearing liquid crystal shutter goggles. They did this under three different visual conditions: 1) full visibility, 2) occlusion at T-2 steps, and 3) occlusion at T-1 steps, where T is the time of obstacle crossing (Kunimune and Okada, 2017). The results showed that age does not significantly influence the effects of visuomotor control on the ability to appropriately navigate obstacles while crossing. Older adults may demonstrate a heightened reliance on visual cues to maintain postural stability. Additionally, when faced with a limited view of obstacles, they may require a wider step width to compensate for the lack of information (Kunimune and Okada, 2017), as shown in Table 2.3.

Also, a study (Muir et al., 2015) looked into whether healthy older adults use strategies to lessen the likelihood of encountering obstacles and how these strategies change with age. The experimental procedure entailed traversing a fixed obstacle while wearing goggles that impeded the lower portion of the visual field. The variables examined included the horizontal distance between the trail toes, the lead distance, the minimum clearance of the trail foot, the width of the step, and the variability in step length (Muir et al., 2015). Out of 840 trials, the findings documented a total of 17 occurrences of obstacle contact, indicating a 2% incidence rate. All age cohorts showed consistent contact rates of 2% (Muir et al., 2015). After that, the Modified Functional Reach Test showed that, in people aged 20 to 25, 78% of the trials had a shorter distance between the lead heel and the obstacle than between the toe and the obstruction (Muir et al., 2015). Similarly, among individuals aged 65–79, this trend Similarly, 89% of the trials observed this trend among individuals aged 65–79, and 85% observed it among individuals aged 80–91. out and toe exhibited greater proximity to the obstruction in comparison to the heel (Muir et al., 2015). All trials conducted on individuals within the age range of 20 to 25 years consistently detected the aforementioned pattern, with a 100% occurrence rate. Similarly, 98% of trials conducted on individuals aged 65 to 79 years and 94% on those aged 80 to 91 years observed the path study aimed to investigate the effect of gait on the leading and trailing limbs when stepping over and leading overshoot tasks. The findings of the study indicate that older individuals demonstrated a more significant decrease in gait speed and displayed a greater degree of overshoot in comparison to their younger adults (Muir et al., 2015), as shown in Table 2.3.

Finally, there was a controlled cross-sectional design with visual and verbal interference while stepping over an obstacle (Di Fabio et al., 2004). This consists of two conditions for cue selection in foot-for-step initiation: a sound cue condition and a visual cue condition. The results showed a significant disparity in foot clearance during obstacle negotiation among elderly individuals at high risk. Specifically, the trailing foot exhibited a noticeably reduced obstacle clearance distance compared to the leading foot. Furthermore, younger and low-risk older individuals (Patla et al., 1996) noted the foot lift symmetry of lower limb movement during stepping over obstacles, as shown in Table 2.3.

2.4 Discussion

This systematic review aims to address these critical gaps by comparing foot clearance during obstacle negotiation under varying task complexities and conditions in younger and older adults. By synthesizing existing evidence, the review seeks to advance our understanding of age-related gait adaptations and inform interventions that enhance mobility and reduce fall risk in older populations.

2.4.1 Age-related changes on foot clearance

The fall study took into account age-related changes in foot clearance. As individuals age, there are several physiological and biomechanical changes that can affect their ability to clear obstacles when stepping over them (Chen et al., 1991). Older adults exhibit diminished approach speed (AS) and crossing velocity (CS), as well as a reduced heel-to-heel crossing step length (SL), in contrast to younger persons (Soma et al., 2010). While older adults exhibited a 5% reduction in stride length (SL) compared to younger individuals, they demonstrated a 5% increase in the distance from the toe of the stance foot to the front edge of the foot (TD) (Chen et al., 1991).Therefore, when the toe of the leading foot encountered the impediment, it exhibited a 10% greater advancement in its swinging trajectory compared to the younger individuals (Potocanac and Duysens, 2017). Researchers have observed that this specific method effectively reduces the risk of toe contact with the obstacle, as it significantly enhances toe clearance during the swing phase (Chen et al., 1991). Next, a study reported that older participants exhibited of 117.5 mm obstacle. This observation was made under the specific conditions of 10% to 20% leg length. While the older group exhibited a higher clearance, leading to a shorter distance between the heel and the obstacle, this may imply a greater likelihood of stumbling (heel-obstacle contact) compared to the younger group (Lu et al., 2006). This approach can be advantageous because contacting the heel or midsole may pose a lower risk of falling compared to toe contact, as suggested by Chen et al. (1991). When positioning the leading toe above the obstacles, the older group used a swing hip flexion strategy to achieve the required foot clearance. In contrast, the younger group consistently employed a swing ankle eversion strategy for all obstacle heights (Lu et al., 2006). To adjust to these changes in the movement of the swinging limb, the older group flexed their hips more, brought their ankles closer together, and dorsiflexed their feet more than the younger group did when their leg length was 10% shorter (Lu et al., 2006). Also, older adults commonly exhibit a flexed position of the trailing stance limb, which results in a lower position of the leading toe and provides enhanced stability (Lu et al., 2006). Additionally, greater crossing flexion at the leading hip contributes to an increased upward position of the leading toe. Then, in the 10% leg length condition, applying two distinct limb positioning techniques resulted in consistent leading toe clearance between the young and older adults (Lu et al., 2006).

2.4.2 Foot clearance during single-task stepping with a different height in young and older adults

The obstacle height is a significant factor in foot clearance. The presence of obstacles of greater height requires a correspondingly increased clearance to mitigate the risk of humans tripping or stumbling. The effects of obstacle height on foot clearance have been extensively researched and have sparked significant controversy. For the leading limb, Chen et al. used the lowest of the heel, toe, and mid-foot markers to calculate the foot clearance when stepping over obstacles of three different heights (25, 51, and 152 mm) (Chen et al., 1991). They found that in 82% of the trials, the leading heel was the lowest, and that foot clearance increased significantly with increasing obstacle height (Chen et al., 1991). Other than that, the difference in the primary end-point control method between the young and older adults was further evidenced by the distinct impact of height on both leading toe clearance and leading heel-obstacle distance (Lu et al., 2006). The younger group exhibited consistent leading toe clearance and leading heel-obstacle distance, irrespective of the height of the obstacle (Lu et al., 2006). In contrast, the older group had to augment the former and decrease the latter in a linear manner as the obstacle height increased (Lu et al., 2006). The height-influenced observed trajectory in the older group suggests that they established a greater margin of safety (Lu et al., 2006). This likely compensated for the fact that older adults' bodies are less capable of recovering from unexpected falls (Lu et al., 2006). An increase in leading toe clearance would also necessitate a corresponding increase in muscular exertion on the swing limb (Lu et al., 2006). Older adults would not be able to recover from tripping over the obstacle, and their risk of falling would also increase if these demands were not met—for example, due to age-related muscle weakness (Lu et al., 2006).

Next, Shin et al. (2015) reported that older adults demonstrate a decline in lower limb strength, as evidenced by decreased ankle dorsiflexion, knee flexion, hip flexion, and foot inversion during the movement pattern of the trailing limb, in comparison to young adults. Consequently, this reduces their ability to elevate their lower limbs with ease (Shin et al., 2015). However, we assume that the elderly woman reduced her walking speed by lowering her toe height before crossing the 20-cm obstacle. This may be the result of a strategy for stepping over the 20-cm obstacle. A study reported that a conservative strategy with age may help in explaining why older adults showed such few obstacle contacts during locomotion (Galna et al., 2009).

2.4.3 Foot clearance during dual-task stepping in young and older adults

Dual-task walking is a psychological and neurological term for performing two tasks simultaneously while walking (Shumway-Cook and Woollacott, 2017). This idea examines the interaction between cognitive and motor functions and the difficulties humans encounter while allocating their attention to two concurrent tasks (Shumway-Cook and Woollacott, 2017). Two articles in this review studied cognitive function: a solitary motor task (Soma et al., 2010) and a verbal fluency task (Harley et al., 2009). The findings of the first article indicate that the performance of dual tasks did not have a significant impact on toe clearance (Soma et al., 2010). However, Soma et al. (2010) observed a decrease in the heel-obstacle distance. In addition, the findings have clarified that stepping over an obstacle during a dual task condition differs from stepping over an obstacle during a comfortable gait (Soma et al., 2010). The second article (Harley et al., 2009) demonstrates that older adults, despite taking precautions to step cautiously, still trip on obstacles. Research has shown that the loss in cognitive and attentional mechanisms associated with aging might have a detrimental effect on postural regulation during dual-task walking (Harley et al., 2009).

2.4.4 Foot clearance during stepping with multiple obstacles in young and older adults

The potential influence of foot clearance during the process of crossing multiple obstacles can be regarded as a complex and multidimensional component of human mobility (Lowrey et al., 2007). Individuals must adjust their stride and cognitive processes to properly navigate a changing environment. It is critical to understand the factors and challenges associated with navigating multiple obstacles in order to design safe and accessible spaces and improve fall prevention and mobility, especially for elderly adults and individuals with mobility limitations (Lowrey et al., 2007). Older adults specifically used the shortened landing distance as the avoidance strategy, as described above, when compared to young adults (Lowrey et al., 2007). This contradicts the findings of the previous study, as the differentiation of the inter-obstacle distance (Krell and Patla, 2002; Lowrey et al., 2007) leads to changes in take-off distances.

2.4.5 Foot clearance during stepping with visual and /or audio condition in young and older adults

The consideration of visual circumstances plays a crucial role in the process of successfully navigating an obstacle. The visual system facilitates the acquisition of information necessary for perception, recognition, and adaptation to real-time challenges (Shumway-Cook and Woollacott, 2017). Understanding the significance of visual factors is critical in developing interventions and environments that facilitate secure obstacle navigation and accident prevention for individuals

(Shumway-Cook and Woollacott, 2017). In this review, first of all, a study highlights three key discoveries in the strategy used to overcome obstacles for both older and younger adults: (1) Following impact, older adults positioned their leading foot in closer proximity to the obstacle in comparison to younger adults (Maidan et al., 2018). This pattern became increasingly evident as the obstacle's height increased. The trailing foot clearance showed a decrease in elderly adults compared to young adults. Unexpected obstacles further accentuated the difference (Maidan et al., 2018). The study discovered a positive correlation between the distance of the leading foot after the obstacle and the clearance of the trailing foot, as well as motor, cognitive, and functional abilities. According to Maidan et al. (2018), higher levels of these abilities were associated with greater distance of the leading foot after the obstacle and better clearance of the trailing foot. The results indicate that there are age-related alterations in the strategies employed for navigating obstacles, which are dependent upon the specific characteristics of the obstacle (Maidan et al., 2018). Additionally, a shorter available response time (ART) diminishes the efficacy of navigating obstacles, as it reduces the available time to adjust movements (Potocanac and Duysens, 2017). Maidan et al. (2018) found a correlation between high motor, cognitive, and functional abilities and the ability to adjust the clearance of the trailing foot during unanticipated obstacles in the presence of a short ART. These findings obtained during the negotiation of unanticipated obstacles may reflect real-life situations that increase the risk of falls. Shorter ART reduces the successful negotiation of obstacles, as it reduces the available time to adjust movements (Maidan et al., 2018).

Secondly, there is no obvious difference in the patterns of visually guided obstacle crossing between healthy young and older adults in circumstances involving consistent walking speed or familiar surroundings (Kunimune and Okada, 2017). Consequently, both groups employ feedforward control mechanisms to ascertain the optimal leading toe clearance (LTC) (Shumway-Cook and Woollacott, 2017; Kunimune and Okada, 2017). However, it is important to acknowledge that older individuals may exhibit an increased dependence on visual signals in order to maintain their balance, which leads them to widen their steps when confronted with environments that lack stability (Kunimune and Okada, 2017). Previous studies have reported that they included trail horizontal toe distance, lead and trail minimum foot clearance, step width, and step length variability. The prevalence of some behaviors seems to increase with advancing age, including decreased gait speed, decreased step length, closer foot placement before and after the obstacle (except for trail foot placement before the obstacle), increased lead overshoot, and a lower head angle during approach.

Thirdly, Muir et al. (2015) studied participants' behaviors when they placed their leading foot closer to the obstacle, increasing the risk of contact. Participants also wore goggles that blocked their view of the obstacle as they came within two steps. Participants managed this risk through a series of strategies outlined below: 1) Step length was gradually shorter with advancing age (Muir et al., 2015). Although the step length decreased as age increased, the distance from the trail toe to the obstacle remained constant across all three age categories (Muir et al., 2015). The idea is that foot positioning is critical just prior to an obstacle to provide sufficient space and time for the trail foot to clear the obstacle (Lowrey et al., 2007; Chen et al., 1991). Consensus evidence suggests that invariant foot positioning along the trail is an essential strategy for decreasing the probability of facing obstacles (Muir et al., 2015; Chen et al., 1991; Chou and Draganich, 1998). 2) To ensure sufficient clearance, older adults tended to execute greater vertical movement after toe-off, which led to a more rectangular trajectory for the lead limb due to the closer positioning of the lead foot before the obstacle (Muir et al., 2015). A bigger rectangular ratio makes the foot rise higher when you toe off, and then it changes direction quickly in the middle of the swing to move the limb forward and make it easier to avoid obstacles before landing (Muir et al., 2015). The execution of more sudden and forceful movements will result in increased difficulties in maintaining equilibrium across the entire body. Hence, the implementation of this particular approach aimed at reducing the likelihood of touch may potentially undermine the overall equilibrium of the body (Muir et al., 2015). 3) The participants exhibited a tendency to surpass the anticipated foot placement during the swing phase with their lead limb, then retract the foot to achieve the intended step length (Muir et al., 2015). This method lowers the chance of foot contact, but it's likely to cause destabilization because the swing limb moves forward more during the single support phase (Muir et al., 2015).

Lastly, adding more mental work—specifically the task of translating sound to foot selection—made the difference in foot lift more noticeable compared to the visual condition for both younger and older people with high and low risk (Di Fabio et al., 2004).

In summary, the interaction between age and obstacle height on foot clearance may be a complicated combination of biomechanical factors, adaptability, and individual variability. Understanding this association is critical for facilitating secure mobility and mitigating the likelihood of falls, especially in the elderly demographic. The ongoing investigation in this area will continue to yield significant findings that contribute to enhancing individuals' overall well-being throughout the aging process. However, dual-task walking is an important concept for investigating the interaction between motor and cognitive functions (Shumway-Cook and Woollacott, 2017). It has practical implications for assessing fall risk, constructing safe workplaces, and devising therapies for a variety of populations, including older people and people with neurological problems. Understanding how people deal with the difficulties of dual-task walking provides insights into the complexity of daily life and human cognition.

2.5 Conclusion

The aim of this systematic review was to evaluate the influence of obstacle height and an additional task on foot clearance while stepping over an obstacle in young and older adults. The older adults employed the following crossing-over strategies: a reduced step length, a slower crossing speed, and a shorter obstacle-heel strike distance when compared to younger adults. As the obstacle height increased, the leading toe clearance increased, but there was no statistically significant difference in the trailing toe clearance between the old and young groups. However, the idea is that foot positioning is critical just prior to an obstacle to provide sufficient space and time for the trail foot to clear the obstacle. Consensus evidence suggests that invariant foot positioning along the trail is an essential strategy for decreasing the probability of facing obstacles.

Table 2.3 highlights various gaps in the articles under review. There are fewer articles that report reliability, gait symmetry, gender differences, or the specific characteristics of an obstacle, such as the depth dimension. This knowledge could help promote individuality among the elderly and reduce the risk of falls. However, this study leads to research questions to determine the research gaps on foot clearance parameters, gait symmetry, gender differences, and obstacle characteristics.

Chapter III: General methods

3.1 Introduction

Stepping over obstacles is a crucial aspect of locomotion, especially in navigating complex terrain. Wide obstacles present unique challenges, requiring greater hip abduction and enhanced clearance of lower limbs. These obstacles affect biomechanical aspects, such as foot positioning and joint movement, leading to alterations in gait and equilibrium strategies. Likewise, a study investigated errors in foot placement and elevation that lead to spontaneous contact with a fixed, visible obstacle in young healthy adults(Heijnen et al., 2012) . Fifteen subjects stepped over an obstacle 300 times, with 92% of the contacts with the trail limb resulting from misjudgments of foot placement or elevation (Heijnen et al., 2012). After contact, trail MFC increased 75% and remained elevated, supporting the idea of independent control for lead and trail limbs during obstacle crossing. Possible causes of this progressive decrease are considered (Heijnen et al., 2012). Thus, understanding the biomechanical requirements of crossing obstacles is essential for identifying persons at risk for falls and establishing adapted therapies. To achieve clinical consistency, it is crucial to determine the repeatability of biomechanical data. However, there are gaps in the articles about reliability, gait symmetry, gender differences, and obstacle features, including depth dimension. To address these, general methods were used, and each chapter provided specific methods for each chapter.

3.1.1 Why heel and toe clearance?

The positioning of the toe and heel increases the likelihood of stumbling when stepping over an obstruction. Following a crossing, the heel's location may shift. Individuals can adjust the clearance of their leading limb's toe based on visual information they acquire when approaching an object, thanks to the visual system feedback control (Patla and Vickers, 1997; Patla et al., 2002; Patla et al., 2004). Studies have demonstrated that older adults can enhance their safety while crossing by extending the distance between their feet and the ground, which reduces the likelihood of tripping (Lu et al., 2006). In addition, the visual field cannot detect the toe of the trailing limb due to its dependence on proprioceptive feedback from the lead leg (Mohagheghi et al., 2004; Draganich and Kuo, 2004). Nevertheless, there has been a limited amount of research conducted using heel markers. Research has indicated that contacting the heel or midsole may have a lower risk of falling compared to making contact when crossing a 25-mm obstacle (Chen et al., 1991). Thus, the present study incorporated four distinct places within a cycle. Figure 3.1 illustrates the measurements of the step distance in front of the box (STEP_FRONT, in centimeters), the toe height over the front of the box (TOE_HEIGHT, in centimeters), the heel height above the back of the box (HEEL_HEIGHT, in centimeters), and the step distance away from the box (STEP_AWAY, in centimeters).

3.1.2 Why an additional task during stepping over?

The definition of dual task is the concurrent performance of two tasks with distinct and separate goals. The identification of characteristics is discriminated between activities with a single goal such as walking (motor) or counting steps to facilitate walking (motor and cognitive components within a single complex task) and activities that have two clearly dissociable goals such as serial-three subtraction while walking (motor and cognitive goals) (McIsaac et al., 2015). However, walking with holding the glass of water may be as a complex single task with one action goal: to transport the water. Studies have reported that this as a single task with low novelty and high complexity. Studied have reported the schema for single task analysis that use two task domains: novelty and complexity (McIsaac et al., 2015). Novelty is a performer characteristic that refers to the experience an individual has with performance of a particular task. Complexity is a task characteristic that refers to the number of components as well as the attentional demands of a particular task (McIsaac et al., 2015).

In addition, comparing walking alone to transporting a full cup while walking captures an increase in task complexity and related increased processing but is insufficient to reveal a dual task interference effect. In this study, the aim was to determine the characteristic of foot clearance when walking with postural constraints on the system such as holding the glass, stepping over an obstacle at different heights obstacle height. The cup and water specified in the study are standard-sized plastic cups. The volume was approximately 250 ml. The filled level was 80%, or approximately 200 ml. Research discusses the practical aspects of using standardized tasks in gait studies to control for attentional demands and balance constraints. Filling the cup to 80% capacity (200 ml) strikes a balance between task difficulty and feasibility, ensuring participants can perform the dual task (walking with the cup) without undue challenge or risk of spillage (Siu et al., 2008). Likewise, using a standardized cup ensures consistency across participants and trials, reducing variability in the dual-task conditions. This approach is common in dual-task studies to maintain experimental rigor and comparability (Plummer et al., 2013).

The act of spilling water while performing a dual-task condition demonstrates the extent to which the secondary job of holding the cup hinders the performance of the primary task of walking and navigating obstacles. Examining spillage instances helps to assess the cognitive and motor demands caused by the dual-task situation, as well as its influence on walking performance. This review paper elucidates the impact of dual task interference on gait and emphasizes the significance of evaluating secondary task performance in order to comprehend its influence on primary task performance (McIsaac et al., 2015). However, our design was to record the number of instances in which the water was spilled. However, the water was not spilled for all trials in this study.

3.1.3 Why an obstacle depth (especially as 35 cm is much bigger than 2-5 cm used in current literature.

The decision to employ a 35 cm barrier depth, which is considerably more than the typical range of 2–5 cm found in existing literature, has multiple objectives: There is an increase in difficulty, differentiation in the safety margin, and diversity in skills. Heightened difficulty: A 35-cm obstacle creates a more demanding situation, necessitating increased exertion in terms of the height of each step, coordination, and balance. This can aid in comprehending the boundaries of participants' physical capacities. Safety margin: elevated obstructions can mimic real-world situations like staircases, curbs, or unforeseen obstacles. The study aims to gain insights into fall prevention and assistive device development by analyzing how participants negotiate these significant obstacles. Presenting a larger obstacle enhances the observation of skill differentiation, highlighting the differences in physical capabilities between younger and older individuals.

Using wide-depth obstacles in gait analysis has numerous advantages, particularly in understanding the complexity of human movement and ensuring safety during locomotion. The primary benefits include a better assessment of stability and equilibrium, improved gait adaptability analysis, a better representation of real-world challenges, and detailed kinematic and kinetic data. Obstacles that are wide and deep may require a stronger foundation and improved coordination, which might provide vital information about an individual's balance and stability. This is especially beneficial for studying susceptible populations, such as the elderly or individuals with neurological diseases, who are prone to falling. When faced with wide obstacles, individuals must make larger modifications to their stride patterns compared to narrow obstacles. This adaptation can provide extensive information about the ability of individuals to change their walking patterns in response to external obstacles, which is critical for understanding gait adaptability and formulating rehabilitative strategies.

Similarly, wide obstacles replicate real-world scenarios with higher precision than narrow ones, providing a more genuine assessment of the ability of an individual to navigate through ordinary environments. Furthermore, gait analysis technologies can capture and analyze larger motions and more complex movements that are required to overcome barriers with greater width and depth. This provides a thorough understanding of the biomechanics of the lower limbs, helping to pinpoint specific weaknesses and facilitate focused therapy (Yogev-Seligmann et al., 2008).

3.2 Material and Methods

3.2.1 Study design

This study design was cross-sectional study.

3.2.2 Study setting

Three-dimensional gait analysis took place in the biomechanics laboratory at the University of Essex.

3.2.3 Target population

The University of Essex staff and student population recruited healthy young adults. We conducted the recruiting process using a poster (Appendix 1), an invitation letter (Appendix 2), and electronic mail. A poster recruited another group and invited them.

3.2.4 Study population

Young adults age ranged between 20 and 30 years old and older adults ≥ 70 years old.

3.2.5 Inclusion criteria

Young adults

There was right leg dominance, which was determined by kicking a ball, picking up an eraser off the floor, and drawing a number eight on the floor. (Komai and Fukuoka, 1934).

Older adults

Older adults were asked to respond to the Essex Ageing and Gait Longitudinal Study Questionnaires.

They involved health, medication, falls and fractures, hearing, vision, smoking, and alcohol. Participants who had no underlying diseases were included in this study.

3.2.6 Exclusion criteria

The exclusion criteria were self-report musculoskeletal disorders or cardiovascular disease, having any difficulty during walking, and taking alcohol or caffeine within 24 hours before testing.

3.2.7 Sample size

There were ten participants in each young group and the older group.

3.2.8 Variables

3.2.8.1 Independent variables

The walking task is an independent variable. There are four categories of tasks in this study. 1) stepping over an obstacle at a low box (15 cm), 2) stepping over an obstacle at a high box (20 cm), 3) stepping over an obstacle at a low box (15 cm) with the holding a glass of water without spilling it, and 4) stepping over an obstacle at a high box (20 cm) with the holding a glass of water without spilling it.

3.2.8.2 Dependent variables

The foot clearance (FC) is a dependent variable. Foot clearance had two categories: horizontal and vertical distances away from the obstacle (described later). The study included three spatial-temporal parameters: walking speed (m/s), double support time (s), and single support time (s).

3.2.9 Laboratory setting

Gait data was collected in the biomechanics laboratory (Figure 31). The researcher collected data using the Vicon system. The study utilized a Vicon T-20 infrared motion capture system (Vicon Motion Systems Ltd., Oxford, UK) with 10 cameras, sampling at a rate of 100 Hz. Additionally, a floor-mounted Kistler 9281CA force plate (Winterthur, Switzerland) was employed, sampling at a rate of 1000 Hz. These instruments were utilized to do three-dimensional motion analysis for the walking tasks. The data processing for all trials of all walking tasks was conducted using Vicon Nexus (v2.5, Oxford, UK.

Figure 3. 1 Laboratory setting

Capture workflow

Figure 3.2 illustrates the workflow from the participant volunteering to data analysis. The Vicon Nexus organizes its workflow across multiple distinct stages. The method involved establishing a new database, generating a new subject, calibrating a Vicon system, recording a static trial, processing the static trial, capturing dynamic trials, processing the dynamic trials, implementing a pipeline for processing dynamic trials, and generating a concise trial report. The first stage is to create a data storage place file for each session and each participant.

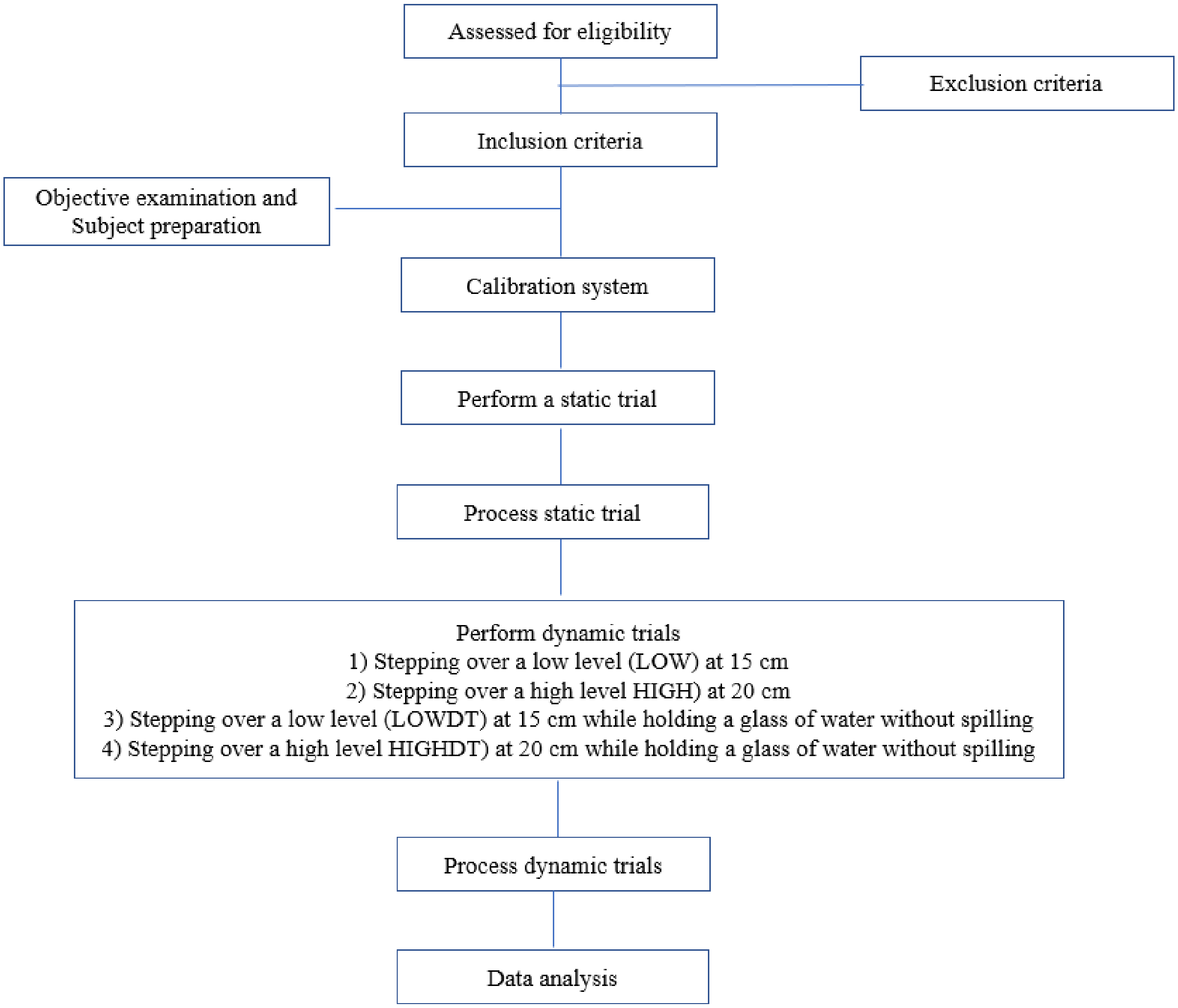

Figure 3. 2 Flow chart of this study

Calibration

The calibration of Vicon system is a critical follow-up procedure. In ‘live mode’ the capture volume was checked to ensure there was no ‘noise’ (reflections) being ‘seen’ by each camera. If this were the case any reflections were covered. Failing this, the unwanted reflections were concealed using the ‘mask cameras’ option in the calibration pipeline. The cameras were calibrated as per the manufacturer’s instructions. The calibration wand (t-frame) was moved within the capture volume, making sure that the markers on the calibration wand were visible to the cameras.

This captured approximately 1000 frames. The calibration was acceptable indicated by ‘green’ output for each camera. The wand was then placed on the ground, ensuring it was aligned with the force plate (not used in this present study) and level to set volume origin. Specifying the volume origin in the global coordinate system gives the Vicon system information about the capture's central point and orientation (x, y, and z axes). This feature allows the Nexus view window to accurately present subjects with the appropriate orientation and three-dimensional perspective. This completes the calibration procedure

Model

This thesis was only going to look at the HEEL and TOE markers for obstacle crossing. However, the Plug-in-gait (PiG) model, briefly described below, was used to ensure data quality as the static calibration pose was used.

Anthropometric measures were taken (table 3.1) and thirty-nine reflective markers (14 mm with a 3 mm thread) were placed on the body: four for the head, five for the torso or trunk, fourteen for the upper extremity, and sixteen for the lower extremity (Vicon, 2016). In this study, the researcher, who is a physical therapist and has worked for more than twenty years, attached reflective markers to the patient, as shown in Figure 3.3. After attaching markers a static calibration trial, as per manufactures recommendations, was performed and processed. During static calibration, the participant maintains a motionless and steady position as a reference stance for a brief duration during the static trial. The NEXUS pipeline runs the static calibration model after labeling the markers for the static trial.

Table 3. 1 Subject measurements

Anthropometric measurement	Description
Body Mass	Patient mass.
Height	Patient height
Starting position for measuring the upper extremity	All participants were measured standing and all measurements were recorded for the right and left limb.
Shoulder Offset (mm)	the vertical distance from the base of the acromion process to the center of shoulder joint
Elbow Width (mm)	The distance between the medial and lateral epicondyles of the humerus is measured by a caliper.
Wrist Width (mm)	The anterior to posterior thickness of the wrist between the distal head of the ulna and radius was measured by a caliper.
Hand Thickness (mm)	the anterior to posterior thickness between the dorsum and palmar surfaces of the hand was measured by a caliper.
Starting position for measuring the lower extremity	All participants were measured standing and all measurements were recorded for the right and left limb.
Leg Length (mm)	the distance between the anterior superior iliac spine and medial malleolus, via the knee joint was measured.
Anterior Superior Iliac Spine Trochanter Distance (mm)	This is automatically calculated by the Plug-in Gait Marker Model
Knee Width (mm)	The distance between the lateral and medial femoral epicondyles was measured by a caliper.
Ankle Width (mm)	The distance across the malleoli was measured by a caliper.

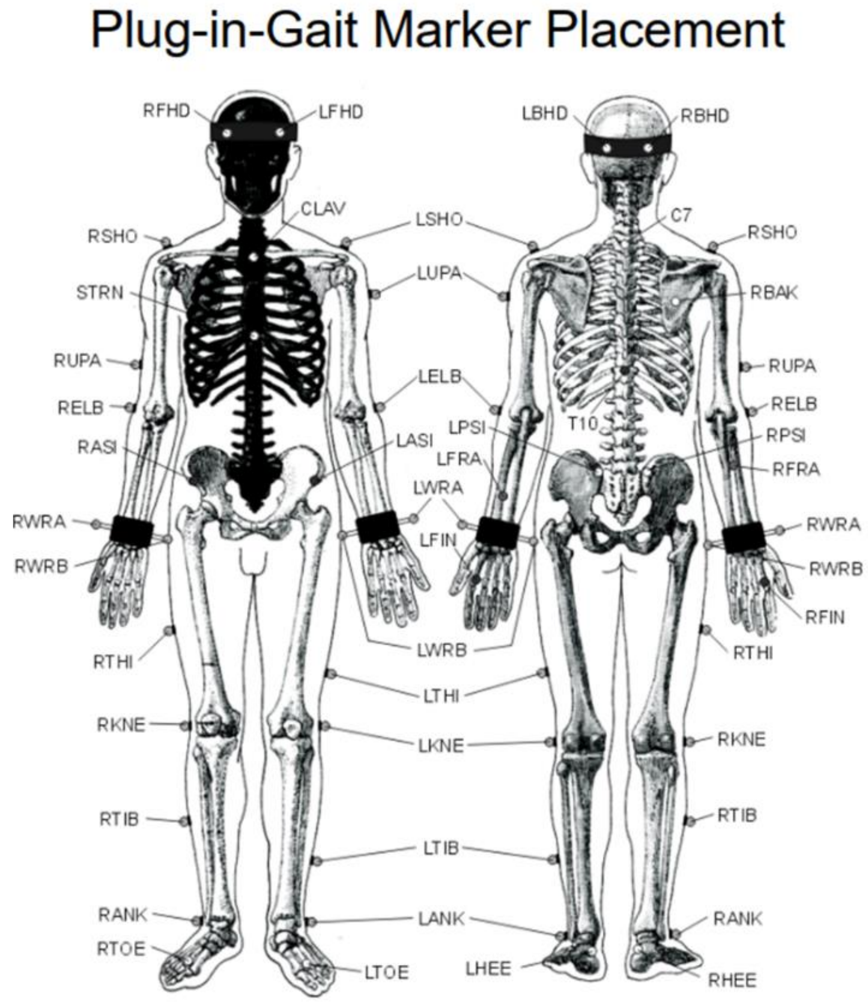

Figure 3. 3 Guideline of marker placement followed by Plug-in-gait model

Plug-in-gait marker placement: LFHD, Left front head; LFHD, Left front head; LBHD, Left back head; RBHD, Right back head; C7, 7th Cervical Vertebrae; CLAV, Clavicle; STRN, Sternum; RBAK, Right Back; LSHO, Left shoulder marker; LUPA, Left upper arm marker; LELB, Left elbow; LFRA, Left forearm marker; LWRA, Left wrist marker A; LWRB, Left wrist marker B; LFIN, Left fingers; LASI, the left anterior superior iliac spine; RASI, Right ASIS over the left anterior superior iliac spine; LKNE, Left knee; LTHI, Left thigh; LANK, Left ankle; LTOE, Left toe; and LHEE Left heel. On the other hand, the alphabet that stands for meaning on the right limb are at the same on the left side.

3.2.10 Data collection

Following the static calibration trial the dynamic walking trials were captured. Each trial was checked after capture to ensure markers were not missing or not being occluded.

Each participant walked along a 12-meter walkway at their own walking speed, stepping over a fixed, stationary, visible obstacle at the midpoint. The participants began their walk at a distance of six meters from the box, which allowed them to accelerate to walking speed and maintain a consistent gait throughout the walkway. The researcher instructed them to walk for an additional 6 meters after they crossed the obstacle. Six meters at either end was a pragmatic choice, as this was the size of the available space. The researcher matched the start position to avoid targeting the obstacle or overreaching, and we shortened our stride before the obstacle appeared. The obstacle location was fixed. We attached tape to the floor to indicate the obstacle location, ensuring it was in the same place for each participant.

The obstacle in this study was a stepper, commercial gym equipment: width, 92 cm; depth, 35 cm; and adjustable height. We divide the obstacle height into two levels: low level (LOW) at 15 cm and high level (HIGH) at 20 cm. Reflective markers were attached at the top of each obstacle's corners, allowing the position-tracking camera system to identify and place them in the 3D reconstructed trial.

Participants performed 3 successful trials per limb (i.e. Left as leading and Right as Leading) for each of the 4 conditions. Successful trials were ‘clean’ trials, all markers were visible. If a trial was not ‘clean’ it was repeated. There was a three-minute interval between trials and a five-minute pause between conditions to ensure no carry-over.

- LOW obstacle – 15 cm heigh
- HIGH obstacle – 20 cm high
- LOW DT (Dual Task) obstacle – holding a cup of water while negotiating an obstacle
- HIGH DT obstacle

These were performed in a random order for four task walking. When randomizing the order of tasks, I allocated a distinct letter to each individual task: A for Task 1, B for Task 2, C for Task 3, and D for Task 4. We made many randomized sequences of these letters, ensuring that each sequence contained all four tasks. A piece of paper was selected from a bag that had the letter sequence. We used this paper to provide participants with the task sequence. We only showed the sequence to the participant when they were ready to start, ensuring randomization and preventing any potential bias in the order. Every participant proceeded to perform the tasks in the assigned order.

Single and additional task walking were applied in this study. The additional task of walking involved holding a glass of water without spilling it. We instructed the participants to walk at their own pace, step over an obstacle at a different height, and hold a glass of water without spilling it.

3.2.11 Processing for analysis.

After data collection the preparation of the data for analysis is the next step. First, the review trials and fill gaps are done after finishing the dynamic trial, resulting in a smooth trajectory throughout the trial. The fill gaps were aimed at monitoring the appropriate marker set for the quality of your data. When Nexus software reconstructs each marker on a subject, ideally, it produces a smooth trajectory throughout the trial. Realistically, some unreconstructed markers or spurious data may cause trajectory breaks in some frames. Next, we need to fill in any gaps in the reconstructed trial data and label them as quality data.

The Label/Edit Tools pane presents a roster of markers in the Gap Filling section. The markers show discontinuities within the specified range of frames. The Trajectory column displays the markers, the Gaps column gives the quantity of gaps in each trajectory, and the Max Gap Length column reveals the size of the largest gap. Only gaps less than 10 frames were filled. A spline fill - representing the geometric properties of the trajectory – was used to fill these gaps.

Other gap-filling options are available: The spline fill function employs cubic spline interpolation to fill the designated gaps. When you have appropriate frames and no gaps on either side of the region, proceed with implementing this strategy. Pattern fill employs a specific pathway's contour to fully fill a selected empty region, ensuring no gaps remain unfilled. Only use this tool if there is an appropriate signal that closely aligns with the trajectory you intend to use to fill the gap. Select the "rigid body fill" option when there is a substantial or substantial correlation between indicators. Kinematic fill is accurate information about how markers and segments in the labeling skeleton template (VST) are connected. To make use of this feature, it is essential to first perform the kinematic fit technique, specifically the cyclic fill, for trials that include cyclic data. This method utilizes patterns from a marker that was not present in previous or subsequent walking cycles to fill in the areas that are missing. After filling in the gaps, Nexus ran the dynamic pipeline to process the dynamic (walking) trials.

3.3 Operational definition

3.3.1 Approach, foot clearance, and departure

Foot clearance refers to the vertical gap between the foot and the ground as the leg is swinging forward during the mid-swing phase of walking or running (Winter, 1992). For the purposes of this study, foot clearance was defined as the vertical measurement from the toe marker when stepping over the front of the obstacle and the heel marker when stepping over the rear of obstacle. How close the foot is placed to the front and rear of an obstacle during approach and departure respectively was also looked at. Four-foot clearance parameters were used within this thesis for the leading and trialing limbs. The leading limb is the first limb to be lifted over an object the trailing limb follows.

- Approach step distance before obstacle – distance between the TOE marker and the front edge of the obstacle in y
- Toe clearance above obstacle – vertical TOE height above the front edge of obstacle
- Heel clearance above obstacle - vertical HEEL height above rear edge of obstacle.
- Departure step distance away from obstacle – distance between the HEEL marker and the rear edge of the obstacle in y

Figure 3.4 and 3.5 illustrates these.

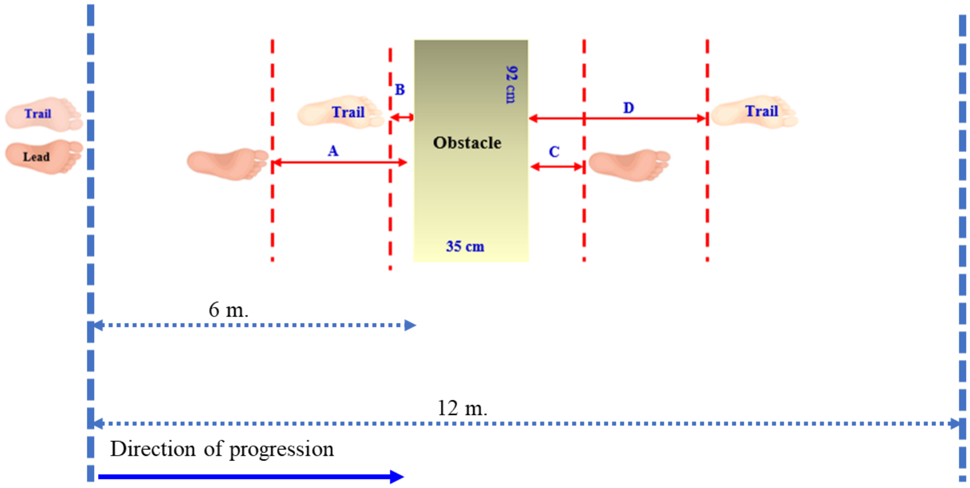

Figure 3. 4 Diagram shows the top view of foot clearance (FC) parameters. A, (A), step distance in front of box of leading limb; (B), step distance in front of box of trailing limb; (C), step distance away box of leading limb; (D), step distance away box of trailing limb. Brown fill indicates lead limb foot and light fill indicates trail limb foot

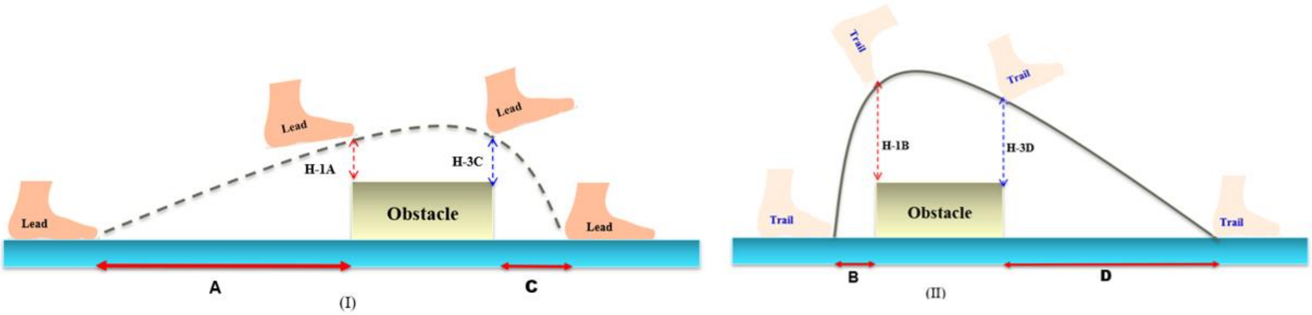

Figure 3. 5 Diagram shows the side view of foot clearance (FC) parameters. A, (A), step distance in front of box of leading limb; B, step distance in front of box of trailing limb; C, step distance away box of leading limb; D, step distance away box of trailing limb; H1A, vertical toe height above front box of leading limb; H3C, vertical heel height above back box of leading limb; H1B, vertical toe height above front box of trailing limb; H3D, vertical heel height above back box of trailing limb; I, leading pattern and II, trailing limb pattern

Table 3. 2 Studies support variables

Variables	Definitions	Evidence supports
Approach step distance before obstacle of leading limb	distance between the TOE marker and the front edge of the obstacle in y of leading limb	(Muir et al., 2015)
Toe clearance above obstacle of leading limb	vertical TOE height above the front edge of obstacle of leading limb	(Muir et al., 2015), (Soma et al., 2010) (Lowrey et al., 2007), (Lu et al., 2006), (Chen et al., 1991)
Heel clearance above obstacle of leading limb,	vertical HEEL height above rear edge of obstacle of leading limb	(Muir et al., 2015), (Kunimune and Okada, 2017), (Soma et al., 2010), (Harley et al., 2009), Lowrey et al., 2007), (Lu et al., 2006), (Di Fabio et al., 2004), Chen et al., 1991)
Departure step distance away from obstacle of leading limb	distance between the HEEL marker and the rear edge of the obstacle in y of leading limb	(Muir et al., 2015),
Approach step distance before obstacle of trailing limb	distance between the TOE marker and the front edge of the obstacle in y of trailing limb	(Muir et al., 2015), (Soma et al., 2010), (Harley et al., 2009), (Lu et al., 2006), Chen et al., 1991)
Toe clearance above obstacle of trailing limb	vertical TOE height above the front edge of obstacle of trailing limb	(Muir et al., 2015), (Harley et al., 2009), Chen et al., 1991)
Heel clearance above obstacle of trailing limb,	vertical HEEL height above rear edge of obstacle of trailing limb	(Muir et al., 2015), (Kunimune and Okada, 2017), (Soma et al., 2010), (Harley et al., 2009), Lowrey et al., 2007), (Lu et al., 2006), (Di Fabio et al., 2004), Chen et al., 1991)
Departure step distance away from obstacle of trailing limb	distance between the HEEL marker and the rear edge of the obstacle in y of trailing limb	(Muir et al., 2015),

3.3.2 Identification of foot clearance parameters

The analysis of vertical toe or heel height during the process of stepping over an obstacle commences with the manual examination of the line graph depicting the trajectories of the left and right toe markers on the Z axis. These trajectories are illustrated in Figures 3.6 and 3.7. These peaks are of considerable size. The initial peak represents the leading limb passing the obstacle, whereas the subsequent peak corresponds to the trailing limb passing the obstacle.

The toe clearance distance is determined by measuring the vertical distance above the front of the obstacle (Z axis) using the toe marker. For instance, the vertical elevation of the toe relative to the front box is determined by calculating the difference between the height of the toe that participants raise at the front edge of the obstacle (marker placed on corners of obstacle) and the height of the obstacle itself. This gives a result for height above the obstacle - and not height above ground level. The height of Heel Z above the obstacle was determined using the same analysis approach. The markers place on the front and rear of the box formed a plane and as such, through manual identification, when the toe marker was aligned with the front of the obstacle i.e. using the toe and obstacle marker coordinates, its height above the obstacle was then recorded. The same principle applied for the heel marker and the rear of the obstacle. As illustrated in Figures 3.6 and 3.7

The step distance in front of the box (cm) was determined by measuring the horizontal distance on the Y axis between the toe and the front of the obstacle marker. The step distance from the box was the horizontal displacement on the Y-axis between the heel marker and the rear obstacle marker. As illustrated in Figures 3.8 and 3.9

The other variables used in the study obtained from the Vicon Nexus Program. Step length, step time, and single and double time were examples of these. Step length, step time, single and double support time were used in this study and were calculated by VICON Nexus software as their default parameters. Vicon calculates these as follows:

- Step length was the distance between the toe markers along the Progression Direction.
- Step time was the time between contralateral and the following ipsilateral foot contact.
- Double support time was defined from ipsilateral foot contact to contralateral foot-off plus time from contralateral foot contact to ipsilateral foot-off.
- Single support is time from contralateral foot-off to contralateral foot contact.

3.4 Data and statistical analysis

Since this differs for each study, these are presented within the individual chapters.

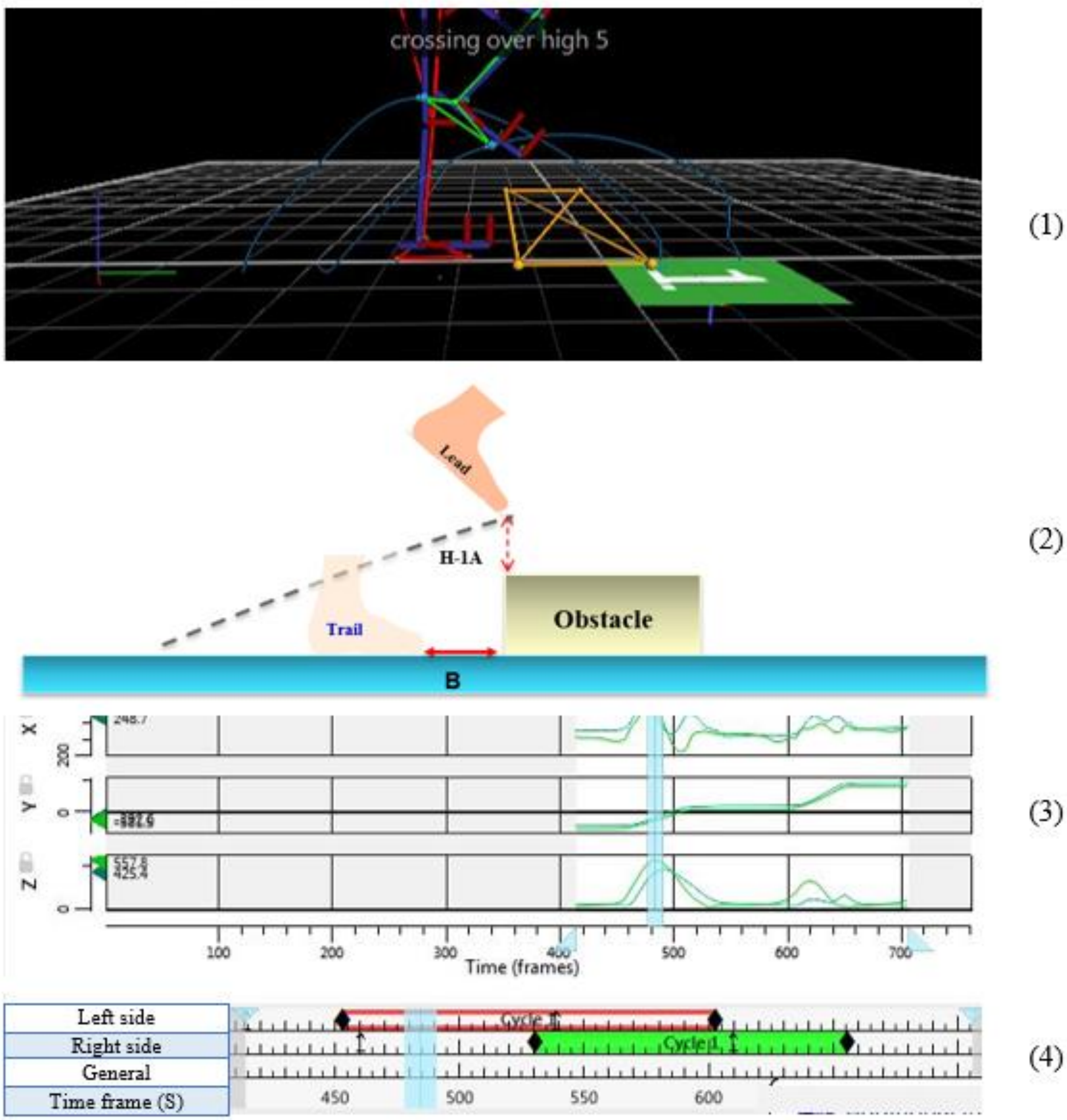

Figure 3. 6 The vertical distance of toe height above front box. An identification of the vertical distance of toe height above front box.: H1A, the vertical distance of toe height above front box of leading limb; B, the horizontal step distance in front of box of trailing limb; (1), the picture in 3D perspective; (2), Picture at side view; (3), Trajectory line of the X axis, the Y axis and The Z axis; (4) a range of frames. All are in Vicon Nexus Software

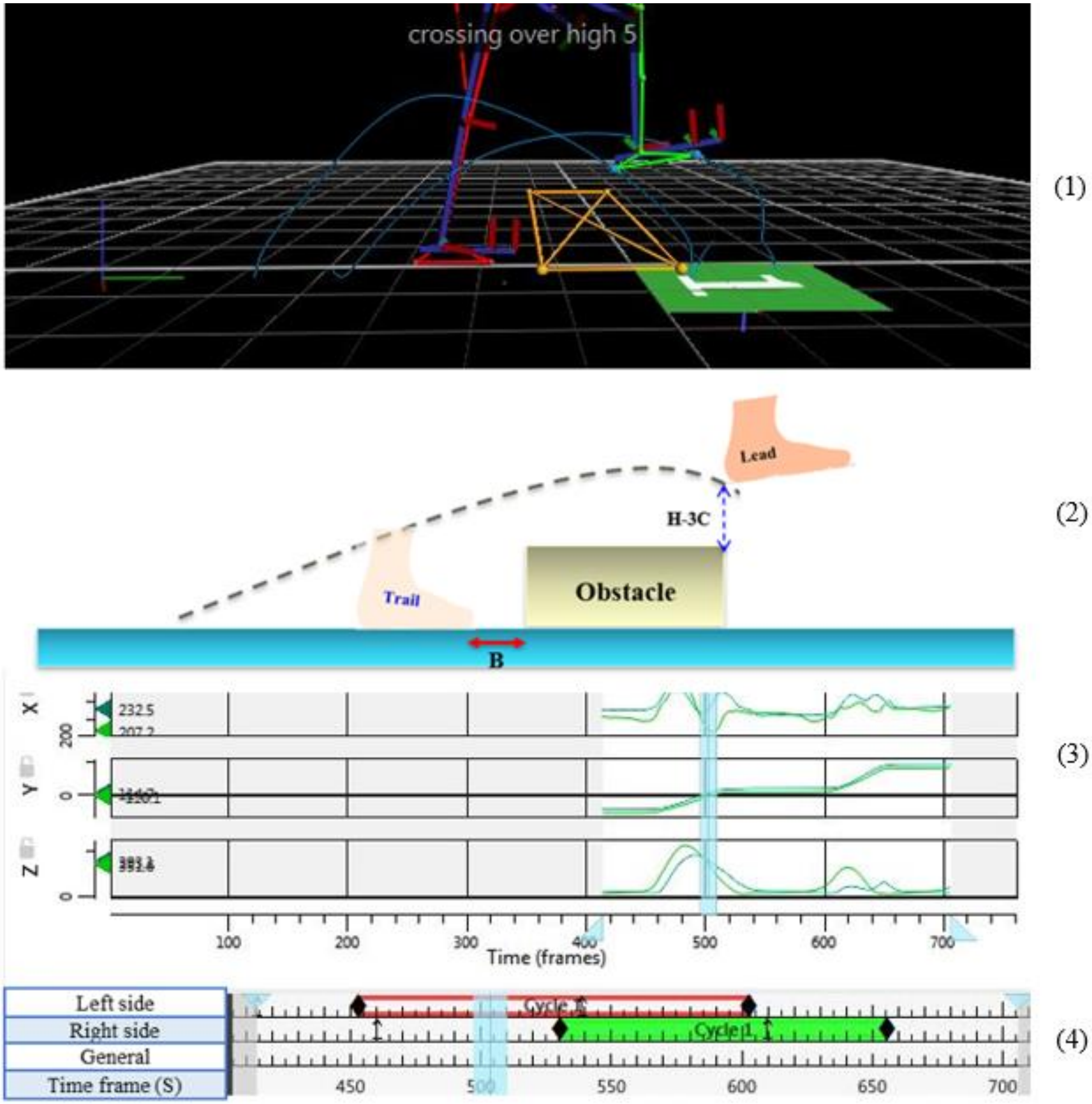

Figure 3. 7 The vertical distance of heel above back box. An identification of the vertical distance of heel above back box: H3C, the vertical distance of heel above back box of leading limb; B, the horizontal step distance in front of box of trailing limb; (1), the picture in 3D perspective; (2), Picture at side view; (3), Trajectory line of the X axis, the Y axis and The Z axis; (4) a range of frames. All are in Vicon Nexus Software

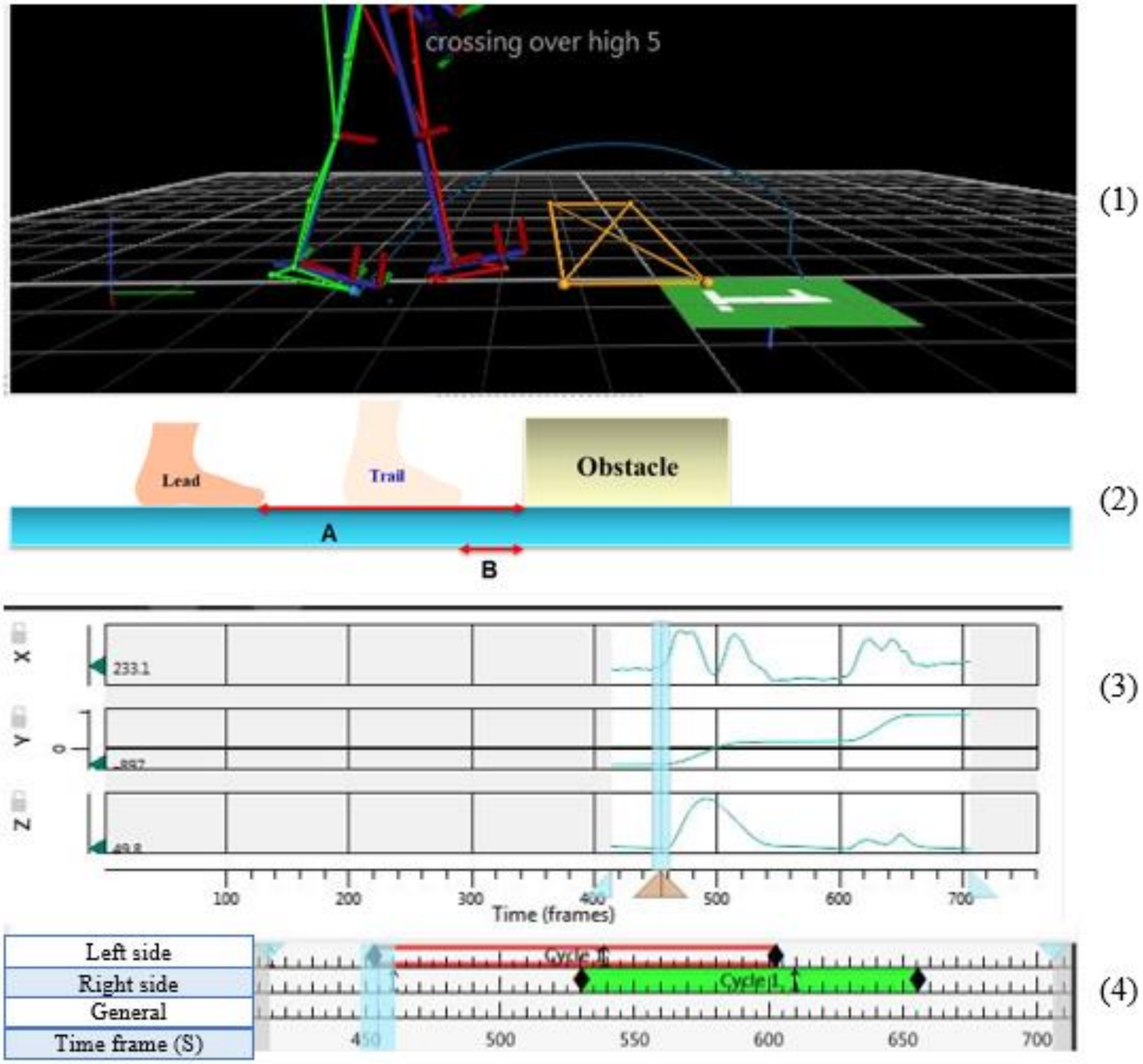

Figure 3. 8 Step distance in front of box. An identification of step distance in front of box.: A, the horizontal step distance in front of box of leading limb; B, the horizontal step distance in front of box of trailing limb; (1) the picture in 3D perspective; (2) Picture at side view; (3) Trajectory line of the X axis, the Y axis and The Z axis; (4) a range of frames. All are in Vicon Nexus Software

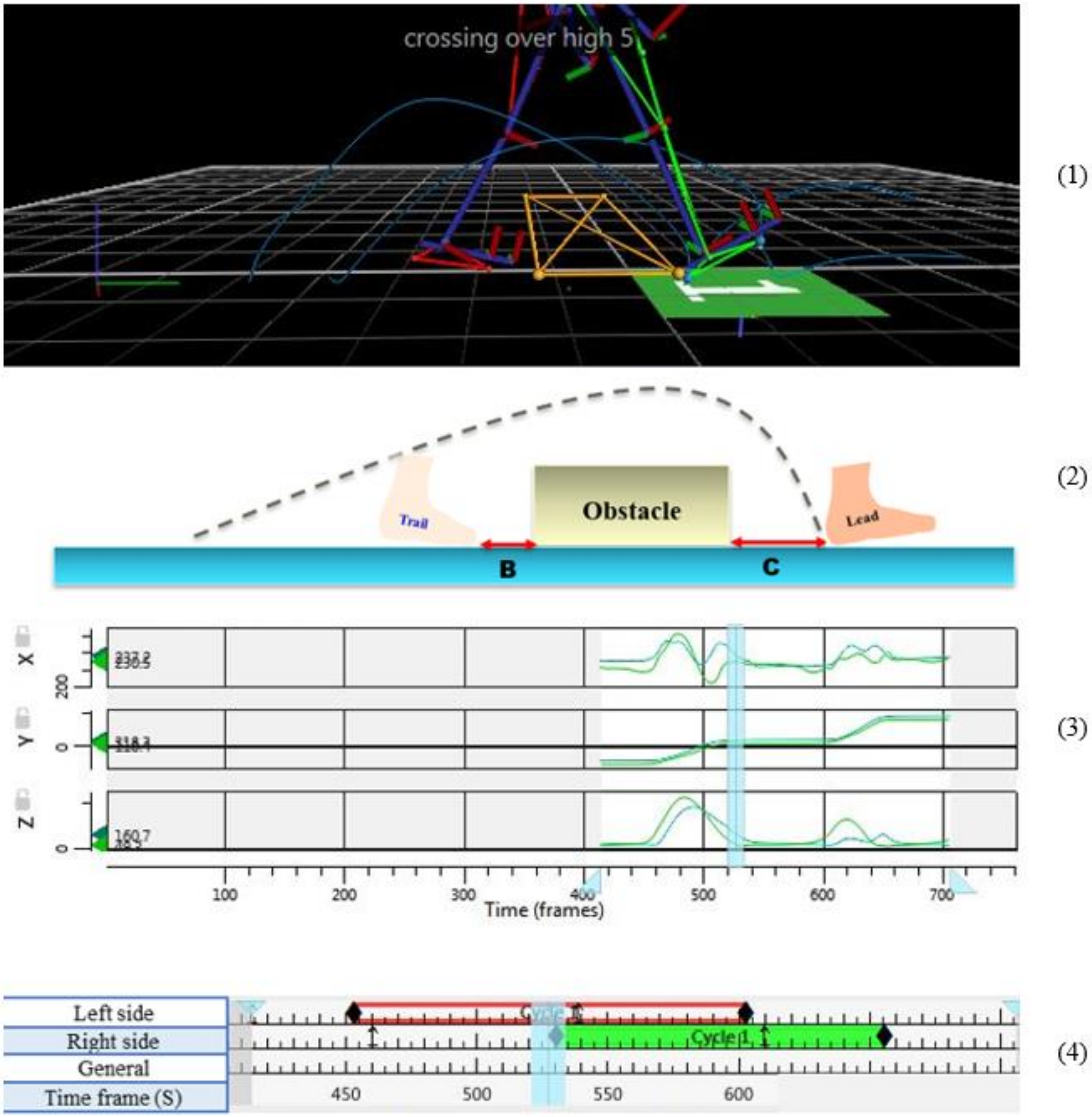

Figure 3. 9 The horizontal distance of heel away from box. An identification of the horizontal distance of the heel away from the box: H3A, the horizontal distance of the heel away from the box of the leading limb; B, the horizontal step distance in front of the box of the trailing limb; (1) 3D perspective view; (2) Side view; (3) Trajectory line of the X-axis, Y-axis, and Z-axis; (4) A range of frames. All are in Vicon Nexus Software.

Chapter III (Subsection): The learning effect: Do 3-trials achieve performance stability while stepping over an obstacle?

3.4.1 Introduction

Test-retest reliability methods can evaluate the stability of a performance variable. This refers to its repeatability across repeated trials (observed performances) over time (Portney and Watkins, 2000). The stability of a variable across trials influences the stability of the mean value of the group of trials. When the mean value is unstable, both its reliability and its ability to represent a more generalized performance (validity) are limited. An individual's trial count in an experiment is believed to impact stability (Bates et al., 1983; Salo et al., 1997) making it a crucial methodological factor in the design of walking experiments. This is because, and is especially important for tasks, a learning effect may be witnessed i.e. a change in performance from trial to trial.

Multiple trials are believed to provide a more stable and representative mean value (Bates et al., 1983). Because there is variability in all human movements, insufficient trials may not accurately reflect an individual's sustained performance over a significant period. Bates et al. (1992) proposed that a protocol consisting of only one trial may be invalid and unreliable since it may not adequately represent the overall performance. It is possible that the single trial could be either a typical representation of average performance or an uncommon representation. Increased movement variability leads to less reliable data and a higher probability of sampling an unusual performance from the entire range of possible performances (James et al., 2007). When obtaining data from continuous actions such as a gait cycle or stepping cycle, stability is particularly important. The aim of this study was to assess if there was learning effect between the 3 trials used in the present work. That is, did the toe clearance parameters differ between trials.

3.4.2 Methodology

Please see more detail in the method chapter 3 (General)

3.4.3 Statistical Analysis

Statistical analyses were carried out in the Statistical Package for the Social Sciences (SPSS) Version 25 for Window. The Shapiro Wilk test was used to determine the distribution of the data. Standard descriptive statistics, mean with standard deviation, were calculated for all variables. A repeated measures ANOVA with between factors (trial) was carried out. A Greenhouse-Geiser was used when appropriate. If there were significant effects (main (task) or interaction effect, then a Bonferroni post-hoc analysis was carried out. All statistical data analyses were performed by setting the level of significant difference at a p-value < 0.05.

3.4.4 Results

When crossing an obstacle with the leading limb, there was no significant main effect (Table 3.2). However, there were three exceptions to this finding. Specifically, the distance of the step away from the obstacle in the LOW condition showed a significant main effect. The post-hoc test revealed for the LOW condition, between trials 1 and 2, there was a significant difference (2.7 cm nearer for trial 2 vs. trial 1) in the distance from the obstacle. In addition, the distance of the heel height above the rear of the obstacle in the HIGH and HIGH_DT conditions showed significant effects with the post hoc test revealed trial 1 having the greatest height compared to the other trials. When crossing an obstacle with the trailing limb, there was no significant difference in main (trial) effect within-subject for all parameters as shown in Table 3.3.

Table 3. 3 The difference between trials for the leading limb when crossing and obstacle

Right Leading limb	Mean (SD)				RM ANOVA and output
	(All trials)	Trial 1	Trial 2	Trial 3	
Step distance in front of obstacle (cm)					
Condition: Low Obstacle	86.3 (14.0)	86.3 (14.1)	86.1 (8.7)	84.8 (11.2)	F (2,18) =0.095, p =0.91
Condition: High Obstacle	84.6 (13.5)	84.6 (13.5)	86.2 (9.8)	86.4 (15.1)	F (2,18) =0.087, p =0.917
Condition: Low Obstacle Dual Task	89.7 (11.1)	89.7 (11.2)	86.9 (9.7)	89.6 (19)	F (1.31,18) =0.224, p =0.709
Condition: High obstacle Dual Task	85.4 (11.8)	85.4 (11.9)	86.2 (8.7)	84.7 (11.9)	F (2,18) =0.075, p =0.928
Toe height above front of obstacle (cm)					
Condition: Low Obstacle	17.4 (3.7)	17.5 (3.8)	17.3 (3)	16.5 (3.4)	F (2,18) =1.317, p =0.293
Condition: High Obstacle	17.0 (3.7)	17 (3.8)	16.9 (2.8)	16.7 (4)	F (2,18) =0.063, p =0.939
Condition: Low Obstacle Dual Task	17.1 (4.0)	17.2 (4.0)	17.5 (3)	16.8 (3.3)	F (2,18) =0.545, p =0.589
Condition: High obstacle Dual Task	17.3 (4.1)	17.3 (4.1)	16.9 (3.3)	16.6 (4)	F (2,18) =0.308, p =0.739
Heel height above back of obstacle (cm)					
Condition: Low Obstacle	10.6 (3.5)	10.6 (3.6)	9.9 (3.7)	9.2 (3.3)	F (2,18) =1.317, p =0.293
Condition: High Obstacle	11.1 (3.9)	11.7 (2.9)	10 (2.9)	9.3 (3.5)	**F (1.271,11.442) =6.36, p =0.022** †[a]
Condition: Low Obstacle Dual Task	10.4 (3.7)	10.4 (3.8)	9.7 (3.7)	9.4 (2.8)	F (2,18) =1.707, p =0.209
Condition: High obstacle Dual Task	11.1 (3.8)	11.2 (3.8)	9.7 (2.9)	9.6 (3.6)	**F (2,18) =3.691, p =0.045** [b]
Step distance away from obstacle (cm)					
Condition: Low Obstacle	19.6 (3.2)	19.7 (3.2)	17 (2.8)	17.9 (2.9)	**F (2,18) =11.197, p =<.001** †[a]
Condition: High Obstacle	20.5 (3.4)	20.5 (3.4)	19.7 (3)	18.8 (3.5)	F (2,18) =2.843, p =0.085
Condition: Low Obstacle Dual Task	17.8 (2.9)	17.8 (3)	17.4 (2.9)	16.2 (3.7)	F (2,18) =1.533, p =0.243
Condition: High obstacle Dual Task	18.0 (3.5)	18.1 (3.6)	18.1 (3)	17.7 (2.9)	F (2,18) =0.202, p =0.819

[a] significantly different between trial 1 and 2, [b] significantly different between trial 1 and 3, [c] significantly different between trial 2 and 3. † Greenhouse-Geisser applied. **Bold indicates a significant effect.**

Table 3. 4 The difference between trials for the trailing limb when crossing and obstacle

Left Trailing limb		Mean (SD)			RM ANOVA and output
	(All trials)	Trial 1	Trial 2	Trial 3	
Step distance in front of obstacle (cm)					
Condition: Low Obstacle	17.0 (3.9)	17.1 (4)	17.2 (3.8)	16.4 (4)	F (2,18) =0.297, p =0.747
Condition: High Obstacle	14.4 (4.9)	14.5 (5)	15.1 (3.4)	16.4 (4.5)	F (2,18) =0.923, p =0.415
Condition: Low Obstacle Dual Task	16.9 (3.9)	16.9 (3.9)	16.6 (3.1)	17.2 (4.6)	F (2,18) =0.113, p =0.894
Condition: High obstacle Dual Task	15.0 (5.1)	15.1 (5.1)	15.9 (3.3)	15.9 (2.5)	F (2,18) =0.315, p =0.734
Toe height above front of obstacle (cm)					
Condition: Low Obstacle	12.4 (3.2)	12.5 (3.3)	12.5 (2.8)	11.3 (3.3)	F (2,18) =0.751, p =0.486
Condition: High Obstacle	12.9 (3.9)	12.7 (3.9)	13.6 (3)	12.2 (4.1)	F (2,18) =0.487, p =0.622
Condition: Low Obstacle Dual Task	12.7 (5.3)	12.7 (5.3)	13.2 (3.7)	11.5 (3.9)	F (2,18) =1.079, p =0.361
Condition: High obstacle Dual Task	13.7 (1.8)	13.7 (1.9)	13.2 (2)	11.7 (3.7)	F (1.176,18) =1.878, p =0.201†
Heel height above back of obstacle (cm)					
Condition: Low Obstacle	42.5 (4.9)	42.6 (4.9)	40.8 (3.2)	42.2 (6.2)	F (2,18) =1.295, p =0.298
Condition: High Obstacle	43.4 (3.6)	43.4 (3.7)	42.4 (2.7)	41.1 (6.8)	F (2,18) =1.52, p =0.245
Condition: Low Obstacle Dual Task	40.6 (2.9)	40.6 (2.9)	40.6 (3.9)	40.4 (5.7)	F (2,18) =0.018, p =0.982
Condition: High obstacle Dual Task	42.6 (3.5)	42.6 (3.6)	41.2 (3.9)	40.5 (5.3)	F (2,18) =2.872, p =0.083
Step distance away from obstacle (cm)					
Condition: Low Obstacle	98.8 (8.1)	98.8 (8.2)	96.9 (6.2)	96.6 (7.3)	F (2,18) =1.193, p =0.326
Condition: High Obstacle	100.5 (6.7)	100.5 (6.7)	99.4 (7.6)	98.2 (7)	F (2,18) =0.975, p =0.396
Condition: Low Obstacle Dual Task	94.7 (5.7)	94.7 (5.6)	95.1 (5.8)	94.8 (6.2)	F (2,18) =0.034, p =0.967
Condition: High obstacle Dual Task	95.7 (5.3)	95.8 (5.3)	96.4 (6.6)	95.2 (5.8)	F (2,18) =0.39, p =0.683

[a] significantly different between trial 1 and 2, [b] significantly different between trial 1 and 3, [c] significantly different between trial 2 and 3. † Greenhouse-Geisser applied. **Bold indicates a significant effect.**

3.4.5 Discussion

This study aimed to determine the equality of trials required to achieve foot clearance parameter stability while stepping over an obstacle. The results suggested that there was stability for 3 trials as for most of the results there was no significant difference between trials. We found that, except for three parameters (step away from the obstacle in the low condition and heel height in the high and high DT conditions), thirteen of the leading limb parameters did not significantly differ between trials thus ensure the stability of the test variables.

For further analysis of leading limb, conducting a pairwise comparison is essential. Trials 1 and 2 had a significant discrepancy in the distance from the obstacle when stepping over, whereas trials 2 and 3 demonstrated no variation. Similarly, under optimal circumstances, there was no difference in the elevation of the heel above the rear of the obstacle. Between trials 1 and 3, there was a notable disparity in the height of heel above the rear of the obstacle, particularly in the HIGH-DT condition. Nevertheless, there was no significant difference between trials 1 and 2, as well as trials 2 and 3. Previous study reported that visual information obtained at least two steps prior to reaching the obstacle is required to maintain appropriate toe clearance of the lead limb (Timmis and Buckley, 2012). However, there was not a significant difference between trials for the trailing limb. This might be that there is stability for single leading stand on the floor to safe during the elevation of trailing limb. Previous study reported that the trail limb depends on proprioceptive feedback from the lead limb, as the trail limb cannot be observed in the visual field (Mohagheghi et al., 2004; Draganich and Kuo, 2004).

For walking gait analysis, it is crucial to conduct a sufficient number of trials to ensure reliable data and stability in measurements. Research suggests that the number of trials required to achieve stability in level walking varies depending on the specific variables being measured and the population being studied. Generally, a minimum of 10 to 15 trials is recommended to capture the natural variability in walking patterns and to achieve stable mean values for key gait parameters (Bates et al., 2004; Owings and Grabiner, 2003). This number of trials helps accommodate any anomalies or outliers in the data, ensuring that the final analysis accurately represents the typical gait characteristics of the participants. In summary, for reliable analysis of level walking gait, conducting 10 to 15 trials is generally sufficient to achieve stability and accurate representation of the walking pattern (Bates et al., 2004; Owings and Grabiner, 2003).

However, the number of trials required for obstacle clarence has not been recommended. The number of trials used in this current thesis was the same as previous study designs for single stepping tasks (Lu et al., 2006), stepping tasks with visual conditions (Kunimune and Okada, 2017), and stepping tasks with anticipated conditions (Maidan et al., 2018). Table 3.4 provides further information. However, there are also studies which have used different number of trials to that used in this present work and it is unclear how many trials are suitable for stepping task (table 3.4). Yet since the results suggest that there was no learning effect for 3 trials it was deemed likely that this would be suitable for his thesis. There was also a degree of pragmatism ensuring participants were able to perform the number of trials within one data collection session.

Increasing the number of trials may also lead to obstacle contact. For example, Heijnen et al (2012) reported that there was a progressive decrease on trial MFC clearance which continues until the obstacle was struck – occurring for 70% of participants. However, these contacts were seen following multiple trials (trial limb contact after median 112 trials (mean 103 trials)) and so will be unlikely to be seen with the number of trials used in this thesis. Contact was also more often seen for the trail limb which is likely due to the reduced visual input as this limb attempts to clear an obstacle. The results from Hijnen et al (2012) were however surprising since obstacle contact is likely to be due to inappropriate foot placement (Chou and Draganich 1998) as opposed to inadequate foot height, and if safety is key to successful clearance are reduction in MFC contradicts this. A biomechanical reason for what is causing this reduction is MFC will require future work to look at the joint kinematics / kinetics – this is beyond the scope of this thesis.

Foot clearance was higher than necessary since the MFC decreased over 103 trials, on average, before obstacle contact occurred. This is likely a cautious behavior, however, this requires more energy and so leading to fatigue (following 100 min of walking) and lower foot placement as the trial numbers increased. Fatigue is unlikely to impact the participants in this thesis since they will have less trials and rest periods between trials/sets.

Table 3. 5 The number of trials per session when stepping over from the literature reviews

No	Authers, year	Titles	Task	Dimension	Sample size (Y_A=young adult, O_A=older adult	The number of trials per session
1	(I. Maidan et.al ,2018)	Age-associated changes in obstacle negotiation strategies: Does size and timing matter?	Single obstacle	D = 20 cm, W=60 cm, H = 2.5 cm and 7.5 cm	Y_A=20, O_A=20	three trials
2	(Kunimune and Okada et.al, 2017)	The effects of object height and visual information on the control of obstacle crossing during locomotion in healthy older adults	Single obstacle	D = 5 cm, W=70 cm, H = 2.5 cm, 5 cm, and 10 cm	Y_A=13, O_A=15	three trials
3	(Muir, BC, 2015)	Proactive gait strategies to mitigate risk of obstacle contact are more prevalent with advancing age	Single obstacle	78 cm wide by 0.5 cm deep, composed of Masonite, painted flat black, and designed to tip if contacted. The obstacle height is 1, 10 and 20 cm	Y_A (20-25) =19, M/F=9/10; O_A (65-79) =11, M/F=3/8, O_A (80-91) =18, M/F=7/11	six trials of each obstacle height (1, 10, and 20 cm)
4	(Soma et al., 2010)	Influence of a Dual-Task on Toe Clearance of the Young and Elderly While Stepping Over an Obstacle	Single obstacle	D = 15 cm, W= 80 cm, H = 2 cm	Y_A=30, O_A=30	five trials
5	(Lowrey et al ,2007)	Age-related changes in avoidance strategies when negotiating single and multiple obstacles	Multi-obstacles	adjusted 45% of lower leg length (a 2.5 cm & 5 cm piece of wood that spanned the width of the GAIT Rite carpet	Y_A=8 (Male=4, Female =4),	six trials
6	(Lu et al., 2006)	Comparisons of the lower limb kinematics between young and older adults when crossing obstacles of different heights	Single obstacle	heights of 20% and 30% of leg length a 1.5 m long aluminum tube with a diameter of 1.5 cm placed across a metal frame	O_A=8	three trials
7	(Di Fabio et al, 2004)	Foot lift Asymmetry During Obstacle Avoidance in High-Risk Elderly	Single obstacle	D = 21 cm, W=51 cm, H = 7.6 cm, 12.7 cm, and 23 cm	Y_A=15, O_A=15	**Sound condition**: six trials for the right leading foot, 9 trials for the left leading foot **Visual condition**: 8 trials cued right foot and 7 trials cued left
8	(Chen, 1991)	Stepping Over Obstacles: Gait Patterns of Healthy Young and Old Adults	Single obstacle	D = 25 mm, W=450 mm, H = 25, 51, and 152 mm	Y_A=24, O_A=24	Data from a minimum of 20 trials with the 25 mm obstacle and a minimum of five of all the other trials were fully processed.

3.4.6 Conclusion

Performance stability is a variable that undergoes repeated assessments over time. The goal of this study was to evaluate the uniformity of attempts required to establish stability in the foot clearance parameter during the process of stepping over an obstruction. The results showed that there was no significant main effect when crossing an obstacle in 13/16 parameters for the leading limb, whereas there was no significant difference between trials for all 16 parameters of the trailing limb. This suggests that there was little to no difference between trials, so three trials have produced a stable measure. However, it remains unclear whether, for example, 5 or 10 trials could have yielded a more stable result than just 3 trials. There is also a degree of pragmatism in the number of trials a participant can perform within a data collection period.

Chapter IV: Test re-test of foot clearance parameters whilst stepping over an obstacle in healthy young male adults.

Abstract

Background: For any measurement, test-retest repeatability is a fundamental requirement. However, the literature has not evaluated obstacle clearance when stepping over obstacles of varying heights during a dual task. The aim of this study was to determine whether foot clearance parameters when stepping over an obstacle were repeatable.

Objective: The aim of this study was to assess the consistency and reliability of foot clearance measurements during the performance of obstacle negotiation tasks.

Methodology: 10 healthy male volunteers (age: 24.8 (1.8) years, height: 1.69 (0.4) m, body mass: 64.2 (6.7) kg) received two separate sessions approximately a week apart. We used a 10-camera Vicon motion capture system operating at 100 Hz. We placed markers (n = 4) on the big toe and heel of both feet. Participants performed four walking tasks at their freely chosen walking speed. Each task had three trials for the leading limb and three trials for the trailing limb. The tasks were 1) stepping over LOW obstacle (15 cm), 2) stepping over a HIGH obstacle (20 cm), 3) stepping over LOW obstacle while performing a dual task, and 4) stepping over a HIGH obstacle while performing a dual task. Carrying a glass of water was an attention-dividing task. We asked participants to perform dual-task walking without spilling any water. The key foot clearance parameters were toe height above the front of the obstacle (cm), heel height above the back of the obstacle, and step distance (cm) before and after stepping over the obstacle (cm). The re-test was performed approximately once a week. Intraclass correlation coefficient (ICC) and minimal detectable change (MDC) were calculated for each parameter.

Results: All ICC foot clearance parameters, both leading and trailing limbs, showed good to excellent reliability for both low and high levels (ICCs between 0.72-0.96). For all conditions, the step distance in front of the obstacle had the greatest MDC (10.5–13.1 cm).

Conclusions: This was the first study to report the repeatability of foot clearance parameters when stepping over an obstacle of different heights and performing a dual task. ICCs were good-to-excellent for all parameters, indicating that stepping over an obstacle using the methods described in this current study was a repeatable task in young male adults. You can use the MDC to determine if a change in these parameters surpasses measurement error and patient variability.

Keywords: foot clearance, toe clearance, younger adults, stepping over, crossing over

4.1 Introduction

Foot clearance is an important event in walking as it ensures that the foot does not contact the surface, resulting in a stumble, trip, or fall. For straight walking on level ground, critical toe clearance occurs approximately midway through the swing phase (Murray and Clarkson, 1966), when the distance between toe and floor reaches a local minimum (Moosabhoy and Gard, 2006). The precision and accuracy investigated during the swing phase of walking have received much attention (Winter, 1992). This local minimum is remarkably small and results in a ground clearance of 1.29 (0.45) cm (Winter, 1992), thus illustrating relatively small margins of error. The biomechanics associated with controlling this precise movement are complex, as they require control and coordination from all segments. The stance limb will need to provide stability, and the swing limb flexes, and the ankle dorsiflexes to ensure toe clearance.

Obstacle clearance increases the likelihood and severity of stumbling or tripping. The locomotor system requires intersegmental coordination and control of the swing limb while relying on the detection of environmental cues (Austin et al., 1999). For example, when stepping over an obstacle, the trailing limb is crossing the object with no visual input, thus increasing the chance of contact. In addition to this, there is also a prolonged and unstable phase where the CoM (the center of mass) is outside of the narrow base of support (Austin et al., 1999). Such a task is achieved with relatively little thought or effort, but Austin et al. (1999) suggested that despite this ease, the system is constrained by the need to ensure a safe and efficient outcome. When clearing an obstacle, successful foot clearance is vital for safe progression. If the obstacle is struck when attempting to clear it, this may result in a trip or stumble. Foot clearance parameters traditionally used in this research are foot (or toe or heel) height above the obstacle, indicating the amount of clearance between the foot and the obstacle, and placement of the limb before (distance from foot to obstacle) and after (distance obstacle to foot) crossing the obstacle. Minimum foot clearance, or toe and heel clearance, is considered a measure for the risk of swing foot contact when negotiating different environments, such as stepping over the edge of a roadside curb or bathtub (Begg and Sparrow, 2000; Austin et al., 1999; Chen et al., 1996; Patla and Rietdyk, 1993; Winter, 1992; Chen et al., 1991).

Walking requires the complex processing of visual, proprioceptive, and vestibular information. In addition to this, when walking in an ever-changing environment, we encounter and therefore need to integrate and negotiate several situations, and as such, we may also be walking while performing another task. This task could be as basic as talking over the phone, interacting with someone else, grasping a cup of coffee, or attempting to recall specific instructions. When carrying out two or more tasks, it is likely that one of the tasks, be it the primary walking task or the secondary task, will be negatively affected. In the laboratory, dual-task walking tends to focus on manual (i.e., carrying an object) or cognitive tasks (i.e., counting backwards, etc.). When walking on level ground, manual tasks (i.e., holding a glass of water) result in significant reductions in spatial and temporal parameters compared to single-task walking (Kwon et al., 2019). Cognitive tasks have a similar impact on walking, but some tasks are less challenging and therefore have less impact on gait than other tasks (i.e., visuomotor reaction time is less challenging than serial subtraction or Stroop) (Patel et al., 2014). When stepping over an obstacle and performing a dual task (serial addition test), toe-obstacle distance has been shown to increase and obstacle-heel distance to reduce compared to single-tasking (Schrodt et al., 2004). But Schrodt et al. (2004) went on to show that there was also a decrease in cognitive performance and that the remaining gait parameters were unaffected, suggesting that participants placed a higher priority on crossing the obstacle. Siu et al. (2008) showed no difference in gait parameters, but there was a determinant in the secondary task, also suggesting that participants prioritize the obstacle task over the additional task.

Despite the different paradigms presented in these studies (obstacle heights, dual task procedures, etc.), there is little evidence of reliability being carried out. Before a gait measure can be used to evaluate a change, the reproducibility of that measure for the specific task and population needs to be determined, and as such, test-retest reliability is a fundamental requirement for any measure. If a change is observed between conditions, then we need to know if that change is real and whether it is due to normal participant variability or error associated with the measurement system (Wittwer et al., 2014). Low reliability may lead to underestimation or failure to detect significant effects (McGinley et al., 2006).

The test-retest reliability of obstacle clearance while performing a dual task or at different obstacle heights has not been reported in the literature. Therefore, repeated measuring of foot clearance analysis is needed for both researchers and clinicians to better understand the outcome. Repeatability in gait is important to interpret that the different measurement of foot clearance parameters through consistency and agreement and presents a real change or only a change within the extents of Standard Error measurement. By understanding this, researchers will be able to take this measure forward into a group of pathological condition or older individuals to establish the clinical utility of any biomechanical measurement. It is first necessary to establish how repeatable measurements are.

Consistency and agreement are crucial when interpreting various foot clearance measures. It is necessary to determine whether a change is a genuine change or simply falls within the range of standard error measurement. By comprehending this, researchers will have the capacity to advance this measure into a cohort of diseased or elderly persons to determine the clinical effectiveness of any biomechanical assessment. Before moving forward, it is crucial to determine the repeatability of the measurements. This study aimed to assess the test-retest reliability and a minimum detectable change (MDC) of foot clearance metrics in younger male adults while stepping over obstacles of varying heights, both with and without a dual task.

4.2 Methodology

This has been described earlier in chapter 3 (methods). For brevity only a summary of the methods and those methods pertinent to this chapter are presented here.

4.2.1 Participants

Ten healthy male volunteers (average age, 24.8 (1.8) years; average height, 1.69 (0.4) m; body mass, 64.2 (6.8) kg; and body mass index, 22.3 (6) kg/m^2) were recruited from the University of Essex staff and student population. The recruiting process was performed by a poster (Appendix 1), an invitation letter (Appendix 2), and electronic mail. Participants were included if their ages were between 20 and 40 years old and their right leg was dominant, as determined by kicking a ball, picking up an eraser off the floor, and drawing a number eight on the floor. The exclusion criteria were self-reported musculoskeletal disorders or cardiovascular disease, having any difficulty walking, and taking alcohol or caffeine within 24 hours before testing. The procedure of this study was approved by the Ethical Approval of Research Involving Human Participants, University of Essex.

4.2.2 Procedure

Gait analysis was captured in the University of Essex biomechanics lab. A 10-camera Vicon Bonita motion capture system (Vicon Motion Systems Ltd., Oxford, UK) was used at a sampling rate of 100 Hz. Chapter 3 provides additional information.

4.2.3 Data analysis

Foot clearance parameters were as described in **chapter 3**. Briefly, these were for both the leading and trailing limbs:

- Step distance in front of obstacle (cm)
- Toe height above front of obstacle (cm)
- Heel height above back of obstacle (cm)
- Step distance away from obstacle (cm)

4.2.4 Statistics analysis

Statistical analyses were carried out in the Statistical Package for the Social Sciences (SPSS) Version 25 for Windows. The different mean and standard deviation of the four variables on four tasks, both right-leading and left-trailing, were calculated between sessions. These include the calculation of the mean difference between two sessions (Diff) (1) and the standard deviation of Diff (SDDiff).

$$Diff = mean(Session\ 1 - Session\ 2) \quad \text{.........} \ (1)$$

To determine test-retest reliability, mixed-effects model intraclass correlation coefficients (ICC) were used with an absolute agreement definition with a 95% confidence interval. The magnitude of reliability is less than 0.5, which is indicative of poor; between 0.5 and 0.75, moderate; between 0.75 and 0.9, good; and greater than 0.90, which is excellent repeatability (Koo and Li, 2016; Portney and Watkins, 2000). We use the ICC to measure absolute repeatability. Therefore, Standard Error of Measurement (SEM) was used to assess absolute repeatability and provide information to analyze intra-individual variability over repeated measurements (Atkinson and Nevill, 1998). SEM arranged measurement errors in the same units as the initial measurements, and then it was calculated using (2) (Bruton et al., 2000):

$$SEM = SD * \sqrt{1 - ICC} \text{ …… (2)}$$

Minimal detectable change (MDC) can facilitate clinical interpretation (Haley and Fragala-Pinkham., 2006 and Wilken et al., 2012). MDC is the minimal amount of change in observed score that must occur in an individual to be sure that the change in score is not simply attributable to measurement error. The formula (3) was calculated by Haley and Fragala-Pinkham (2006):

$$MDC = SEM * 1.96 * \sqrt{2} \text{…… (3)}$$

4.3 Results

Table 4.1 shows the day 1 versus day 2 results for both leading and trailing limbs. Week-to-week agreements showed good and excellent reliability for all foot clearance parameters except step distance away from the obstacle of the leading limb when stepping over a low-task condition and step distance in front of the obstacle of the leading limb when stepping over a high-task condition. ICC 19% of variables were classified as having excellent repeatability (ICC >0.9), 75% were classified as having good repeatability (ICC 0.89–0.75), and one variable (6%) had moderate repeatability (0.5–0.74). The average ICC was 0.85. The SEM ranged from 0.7 to 4.7 cm.

Table 4. 1 Average mean and standard deviation of repeatability test four clearance tasks of right leading limb and left trailing limb day to day.

	Mean (SD) (N=10)			
	Right leading limb		Left trailing limb	
	Day 1	Day 2	Day 1	Day 2
Condition: Low Obstacle				
Step distance in front of obstacle (cm)	86.3 (14.0)	86.0 (8.6)	17.0 (3.9)	17.2 (3.7)
Toe height above front of obstacle (cm)	17.4 (3.7)	17.2 (3.0)	12.4 (3.2)	12.5 (2.7)
Heel height above back of obstacle (cm)	10.6 (3.5)	9.8 (3.8)	42.5 (4.9)	40.7 (3.1)
Step distance away from obstacle (cm)	19.6 (3.2)	15.7 (3.2)	98.8 (8.1)	96.9 (6.1)
Condition: High Obstacle				
Step distance in front of obstacle (cm)	84.6 (13.5	86.3 (10.8)	14.4 (4.9)	15.2 (4.4)
Toe height above front of obstacle (cm)	17.0 (3.7)	16.9 (2.8)	12.9 (3.9)	13.2 (3.3)
Heel height above back of obstacle (cm)	11.1 (3.9)	9.6 (3.1)	43.4 (3.6)	42.4 (2.6)
Step distance away from obstacle (cm)	20.5 (3.4)	19.7 (2.9)	100.5 (6.7)	99.4(7.5)
Condition: Low Obstacle Dual Task				
Step distance in front of obstacle (cm)	89.7 (11.1)	86.9 (9.7)	16.9 (3.9)	16.7 (4.0)
Toe height above front of obstacle (cm)	17.1 (4.0)	17.4 (2.9)	12.7 5.3)	13.2 (3.6)
Heel height above back of obstacle (cm)	10.4 (3.7)	9.7 (3.8)	40.6 (2.9)	40.5 (3.8)
Step distance away from obstacle (cm)	17.8 (2.9)	17.6 (3.3)	94.7 (5.6)	95.0 (5.7)
Condition: High obstacle Dual Task				
Step distance in front of obstacle (cm)	85.4 (11.8)	86.2 (8.7)	15.0 (5.1)	15.6 (3.8)
Toe height above front of obstacle (cm)	17.3 (4.1)	16.8 (3.2)	13.7 (1.8)	13.1 (1.9)
Heel height above back of obstacle (cm)	11.1 (3.8)	9.6 (2.8)	42.6 (3.5)	41.2 (3.9)
Step distance away from obstacle (cm)	18.0 (3.5)	18.1 (2.9)	95.7 (5.3)	96.4 (6.5)

Table 4. 2 Reliability and absolute reliability of for four clearance tasks of right leading limb and left trailing limb.

Variable /statistical analysis	**ICC**	**(95% CI)**	**Mean**	**D**	**SD (Diff)**	**SEM**	**MDC**
Condition: Low Obstacle							
Leading limb							
Step distance in front of obstacle (cm)	**0.769**	-0.06, .944	86.21	-0.3	10.4	9.6	26.6
Toe height above front of obstacle (cm)	**0.923**	.688, .981	17.39	0.2	1.9	3.3	9
Heel height above back of obstacle (cm)	**0.940**	771, .985	10.27	0.8	1.9	1.8	5.1
Step distance away from obstacle (cm)	0.723	-.246, 939	18.31	3.9	2.1	1.4	3.9
Trailing limb							
Step distance in front of obstacle (cm)	**0.790**	.155, .948	17.14	0.1	3.2	3.4	9.4
Toe height above front of obstacle (cm)	**0.887**	.545, .972	12.5	0	1.9	2.8	7.8
Heel height above back of obstacle (cm)	**0.843**	.367, 961	41.66	1.08	3.1	1.8	4.9
Step distance away from obstacle (cm)	**0.891**	.56, .973	97.87	1.9	4.5	2.5	6.8
Condition: High Obstacle							
Leading limb							
Step distance in front of obstacle (cm)	0.738	-.053, .935	85.39	1.7	10.6	10.2	28.3
Toe height above front of obstacle (cm)	**0.833**	.326, .958	16.97	0.1	2.5	3.0	8.3
Heel height above back of obstacle (cm)	**0.955**	.817, .989	10.83	1.5	1.9	1.7	4.8
Step distance away from obstacle (cm)	**0.873**	.488, .968	20.12	0.8	2.2	1.6	4.5
Trailing limb							
Step distance in front of obstacle (cm)	**0.83**	.316, .958	14.77	0.7	3.6	4.2	11.7
Toe height above front of obstacle (cm)	**0.756**	.016, .939	13.25	-0.5	3	3.1	8.5
Heel height above back of obstacle (cm)	**0.82**	.275, .955	42.93	1.1	2.5	1.6	4.3
Step distance away from obstacle (cm)	**0.934**	.735, .984	99.98	1	3.6	2.6	7.1
Condition: Low Obstacle Dual Task							
Leading limb							
Step distance in front of obstacle (cm)	**0.838**	.35, .96	88.32	-2.8	7.8	9.1	25.2
Toe height above front of obstacle (cm)	**0.937**	.745, .984	17.31	-0.3	1.7	3.4	9.4
Heel height above back of obstacle (cm)	**0.917**	.666, .979	10.07	0.7	2.1	1.8	5.1
Step distance away from obstacle (cm)	**0.861**	.422, .966	17.61	0.2	2.4	1.6	4.4
Trailing limb							
Step distance in front of obstacle (cm)	**0.81**	.233, .953	16.75	-0.2	3.2	3.5	9.7
Toe height above front of obstacle (cm)	**0.80**	.195, .950	12.98	-0.5	3.7	4	11.2
Heel height above back of obstacle (cm)	**0.883**	.528, .971	40.61	0	2.2	1.7	4.8
Step distance away from obstacle (cm)	**0.901**	.602-.975	94.88	-0.4	3.4	2.2	6.2
Condition: High obstacle Dual Task							
Leading limb							
Step distance in front of obstacle (cm)	**0.809**	.231, .953	85.83	0.8	8.4	8.9	24.7
Toe height above front of obstacle (cm)	**0.806**	.221, .952	17.1	0.4	3.3	3.3	9.1
Heel height above back of obstacle (cm)	**0.866**	.460, .967	10.43	1.5	1.6	1.6	4.5
Step distance away from obstacle (cm)	**0.854**	.411, .964	18.09	0	1.6	1.6	4.6
Trailing limb							
Step distance in front of obstacle (cm)	**0.844**	.371, .961	15.49	0.5	3.3	4.1	11.4
Toe height above front of obstacle (cm)	**0.843**	.366, .961	13.46	1.6	1.4	1.7	4.8
Heel height above back of obstacle (cm)	**0.837**	.345, .960	41.93	1.4	2.8	1.7	4.7
Step distance away from obstacle (cm)	**0.909**	.633, .977	96.1	-0.7	3.5	2.3	6.4

Repeatability (ICC); 95% confidence interval for the ICC (95% CI); mean of measurements at time one and time two (Mean); mean of the difference between measurements at the first time and the second time (D) and its standard deviation SD (Diff); standard error of measurements (SEM) and minimal detectable change (MDC) *D*T, Dual Task. An ICC value which is less than 0.5 is indicative of poor, between 0.5 and 0.75 moderate, between 0.75 and 0.9 good, and greater than 0.90 as excellent repeatability **bold** indicates good to excellent reliability.

4.4 Discussion

This study is the first to assess the reliability (ICC) and minimum detectable change (MDC) of foot clearance parameters during the act of stepping over obstacles of varying heights, both with and without the additional task of dual-task performance. It is crucial to determine whether the movement of interest, such as walking, jumping, turning, or obstacle clearance, can be consistently replicated. A statistical method establishes a threshold for comparing the size of foot clearance parameters derived from two measurements, to assess their consistency and agreement. In this investigation, a two-way mixed model and absolute agreement type were selected, along with a 95% confidence range. In addition, the procedure of choosing the ICC for test-retest and interrater reliability is simpler compared to picking it for interrater reliability. A difficulty arises from the fact that the application will rely either on a single measurement or the average of several measurements (Koo and Li, 2016). Research has indicated that the most suitable approach for assessing interrater reliability when dealing with several scores from the same rater is a two-way mixed-effects model. This is because it is not logical to extend the scores of one rater to a broad group of raters (Shrout and Fleiss, 1979). For the test-retest reliability study, it is recommended to apply a 2-way mixed-effects model to analyze the data. This is because the repeated measurements cannot be treated as randomized samples, as stated by Portney and Watkins (2009). Moreover, it is crucial to consistently employ the absolute agreement definition in both test-retest and interrater reliability investigations. This is because the act of measuring would lack significance if there was no concurrence between repeated measures (Koo and Li, 2016). The objective of this study was to assess the consistency of test results and the smallest detectable change in foot clearance parameters when stepping over obstacles of varying heights, both with and without a secondary task, in young adult males.

For context, obstacle clearance distance was comparable to other studies with young adults. For example, Harley et al. reported lead toe and trial clearance of 14.1 (0.6) and 13.6 (1.2) cm, respectively. Worden et al. reported lead toe and trial clearance of 18 (0.02) cm and 14 (0.02) cm, respectively. The range of toe clearance reported in the present work was 12.4–17.4 cm (depending on if they were the leading or trailing limbs). Sparrow et al., who used the heel marker for obstacle clearance, reported trail limb clearance (~40 cm) comparable to those reported in this current work. Worden et al. described step distance in front of an obstacle as the take-off distance (horizontal distance between the trial foot toe and obstacle) and reported it to be 28 (0.03) cm, and step distance away from the obstacle, defined as the distance (horizontal distance between the leading foot heel and the obstacle), was 24 (0.06) cm. These values sit within the range for step distance in front (14.4–17.0 cm) and away (17.8–20.5 cm) from the box reported in this present work. This suggests that the current work is comparable to previous obstacle clearance studies.

The mean ICC for all parameters was 0.85, which suggests that just 15% of the obtained variance was either due to measurement error or within-subject variability between testing sessions. The test-retest findings (good to excellent) are comparable to other obstacle clearance studies, which have also reported ICCs for a selection of parameters. For example, vertical foot clearance has been shown to have good to excellent reliability for all four standing and stepping tasks (ICC ≥ 0.85) (Grinberg et al., 2022). When approaching an obstacle, Said et al. have reported excellent ICC for toe clearance (ICC 0.95) and post-obstacle distance (ICC 0.99) (Said et al., 2009). Said et al. furthered this work and included pre- and post-obstacle distance for trailing and leading limbs, as well as toe clearance for both leading and trailing limbs (Said et al., 2009). The ICCs for unaffected limbs (participants with strokes) showed moderate to strong correlations (ICC 0.61–

0.92). The trail toe clearance showed moderate reliability (ICC 0.61) when the unaffected limb was following the affected limb over the obstacle. The current work further expanded on these studies and looked at pre- and post-clearance, as per Said et al., but also tested different obstacle heights and when performing dual tasks (Said et al., 2009). The mean ICCs for LOW were 0.85 (0.07) and were comparable to the ICCs for HIGH condition (0.84 (0.05)), suggesting there was little difference in repeatability when going over different heights. Furthermore, this was repeated when comparing the range of ICCs between LOW dual task (0.83 (0.03)) and HIGH dual task (0.87 (0.05)). From these ranges, we can also see that repeatability was comparable regardless of the task. However, the 95%CI for some of these parameters was wide suggesting a degree of caution needs to be given

The obstacle clearance literature does not always report the value of SEM and MDC, which we used to calculate absolute reliability. It is the difference between an observed score on any given test and the actual score or true score for the method. The value of SEM and MDC provides a threshold for interpreting the foot clearance parameters over time in this study. For example, the MDC value of step distance for the leading limb in front of the low obstacle was 12.4 centimeters. For the interpretation of this parameter, if the next test uses the same method, a difference greater than the MDC suggests a meaningful change for that participant.

The SEM was small for most measures, but the SEM and MDC were generally higher for step distance in front of obstacles. This may suggest that participants were adjusting their approach to ensure obstacle clearance was the most repeatable phase when stepping over an obstacle. When approaching an obstacle, motor planning occurs to ensure a safe clearance, and this can depend on the height of the obstacle. For higher obstacles (20–25 cm), adjustment to the approach occurs 3–4 steps before the obstacle—a safer strategy to provide time to adjust before the obstacle. For lower obstacles (5–10 cm), this adjustment occurred 1 step before the obstacle (Simieli et al., 2017). The difference between these may be due to the perceived challenge of the higher obstacle, thus requiring more adjustments in approach. Furthermore, it may be possible that when introducing a dual task, the adjustment may occur even earlier. Such work, however, has yet to be reported in the literature.

The dimension of an obstacle in this study differs from those reported in other studies. However, there is no consensus about what dimensions an obstacle should take. The obstacle heights we used (15/20 cm) were chosen to represent the daily activity faced by individuals. For example, based on negotiating daily activities (Austin et al., 1999), (1) the height of a standard curb or parking stone is approximately ten to twenty centimeters, and (2) the height of a standard doorstop is approximately thirty-one millimeters. The main difference between this study and other obstacle clearance studies was the use of a deeper obstacle (35 cm) than what is commonly reported in the literature, which tends to be a ‘hurdle’ type construction. A deeper obstacle may lead to an impact during crossing, yet this was not observed in this current work. We have assumed that the width of the obstacle is close to a real situation when negotiating around the built environment. It then replicates movement for learning in the lab. Despite this difference and arguably a more challenging negotiation, the reliability of these parameters was acceptable.

The DT in this study was carrying a glass of water without spilling water. The participants achieved this, and the ICCs for DT conditions were comparable to non-DT conditions. No literature has examined the reliability (absolute or relative) of the above task. For walking on level ground and performing the same dual task as this current work, (Doe, Smith & Brown, 2021) reported substantial to perfect' relative reliability (ICC) for spatial-temporal parameters. However, there also appears to be no published studies that have established the repeatability of toe clearance parameters during 'flat' overground walking while performing a dual task. Thus, denying a comparison to a similar, although not the same, task as the current work.

This study had a few limitations. First, this was a repeatability study that involved a group of healthy male younger adults who participated in a single lab session a week apart and, as such, are not generalizable to females, older adults, or those with a pathology.

The current study employed a manual dual task. This was chosen as one can argue that it is used in the 'real world', compared to the cognitive dual tasks such as counting backwards. The reliability of dual-task obstacle clearance may be dependent upon the challenge associated with the secondary task (Muhaidat et al., 2013), and as such, reliability may differ from that reported in this present work. However, there is no published work that has tested the reliability of different DTs when clearing an obstacle. Finally, this study looked at the approach for the trailing and leading limbs, but this was only one step prior to the obstacle. It is acknowledged that adjustments to walking may happen several steps away from the obstacle as one approaches and adjustments made after the obstacle to return to a 'normal' level ground walking pattern. Future work should investigate this.

4.5 Conclusion

The results suggested that all ICC foot clearance parameters showed good to excellent reliability. Additionally, we can use the MDC value to assess if a change in these parameters surpasses measurement error and patient variability. These results will be useful for providing a basis for future work when establishing if there is a meaningful difference. This study suggests that the toe-clearance parameters used throughout this thesis are repeatable for the tasks in young healthy adults.

Chapter V: Are foot clearance parameters symmetrical when stepping over an obstacle?

Abstract

Background: Limb symmetry is an important gait characteristic. It is an essential component of maintaining independence. Obstacle clearance during walking is a fundamental activity for all human movement in a variety of environments. It is unclear whether foot clearance is asymmetrical when stepping over an obstacle. Furthermore, walking gait studies commonly use several asymmetry indices.

Objective: The aim of this study was to a) establish if foot clearance parameters are symmetrical when stepping over an obstacle and b) compare four commonly used gait symmetry indices, namely, symmetry ratio (RI), symmetry index (SI), gait symmetry (GA) and symmetry angle (SA).

Methodology: This study recruited ten healthy male volunteers, with an average age of 25.1 (3.2) years, an average height of 1.69 (0.4) m, and a body mass of 64.14 (6.7) kg. We used a 10-camera Vicon motion capture system operating at 100 Hz. We placed markers (n = 4) on the big toe and heel of both feet. Participants performed four walking tasks at their freely chosen walking speed. Each task had three trials for the leading limb and three trials for the trailing limb. The tasks were: 1) stepping over a LOW box (15 cm), 2) stepping over a HIGH box (20 cm), 3) stepping over a LOW box while performing a dual task (LOW-DT), and 4) stepping over a HIGH box while performing a dual task (HIGH-DT). The dual task involved holding a glass of water while walking.

Results: The ratio index classified most foot clearance measures as symmetrical (i.e., = 1.0). The symmetry index and gait symmetry measures produced the same results, and using the 10% cut-off for asymmetry, most of the measures were asymmetrical. Using a paired t-test revealed that all but two measures were symmetrical (i.e., there were no significant differences between the right and left limbs). There were significant correlations between all indices for each of the measures and tasks.

Conclusions: The results demonstrated statistical symmetry in obstacle clearance, thereby offering an intriguing challenge to determine the existence of symmetry and its potential use as a pathology indicator. However, based on the arbitrary cut-off of 10%, the symmetry indices yielded differing results, with the RI primarily suggesting that obstacle clearance was symmetrical, while SI and GA suggested the opposite. Despite different interpretations based on cut-offs, these indices correlated with each other.

Keywords: foot clearance, toe clearance, younger adults, stepping over, crossing over, symmetry gait

5.1 Introduction

By its very nature, human walking is bipedal. Yet despite the apparent simplicity of walking and, to a certain extent, clearing an obstacle when walking, it is a complex act, and any deviation from normal is a useful indicator of cognitive decline (Verghese et al., 2007) and fall risk (Beauchet et al., 2009). Assessing gait asymmetry is therefore useful in both clinical and research settings, and it is a common clinical and research objective. Asymmetry is the amount of divergence between left and right limbs or between affected and unaffected limbs, and as such, asymmetry is not only associated with pathology but is also present in able-bodied people (Sadeghi et al., 2000). Laterality is the dominance of one side of the body over the other, i.e., the hand one writes with or the foot one kicks with (Sadeghi et al., 2000). People sometimes assume that symmetry simplifies data collection and analysis (Griffin et al., 1995). Conversely, researchers have observed asymmetry in able-bodied gait, which signifies the functional difference between the limbs (Patterson et al., 2008); for instance, in right dominant individuals, the right limb serves as a propulsion function through joint kinetics, while the left leg serves as a support limb (Robinson et al., 1987).

Asymmetry, therefore, may help differentiate between a normal and pathological gait (Patterson et al., 2008) and/or between functions. Gait symmetry in challenging walking conditions, such as dual-task walking, can be useful for early identification of future fallers (Gillain et al., 2019). However, the majority of research on symmetry or asymmetrical behaviors in healthy individuals has focused on level walking; no studies have documented gait symmetry when stepping over an obstacle.

Minimum foot clearance (MFC) is an important event in the swing phase. If foot clearance is too low when negotiating an obstacle, it can result in a trip and possibly a fall. Thus, the symmetrical or asymmetrical behavior of the lower limbs while stepping would provide unique information about walking control. Since obstacle crossing is not cyclical, asymmetry may be present during the approach, crossing, or departure phases.

Finding a single discrete value, known as an index, and describing symmetry or asymmetry for a parameter—in this case, foot clearance parameters—between the right and left sides characterizes the functional imbalance between an individual's limbs (Zifchock et al., 2008; Herzog et al., 1989; Gundersen et al., 1989). Researchers classify the normal level of asymmetry in healthy individuals, which enables them to compare with pathologic individuals (Cho et al., 2019; Logerstedt et al., 2013; Hodt-Billington et al., 2012; Gardinier et al., 2012).

There are several approaches used to assess symmetry. Two essential components of a symmetry measure are considered: the equation to calculate symmetry and the gait feature used in the equation. First, we commonly use two types of symmetry equations to calculate symmetry: symmetry ratio (Sadeghi et al., 2000) and symmetry index (Herzog et al., 1989; Robinson et al., 1987). Additionally, there are two variations of the ratio approach. Gait asymmetry, a log transformation of the ratio of right and left limbs (Plotnik et al., 2007), forms the symmetry angle by plotting the right and left values of a discrete gait parameter on the x axis and creating a vector (Zifchock et al., 2008). The most widely used measures for calculating symmetry are the spatiotemporal parameters of gait (Sadeghi et al., 2000).

5.2 Research objectives

The aim of this study was to a) establish if foot clearance parameters are symmetrical when stepping over an obstacle and b) compare four commonly used gait symmetry indices, namely, symmetry ratio (RI), symmetry index (SI), gait symmetry (GA) and symmetry angle (SA).

5.3 Hypothesis

Foot clearance parameters will not be asymmetrical when stepping over an obstacle.

5.4 Methodology

Further methods information is in chapter 3. An overview is provided here.

5.4.1 Participants

Participants were included in their ages were between 20 to 40 years, right leg dominant, as determined by kicking a ball, picking up an eraser off the floor and drawing a number eight on the floor. The procedure of this study was approved by Ethical Approval of Research Involving Human Participants, University of Essex.

5.4.2 Procedure

Gait analysis took place at the biomechanics lab in the University of Essex. A 10-camera Vicon Bonita motion capture system (Vicon Motion Systems Ltd., Oxford, UK) was used at a sampling of 100 Hz. Markers were placed on the left/right toe and heel as per Plug-in-gait landmarks.

Each participant walked at their freely chosen walking speed on a12-meter walkway and stepped over a stationary visible obstacle placed at a midpoint of walkway. Everyone chose which limb to lift first. An obstacle in this study was a stepper - commercial gym equipment: length, 92 cm; width, 35 cm; and adjustable height. There are two levels of obstacle height: low level (LOW) at 15 cm and high level (HIGH) at 20 cm. Four walking tasks were performed in a random order. The tasks were; 1) stepping over the low box (15 cm - LOW), 2) stepping over a high box (20 cm-HIGH), 3) stepping over low box while performing an additional task (LOW-DT), and 4) stepping over a high box while performing an additional task (HIGH-DT). The additional task walking was holding a glass of water. Then participants were asked not to spill water from the glass while walking. Three successful (clean data) trials for the leading limb and three trials for trailing limb were captured.

MFC parameters were measured from the toe and heel markers, namely step distance in front of box (STEP_FRONT), step distance away from box (STEP_AWAY), toe height above front box (TOE_HEIGHT) and heel height above back box (HEEL_HEIGHT).

5.4.3 Data analysis

Foot clearance (FC) parameters were measured from the toe and heel markers, namely step distance in front of the box (STEP_FRONT), step distance away from the box (STEP_AWAY), toe height above the front box (TOE_HEIGHT), and heel height above the back box (HEEL_HEIGHT). Further information is in Chapter 3.

Asymmetry level is associated with the amount of difference the left and right of the body whilst stepping over an obstacle (Sadeghi et al., 2000; Herzog et al., 1989; Soames, 1985; Chodera, 1974) – that is left leading vs. right leading and left trailing vs. right trailing. To quantify symmetry

/asymmetry level, the outcomes were calculated by the different index of average data. This study focused on amplitude of asymmetry to compare models of symmetry measures in the subsequent analysis. In case of the negative SI, GA and SA values, the absolute was used.

The measures consist of four symmetry equations: symmetry ratio or ratio index (RI), Symmetry index (SI), Gait asymmetry (GA) and Symmetry angle (SA) (Vaverka et al., 2015; Patterson et al., 2010; Zifchock et al., 2008; Plotnik et al., 2007; Bowen et al., 2001).

Further information about the four symmetry equations is as follows: The calculation of RI involves dividing the discrete value of one limb by the discrete value of the contralateral limb. The general formula for a ratio is:

$$RI = X\ \text{Non-D} / X\ D, \qquad (1)$$

Where X may refer to any gait variable, X D is the value of the gait parameter determined for the dominant limb, and X Non-D is the value of the gait parameter determined for a non-dominant limb. A given value of the perfect theoretical symmetry is obtained when the ratio equals one. However, the limitation of this measure is that there is no upper limit to the results. Furthermore, whether greater values are used as the numerator or denominator affects the result of a difference in symmetry level

Symmetry ratio or ratio index (RI). For this example, the distance of the right leading limb is 86.3 cm, whereas the left leading limb is 92.2 cm. The distance of the right trailing limb is 19.7 cm, whereas the left trailing limb is 17.0 cm.

RI of step distance in front of obstacle (cm) for leading limb is calculated by dividing the left leading limb distance by the right leading limb distance.

RI = X Non-D /X D,

RI (leading limb) = Left leading limb / Right leading limb

RI (leading limb) = 92.2/86.3 = 1.1

However, RI (trailing limb) = (Left trailing limb / Right trailing limb)

RI (trailing limb) = 15.31/19.75 = 1.3

The Symmetry Index (SI) is a quantitative method for measuring the degree of asymmetry between discrete measures (first described by Robinson et al. in 1987). It represents the percentage difference between two limbs. The assumption made by SI is that there is a singular value representing the degree of imbalance between the two sides. A higher value in the SI indicates a greater level of asymmetry. The basic formula is:

SI = [(X Non-D – XD) / 0.5 (X Non-D + X D)] x100% (2)

The values of the gait variable measured for the right and left limbs are XD and X Non-D, respectively. An SI value of 0% indicates perfect symmetry, while 100% indicates that the two values are opposite in magnitude. The negative value represented that the raw value of the non-D limb was less than that of the D limb, whereas the positive value had the opposite meaning. However, this measure is limited by the requirement to normalize SI to a reference value.

Symmetry index (SI) example. For this example, the distance of the right leading limb is 86.3 cm, whereas the left leading limb is 92.2 cm. The distance of the right trailing limb is 19.7 cm, whereas the left trailing limb is 17.0 cm.

SI, where the minus symbol means non-dominant limb, is notable. Follow the calculation:

SI = [(X Non-D – XD) / 0.5 (X Non-D + X D)] x100%

SI= [(non-dominant limb-dominant limb)/0.5(non-dominant limb + dominant limb)] *100%

SI (leading limb) = [(left leading limb -right leading limb)/0.5(left leading limb + right leading limb)] *100%

SI (leading limb) = [(92.2-86.3) /0.5(92.2+86.3)] *100% = 6.6

SI (trailing limb) = [(left trailing limb -right trailing limb)/0.5(left trailing limb + right trailing limb)] *100%

SI (trailing limb) = [(15.31-19.75) /0.5(15.31+19.75)] *100% = -14.7

Gait asymmetry (GA) is the equation that is a logarithmic transform of the RI factor. Plotnick et al. (2007) used this to calculate asymmetry based on the duration of the swing phase. GA = 0 and GA ≥ 100% revealed symmetry and asymmetry, respectively. The meaning of the negative and positive values of symmetry level was the same as the SI measure. The basic formula is:

GA = (100 x [ln (X Non-D / X D)] (3)

Gait asymmetry (GA) example for this example, the distance of the right leading limb is 86.3 cm, whereas the left leading limb is 92.2 cm. The distance of the right trailing limb is 19.7 cm, whereas the left trailing limb is 17.0 cm.

GA = (100 x [ln (X Non-D / X D)]

This equation is calculated in Excel spreadsheet. Thus, the formula is:

GA =100*LN (X Non-D / X D)

GA, where the minus symbol means non-dominant limb, is notable.

GA =100*LN (non-dominant limb/dominant limb)

GA (leading limb) =100*LN (left leading limb/ Right leading limb) =100*LN (92.2/86.3) = 6.6

GA (trailing limb) =100*LN (left trailing limb/Right trailing limb) =100*LN (15.31/19.75) =-14.7

Symmetry angle (SA) is a measure of the relationship between discrete values determined from the left and right sides (Zichock et al., 2008). In 2008, Zichock et al. utilized this method to calculate the angle of the vector plotted from the right and left values of discrete gait parameters with the OX axis [2]. As in the previous cases, $SA = 0$ indicates full symmetry, and $SA \geq 100\%$ indicates asymmetry. The direction of the symmetry level shows that the negative value represents the raw value of XD less than X Non-D, whereas the positive value shows XD greater than X Non. The basic formula is:

$$SA = [(45^\circ - \arctan(X\ \text{Non-D} / X\ \text{D})) \text{ x } 100\%] / 90 \qquad (4)$$

Gait asymmetry (GA), for this example, the distance of the right leading limb is 86.3 cm, whereas the left leading limb is 92.2 cm. The distance of the right trailing limb is 19.7 cm, whereas the left trailing limb is 17.0 cm.

Symmetry angle (SA)

$SA = [(45^\circ - \arctan(X\ \text{Non-D} / X\ \text{D})) \text{ x } 100\%] / 90$

This equation is calculated in Excel spreadsheet. Thus, the formula is:

SA = (45-ATAN (X Non-D / X D) *180/PI ()) *100/90

SA= [(45 – arctan (non-dominant limb/dominant limb)) *180/PI ()) *100/90

SA = (45-ATAN (Left limb/Right limb) *180/PI ()) *100/90

SA (leading limb) = (45-ATAN (92.2/86.3) *180/PI ()) *100/90 = -2.1

SA (trailing limb) = (45-ATAN (15.31/19.75) *180/PI ()) *100/90 = 4.7

Asymmetry level is associated with the amount of difference between the left and right sides of the body (Sadeghi et al., 2000; Herzog et al., 1989; Soames, 1985; Choder, 1974). We calculated the outcomes of the different indices of the average data to quantify the symmetry or asymmetry level.

5.4.4 Statistics analysis

Foot clearance (FC) parameters whilst stepping over an obstacle were extracted data from Vicon Nexus system. Participants performed three trials for each task walking. The mean and standard deviation (SD) for each were calculated along with the four symmetry indices described in section 5.4.3. In addition, a paired t-test was calculated comparing Left and Right limbs for each foot clearance parameter and correlations were performed to test the association between each symmetry indices. Where normality was violated, the appropriate non-parametric equivalents were used. The p value for significance was set a p<0.05.

5.5 Results

5.5.1 Characteristics of Participants

The characteristics of the participants are shown in Table 5.1. There were no significant differences for right and left leg lengths. All participants were a right limb dominant as defined by the limb which was used to kick a ball.

Table 5. 1 The characteristics of participants

	Mean (SD)
Age (years)	24.8 (1.8)
Mass (kg)	64.2 (6.7)
Height (m)	1.7 (0.4)
BMI (kg/m2)	22.3 (2.3)
Dominant leg length, right (cm)	90.1 (3.2)
Non-dominant leg length, left (cm)	90.1 (3.2)

Statistically (table 5.2a and 5.2 b) symmetry was present for most measures except for toe height above front of obstacle (LOW) and heel height above back of obstacle (HIGH) for the trailing limb. Both measures were reduced for Left leg compared to the Right leg.

This is not reflected in the symmetry indices where for the leading limb, using a 10% cut-off for SI 13/16 measures were asymmetrical for leading and 9/16 for trailing limb (table 5.3). All indices were significantly ($p<0.001$) correlated to each other, with r values ranging from 0.974-1.000 (table 5.4 and 5.6).

Table 5. 2a Descriptive statistics for right and left limbs when acting as both the leading and trailing limbs.

	Mean (SD) (n=10)			
	Leading limb		Trailing limb	
	Right limb	Left limb	Right limb	Left limb
Condition: Low Obstacle				
Step distance in front of obstacle (cm)	86.3 (14.0)	92.2 (14.7)	19.7 (4.7)	17.0 (3.9)
Toe height above front of obstacle (cm)	17.4 (3.7)	17.2 (3.2)	16.4 (6.8)	12.4 (3.2) *
Heel height above back of obstacle (cm)	10.6 (3.5)	9.3 (3.3)	44.0 (5.5)	42.5 (4.9)
Step distance away from obstacle (cm	19.6 (3.2)	17.9 (3.9)	99.0 (8.5)	98.8 (8.1)
Condition: High Obstacle				
Step distance in front of obstacle (cm)	84.6 (13.5	85.8 (16.8)	14.5 (5.1)	14.4 (4.9)
Toe height above front of obstacle (cm)	17.0 (3.7)	17.7 (4.1)	16.8 (5.7)	12.9 (3.9)
Heel height above back of obstacle (cm)	11.1 (3.9)	12.2 (4.3)	46.4 (5.6)	43.4 (3.6) *
Step distance away from obstacle (cm	20.5 (3.4)	19.0 (3.6)	100.3 (6.4)	100.5 (6.7)
Low Obstacle Dual Task				
Step distance in front of obstacle (cm)	89.7 (11.1)	85.4 (14.6)	16.8 (4.8)	16.9 (3.9)
Toe height above front of obstacle (cm)	17.1 (4.0)	16.7 (3.4)	14.8 (6.6)	12.7 (5.3)
Heel height above back of obstacle (cm)	10.4 (3.7)	10.1 (2.8)	42.3 (4.2)	40.6 (2.9)
Step distance away from obstacle (cm	17.8 (2.9)	16.9 (3.1)	96.4 (7.8)	94.7 (5.6)
High Obstacle Dual Task				
Step distance in front of obstacle (cm)	85.4 (11.8)	83.5 (11.1)	16.3 (4.5)	15.0 (5.1)
Toe height above front of obstacle (cm)	17.3 (4.1)	16.9 (3.8)	14.2 (5.4)	13.7 (1.8)
Heel height above back of obstacle (cm)	11.1 (3.8)	11.8 (3.3)	45.5 (6.2)	42.6 (3.5)
Step distance away from obstacle (cm	18.0 (3.5)	18.5 (3.7)	96.4 (6.9)	95.7 (5.3)

Leading limb: the first limb is lifted, Trailing limb: the second limb is lifted. *Indicates significant difference compared R vs. L (trailing limb) -see table 5.2b for t-test output.

Table 5.2b t-test output (to complement table 5.2a) comparing right vs. left limbs when acting as leading and trailing limb.

	T-test	
Low Obstacle	Leading limb (R vs. L)	Trailing limb (R vs. L)
Step distance in front of obstacle	t (9) = -1.581, p= 0.148	t (9) = 1.193, p= 0.085
Toe height above front of obstacle	t (9) = 0.583, p= 0.574	**t (9) = 2.616, p= 0.028**
Heel height above back of obstacle	t (9) = 1.623, p=0.139	t (9) = 1.185, p= 0.266
Step distance away from obstacle	W 40.00, z1.274, p=0.232	t (9) = 0.140, p= 0.892
High Obstacle		
Step distance in front of obstacle	t (9) = -0.147, p= 0.886	t (9) = 0.026, p= 0.980
Toe height above front of obstacle	t (9) = -0.408, p= 0.692	t (9) = 1.971, p= 0.080
Heel height above back of obstacle	t (9) = -0.350, p=0.734	**t (9) = 2.486, p= 0.035**
Step distance away from obstacle	t (9) = 0.875, p=0.404	t (9) = -0.146, p= 0.887
Low Obstacle Dual Task		
Step distance in front of obstacle	t (9) = 2.067, p= 0.069	t (9) = 0.158, p= 0.878
Toe height above front of obstacle [a]	t (9) = 1.149, p=0.280	W 10.00, z-1.784, p=0.084
Heel height above back of obstacle	t (9) = 0.509, p=0.623	t (9) = -1.363, p= 0.206
Step distance away from obstacle	t (9) = 0.220, p=0.831	t (9) = -1.163, p= 0.275
High Obstacle Dual Task		
Step distance in front of obstacle	t (9) = 0.910, p=0.386	t (9) = 1.819, p= 0.102
Toe height above front of obstacle	t (9) = 0.643, p=0.536	t (9) = 0.352, p= 0.733
Heel height above back of obstacle	t (9) = -0.644, p=0.536	t (9) = 1.438, p= 0.184
Step distance away from obstacle	t (9) = -0.837, p=0.425	t (9) = 0.457, p= 0.659

Bold indicates significant difference; [a] Shapiro-Wilks test was significant ($p < .05$), suggesting a violation of the equal variance assumption, therefore Wilcoxen signed-rank (W) is reported.

Table 5. 3. Symmetry indices for the leading limb (right vs. left)

Four FC parameters of leading limb / Tasks	**Mean (SD) of four symmetry equations (n=10)**			
	Ratio	SI	GA	SA
Condition: Low Obstacle				
Step distance in front of obstacle	**1.1 (0.2)**	**16.0 (11.9)**	**16.0 (11.9)**	**5.0 (3.6)**
Toe height above front of obstacle	**1.0 (0.2)**	**15.1 (16.7)**	**15.1 (16.1)**	**4.7 (4.9)**
Heel height above back of obstacle	**0.9 (0.3)**	**29.9 (29.7)**	**29.9 (28)**	**9.0 (7.7)**
Step distance away from obstacle	**0.9 (0.2)**	**14.8 (19.4)**	**14.8 (18.5)**	**4.6 (5.6)**
Condition: High Obstacle				
Step distance in front of obstacle	1.0 (0.1)	6.7 (4.5)	6.7 (4.3)	2.1 (1.4)
Toe height above front of obstacle	**1.0 (0.1)**	**11.6 (6.3)**	**11.6 (6.3)**	**3.7 (2.0)**
Heel height above back of obstacle	**1.0 (0.2)**	**16.7 (12.8)**	**16.7 (12.3)**	**5.3 (3.8)**
Step distance away from obstacle	**0.9 (0.1)**	**13.6 (9.8)**	**13.6 (10.3)**	**4.3 (3.2)**
Condition: Low Obstacle Dual Task				
Step distance in front of obstacle	**0.9 (0.1)**	7.0 (6.7)	7.0 (6.3)	2.2 (2.0)
Toe height above front of obstacle	1.0 (0.1)	6.7 (5.0)	6.7 (4.7)	2.1 (1.5)
Heel height above back of obstacle	**1.0 (0.2)**	**17.8 (9.3)**	**17.8 (9.5)**	**5.6 (3.0)**
Step distance away from obstacle	**1.0 (0.1)**	**11.8 (9.7)**	**11.8 (9.9)**	**3.7 (3.1)**
Condition: High Obstacle Dual Task				
Step distance in front of obstacle	**1.0 (0.2)**	**12.2 (9.6)**	**12.2 (9.2)**	**3.8 (2.9)**
Toe height above front of obstacle	**1 .0 (0.2)**	**16.2 (15.4)**	**16.2 (14.7)**	**5.1 (4.5)**
Heel height above back of obstacle	**1.1 (0.3)**	**27.4 (26.2)**	**27.4 (26.4)**	**8.3 (7.5)**
Step distance away from obstacle	**1.0 (0.2)**	**17.3 (10.5)**	**17.3 (10.8)**	**5.5 (3.3)**

Four equations: RI, symmetry ratio; SI, symmetry index; GA, Gait asymmetry, SA, symmetry angle**. bold** asymmetrical – based on 10% cut-off for SI.

Table 5. 4 Correlation testing the association between the symmetry indices – leading limb

Leading limb/tasks		Symmetry indices			
Condition		GA	SA	SI	RI
Condition: Low Obstacle					
Step distance in front of obstacle	GA	—			
	SA	1.000***	—		
	SI	1.000***	1.000***	—	
	RI	0.995***	-0.993***	0.995***	—
Toe height above front of obstacle	GA	—			
	SA	1.000***	—		
	SI	1.000***	1.000 ***	—	
	RI	0.985***	-0.986 ***	0.985 ***	—
Heel height above back of obstacle	GA	—			
	SA	-0.997***	—		
	SI	0.997***	1.000***	—	
	RI	0.997***	1.000***	1.000***	—
Step distance away from obstacle	GA				
	SA	-0.997***	—		
	SI	0.997***	1.000***	—	
	RI	0.997***	1.000***	1.000***	—
Condition: High Obstacle					
Step distance in front of obstacle	GA	—			
	SA	-1.000***	—		
	SI	1.000***	-1.000***	—	
	RI	0.999***	-0.999***	0.999***	—
Toe height above front of obstacle	GA	—			
	SA	-1.000***	—		
	SI	1.000***	-1.000***	—	
	RI	0.999***	-0.999***	0.999***	—
Heel height above back of obstacle	GA	—			
	SA	-1.000***	—		
	SI	1.000***	-1.000***	—	
	RI	0.996***	-0.996***	0.996***	—
Step distance away from obstacle	GA	—			
	SA	-1.000***	—		
	SI	1.000***	-1.000***	—	
	RI	0.996***	-0.996***	0.996***	—
Condition: Low Obstacle Dual Task					
Step distance in front of obstacle	GA	—			
	SA	-1.000***	—		
	SI	1.000***	-1.000***	—	
	RI	0.999***	-0.999***	0.999***	—
Toe height above front of obstacle	GA	—			
	SA	-1.000***	—		
	SI	1.000***	-1.000***	—	
	RI	0.999***	-0.999***	0.999***	—

Leading limb/tasks		Symmetry indices			
Condition		GA	SA	SI	RI
Heel height above back of obstacle	GA	—			
	SA	-1.000***	—		
	SI	1.000***	-1.000***	—	
	RI	0.997***	-0.997***	0.997***	
Step distance away from obstacle	GA	—			
	SA	-1.000***	—		
	SI	1.000***	-1.000***	—	
	RI	0.997***	-0.998***	0.997***	—
Condition: High Obstacle Dual Task					
Step distance in front of obstacle	GA	—			
	SA	-1.000***	—		
	SI	1.000***	-1.000***	—	
	RI	0.997***	-0.996***	0.996***	—
Toe height above front of obstacle	GA	—			
	SA	-1.000***	—		
	SI	1.000***	-1.000***	—	
	RI	0.991***	-0.992***	0.991***	—
Heel height above back of obstacle	GA	—			
	SA	-0.999***	—		
	SI	1.000***	-0.999***	—	
	RI	0.974***	-0.980***	0.974***	—
Step distance away from obstacle	GA	—			
	SA	-1.000***	—		
	SI	1.000***	-1.000***	—	
	RI	0.994***	-0.995***	0.994***	—

* p < .05, ** p < .01, *** p < .001

Table 5. 5 Symmetry indices for the trailing limb (right vs. left).

Four FC parameters of trailing limb / Tasks	Mean (SD) of four symmetry equations (n=10)			
	Ratio	SI	GA	SA
Condition: Low Obstacle				
Step distance in front of obstacle	0.9 (0.3)	27.4 (23.2)	27.4 (23.1)	8.4 (6.7)
Toe height above front of obstacle*	0.8 (0.3)	30.0 (27.5)	30.0 (26.0)	9.1 (7.4)
Heel height above back of obstacle	1.0 (0.1)	9.6 (5.7)	9.6 (5.6)	3.0 (1.8)
Step distance away from obstacle	1.0 (0.1)	5.7 (4.7)	5.7 (4.4)	1.8 (1.4)
Condition: High Obstacle				
Step distance in front of obstacle	1.0 (0.1)	10.2 (7.6)	10.2 (7.1)	3.2 (2.3)
Toe height above front of obstacle	0.8 (0.3)	36.7 (29.4)	36.7 (27.7)	11.1 (7.9)
Heel height above back of obstacle*	0.9 (0.1)	7.9 (6.9)	7.9 (6.5)	2.5 (2.0)
Step distance away from obstacle	1.0 (0.0)	2.5 (1.9)	2.5 (2.3)	0.8 (0.7)
Low Obstacle Dual Task				
Step distance in front of obstacle	1.0 (0.3)	15.2 (17.1)	15.2 (16.7)	4.7 (5.0)
Toe height above front of obstacle	1.0 (0.4)	33.0 (26.4)	33.0 (25.7)	10.0 (7.5)
Heel height above back of obstacle	1.0 (0.1)	8.3 (5.3)	8.3 (5.1)	2.6 (1.6)
Step distance away from obstacle	1.0 (0.0)	3.8 (2.9)	3.8 (2.7)	1.2 (0.9)
High Obstacle Dual Task				
Step distance in front of obstacle	1.0 (0.3)	21.5 (25.6)	21.5 (25.0)	6.5 (7.2)
Toe height above front of obstacle	1.1 (0.4)	28.6 (19.5)	28.6 (18.8)	8.8 (5.7)
Heel height above back of obstacle	0.9 (0.1)	11.9 (8.6)	11.9 (8.6)	3.8 (2.7)
Step distance away from obstacle	1.0 (0.1)	5.6 (4.7)	5.6 (4.6)	1.8 (1.5)

Four equations: RI, symmetry ratio; SI, symmetry index; GA, Gait asymmetry, SA, symmetry angle. *Indicate where the statistically significant differences were (see table 6.2a and 6.2b) bold symmetrical – based on 10% cut-off for RI, SI and GA.

Table 5. 6 Correlation testing the association between the symmetry indices – trailing limb.

Trailing limb/tasks		Symmetry indices			
Condition		GA	SA	SI	RI
Condition: Low Obstacle					
Step distance in front of obstacle	GA	—			
	SA	-0.999**	—		
	SI	1.000***	-0.999***	—	
	RI	0.984***	-0.989***	0.984***	—
Toe height above front of obstacle	GA	—			
	SA	-0.999**	—		
	SI	1.000***	-0.999***	—	
	RI	0.985***	-0.991***	0.985***	—
Heel height above back of obstacle	GA	—			
	SA	-1.000***	—		
	SI	1.000***	-1.000***	—	
	RI	1.000***	-1.000***	1.000***	—
Step distance away from obstacle	GA	—			
	SA	-0.999**	—		
	SI	1.000**	-0.999***	—	
	RI	0.984**	-0.989***	0.984***	—
Condition: High Obstacle					
Step distance in front of obstacle	GA	—			
	SA	-1.000***	—		
	SI	1.000***	-1.000***	—	
	RI	0.999***	-0.999***	0.999***	—
Toe height above front of obstacle	GA	—			
	SA	-0.999***	—		
	SI	1.000***	-1.000***	—	
	RI	0.985***	-0.991***	0.985***	—
Heel height above back of obstacle	GA	—			
	SA	-1.000***	—		
	SI	1.000***	-1.000***	—	
	RI	0.999***	-0.999***	0.998***	—
Step distance away from obstacle	GA	—			
	SA	-1.000***	—		
	SI	1.000***	-1.000***	—	
	RI	1.000***	-1.000***	1.000***	—
Condition: Low Obstacle Dual Task					
Step distance in front of obstacle	GA	—			
	SA	-1.000***	—		
	SI	1.000***	-1.000***	—	
	RI	0.999***	-0.999***	0.999***	—
Toe height above front of obstacle	GA	—			
	SA	-1.000***	—		
	SI	1.000***	-1.000***	—	
	RI	0.999***	-0.999***	0.999***	—

Trailing limb/tasks		Symmetry indices			
Condition		GA	SA	SI	RI
Heel height above back of obstacle	GA	—			
	SA	-1.000***	—		
	SI	1.000***	-1.000***	—	
	RI	0.997***	-0.997***	0.997***	—
Step distance away from obstacle	GA	—			
	SA	-1.000***	—		
	SI	1.000***	-1.000***	—	
	RI	1.000***	-1.000***	1.000***	—
Condition: High Obstacle Dual Task					
Step distance in front of obstacle	GA	—			
	SA	-0.999***	—		
	SI	1.000***	-0.999***	—	
	RI	0.981***	-0.988***	0.981***	—
Toe height above front of obstacle	GA	—			
	SA	-1.000***	—		
	SI	1.000***	-1.000***	—	
	RI	0.987***	-0.989***	0.987***	—
Heel height above back of obstacle	GA	—			
	SA	-1.000***	—		
	SI	1.000***	-1.000***	—	
	RI	0.998***	-0.998***	0.998***	—
Step distance away from obstacle	GA	—			
	SA	-1.000******	—		
	SI	1.000***	-1.000******	—	
	RI	0.999***	-0.999***	0.999***	—

* p < .05, ** p < .01, *** p < .001

5.6 Discussion

The aim of this study was to: a) determine if obstacle clearance was symmetrical; and b) compare commonly used limb symmetry indices. The results suggest that, when using the symmetry index (SI), 13 and 11/16 parameters were asymmetrical for the leading and trailing limbs, respectively. For RI 6/16, the parameters were asymmetrical. Both the SI and GA produce the same results, which were also reported by Błażkiewicz et al. (2014) for straight walking. However, this was not the case when using a paired t-test where 2/16 parameters were asymmetrical. Later on, we will discuss the cut-offs and thresholds used to determine asymmetry from these indices. The results also suggested that all indices correlated with each other.

The paired t-test suggests that obstacle crossing was symmetrical for 14 of the parameter and task combinations. This suggests that obstacle crossing was symmetrical in young, healthy individuals; as such, it may be a useful measure to detect asymmetry. For instance, a deviation from a symmetrical gait can manifest in various ways, potentially signaling the presence of underlying musculoskeletal, neurological, or functional issues. A symmetrical gait is characterized by a walking pattern in which the actions of the left and right sides of the body closely resemble each other or are mirror images of each other (Griffin et al., 1995). Then, a symmetrical gait pattern entails the synchronized movement of both legs with equal step lengths, timing, and force distribution. Similarly, asymmetrical gait refers to a walking pattern characterized by variations or inconsistencies in the movements of the left and right sides of the body while walking. The deviation from a balanced walking pattern may appear in different forms and can suggest the presence of underlying problems related to the muscles, bones, nerves, or overall functionality. For example, Yogev et al. (2007) found that elderly fallers have a higher level of walking gait asymmetry than non-fallers, and Bautmans et al. (2011) found a positive correlation between asymmetrical gait, fall risk, and dependency on daily living activities. Obstacle clearance, arguably more demanding than level walking, may reveal asymmetry earlier than during level walking.

5.6.1 Symmetry indices

In this current work, discrete symmetry indices were used. These are the most commonly used methods to evaluate symmetry (Viteckova et al., 2018). These methods examine a measure at a specific time point, specifically the 4 obstacle clearance events in this chapter, and also consider measures of distance, such as the height above the obstacle and the distance in front or behind the obstacle. Researchers more commonly use discrete indices with spatial temporal data (Viteckova et al., 2018).

Each measure used in this present work has limitations. The ratio index has low sensitivity and fails to provide the location of the asymmetry level (Viteckova et al., 2018; Błażkiewicz et al., 2014; Sadeghi et al., 2000).

In this study, ratio measures tended to report more symmetric findings. The SI must be normalized to a reference value, and the selection of the reference value is typically dependent on the question being asked (Zifchock et al., 2008; Robinson et al., 1987). It can be challenging to assess symmetry in a healthy population using the SI measure because there is no obvious side to use as a reference; therefore, researchers typically use the average of two sides (Zifchock et al., 2008). Furthermore, the SI measure's value has the potential for artificial inflation (Zifchock et al., 2008). Hazog et al. (2000) clarified that we can reference the difference between a positive value on one side and a negative value on the other to the average of the two values, which will be near zero. Despite these limitations, this study calculated the SI measure using the same direction of value, where the negative value represents the horizontal distance before the box and the positive value represents the horizontal and vertical distance after the box. The GA is a simple log-transformed symmetry ratio or ratio index (RI), often used to assess the swing time performed by one leg (Plotnik et al., 2007) against that performed by the other. Previous studies used the GA measure to assess gait symmetry in healthy young and older adults, as well as individuals with pathological conditions such as Parkinson's disease and stroke (Patterson et al., 2010). In this study, the GA measure produced the same results as the SI measure. The SA, as proposed by Zifchock et al. (2008), does not require a reference value like the SI measure. The SA measure's value tends to be lower than the SI measure. The values from SA measures in this study were the same quantity as the previous study, which tested level walking (Blazkiewicz, 2015). However, the interpretation and cut-offs (thresholds) are difficult to ascertain.

Asymmetry, in the context of gait and this current work, describes a divergence between the left and right lower limbs at its most simple (Viteckova et al., 2018). According to Sadeghi et al. (2000), the threshold for defining asymmetry as a 10% divergence from perfect symmetry appears to be arbitrary. Despite this, Hodt-Billington et al. (2012) did suggest that the 10% was valid and did not classify asymmetry in able-bodied subjects as pathological. Although Viteckova et al. (2018) do provide a comprehensive review of symmetrical measures used in gait, they do not appear to provide a review of the approaches (cut-offs or thresholds) used to define symmetry. When setting thresholds, people often cite Herzog et al., but a closer examination of this paper reveals that 'normal gait asymmetries cannot be defined using a single percent value, e.g., 10%'. A review of the literature (Parkinson et al., 2021) that looked at asymmetry and measures of strength and performance found that 30 of the 53 articles used an asymmetry threshold to describe the point at which differences between limbs could be considered asymmetrical. A threshold of 10–15% was the most common.

The discrete methods used in this study do have the advantage of being easy to interpret if there is consensus about thresholds. We also employed a paired t-test for these discreate points, and this method revealed significant differences only in two parameters, such as asymmetry.

However, a drawback of this method is its discrete nature; it only captures a single moment during a complicated movement. In this case, that means stepping over an obstacle. There are other methods to calculate asymmetry that may offer different results than those reported in this current work. For example, approaching, stepping over, and then departing after obstacle clearance is a continuous movement; the trajectory of the foot (toe or heel marker) may be asymmetrical. To address this, Viteckova et al. (2018 reviewed four methods: trend symmetry (Crenshaw and Richards, 2006), the cyclogram-based method (Goswami, 1998), region-of-deviation (Shorter et al., 2008), and the symbol-based method (Goswami, 1998). First, trend symmetry refers to the analysis of temporal movement data in order to detect patterns that are either symmetrical or asymmetrical. The focus of this analysis is on trends in movement variables, specifically joint angles, velocities, and accelerations. However, gait analysis frequently applies trend symmetry analysis to evaluate the symmetry of the walking pattern. Clinicians can identify gait abnormalities or pathology by analyzing the differences in movement patterns between the left and right sides of the body (Viteckova et al., 2018). Second, the cyclogram-based method involves plotting joint or limb trajectories in cyclograms, which are graphical representations of movement cycles. This method allows for visualizing and quantifying movement patterns and asymmetries (Viteckova et al., 2018). By analyzing cyclograms, researchers and clinicians can identify asymmetrical movement patterns and their potential causes (Viteckova et al., 2018). Third, researchers implement the region-of-deviation method by dividing movement data into regions of interest and quantifying deviations from expected values within each region (Viteckova et al., 2018). The primary objective is to pinpoint certain regions or stages of motion where asymmetries occur. Others, such as functional movement screening, gait analysis, and sports biomechanics, employ region-of-deviation analysis (Viteckova et al., 2018). By identifying areas of divergence, professionals can focus interventions on addressing specific deficiencies that contribute to imbalanced movement patterns. In the fourth method, movement data is stored in the form of symbolic sequences that match specific movement characteristics or patterns (Viteckova et al., 2018). Subsequently, we employ symbolic analysis methodologies such as symbolic dynamics or symbolic complexity to identify symmetrical or asymmetrical sequences (Viteckova et al., 2018). However, various disciplines such as human movement analysis, robotics, and machine learning utilize symbol-based approaches. Through the process of transforming movement data into symbolic representations, researchers can reveal hidden patterns and imbalances that may not be evident when using conventional numerical analysis methods. In conclusion, these methodologies provide useful tools for assessing movement symmetry and detecting deviations that may indicate disease, changed motor control, or an increased risk of falls.

5.6.2 Relationships between equations

Despite the plethora of indices, very few studies have compared symmetry indices. The present work's results revealed a significant correlation between symmetry measures, indicating that no symmetry equation clearly demonstrated an advantage for obstacle clearance using discrete measures. Coefficients ranged from 0.974 to 1.000 ($p < 0.001$) for all parameters and all tasks. If you look at Patterson et al. (2010), they found similar results. The coefficients for step length were between 0.99 and 1.0 ($p < 0.003$), for swing time they were between 0.97 and 0.98 ($p < 0.003$), for double support time they also found between 0.99 and 1.0 ($p < 0.003$), and for the intra-limb ratio of swing to stance time (SW/ST) for both healthy people and people who had a stroke. Because of this, Patterson et al. (2010) recommended the ratio equation as the index of choice, as it may be easier to interpret. Patterson et al. (2010) and Błażkiewicz et al. (2014) both agreed that different equations didn't show any significant differences and that all four measures (used in this study and Patterson et al., 2010) were strongly connected for seven measures of space and time during straight walking. However, Błażkiewicz et al. (2010) found the SI ratio to be superior, suggesting that this should be used as the most sensitive assessment of gait symmetry.

5.7 Conclusion

The results demonstrated statistical symmetry in obstacle clearance, presenting an intriguing challenge to determine the presence of symmetry and its potential use as a pathology indicator, such as a fall risk or a shift in motor control. However, the symmetry indices provided differing results based on the arbitrary cut-off of 10%, with the RI mainly suggesting obstacle clearance was symmetrical, while SI and GA suggested asymmetry. Despite the different interpretations based on cut-offs, these indices correlated with each other, suggesting they are showing the same results.

Chapter VI: Obstacle height, dual task, and gender differences of foot clearance parameters whilst stepping over an obstacle.

Abstract

Background: The interaction of these internal and external elements in the body is most likely responsible for tripping while negotiating obstacles. It should be beneficial in lowering the risk of falling. Researching the behavior of crossing obstacles in individuals of various ages, starting with adolescence and gender changes, could potentially yield valuable data for clinical use.

Objective: The aim of this study was a) to compare MFC variables when stepping over an obstacle of different heights or when performing a different task, and b) to compare obstacle clearance between males and female participants both pre- and post-normalization to stature.

Methodology: This study recruited ten healthy male volunteers with an age of 24.8 (1.8) years, a height of 1.69 (0.4) m, a body mass of 64.1 (6.7) kg, and a body mass index of 22.2 (2.3) kg/m2, as well as ten healthy female volunteers with an age of 26.5 (3.4) years, a height of 1.59 (0.4) m, a body mass of 51.1 (6.1) kg, and a body mass index of 20.4 (2.1) kg/m2. A 10-camera Vicon motion capture system (100 Hz). The markers on the big toe and heel of both feet were analyzed. Participants perform four walking tasks at their own pace. The four walking tasks were: 1) stepping over a LOW box (15 cm), 2) stepping over a HIGH box (20 cm), 3) stepping over a LOW box while performing a dual task, and 4) stepping over a HIGH box while performing a dual task. The dual task involved holding a glass of water while walking. Four-foot clearance parameters—step distance in front of obstacle, toe height above front of obstacle, heel height above back of obstacle, and step distance away from obstacle—were dependent variables.

Results: The four-foot clearance parameters exhibited significant between-factor effects, with the exception of the step distance in front of the obstacle. Also, the parameter was always significantly greater for male participants. When normalized to leg length, only the step distance away from the obstacle for the leading limb remained significantly different between genders. For the HIGH condition, the step distance from the obstacle was significantly longer than for all other conditions. Interestingly, the step distance away from the obstacles with an additional task was shorter than without an additional task for the LOW condition.

Conclusions: Gender-specific differences were evident, with females placing limbs closer to obstacles. However, when normalized for leg length, only leading limb departure distances remained significantly different. It is possible that the young females used a shorter step distance away from the obstacle for the leading leg for being as a strategy to prevent heel contact, whereas male used a long distance. This understanding may be useful in establishing the basis for future employment as an older adult.

Keywords: foot clearance, toe clearance, younger adults, stepping over, crossing over, gender

6.1 Introduction

Stepping over an obstacle is a challenging task in everyday life. It is a motor task that requires walking while navigating an obstruction in the way. To achieve safe and efficient obstacle clearing, this movement necessitates the exact coordination of multiple body segments. However, stepping over is an activity that involves both intrinsic and extrinsic elements relating to the individual and the environment (Galna et al., 2009; Pan et al., 2016). Intrinsic factors include musculoskeletal elements, reaction time, alterations in balance and gait, as well as cognitive elements such as executive function, attention, and visual special abilities (Galna et al., 2009; Chen et al., 1991; Chen et al., 1994). Extrinsic factors include environmental characteristics, such as anticipated and unexpected challenges (Galna et al., 2009). Because of the combination of these intrinsic and external factors, tripping while negotiating obstacles is likely one of the most common causes of falls in older people. Next, stepping involves two lower limbs (the leading and trailing limbs) lifting alternately to clear the floor. The leading limb is the leg that initiates the step and passes over an obstacle, while the trailing limb is the leg that follows the leading limb and crosses over an obstacle. For successful obstacle clearance, proper coordination and movement of the leading leg are required. Previous research found that the leading limb requires visual information obtained at least two steps before reaching the obstruction in order to maintain acceptable toe clearance (Timmis and Buckley, 2012). Because there is no visual information for the trailing limb, it relies on proprioceptive feedback from the leading limb (Mohagheghi et al., 2004; Draganich and Kuo, 2004). Thus, the researchers are also interested in the outcomes resulting from the effects of external and internal factors of obstacle-crossing in different environments to discover the mechanisms that cause tripping or slipping.

Foot clearance has been utilized as a crucial metric to assess the effectiveness of tactics employed in traversing obstacles of varying heights. Foot clearance refers to the minimum vertical distance between the foot and the ground when the leg is swinging forward. Previous research has investigated the measurement of the distance between the foot and the floor while crossing an obstacle. The study by Muir et al. (2015) measured the horizontal toe-obstacle distance of the leading limb, as well as the horizontal heel-obstacle distance of the leading limb. Other studies (Muir et al., 2015; Soma et al., 2010; Lowrey et al., 2007; Lu et al., 2006; Chen et al., 1991) also examined the trailing limb's horizontal toe-obstacle distance and horizontal heel-obstacle distance. Studies by Kunimune and Okada (2017), Muir et al. (2015), Soma et al. (2010), Harley et al. (2009), Lowrey et al. (2007), Lu et al. (2006), Di Fabio et al. (2004), and Chen et al. (1991) also measured the vertical toe distance of both the leading and trailing limbs. Muir et al. (2015) also measured the vertical heel distance of both the leading and trailing limbs. Obstacle heights in the environment and previous work vary (Chen et al., 1991). Nevertheless, several of these studies have not integrated the primary or secondary limbs with the approach or departure from the obstruction, as pointed out by Chou and Draganich (1998) and Austin et al. (1999).

Dual-tasking, as opposed to concurrent-tasking, could be a factor that influences walking or stepping over. Studies show that when two tasks, particularly manual or cognitive ones, divert attention, gait instability increases (Nascimbeni et al., 2015; Smith et al., 2017). In various populations, there is a decline in gait performance when doing two concurrent walking tasks (Carcreff et al., 2019; Ali et al., 2022; Nascimbeni et al., 2015; Rogan et al., 2019; Wittwer et al., 2014). Such dual-tasking coupled with gait performance modification is significant in supporting the role of higher-level cognition function in walking, which is involved in most daily activities (Shumway-Cook and Woollacott, 2012).

The literature has reported gender differences during level walking. For example, several spatiotemporal domains differed between males and females (Hollman et al., 2011). Females also walk with their pelvis tilted more anteriorly and with a more up-and-down oblique motion; hip joints are more flexed, adducted, and internally rotated; and the knee joint is in more valgus (Cho et al., 2004). In addition, Bruening et al. (2015) found that in the pelvis and torso motion discriminators between male and female gaits, females demonstrated greater pelvic obliquity than males in the frontal plane, while maintaining a more stable torso and head. In terms of transverse plane pelvic and torso rotation, as well as arm movement, women exhibited superior performance (Bruening et al., 2015). Studies have demonstrated that males generally exhibit higher levels of muscular mass and strength in comparison to females (Gentil et al., 2016). This difference may impact their ability to overcome obstacles. If there are differences between males and females on level ground, crossing an obstacle is likely to reveal these differences. However, this has received little attention in the literature, and it is possible that any gender difference may be a consequence of body size. As such, it is important to scale (normalize) parameters to leg length, following Hof (1996). This will enable us to determine whether the difference is due to anthropometric factors or gender-related factors.

The interaction of these internal and external factors most likely leads to tripping while negotiating obstacles. Studies have reported that advanced age contributes to a decrease in function in many sensory and motor systems that are considered effective and safe locations (Shumway-Cook and

Woollacott, 2017). Therefore, it could potentially aid in lowering the risk of falls. By examining the obstacle-crossing behavior of individuals across various age groups, starting from adolescence and gender transitions, we can gather valuable insights for clinical implementation. As a result, this study concentrated on a concurrent activity (manual type) while stepping over an obstacle of different heights. This study investigated gender differences in stepping over an obstruction in young males and females.

6.2 Research objectives

The aim of this study was a) to compare foot clearance parameters when stepping over different an obstacle of different height or when performing a different task, and b) comparing obstacle clearance between males and female participants both pre and post normalization to stature.

6.3 Hypothesis

1 There will be significant difference in foot clearance and spatial temporal parameters whilst stepping over an obstacle based on obstacle height (two obstacle heights: 15 cm. and 20 cm.).

2 There will be significant difference in foot clearance and spatial temporal parameters whilst stepping over an obstacle based on two task demands (with and without holding a glass of water).

3 There will be significant difference in foot clearance and spatial temporal parameters whilst stepping over an obstacle based on gender.

6.4 Methodology

This has been described earlier in the chapter 3 (methods). For brevity only a summary of methods and those methods pertinent to this chapter are presented here.

6.4.1 Participants

The study recruited ten healthy male volunteers with an average age of 24.8 (1.8) years, an average height of 1.69 (0.4) m, a body mass of 64.1 (6.7) kg, and a body mass index of 22.2 (2.3) kg/m2, and ten healthy female volunteers with an average age of 26.5 (3.4) years, an average height of 1.5 (0.4) m, a body mass of 51.1 (6.1) kg, and a body mass index of 20.4 (2.1) kg/m^2. The Ethical Approval of Research Involving Human Participants, University of Essex, approved the procedure of this study.

6.4.2 Procedure

Gait analysis was captured in the University of Essex biomechanics lab. A 10-camera Vicon Bonita motion capture system (Vicon Motion Systems Ltd., Oxford, UK) was used at a sampling rate of 100 Hz. Chapter 3 provides additional information.

6.4.3 Data analysis

Foot clearance parameters were as described in **chapter 3**. Briefly, these were for both the leading and trailing limbs:

- Step distance in front of obstacle (cm)
- Toe height above front of obstacle (cm)
- Heel height above back of obstacle (cm)
- Step distance away from obstacle (cm)

Walking speed (m/s), single support time (seconds), and double support time (seconds) were all measured. Walking speed is estimated by dividing the distance by the number of seconds. The double-support time is the period between ipsilateral foot contact and contralateral foot contact, and ipsilateral foot contact and contralateral foot contact. The interval between contralateral foot-off and contralateral foot contact is referred to as the single-support time

Normalization of parameters

Sutherland (1996) normalized the foot clearance data to eliminate the impact of body size on gait parameters. This would result in dimensionless parameters for length (i.e., step length, foot height above box), speed, and time, following Hof (1996).

Length measures were normalized using:

$$\hat{l} = \frac{l}{l_0}$$

Where l is length (or height) and l_0 is leg length measured from anterior superior iliac spine (ASIS) to medial malleolus.

Walking speed was normalized using:

$$\hat{v} = \frac{v}{\sqrt{g l_o}}$$

Where v is walking velocity, g, is the acceleration due to gravity (9·81 m. s^{-2}), and l_0 is leg length.

Time (t) was normalized using:

$$\hat{t} = \frac{t}{\sqrt{g / l_o}}$$

6.4.4 Statistics analysis

Statistical analyses were carried out in the Statistical Package for the Social Sciences (SPSS) Version 25 for Windows. The Shapiro-Wilk test was used to determine the distribution of the data. Standard descriptive statistics (mean with standard deviation) were calculated for all variables. An independent T-test was carried out to compare the demographic differences between male and female participants. A repeated measures ANOVA with between factors (gender) was carried out. We conducted a Bonferroni post-hoc analysis if the main (task), between (gender), or interaction (task*gender) effects were significant. This was carried out for the ‘raw’ non-normalized data and the normalized data following Hof (1996). All statistical data analyses were performed by setting the level of significant difference at $p < 0.05$.

6.5 Results

6.5.1 Characteristics of participants

The characteristics of the participants are shown in Table 6.1. There were no significant differences in age and BMI between male and female participants. Males had significantly greater mass, height and leg length compared to females.

Table 6. 1 Mean (SD) of the characteristics of participants

	Mean (SD)			95% CI for Mean Difference
	Male (n=10)	Female (n=10)	T-test	Lower, Upper
Age (years)	24.8 (1.8)	26.5 (3.4)	t (18) = 1.648, p 0.117	-4.323, 0.523
Mass (kg)	64.2 (6.7)	51.8 (6.1) *	t (18) = 4.267, p <.001	6.254, 18.386
Height (cm)	169.8 (4.4)	159.0 (4.7) *	t (18) = 5.200, p <.001	6.407, 15.093
BMI	22.3 (2.3)	20.5 (2.1)	t (18) = 1.845, p .082	-0.253, 3.893
Dominant leg length: right (cm)	90.1 (3.2)	83.4 (3.2) *	t (18) = 4.717, p <.001	3.727, 9.713
Non-dominant leg length left (cm)	90.1 (3.2)	82.9 (3) *	t (18) = 4.721, p.<.001	3.718, 9.682

Note. Student's t-test.: *Significant difference at $p < 0.05$

6.5.2 Task and gender differences for the leading limb when clearing an obstacle.

When crossing an obstacle for the leading limb, there was no significant main effect, between factors (gender) effect, or interaction for step distance in front of the obstacle and heel height above the back of the obstacle (table 6.2). There was a significant between factors (gender) effect (table 6.2) for toe height above the front of the obstacle which was greater for males compared to females (mean difference 3.1 cm; 95%CI 0.4 – 5.8 cm), but there was no significant main effect for condition or interaction. When stepping away from the obstacle, the leading limb was placed significantly (table 6.2) further away from the obstacle (mean difference 4.8 cm; 95%CI 2.5 – 7.1 cm) for males compared to females. There was also a significant main effect for condition. The post-hoc analysis revealed that the step distance for the HIGH condition was significantly longer compared to all other conditions (effect size (ES) Low vs High, -0.5; High vs. LowDT, 1.09; High vs HighDT, 0.77), and the LOW condition step distance was significantly longer compared to LOW Dual Task condition (ES, 0.59) (table 6.2)

Table 6. 2 Task and gender differences for the leading limb when clearing an obstacle

Leading limb	Group Mean (SD)	Female Mean (SD)	Male Mean (SD)	RM ANOVA with between factors (gender)
Step distance in front of obstacle (cm)				
Condition: Low Obstacle	84.4 (11.0)	82.4 (7.0)	86.3 (14.0)	†Main effect (condition): (F (2.126, 38.266) = 2.213, p =.120) Between factors (gender): (F (1, 18) = 1.352, p =.260) †Interaction (condition*gender): (F (2.126, 38.266) = 0.077, p=.935
Condition: High Obstacle	82.7 (11.0)	80.8 (8.0)	84.6 (13.5)	
Condition: Low Obstacle Dual Task	87.2 (9.5)	84.7 (7.1)	89.7 (11.1)	
Condition: High Obstacle Dual Task	82.8 (9.4)	80.1 (5.5)	85.4 (11.8)	
Toe height above front of obstacle (cm)				
Condition: Low Obstacle	15.8 (3.3)	14.1 (1.4)	17.4 (3.7)	†Main effect (condition): (F (1.906, 34.314) = 0.739, p = .479) **Between factors (gender): (F (1, 18) = 5.738, p = .028)** †Interaction (condition*gender): (F (1.906, 34.314) = 0.302, p=.731
Condition: High Obstacle	15.4 (3.5)	13.8 (2.4)	17.0 (3.7)	
Condition: Low Obstacle Dual Task	15.8 (3.3)	14.3(1.3)	17.1 (4.0)	
Condition: High Obstacle Dual Task	15.9 (3.4)	14.5(1.7)	17.3 (4.1)	
Heel height above back of obstacle (cm)				
Condition: Low Obstacle	10.8 (2.5)	10.9 (1.0)	10.6 (3.5)	†Main effect (condition): (F (2.011, 36.189) = 0.155, p = .858) Between factors (gender): (F (1, 18) = 0.047, p = .831) †Interaction (condition*gender): (F (2.011, 36.189) = 2.036, p=.145
Condition: High Obstacle	10.9 (3.0)	10.2 (3.0)	11.1 (3.9)	
Condition: Low Obstacle Dual Task	10.7 (2.7)	11.0 (1.2)	10.4 (3.7)	
Condition: High Obstacle Dual Task	11.0 (3.1)	10.8 (2.2)	11.1 (3.8)	
Step distance away from obstacle (cm)				
Condition: Low Obstacle	16.9 (4.1) ^{a*}	14.1(2.7)	19.6 (3.2)	**Main effect (condition): (F (3, 54) = 12.749, p = <.001)** **Between factors (gender): (F (1, 18) = 19.342, p = <.001)** Interaction (condition*gender): (F (3, 54) = 1.104, p=.355
Condition: High Obstacle	18.3 (3.6)	16.1(2.1)	20.5 (3.4)	
Condition: Low Obstacle Dual Task	15.2(3.8) ^{a***b*}	12.6 (2.5)	17.8 (2.9)	
Condition: High Obstacle Dual Task	16.1(3.4) ^{a***}	14.1 (1.9)	18.0 (3.5)	

[a] significantly different to High Obstacle [b] significantly different to Low Obstacle, [c] significantly different to High DT.
† Greenhouse-Geisser applied. **Bold indicates a significant effect.** Post-hoc; * p<0.05; **p< 0.01, ***p<0.001.

6.5.3 Task and gender differences for the trailing limb when clearing an obstacle.

When crossing an obstacle with trailing limb, there was a significant main effect for step distance in front of the obstacle (table 6.3). The post-hoc analysis revealed that step distance was significantly further away from the obstacle on approach for the LOW (ES, 0.63) and LOW Dual Task (ES, 0.69) conditions compared to the HIGH condition. There was no significant difference between factors (gender) effect or interaction. The toe height above the front of the obstacle showed a significant between factors (gender) effect (table 6.3), with a greater toe clearance height for males compared to females (mean difference 2.7 cm; 95%CI 0.6-4.7 cm). There was no significant main effect or interaction. Heel height above the back of the obstacle revealed a significant main effect for condition. The post hoc analysis showed that heel height was significantly lower for LOW Dual Task (ES: vs. HIGH, 0.59; vs LOW 0.41; vs. HIGH Dual Task, 0.39), compared to all other conditions (table 6.3). There was a significant between factors (gender) effect with heel height above the obstacle significantly higher for males compared to females (mean difference 5.7 cm: 95%CI 2.1 – 9.4 cm). Step distance away from obstacle revealed a significant main effect for condition. The post hoc analysis showed that step length was significantly longer for HIGH condition (ES: vs. LOW 0.49; LOW Dual Task, 1.19; HIGH Dual Task, 1.03) compared to all other conditions and LOW condition was significantly longer than HIGH (ES, 0.53) and LOW (0.69) Dual Task conditions respectively (table 6.3). There was a significant between factors (gender) effect with step length in front of box significantly longer for males compared to females (mean difference 10.9 cm; 95%CI 5.8 – 15.9 cm).

Table 6. 3 Task and gender differences for the trailing limb when clearing an obstacle.

Trailing limb	Group Mean (SD)	Female Mean (SD)	Male Mean (SD)	RM ANOVA with between factor (gender)
Step distance in front of obstacle(cm)				
Condition: Low Obstacle	16.2 (3.6)	15.2 (3.0)	17.0 (3.9)	**†Main effect (condition): (F (1.759, 31.653) = 6.348, p =.006)** Between factors (gender): (F (1, 18) = 1.585, p =.224) †Interaction (condition*gender): (F (1.759, 31.653) = .025, p =.964)
Condition: High Obstacle	13.6 (3.8) ^{b**,d**}	12.8 (2.2)	14.4 (4.9)	
Condition: Low Obstacle Dual Task	16.2 (3.3)	15.4 (2.7)	16.9 (3.9)	
Condition: High Obstacle Dual Task	14.2 (4.0)	13.2 (2.3)	15.0 (5.1)	
Toe height above front of obstacle(cm)				
Condition: Low Obstacle	11.5 (3.0)	10.5 (2.3)	12.4 (3.2)	†Main effect (condition): (F (1.869, 33.642) = .203, p =.803) **Between factors (gender): (F (1, 18) = 7.292, p =.015)** †Interaction (condition*gender): (F (1.869, 33.642) = .447, p =.630)
Condition: High Obstacle	11.8 (3.4)	10.6 (2.6)	12.9 (3.9)	
Condition: Low Obstacle Dual Task	11.4 (4.0)	10.0 (1.2)	12.7 (5.3)	
Condition: High Obstacle Dual Task	11.9 (2.5)	10.0 (1.2)	13.7 (1.8)	
Heel height above back of obstacle(cm)				
Condition: Low Obstacle	39.7 (5.9)	36.8 (5.5)	42.5 (4.9)	**Main effect (condition): (F (3, 54) = 22.297, p =.001)** **Between factors (gender): (F (1, 18) = 10.647, p =.004)** Interaction (condition*gender): (F (3, 54) = .114, p =.951)
Condition: High Obstacle	40.5 (5.2)	37.5 (5.0)	43.4 (3.6)	
Condition: Low Obstacle Dual Task	38.0 (4.2) $^{a***.b*,c*}$	35.3 (3.6)	40.6 (2.9)	
Condition: High Obstacle Dual Task	39.6 (4.8)	36.7 (4.1)	42.6 (3.5)	
Step distance away from obstacle(cm)				
Condition: Low Obstacle	93.1 (8.9) ^{a,*} ^{c***,d**}	87.3 (5.3)	98.8 (8.1)	**Main effect (condition): (F (3, 54) = 23.796, p = < .001)** **Between factors (gender): (F (1, 18) = 20.751, p = <.001)** Interaction (condition*gender): (F (3, 54) = .790, p =.413)
Condition: High Obstacle	96.0 (7.5) $^{, c***}$	91.5 (5.3)	100.5 (6.7)	
Condition: Low Obstacle Dual Task	88.9 (8.0) ^{a***}	83.2 (5.4)	94.7 (5.7)	
Condition: High Obstacle Dual Task	89.9 (7.8)	84.1 (5.0)	95.7 (5.3)	

[a] significantly different to High Obstacle [b] significantly different to Low Obstacle, [c] significantly different to High DT, [d] significantly different to Low DT. † Greenhouse-Geisser applied. **Bold indicates a significant effect.** Post-hoc; * p<0.05; **p< 0.01, ***p<0.001

6.5.4 Obstacle clearance parameters when normalized to leg length.

Table 6.4 summaries the between factors from tables 6.2 and 6.3. For those which showed a significant difference between factors effects the parameter was always significantly greater for male participants. To see if this was due to stature (males were significantly taller than females in this study – table 6.1) the analysis was repeated for normalized data based on Hof (1996), but only for the parameters in table 6.4 where there was a gender difference. When normalized to leg length only the step distance away from obstacle for the leading limb remained significantly different between genders.

Table 6. 4 Summary of between factors effects (tables 6.2 and 6.3) and when normalized to leg length.

	Summarised from tables 6.2 and 6.3		Between factors effect (gender) **normalised** to leg length	
	Leading	Trailing	Leading	Trailing
Step distance in front of obstacle(cm)	-	-	-	-
Toe height above front of obstacle(cm)	↑ male	↑ male	(F (1, 18) = 2.008, p = .174)	(F (1, 18) = 2.613, p = .123)
Heel height above back of obstacle(cm)	-	↑ male	-	(F (1, 18) = 1.683, p = .211)
Step distance away from obstacle(cm)	↑ male	↑ male	**(F (1, 18) = 11.337, p = .003)**	(F (1, 18) = 3.021, p = .099)

Bold indicates a significant effect.

6.5.5 Task and gender differences for spatial temporal parameters for the leading limb when clearing an obstacle.

Walking speed on the leading limb side, although slower for HIGH DT compared to the other conditions and males walking faster than females, there was no significant main, between, or interaction effects (table 6.5). There was significant main effect (condition) for single support time, with the post-hoc test revealing the LOW obstacle condition having a significantly shorter single support time than all other conditions (ES: vs HIGH, 0.55; HIGH Dual Task, 0.70; LOW Dual Task, 0.41) (table 6.5). There was also no significant main, between, or interaction effects for double support time (table 6.5).

Table 6. 5 Task and gender differences (spatial temporal parameters) for the leading limb when clearing an obstacle.

Leading limb	Group Mean (SD)	Female Mean (SD)	Male Mean (SD)	RM ANOVA with between factors (gender)
Walking speed (m/s)				
Condition: Low Obstacle	1.24 (0.27)	1.31 (0.29)	1.16 (0.29)	†Main effect (condition): (F (1.295, 23.312) = 1.491, p =.241)
Condition: High Obstacle	1.25 (0.19)	1.27 (0.23)	1.23 (0.15)	
Condition: Low Obstacle Dual Task	1.20 (0.25)	1.25 (0.21)	1.14 (0.28)	Between factors (gender): (F (1, 18) = 0.853, p =.368)
Condition: High Obstacle Dual Task	1.18 (0.16)	1.19 (0.21)	1.17 (0.10)	†Interaction (condition*gender): (F (1.295, 23.312) = 1.131, p=.316
Single support time (s)				
Condition: Low Obstacle	0.54 (0.07) ^{a***,c***,d**}	0.52 (0.07)	0.57 (0.07)	**Main effect (condition): (F (3, 54) = 11.987, p = <.001**) Between factors (gender): (F (1, 18) = 0.930, p = .348)
Condition: High Obstacle	0.59 (0.09)	0.58 (0.09)	0.60 (0.10)	Interaction (condition*gender): (F (3, 54) = 0.338, p=.798
Condition: Low Obstacle Dual Task	0.58 (0.08)	0.53 (0.08)	0.60 (0.08)	
Condition: High Obstacle Dual Task	0.61(0.09)	0.59 (0.09)	0.62 (0.10)	
Double support time (s)				
Condition: Low Obstacle	0.16 (0.04)	0.15(0.03)	0.17 (0.04)	Main effect (condition): (F (3,54) = 0.926, p = .435)
Condition: High Obstacle	0.15(0.03)	0.15(0.03)	0.15(0.03)	Between factors (gender): (F (1, 18) = 2.246, p = .151)
Condition: Low Obstacle Dual Task	0.15(0.03)	0.14(0.03)	0.16(0.03)	Interaction (condition*gender): (F (3,54) = 1.528, p=.218
Condition: High Obstacle Dual Task	0.16 (0.03)	0.15(0.02)	0.16(0.03)	

^{a} significantly different to High Obstacle ^{b} significantly different to Low Obstacle, ^{c} significantly different to High DT, ^{d} significantly different to Low DT. † Greenhouse-Geisser applied. **Bold indicates a significant effect.** Post-hoc; * p<0.05; **p< 0.01, ***p<0.00

6.5.6 Task and gender differences for spatial temporal parameters for the trailing limb when clearing an obstacle.

Walking speed (table 6.6) on the trailing limb side showed a main effect for condition and the post-hoc analysis revealed HIGHT DT condition was significantly slower compared to all other conditions (ES; LOW, 0.81; HIGH, 0.49; LOW Dual Task, 0.49). There were no between or interaction effects for walking speed (table 6.6). Single support time showed a main effect for conditions with LOW obstacle having a significantly shorter contact time than HIGH (ES, 0.52) and HIGH DT (ES, 0.91) conditions. LOW DT single support time was also significantly shorter compared to the HIGH DT (ES, 0.75) condition (table 6.6). There were no between or interaction effects for single support time (table 6.6). There was also no significant main, between, or interaction effects for double support time (table 6.6).

Table 6. 6 Task and gender differences (spatial temporal parameters) for the trailing limb when clearing an obstacle.

Trail limb	Group Mean (SD)	Female Mean (SD)	Male Mean (SD)	RM ANOVA with between factors (gender)
Walking speed (m/s)				
Condition: Low Obstacle	1.21 (0.17)	1.22 (0.21)	1.19 (0.13)	**†Main effect (condition): (F (1.956, 35.207) = 12.040, p = <. 001)**
Condition: High Obstacle	1.15 (0.17)	1.16 (0.20)	1.15 (0.13)	
Condition: Low Obstacle Dual Task	1.25 (0.14)	1.15 (0.12)	1.15 (0.17)	Between factors (gender): (F (1, 18) = 0.004, p =.953)
Condition: High Obstacle Dual Task	1.10 (0.15) ^{a**,b***,d**}	1.10 (0.19)	1.10 (0.18)	†Interaction (condition*gender): (F (1.956, 35.207) = 0.265, p=.764
Single support time (s)				
Condition: Low Obstacle	0.61 (0.06) ^{a**,c***}	0.63 (0.04)	0.60 (0.08)	**Main effect (condition): (F (3, 54) = 10.332, p = <.001)**
Condition: High Obstacle	0.65 (0.08)	0.67 (0.05)	0.64 (0.10)	Between factors (gender): (F (1, 18) = 0.869, p = .364)
Condition: Low Obstacle Dual Task	0.63 (0.08) ^{c***}	0.63 (0.07)	0.62 (0.08)	Interaction (condition*gender): (F (3, 54) = 0.305, p=.0.822
Condition: High Obstacle Dual Task	0.68 (0.08)	0.70 (0.04)	0.67 (0.10)	
Double support time (s)				
Condition: Low Obstacle	0.15 (0.03)	0.16 (0.03)	0.14 (0.03)	Main effect (condition): (F (3,54) = 0.972, p = .413)
Condition: High Obstacle	0.14 (0.03)	0.15 (0.03)	0.14 (0.03)	Between factors (gender): (F (1, 18) = 0.942, p = .345)
Condition: Low Obstacle Dual Task	0.14 (0.02)	0.15 (0.02)	0.14 (0.02)	Interaction (condition*gender): (F (3,54) = 1.306, p = .282)
Condition: High Obstacle Dual Task	0.15 (0.03)	0.15 (0.03)	0.15 (0.03)	

^{a} significantly different to High Obstacle ^{b} significantly different to Low Obstacle, ^{c} significantly different to High DT, ^{d} significantly different to Low DT. † Greenhouse-Geisser applied. **Bold indicates a significant effect.** Post-hoc; * p<0.05; **p< 0.01, ***p<0.001

6.5.7 Spatial temporal parameters when clearing an obstacle normalized to leg length.

Because there was no between factors (gender) effect for walking speed, single support time, or double time an analysis normalizing these measures to stature was not carried out.

6.6 Discussion

The aim of this study was a) to compare MFC variables when stepping over an obstacle of different heights or when performing a different task, and b) to compare obstacle clearance between males and female participants both pre- and post-normalization to stature. The results indicate the presence of some main effects related to the obstacle condition and some between-factor effects related to gender. However, normalizing gender differences to stature eliminated these effects, except for one variable.

6.6.1 Main effect – condition (leading limb)

When crossing over an obstacle, there were a few main effects (tasks). The results indicate that when crossing the HIGH obstacle condition, the trailing limb's foot placement was significantly closer to the obstacle, and when walking away from the obstacle, it was significantly farther away than in the other conditions. This could be attributed to the foot's proximity to the obstacle during approach, which in turn led to its subsequent distance upon departure. The lead limb partially replicated this, placing the lead foot significantly farther away from the obstacle under the HIGH obstacle condition than when departing from it, but the leading limb at approach did not significantly change. With the leading limb at approach placed the same distance away from the object for all conditions, when stepping over the HIGH obstacle, the trail foot was swung closer to the obstacle. This placement had no effect on the foot's height; it cleared the obstacle. This strategy was not repeated for the HIGH DT condition.

Begg et al. (1996) demonstrated an increase in step length as obstacle height increased, but they calculated this as the step distance between the leading and trailing limbs before crossing, not the distance between the foot and the obstacle. Sparrow et al. (1996) also recorded the step length, but they calculated it based on the position of the trailing foot before the obstacle and the leading limb foot after the obstacle. The step length was greater than in the no-obstacle condition, but there was little change in step length with an increase in obstacle height. However, both of these studies employed a different method to measure "step length" compared to the current work. The remaining discussion focuses on work that used similar measures to those used in the present work. The trailing limb's horizontal toe distance on approach before obstacle clearance was significantly closer in the HIGH condition, but it was only 2.6 cm closer than in the LOW conditions. Therefore, even though this was a significant finding, it is unlikely to be meaningful. Chou et al. (2001) reported no difference in trailing limb distance (range of 25.5-26.5 cm) before the obstacle as the height increased (2.5, 5, 10, 15% of stature). Vitório et al. (2010) reported a trailing foot distance before the obstacle of 24.9 (7.4) cm for low obstacles (ankle height) and 24.8 (6.4 cm) for high obstacles (knee height). These results indicate a greater distance between the trail leg and the obstacle compared to the present study's reported distance of 13.6–16.2 cm. This may be the result of studies on different populations. Vitorio et al. investigated a mild Parkinson's disease population. However, there was no gender difference in walking speed in this study. The high condition had a similar walking speed to the LOW condition. Thus, it may imply stable behavior for an obstacle at a similar distance and a different height.

The participant self-selected the approach distance for both the leading and trailing limbs, without any enforcement. The self-selected approach (and departure) distance for the leading limb does not change significantly with an increase in obstacle height (Austin et al., 1999), partly agreeing with the findings of this current work. Austin et al. (1999) examined three different obstacle heights (and 0 mm height): 31 mm, 76 mm, and 126 mm. The approach step distance of the leading limb was similar to those reported in this current work, with a range across the four heights (0–126 mm) of 0.84–0.86 (0.12-0.14) m. These values for the leading limb at approach are comparable to those reported in the literature. For example, Vitorio et al. (2010) reported a step distance of 86.5 (12.7) cm and 87.0 (11.8) cm for low (ankle height) and high (knee height) conditions, respectively. Austin et al. (1999) did not report the mean (SD) for the heel distance for the leading limb away from the obstacle.

Despite the nonsignificant findings, Austin et al. (1999) suggested that foot placement was likely to play an important role as the height of the obstacle increased. This was due to the corresponding increase in angular velocity as obstacle height increased. Therefore, they proposed that the crucial factor wasn't the distance, but rather the duration required to overcome the obstacle, and that the system's limitations stem from the time required to clear the obstacle's upper edge, not the foot's placement. The current study's leading foot placement matched Austin et al. in both low and high conditions. Similarly, studies found that when young adults stepped over obstacles at 10%, 20%, and 30% of leg length, the toe clearance for the leading limb remained constant and the trailing toe clearance was unaffected by obstacle height ($p > 0.05$). (Lu et al., 2006). We can suggest that the increase in obstacle height (150 mm and 200 mm) did not impact this time constraint, demonstrating a similar response to Austin et al. (1999). However, the current study didn't examine angular displacement or velocities, making it impossible to determine the adjustments needed to overcome a taller obstacle than those described by Austin et al. (1999), given the same amount of time and similar distances from the obstacle.

For the HIGH condition, the heel distance for the leading limb away from the obstacle was significantly further away (between 1.4 and 3.1 cm) compared to the other conditions. We will discuss the dual task crossing in Section 5.6.3. Chen et al. (1992) reported an increase in heel distance away from the obstacle as the obstacle height increased, whereas Watanabe and Miyakawa (1991) reported that this distance plateaus as the obstacle height increases between 80 and 120 m. Austin et al. (1999), while reporting a significant obstacle height effect for heel distance, did not reveal any significant differences among any of the paired comparisons for obstacle height. This may be because the visual system provides feedforward control, allowing the toe clearance of the lead limb to be adjusted based on visual information gained while approaching an object (Patla and Vickers, 1997; Patla et al., 2004). Despite greater obstacle heights in the current work, the step distance away from the obstacle for the leading limb was markedly less than that reported by Austin et al. (1999) (15.2-16.9 cm vs. 26.5-29.6 cm) but was comparable to that reported by Maiden et al. (2018).

The current study and those discussed so far have let participants self-select their foot placement as they approach the obstacle. However, manipulating the placement of the trailing limb closer to the obstacle results in a linear decrease in the hip, knee, and ankle flexion of the trailing limb in swing as it approaches the obstacle (Chou and Draganich, 1998). As the foot approached the obstacle, the change in joint kinematics led to a reduction in toe clearance. Placing the foot closer to the obstacle reduces the time to flex the knee, underscoring the importance of generating sufficient angular velocity for safe obstacle crossing. Placing the trailing limb closer to the obstacle causes kinetic changes as well as kinematic changes. This leads to a decrease in the maximum plantarflexion moment (Chou and Draganich, 1998), which may have been caused by the slower crossing speed needed to get past the obstacle and the resulting decrease in vertical ground reaction force. The manipulation of the placement resulted in a decrease in knee flexor and hip extensor moments due to the reduced step length approaching the obstacle (Chou and Draganich, 1998). The central nervous system precisely controls the relatively stable placement of the leading and trailing limbs prior to obstacle clearance across conditions in this and other studies, allowing enough time to flex the joints, elevate the limb, and clear the obstacle (Chou and Draganich, 1998).

Compared to the other conditions, the low-DT condition showed a significant difference in foot height (toe or heel marker) above the obstacle. When the trailing limb was going over the obstacle, the heel height above the box for LOW DT was significantly lower than in all other conditions, suggesting a trip hazard. However, the difference between conditions, compared to LOW DT, ranged from 1.6 to 2.5 cm, and there was still 38.0 (4.3) cm of clearance above the obstacle, suggesting this was still a safe crossing. The toe and heel clearance for the leading limb were comparable to Austin et al. (1999), ranging from 10.4 to 15.7 cm for the toe and 8.6 to 12.7 cm for the heel clearance. The lower values for Austin et al. (1999) represent the lowest obstacle height (31 mm). The higher obstacles (76 mm and 126 mm) resulted in a toe clearance of ~ 15.4 cm and a heel clearance of 12.6 cm. For the current work, heel clearance ranged from 10.7 to 11.0 cm, which is lower than that of Austin et al. (1999). The present study may have used a deeper obstacle, which altered the limb's trajectory over the obstacle and lowered it as it prepared for landing.

Austin et al. (1999) showed a significant obstacle height effect for toe and heel clearance, but the pairwise comparisons did not show any significant differences between the two highest obstacle heights, suggesting the emergence of a plateau at these heights (126 mm). This led Austin et al. (1999) to propose two models (Fig. 5.1) to explain this. The first model proposed that as the height of the obstacle increases, toe/heel clearance increases linearly, but once the obstacle reaches a critical height, the clearance starts to decrease until it reaches an 'interference point' i.e., striking the obstacle. The second model proposes a transitional phase—this – this when the height of the obstacle does not affect toe or heel clearance height, even though the obstacle height is increasing; it has plateaued. However, there is a point when the obstacle height increases and leads to a linear decrease in toe and heel height until the interference point strikes the obstacle.

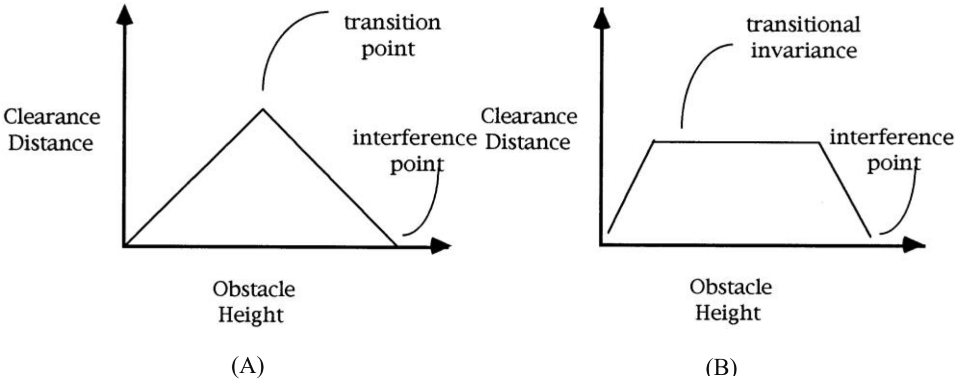

Figure 6. 1 Obstacle crossing models proposed by Austin et al. A (left) shows a distinct transition point with increasing obstacle height, and B (right) shows a gradual transitional phase of clearance as obstacle height increases.

These models were proposed based on the three obstacle heights used by Austin et al.: 31 mm, 76 mm, and 126 mm, and because of the plateau in height, it was not clear if 126 mm was a transition point or the start of the transitional invariance phase. The second model may explain the plateau in toe/heel height seen for the current work; the height of the obstacles was markedly greater (150 and 200 mm) than that of Austin et al. (1999). To help explain this, the two obstacle heights used in the present study—150 mm and 200 m—were added to the data published by Austin et al. Figure

6.2 shows the three obstacle heights, including ground level (0 mm), from Austin et al. (surrounded by the blue box). The 150 mm and 200 mm data are from this present study (surrounded by the red box). Since Austin et al. noted that the toe clearance data revealed a strong cubic trend, this trend was also added to the data. The data suggests a model similar to that of the transitional invariance model when crossing an obstacle. However, the data from the current study was also from a wider obstacle compared to that of Austin et al., and so these data can only suggest support for the transitional variance model. Chen et al. looked at 5 tasks: obstacle-free and 4 obstacle heights (0 mm (i.e., flat tape on the floor), 25 mm, 52 mm, and 152 mm). With the inclusion of obstacle-free and 0 mm tasks, they reported a non-linear increase in foot clearance as height increased. It was not clear if the 152 mm height was the start of a plateau, as suggested in Fig. 6.2, or the start of a transition point. Further work is needed to test a range of different obstacle heights to fully test both models.

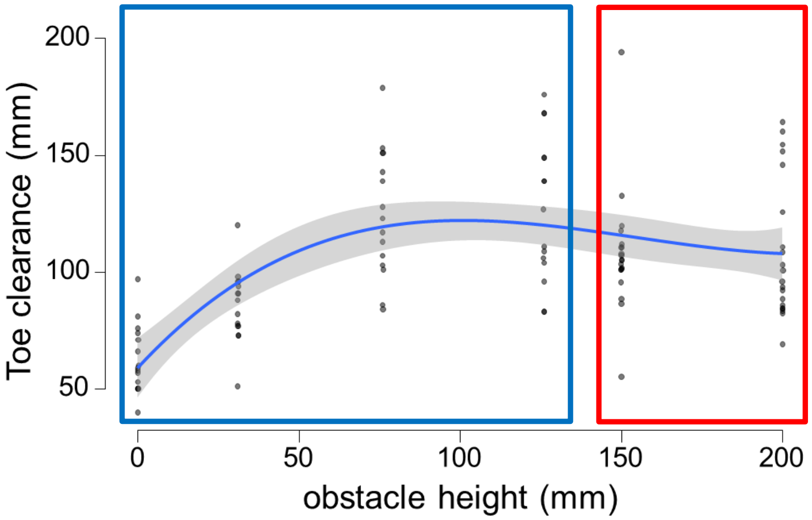

Figure 6. 2 Toe clearance and obstacle height from Austin et al and this current study. From Austin et al (data in blue box) and data from this current work (red box). A cubic trend was added (via JASP) to the data with confidence bands.

6.6.2 Main effect – condition (trailing limb)

When crossing an obstacle, the trailing limb presents a challenge because of the visual system, which provides feedforward control that allows one to adjust the toe clearance of the lead limb based on visual information obtained while approaching an object (Patla and Vickers, 1997). When bringing the trailing limb over an obstacle, it loses its control (Patla et al., 2004). Therefore, the trail limb relies on proprioceptive feedback from the lead limb to maintain appropriate toe clearance, as the trail limb is not visible in the visual field (Mohagheghi et al., 2004; Draganich and Kuo, 2004). This presents a situation that may increase the chance of contact when negotiating an obstacle leading to a trip or a fall. In the current study, no contact occurred. Reducing the time to clear an obstacle, which involves placing the foot closer to it before crossing, significantly increases the number of contacts with a higher obstacle (i.e., 204 mm) (Chou and Draganich, 1998). When participants self-select foot placement, as seen in this present work, there are no contacts (Chou and Draganich, 1998). In line with the lead limb's findings, the trailing limb negotiated the HIGH condition significantly closer to the obstacle than it did in the LOW and LOW conditions. After clearing the high condition, the trailing limb likely moved significantly further away from the obstacle. Even though this was a closer placement, it did not result in contact.

Reducing the horizontal distance between the foot and the obstacle reduces the flexion of the trailing limb ankle, knee, and hip in a swing over the obstacle (Chou and Draganich, 1998). If we didn't adjust, the reduction in hip flexion and hip angular (flexion) velocity would likely lead to contact. According to Chou and Draganich (1998), an adaptation appears to be greater knee angular (flexion) velocity to avoid contact with the obstacle. Despite the step-distance in Chou and Draganich (1998) being closer than the self-select distance in this present work, it's plausible that some of the mechanisms described by Chou and Draganich (1998) still contribute to successful clearance, particularly given the use of a wider obstacle in this present work. Future research should investigate the biomechanics (joint kinematics during swing) when clearing a wider obstacle to determine if the changes in joint kinematics mirror those reported by Chou and Draganich (1998).

When stepping over a ‘narrow’ hurdle-type obstacle (such as 6.4 mm wide), Chou and Draganich (1997) reported no difference in toe height clearance. The present work partially supports this, demonstrating no variation in toe height when clearing the obstacle's front edge. However, the LOW condition significantly reduced heel clearance at the obstacle's rear compared to all other conditions, indicating that as the task became more complex (i.e., height increased), the heel raised more to ensure a safety margin for clearing the obstacle's back edge. The leading limb did not exhibit this behavior. Maintaining the toe clearance height at the front of the obstacle and then adjusting the heel clearance height at the back of the obstacle is likely to be primarily a result of increasing knee flexion in swing (Chou et al., 1997).

6.6.3 Dual task and obstacle clearance

In this study, the secondary task involved holding a glass of water without spilling it. This is the concurrent performance of two tasks (walking and holding an object) with distinct and separate goals. There are two types of activities: those with one clear goal, like walking (motor) or counting steps to help with walking (motor and cognitive components within a single complex task); and those with two clear but separate goals, like doing serial-three subtraction while walking (motor and cognitive goals) (McIsaac et al., 2015). Studies have reported the schema for single task analysis that uses two task domains: novelty and complexity (McIsaac et al., 2015). Novelty is a performance characteristic that refers to the experience an individual gets from performing a particular task. Complexity is a task characteristic that refers to both the number of components and the attentional demands of a particular task (McIsaac et al., 2015). Then walking while holding the glass of water is a single task with low novelty and high complexity (McIsaac et al., 2015). Although less cognitively demanding than literature-cited 'count-backwards' tasks, this one may be more functional.

The dual-task condition had a minimal impact on obstacle clearance in the current study. The results indicate a significant decrease in the heel distance for the leading limb when placed closer to the obstacle under the dual-task conditions (HIGH and LOW: 16.1 (3.4) cm, 15.2 (3.8) cm) compared to the single-task conditions (HIGH and LOW: 18.3 (3.6) cm, 16.1 (2.1) cm, respectively). This was similar to Soma et al. (2010) and Schrodt et al. (2004), who also showed a decrease in the heel obstacle distance for the leading limb (single and dual task: 16.6 (4.0) cm, 13.2 (5.0) cm, and 18.8 (0.07) cm, respectively). One may perceive the close placement of the heel on the obstacle as increasing the likelihood of contact. However, Schrodt et al. (2004) proposed that by placing the foot significantly farther away from the obstacles during approach, the trailing limb will subsequently be closer to the obstacle after crossing. A foot placement farther away when performing a dual task will result in toe clearance of the obstacle occurring later in the swing phase, ensuring a safer crossing of the obstacle. Even though this may compromise the distance between the rear and the obstacle, heel contact with an obstacle may pose less risk than toe contact because it is less likely to result in a trip (Chen et al., 1991). However, the current study's results only partially align with Schrodt et al.'s findings, despite the fact that foot placement was more favorable for DT participants. In some cases, prior to the obstacle, there were no statistically significant differences.

The heel clearance for the trailing limb was significantly lower for the LOW dual task, measuring 38.0 (4.2) cm, compared to all other conditions (LOW, HIGH, and HIGH dual-task conditions: 39.7 (5.9) cm, 40.5 (5.2) cm, and 39.6 (4.8) cm). A longer step distance in front of the obstacle can cause heel contact for trailing limbs (LOW, HIGH, and LOW and HIGH dual-task conditions: 16.2 (3.6) cm., 13.6 (3.8) cm., 16.2 (3.3) cm., and 14.2 (4.4) cm., respectively) (Soma et al., 2010). This strategy may serve as a preventive measure. This strategy ensures successful toe clearance in front of the obstacle. There was also no significant difference in toe clearance above the obstacle when performing a dual task. This result was similar to Soma et al. (2010) and Schrodt et al. (2004), who also reported no difference in toe clearance when performing a dual task.

The current study found a slight difference in obstacle clearance parameters between dual-task and single-task tasks. This may suggest the distribution of attention resources while holding a glass of water without spilling it, as the motor tasks included maintaining a self-selected walking speed. Stepping over obstacles is unlikely to influence the second task. It is crucial to keep in mind that these parameters serve as outcome measures. Understanding the factors that influence limb control or how the limbs adjust before an obstacle may provide additional insight into how a DT modifies joint biomechanics to maintain stable outcome measures. The results for the additional task in this study indicate that the gait mechanism influences only the heel-obstacle distance.

6.6.4 Between factor effect – gender

The aim of this study was to compare the foot clearance parameters while stepping over an obstacle between genders. This has received little attention in the literature, and it is likely that there will be differences since these are evident when walking on level ground (Rowe et al., 2021; Bruening et al., 2015; Cho et al., 2004).

The results of this current work showed that there were significant differences between males and females for toe height above the obstacle (significantly lower for females, leading and trailing limbs), heel height above the obstacle (significantly lower for females, trailing limbs), and step distance away from the obstacle (significantly closer for females, leading and trailing limbs). Our results were partly in agreement with Chen et al. (1991) and Sparrow et al. (1996). The current study showed that females placed the leading and trailing limbs significantly closer to the obstacle than males. Neither Sparrow et al. (1996) nor Chen et al. (1991) reported this finding. However, both studies demonstrated that the approach distance of the leading and trailing limbs was proportionally farther away for males compared to females (67% and 62%, respectively), and the trail toe distance after stepping was 19% and 15% for males and females, respectively. This was not consistent with the current work. Sparrow et al. (1996) also reported greater absolute clearance for males compared to females (agreeing with the current findings), whereas Chen et al. (1991) reported the opposite. However, it is clear that the females in both studies also reported being significantly shorter in stature and leg length, which may explain these differences between males and females. Indeed, Sparrow et al. (1996) state that *'…determining the cause of these differences (gender) in terms of anthropometric characteristics…would be an intriguing avenue of research'*.

Scaling or normalizing is critical because it reduces the intersubject variation associated with body size, specifically mass and height. People commonly use these approaches to measure ground reaction forces (N/kg) or joint kinetics (W/kg). Hof (1996) proposed ‘a physically sensible and coherent strategy’ to scale data to generate dimensionless numbers, i.e., dividing step length by lower limb length. When normalizing their data to stature, Chen et al. (1991) showed that the only significant difference between genders (stride length) was no longer the case. The present study normalized the clearance parameters for leg length, and according to Hof (1996), the only remaining difference was the step distance away from the obstacle for the leading limb. This suggests that all other parameters differed due to leg length and not gender, but when normalizing for leg length, the step-distance away from the obstacle was a gender-specific motor control process. For example, when walking, ankle co-contractions occur in a higher number of strides for females compared to males, suggesting females need a higher level of ankle-joint stabilization (Mengarelli et al., 2017). Balancing challenges, such as stepping over an obstacle, may exacerbate this.

6.6.5 Spatial-temporal parameters

While stepping, there was no significant difference in walking speed or support time on the leading leg between genders. Researchers have used the double support time to assess balance while walking (Bowen et al., 2001). In this study, walking between genders had no effect on lead leg balance.

In HIGH DT, walking speed on the trailing leg was significantly slower than in all other situations. Walking slower in HIGH-DT situations may give more time to gather proprioceptive data from the lead limb than in other conditions. (Patla and Vickers, 1997). This is comparable to Muir et al., except for a deep obstacle in their experiment (Muir et al., 2015). Previous studies reported that walking slower increases the time available to gather visual information and plan movements during the approach (Patla and Vickers, 1997; Muir et al., 2015). Typically, a slower gait speed results in a shorter step length, which correlates with more stable behavior (Winter et al., 1990; Menz et al., 2003). This suggests that walking slower in HIGH DT could serve as a strategy to increase stability during stepping. However, the longer contact time of a single support on a trial limb supplements this effect. According to our findings, the HIGH condition has a longer contact time for a single support period than the LOW condition.

6.6.6 The deep obstacle

There are few studies looking at the depth of the obstacle. A deeper barrier may differ from previous findings described in the literature. Maiden et al. (2018) studied the direct impact on successful obstacle avoidance when stepping over two different obstacle heights (25mm and 75mm) and two different task situations (anticipated and unanticipated obstacles). The depth dimension of an obstacle in a previous study is identical to the depth dimension of an obstacle in our investigation (30 cm). Maiden et al. (2018) provided no information on gender differences in young adults. Their results showed that age-related changes in obstacle crossing strategies are dependent on the specific characteristics of the obstacle. They also noted that it has substantial implications for clinical practice, such as obstacle-negotiating training with varying height practices and available response times (Maidan et al., 2018). As a result, the depth obstacle could be a useful tool for predicting the danger of tripping or slipping.

6.7 Conclusion

The study revealed a significant association between several criteria, except for the distance in front of the obstruction, compared to four-foot clearance parameters. Male participants consistently exhibited a substantial disparity in distance, while leg length adjusted for gender differences showed only a significant difference in distance between the leading limb and obstruction. The distance between steps and barriers was shorter when additional tasks were present, suggesting that male adolescent participants used extended stride lengths.

Chapter VII: Foot clearance whilst stepping over an obstacle of different heights with and without an additional task: A comparison between younger and older adults

Abstract

Background: Stepping over obstacles, a common cause of falls in the elderly, can increase the risk of falling. Detecting age-related gait adaptation changes while stepping over could help identify strategies to avoid tripping.

Objective: The aim of this chapter was to establish if older adults negotiated an obstacle differently (based on obstacle clearance parameters) compared to younger adults. This was possible because of differences in walking gait between older and younger adults.

Methodology: This study recruited twenty healthy young adults with an average age of 25.8 (2.7) years, an average height of 164.4 (7.1) cm, and a body mass of 58.0 (8.9) kg, as well as ten healthy older adults with an average age of 72.7 (7.3) years, an average height of 164.0 (11.4 cm), and a body mass of 68.8 (14.4) kg. A 10-camera Vicon motion capture system was used (100 Hz). Markers (n = 4) were placed on the big toe and heel of both feet. Participants performed four walking task conditions at their freely chosen walking speed. For each task, three trials were conducted for the leading limb, and an additional three trials were conducted for the trailing limb. The task conditions were 1) stepping over a LOW box (15 cm), 2) stepping over a HIGH box (20 cm), 3) stepping over a LOW box while performing a dual task, and 4) stepping over a HIGH box while performing a dual task. The dual task involved holding a glass of water while walking. The obstacle clearance parameters were toe height above the obstacle (cm), heel height above the obstacle (cm), and step distance away from and in front of the obstacle (cm).

Results: The older adults had a significantly greater mean age and body mass compared to younger adults, with no significant differences in height. The leading limb during obstacle crossing had no significant main effects, between-factor effects, or interactions. However, older adults placed their leading limb closer to the obstacle during the stepping away phase. Step distance was significantly greater in the LOW and LOW Dual Task conditions compared to the HIGH condition. A significant between-factor effect was observed for the trailing limb, with older adults demonstrating a greater clearance height compared to younger adults. Heel height above the back of the obstacle was significantly lower in the LOW Dual Task condition compared to the HIGH condition.

Conclusions: The study reveals age-related changes in stepping over depth obstacles. Older adults may use a different strategy, positioning their trailing foot further away, achieving higher toe clearance, and exhibiting a shorter distance to the obstacle after landing, potentially to reduce tripping or slipping. Future studies could explore the impact of different dual-task conditions, targeted training programs, environmental factors, and longitudinal changes in obstacle negotiation strategies with aging.

Keywords: foot clearance, toe clearance, younger adults, stepping over, crossing over, and older adults

7.1 Introduction

Falls remain a leading cause of morbidity and loss of independence in older adults, accounting for significant proportions of hip and wrist fractures, as well as head injuries (Grisso et al., 1990; Hayes et al., 1993; Palvanen et al., 2000). Among the various causes of falls, tripping over obstacles is particularly prevalent, with older adults frequently encountering difficulty in negotiating such hazards (Chen et al., 2015; McFadyen & Carnahan, 1997; Patla & Reidy, 1993). These incidents underscore the critical need to understand how aging impacts obstacle clearance during walking, a fundamental component of daily mobility.

The mechanisms underlying age-related differences in gait and obstacle negotiation are complex, involving both intrinsic and extrinsic factors. Intrinsic factors such as musculoskeletal deterioration, diminished balance, slower reaction times, and cognitive decline in attention and executive function contribute to impaired mobility in older adults (Galna et al., 2009; Chen et al., 1994). Extrinsic factors, including the presence of environmental hazards, amplify the difficulty of locomotion. The interplay between these factors heightens the risk of tripping and subsequent falls in older individuals (Robinovitch et al., 2013; Pan et al., 2016).

Research has established that aging significantly alters gait characteristics, including reduced step length, increased step width, and heightened variability in stride timing (Aboutorabi et al., 2016; Hagoort et al., 2023). While these changes are well-documented during level walking, fewer studies have examined their effects during complex tasks, such as stepping over obstacles. Negotiating obstacles requires precise motor control and coordination, with the leading and trailing limbs playing distinct roles in ensuring safe clearance. Previous studies (table 7.0) have yielded conflicting findings regarding the influence of age on foot clearance. For example, some studies report no significant age effects on lead limb toe clearance (Chen et al., 1991; Lowrey et al., 2007), whereas others have found that older adults increase toe clearance as obstacle height increases (Lu et al., 2006). Similarly, research on trailing limb clearance has produced mixed results (McFadyen & Prince, 2002; Draganich & Kuo, 2004).

Dual-task conditions, which simulate real-world scenarios involving concurrent cognitive or physical demands, further exacerbate the challenge of obstacle negotiation. Dividing attention between tasks has been shown to impair performance in both young and older adults, with older individuals experiencing a greater decline in obstacle avoidance capabilities (Chen et al., 1996). Despite these findings, there is limited research on how dual-tasking involving physical activities, such as carrying an object, impacts foot clearance parameters during obstacle negotiation.

This study seeks to address these gaps by examining the effects of age and dual-task conditions on foot clearance during obstacle crossing at varying heights. By comparing younger and older adults, this research aims to identify age-related differences in gait adaptation strategies under single- and dual-task conditions.

Table 7. 0 Summary of leading limb toe clearance differences between younger and older adults.

Studies	Finding	Obstacle methods used	obstacle height
Chen et al., 1991	No difference older vs. younger adult	Walk along a 3 m walkway and then stepping over the obstacle in their usual manner, continuing at least 2 m past before stepping	D = 25 mm, W=450 mm, H = 25, 51, and 152 mm
Lowrey et al., 2007	No difference older vs. younger adult	Walk along 5 m and stepping over one or two obstacles	adjusted 45% of lower leg length (a 2.5 cm & 5 cm piece of wood that spanned the width of the GAITRite)
Lu et al., 2006	Increased older vs. younger	Walk along 8 m and crossed a height-adjustable obstacle	heights of 20% and 30% of leg length a 1.5 m long aluminum tube with a diameter of 1.5 cm placed across a metal frame
McFadyen and Prince, 2002	Lower older vs. younger	walking on the level, avoiding a 11.75-cm-high obstacle, and accommodating a change in floor height of 11.75 cm. All subjects were tested under three conditions: unobstructed walking, obstacle avoidance, and platform accommodation.	Both obstacles were 122 cm wide and 11.75 cm high. The obstacle was 5 cm in depth, and the platform was 366 cm in length.
Soma et al., 2010	Lower older vs. younger	Walk at comfortable speed, and stepping over. During walking, repetitive subtract 7 starting from 100, and answer our questions	D = 15 cm, W= 80 cm, H = 2 cm

D=depth (cm), W= width (cm), H=heights(cm)

7.2 Research objectives

The aim of this chapter was to establish if older adults negotiated an obstacle differently – under single and dual task conditions - (based on obstacle clearance parameters) compared to younger adults.

7.3 Hypothesis

1. There will be significant difference in foot clearance parameters whilst stepping over an obstacle based on obstacle height (two obstacle heights: 15 cm. and 20 cm.).
2. There will be significant difference in foot clearance parameters whilst stepping over an obstacle based on two task demands (with and without holding a glass of water).
3. There will be significant difference in foot clearance parameters whilst stepping over an obstacle between healthy young and older adults

7.4 Methodology

This has been described earlier in the chapter 3 (methods). For brevity only a summary and the methods pertinent to this chapter are presented here.

7.4.1 Participants

This study recruited twenty healthy young adults (average age, 25.8 (2.7) years; average height, 164.4 (7.1) cm; body mass, 58.0 (8.9) kg; and ten healthy older adults (average age, 72.7 (7.3) years; average height, 164.0 (11.4 cm; body mass, 68.8 (14.4) kg), as shown in table 7.1. The Ethical Approval of Research Involving Human Participants, University of Essex, approved the procedure of this study.

7.4.2 Procedure

The University of Essex biomechanics lab conducted the gait analysis. We used a 10-camera Vicon Bonita motion capture system (Vicon Motion Systems Ltd., Oxford, UK) at a sampling rate of 100 Hz. The Vicon Nexus program's overall process consists of calibrating a Vicon system, preparing a subject, capturing motion trials, reviewing trials, filling gaps, and performing any required modeling, such as dynamic plug-in gait. Chapter 3 provides additional information.

7.4.3 Data analysis

Foot clearance parameters were in the same approaches as described in **chapter 3**. Briefly, these were:

- Step distance in front of obstacle (cm)
- Toe height above front of obstacle (cm)
- Heel height above back of obstacle (cm)
- Step distance away from obstacle (cm)

7.4.4 Statistics analysis

Statistical analyses were carried out in the Statistical Package for the Social Sciences (SPSS) Version 25 for Windows. The Shapiro-Wilk test was used to determine the distribution of the data. Standard descriptive statistics (mean with standard deviation) were calculated for all variables. The researchers conducted an independent T-test to compare the demographic differences between young and older adults. The researchers conducted a repeated measures ANOVA between factors (gender). If there were significant effects (main (task), between (age), or interaction (task*age)), then a Bonferroni post-hoc analysis was carried out. The research performed all statistical data analyses by setting the level of significant difference at $p < 0.05$.

7.5 Results

7.5.1 Characteristics of participants

The characteristics of the participants are shown in Table 7.1. Age, unsurprisingly, was significantly greater in the older group compared to the younger group. Mass was also significantly greater for the older group, but there was no significant difference between groups for height. Male and female participants were grouped together in this analysis since there were not enough older adults to warrant a split by gender. There was also no difference in height between older adults and younger adults – therefore it is likely that any differences between the two groups will be a consequence of age and not of height.

Table 7. 1 Participant characteristics.

	Whole group (n=30)	Younger adults (n=20)	Older adults (n=10)	Younger vs. Older adults
Gender (m/f)	14/16	10/10	4/6	
Age (years)	41.4 (23.0)	25.8 (2.7)	72.7 (7.3)	**t (28); 25.806, p=<.001**
Mass (kg)	61.6 (12.0)	58.0 (8.9)	68.8 (14.4)	**t (28); 2.535, p=.017**
Height (cm)	164.3 (8.6)	164.4 (7.1)	164.0 (11.4)	t (28); -0.096, p= .924

Bold indicates significant differences.

7.5.2 Leading limb

When crossing an obstacle for the leading limb, there was no significant main effect, between factors (age group) effect, or interaction for step distance in front of the obstacle and heel height above the back of the obstacle (table 7.2). Mirroring the results of chapter 5. There was a significant main factor (condition) effect (table 7.2) for toe height above the front of the obstacle. The post-hoc analysis revealed that the toe height was greater for the LOW condition compared to the HIGH condition only. When stepping away from the obstacle, the leading limb was placed significantly (table 7.2) closer to the obstacle (mean difference 3.9 cm; 95%CI 1.2 – 6.7 cm) for older adults compared to younger adults. There was also a significant main effect for condition. The post-hoc analysis revealed that the step distance for the HIGH condition was significantly further away from the obstacle for compared to all other conditions.

Table 7. 2 Leading limb parameters for younger and older adults

Leading limb	Group Mean (SD)	Younger Mean (SD)	Older Mean (SD)	RM ANOVA with between factors (age group)
Step distance in front of obstacle (cm)				
Condition: Low Obstacle	85.5 (10.9)	84.4 (11.0)	87.6 (10.8)	Main effect (condition): (F (3, 84) = 2.150, p =.100) Between factors (age): (F (1, 28) = 0.002, p =.965) Interaction (condition*age): (F (3, 84) = 1.171, p=.326)
Condition: High Obstacle	82.7 (9.8)	82.8 (11.0)	82.6 (7.5)	
Condition: Low Obstacle Dual Task	86.1 (9.9)	87.2 (9.5)	83.9 (10.8)	
Condition: High Obstacle Dual Task	82.7 (9.4)	82.8 (9.4)	82.4 (9.9)	
Toe height above front of obstacle (cm)				
Condition: Low Obstacle	16.4 (3.4) [a]	15.8 (3.3)	17.7 (3.4)	**†Main effect (condition): (F (1.853, 51.878) = 3.697, p = .035)** Between factors (age): (F (1, 28) = 0.211, p = .650) †Interaction (condition*age): (F (1.853, 51.878) = 0.302, p=.096)
Condition: High Obstacle	15.3 (3.5)	15.4 (3.5)	15.0 (3.6)	
Condition: Low Obstacle Dual Task	16.0 (3.0)	15.8 (3.3)	16.6 (2.6)	
Condition: High Obstacle Dual Task	15.8 (3.1)	15.9 (3.4)	15.6 (2.7)	
Heel height above back of obstacle (cm)				
Condition: Low Obstacle	10.9 (2.5)	10.8 (2.5)	11.0 (2.6)	†Main effect (condition): (F (2.121, 59.388) = 0.073, p = .938) Between factors (gender): (F (1, 28) = 0.131, p = .720) †Interaction (condition*age): (F (2.121, 59.388) = .102, p=.913)
Condition: High Obstacle	11.1 (3.5)	10.9 (3.0)	11.4 (4.6)	
Condition: Low Obstacle Dual Task	10.9 (3.4)	10.7 (2.7)	11.4 (4.7)	
Condition: High Obstacle Dual Task	11.0 (3.0)	11.0 (3.1)	11.0 (3.0)	
Step distance away from obstacle (cm)				
Condition: Low Obstacle	15.3 (4.7) [a]	16.9 (4.1)	12.3 (4.3)	**Main effect (condition): (F (3, 84) = 14.213, p = <.001)** **Between factors (age): (F (1, 28) = 8.697, p = .006)** Interaction (condition*age): (F (3, 84) = 0.671, p=.572)
Condition: High Obstacle	17.2 (4.2)	18.3 (3.6)	15.1 (4.5)	
Condition: Low Obstacle Dual Task	14.0 (4.0) [a]	15.2 (3.8)	11.5 (3.2)	
Condition: High Obstacle Dual Task	14.7 (4.2) [a]	16.1 (3.4)	12.0 (4.2)	

[a] significantly different to High Obstacle. † Greenhouse-Geisser applied. **Bold indicates a significant effect.**

7.5.3 Trailing Limb

When crossing an obstacle with trailing limb, there was a significant main effect for step distance in front of the obstacle (Table 7.3). The post-hoc analysis revealed that step distance was significantly further away from the obstacle on approach for the LOW and LOW Dual Task conditions compared to the HIGH condition. With the inclusion of the older adults into the group these results were comparable to chapter 5. There was no significant effect for interaction. There was a significant between factors (age group) effect with the foot placed significantly further (mean difference 3.2 cm (95% CI 0.3-6.1cm) away for older adults compared to younger adults. The toe height above the front of the obstacle showed a significant difference between factors (age) effect (table 7.3) with a greater toe clearance height for older adults to younger adults (mean difference 4.0 cm (95% CI 0.7 – 7.4 cm)). There was no significant main effect or interaction. Heel height above the back of the obstacle revealed a significant main effect for condition. The post hoc analysis showed that heel height was significantly lower for LOW Dual Task compared to HIGH (table 7.3). There was no significant between factors (age) effect. Step distance away from obstacle revealed a significant main effect for condition. The post hoc analysis showed that step length was significantly closer to the obstacle for LOW compared to all other conditions. There was a significant between factors (age) effect with step length away from obstacle significantly closer to the obstacle for older compared to younger adults (mean difference 9.7 cm (95% CI 4.1 – 15.3 cm)).

Table 7. 3Trailing limb parameters for younger and older adults

Trailing limb	Group Mean (SD)	Younger Mean (SD)	Older Mean (SD)	RM ANOVA with between factor (Age group)
Step distance in front of obstacle(cm)				
Condition: Low Obstacle	17.4(4.6) [ab]	16.2 (3.6)	19.9(5.5)	**†Main effect (condition): (F (1.924, 53.876) = 9.400, p = <.001)** **Between factors (age): (F (1, 28) = 5.223, p =.030)** †Interaction (condition*age): (F (1.924, 53.876) = .716, p =.488)
Condition: High Obstacle	14.9(4.7)	13.6 (3.8)	17.5(5.3)	
Condition: Low Obstacle Dual Task	17.2(4.1) [ab]	16.2 (3.3)	19.1(5.0)	
Condition: High Obstacle Dual Task	14.9(4.2)	14.2 (4.0)	16.4(4.3)	
Toe height above front of obstacle(cm)				
Condition: Low Obstacle	13.4(4.9)	11.5 (3.0)	17.1(5.9)	Main effect (condition): (F (3,84) = 2.187, p =.096) **Between factors (age): (F (1, 28) = 6.238, p =.019)** Interaction (condition*age): (F (3,84) = 1.762, p =.161)
Condition: High Obstacle	13.0(5.3)	11.8 (3.4)	15.4(7.4)	
Condition: Low Obstacle Dual Task	12.3(5.0)	11.4 (4.0)	14.0(6.4)	
Condition: High Obstacle Dual Task	13.3(5.0)	11.9 (2.5)	16.2(7.4)	
Heel height above back of obstacle(cm)				
Condition: Low Obstacle	38.9(6.1)	39.7 (5.9)	37.4(6.5)	**Main effect (condition): (F (**3,84**) = 2.923, p =.039)** Between factors (age): (F (1, 28) = 1.889, p =.180) Interaction (condition*age): (F (3,84) = .795, p =.500)
Condition: High Obstacle	39.5(5.7)	40.5 (5.2)	37.6(6.3)	
Condition: Low Obstacle Dual Task	37.4(5.2) [a]	38.0 (4.2)	36.2(7.0)	
Condition: High Obstacle Dual Task	38.4(5.3)	39.6 (4.8)	35.8(5.4)	
Step distance away from obstacle(cm)				
Condition: Low Obstacle	90.1(9.8)	93.1 (8.9)	84.1(9.1)	**†Main effect (condition): (F (2.164, 60.598) = 10.266, p = < .001)** **Between factors (age): (F (1, 28) = 12.656, p = .001)** †Interaction (condition*age): (F (2.164, 60.598) = .326, p =.740)
Condition: High Obstacle	92.6(8.9)	96.0 (7.5)	85.7(7.6)	
Condition: Low Obstacle Dual Task	86.1(8.9) [albic]	88.9 (8.0)	80.4(8.2)	
Condition: High Obstacle Dual Task	86.3(9.9) [a]	89.9 (7.8)	79.0(9.6)	

[a] significantly different to High Obstacle; [b] significantly different to HIGH dual task; [c] significantly different to LOW;
† Greenhouse-Geisser applied. **Bold indicates a significant effect.**

7.6 Discussion

The aim of this chapter was to establish if older adults negotiated an obstacle differently (based on obstacle clearance parameters) compared to younger adults. It was possible that this would be the case due to differences in walking gait between older and younger adults.

The main effects with the inclusion of the older adult group, to a certain extent, mirrored those reported in chapter 6 This suggests that differences seen between obstacle height and DT, as discussed in chapter 6 are applicable here. Similarly, there was no interaction affect. The focus of this chapter will therefore be the between effects for age – younger adults vs. older adults (table 7.4).

Table 7. 4 Summary of older vs. younger adult differences

Limb	Measure	Older vs. younger adult
Leading limb	Step distance away from obstacle	Older **significantly closer** to obstacle after clearance
Trailing limb	Step distance in front of obstacle	Older **significantly farther away** from obstacle before clearance
	Toe height above front of obstacle	Older **significantly greater** toe height during clearance.
	Step distance away from obstacle	Older **significantly closer** to obstacle after clearance

For older adults when stepping over an obstacle the trailing limb was positioned further away from the obstacle compared to younger adults (though this was not reciprocated by the corresponding leading foot position during approach). There was also a higher toe clearance of the trailing limb as it went over the front edge of the obstacle, and the limb was positioned closer to the obstacle when it landed back on the ground. This was replicated by the leading limb which was also placed closer to the obstacle once it had crossed over. The closer placement of the trailing and leading limbs after crossing is likely due to the further away position of the trailing limb during the approach compared to younger adults.

7.6.1 Trailing toe height above the front of obstacle

Older adults had a significantly greater trailing toe height during clearing than young adults. This finding presents a contradiction to the outcomes of a previous study. Chen et al. (1991) found that age did not affect the clearance of the lead and trail limbs when navigating obstacles of three different heights (25, 51, and 152 mm) at their preferred speeds. However, in comparison to the younger individuals, the older adults implemented several crossing-over strategies, including a decrease in step length, a decrease in crossing speed, and a decrease in obstacle-heel striking distance. Likewise, Lu et al. (2006) examined the obstacle clearance parameters in both young and older persons throughout the process of crossing obstacles with heights equivalent to 10%, 20%, and 30% of their leg length. This result shows that there was no statistically significant difference in trailing toe clearance between the older and younger groups (Lu et al., 2006). In contrast, Soma et al. (2010) reported that toe clearance did significantly differ between ages for leading and trailing toe clearance. Soma et al. (2010) conducted an examination of foot clearance in both young and older individuals during a dual-task walking task over a 2-centimeter-high wooden obstacle. Young adults had significantly higher mean trailing toe clearance values for single and dual tasks (3.2 (1.2) cm and 4.0 (1.6) cm, respectively) compared to older adults (3.0 (1.1) cm and 2.9 (1.4) cm, respectively) (Soma et al., 2010). Maidan et al. (2018) reported similar findings in that older adults had lower clearance over the obstacles compared to young adults.

When crossing an obstacle, older adults may increase the height of the trailing limb to compensate for declines in strength, balance, and proprioception. They reduce the risk of tripping over an obstacle by lifting the trailing limb higher. However, it might depend on the specific strategy and mechanical requirements. First, the trailing limb's movement depends on proprioceptive feedback from the leading limb, as the trailing limb itself is not visible in the visual field (Mohagheghi et al., 2004; Draganich and Kuo, 2004). Next, the mechanical requirements on the trailing and leading limbs were different, as they provided support for the body during the crossing of the ipsilateral limb (Lu et al., 2006). When the leading limb crossed and the trailing limb supported the body, the trailing foot represented the displacement of the center of mass (COM) away from the base of support. Consequently, this displacement rendered the recovery of balance following instances of tripping or stumbling more challenging (Lu et al., 2006). Conversely, when the trailing limb crossed, the center of mass (COM) exhibited a trajectory towards the leading stance foot, thereby reducing the likelihood of instability in the stance limb. Therefore, the following leg may have a higher potential for easier recovery from tripping or stumbling compared to situations where the leading limb is at fault (Lu et al., 2006). Lastly, the obstacle depth might affect the foot clearance of the trailing limb, necessitating a more cautious clearance from older adults at the front edge of the obstacle.

7.6.2 Leading toe height above the front of obstacle

In the present study, when the leading toe was above the obstacle, the toe height above the obstacle while stepping over a 35-cm-deep obstacle was unaffected by age. Although there were differences in the experimental methods employed, this finding is consistent with previous studies (Chen et al., 1991; Lowrey et al., 2007). Table 7.0 provides a summary of the leading limb toe clearance differences between younger and older adults. However, this is not conclusive. In contrast, Lu et al. (2006) demonstrated that older people increased toe clearance with obstacle height, whereas younger adults did not show this pattern. Older adults exhibited greater lead limb toe clearance in comparison to younger adults for obstacles of 20% and 30% of leg length (Lu et al., 2006). This suggests that regardless of obstacle height (only to a certain extent, as discussed in Chapter 6), older adults increase the height of the leading limb when crossing an obstacle. Alternatively, McFadyen and Prince (2002) and Soma et al. (2010) have reported lower leading toe clearance for older adults when compared to younger adults. The difference between studies is that decreased toe clearance height may be due to age-related declines in muscle strength, flexibility, and coordination, which can reduce the ability to lift the foot sufficiently to avoid an obstacle (McFadyen and Prince, 2002; Soma et al., 2010). Likewise, studies demonstrated that older people increased toe clearance with obstacle height (Lu et al., 2006). Older adults may raise the leading limb higher when crossing an obstacle to compensate for decreased strength, balance, and proprioception. They mitigate the chance of stumbling over an obstacle by lifting the leading limb to a greater height. In this study, there was no effect of age on the toe height above the obstacle while stepping over a 35-cm-deep obstacle for the leading limb. The difference in physical capability may not be immediately apparent, as the sample characters include a highly active group of older people. During that period, there was no mechanism in place to compensate for declines in physical strength, balance, or body proprioception. Older individuals might mitigate any potential decline in strength or flexibility by modifying their movement patterns or adopting different strategies to effectively accomplish the objective. Additionally, table 7.0, highlighted a mixed picture of how toe clearance of the leading limb is altered, or not, between young and older adults. The results from this thesis were similar to the studies of Chen et al. (1991) and Lowrey et al. (2007) in that there was no difference between young and older adults. There does not seem to be a pattern of why some studies have shown contradictory results (table 7.0).

The position of the leading foot prior to crossing an obstacle provided sufficient clearance. For this experiment, we set up a controlled environment in a laboratory. We precisely measured the pathway before the obstacle at 6 meters, ensuring sufficient visual cues for the participants. Likewise, the visual system employs feedforward control mechanisms, allowing humans to adjust their lead-toe clearance based on the visual information they collect when approaching an object (Patla and Vickers, 1997; Patla et al., 2004). Timmis and Buckley's (2012) study emphasizes the importance of gathering sufficient visual information at least two steps before encountering an obstacle to guarantee the effectiveness of lead-toe clearance. Moreover, when faced with an obstacle, young and old people did not significantly differ in the step distance the leading limb took.

When older adults stepped away from the obstacle, they placed their leading limb significantly closer to it than younger adults did. This finding is consistent with previous research that examined obstacle clearance parameters while stepping over with a single task. Older adults had a tendency to achieve a shorter distance from the obstacle while crossing (Lowrey et al., 2007; McFadyen and Prince, 2002; Maidan et al., 2018; Lu et al., 2006). It is likely that the placement of the trailing and leading limbs as participants approach the obstacle will impact the foot placement after the obstacle. Older adults placed the trailing limb farther away from the obstacle on approach, but the leading limb did not differ. Once cleared, the farther placement will likely lead to a closer step distance to the obstacle. In this study, older adults exhibited an ability to cover a shorter distance when crossing a wide obstacle (35 cm) in comparison to younger adults. Older individuals frequently encounter reductions in balance and stability as a result of age-related alterations in muscle strength, proprioception, and vestibular function. Consequently, individuals may choose to be more careful while dealing with obstacles, causing them to position their front limb in greater proximity to the object as a means to maintain balance while moving away.

Additionally, when walking through an obstacle course while negotiating anticipated and unanticipated obstacles, older adults tended to position their leading foot in closer proximity to the obstacle after landing, in contrast to younger adults (Maidan et al., 2018). Compared to young adults, the older adults demonstrated a higher clearance, which resulted in a shorter distance between the heel and the obstacle, potentially indicating a higher risk of stumbling due to the foot's proximity to the obstacle. Additionally, this approach can be advantageous since contact with the heel or midsole may pose a lower risk of falling compared to toe contact (Chen et al., 1991).

7.6.3 Trailing step distance in the front and away from obstacle:

When crossing an obstacle with a trailing limb, there was a significant main effect on step distance in front of the obstacle. This finding is inconsistent with the previous study. According to Lu et al. (2006), older adults exhibited shorter leading heel-obstacle lengths and longer trailing toe-obstacle distances. As mentioned above, the present study showed that although the older group showed shorter leading heel-obstacle lengths and a longer step distance in front of the obstacle of trailing limbs, there were not significantly different leading-toe clearances for older adults when compared to young adults. Interestingly, when crossing a 35-cm obstacle with a trailing limb, older adults placed their feet farther in front of the obstacle than younger adults, a difference that could potentially lead to toe clearances.

Young and older adults may alter their step length when approaching an obstacle, as evidenced by the difference in approach step distances. Researchers have reported motor planning (and motor adaptations), such as adjustments to step length, in both healthy controls and participants with Parkinson's disease (Simieli et al., 2017). The present study did not measure this, but the changes in foot placement distance prior to the obstacle (older vs. young, and HIGH vs. LOW) suggest the presence of motor planning. Earlier in the approach for higher (3–4 steps) compared to lower (1 step) obstacles, we plan adjustments to step lengths (feedforward control) before the obstacle (Simieli et al., 2017). Planning a change to step length 1 step before the obstacle suggests limited time to readjust walking if the adjustment performed was inadequate, especially since most falls occur during the approach phase in the steps nearest the obstacle (Stolze et al., 2004). Future research should investigate how older adults, particularly those who fall, approach obstacles to determine if they employ different motor planning strategies.

7.7 Conclusion

The stepping gait had different obstacle clearance parameters between older and younger adults. When compared to young adults, the step distance away from obstacles for leading and trailing limbs was significantly closer for older adults. When crossing an obstacle with a trailing limb, older adults demonstrated a higher toe clearance as they crossed the obstacle's front edge, and they also positioned themselves closer to the obstacle after crossing it. Older adults may increase the height of the trailing limb to compensate for declines in strength, balance, and proprioception when crossing an obstacle. Compared to young adults, older adults reduce the risk of tripping over an obstacle by lifting the trailing limb higher, results in it being closer to the obstacle after clearance – thus increasing a chance of a stumble. This might be a strategy for gait adaptation when crossing a deep obstacle.

Chapter VIII: Discussion and Conclusion

Discussion

The aim of this study was to determine:

a) The repeatability of foot clearance parameters while stepping over an obstacle

b) If foot clearance parameters were symmetrical when crossing an obstacle.

c) If there were a difference in foot clearance parameters for different height obstacle and when performing a dual task

d) If there were a difference between genders when crossing an obstacle

e) whether older individuals stepped over an obstacle differently (based on obstacle clearance criteria) compared to younger adults.

This study included four parameters of foot clearance. These were: 1) step distance in front of the obstacle (cm); 2) toe height above the front of the obstacle (cm); 3) heel height above the back of the obstacle (cm); and 4) step distance away from the obstacle (cm). Furthermore, this study included four task demands. 1) stepping over an obstacle at a low box (15 cm), 2) stepping over an obstacle at a high box (20 cm), 3) stepping over an obstacle at a low box (15 cm), and 4) stepping over an obstacle at a high box (20 cm). Additionally, the study consisted of five research questions.

8.1 What is the gap in research knowledge regarding foot clearance parameters when stepping over an obstacle in young and older adults?

Investigations into foot clearance metrics during obstacle negotiation have been limited, especially among older adults. The reliability of measures, gait symmetry analysis, gender variations, obstacle characteristics, cognitive and motor interactions, kinematic adaptations, postural threats are inadequately comprehended. These problems make it clear that more research is needed to understand how foot clearance parameters are affected when clearing an obstacle. The systematic review (Chapter 2) highlighted various gaps in the literature. There were few articles that report reliability, gait symmetry, gender differences, or the specific characteristics of an obstacle, such as the depth dimension. These gaps were further explored within this thesis (Chapters 4-7).

The results of this review have shown that older adults exhibit distinct strategies in obstacle negotiation, positioning their leading foot closer to the obstacle and maintaining lower clearance than younger adults. This highlights the impact of aging on motor control and suggests incorporating obstacle training with varied heights and timings in exercise programs (Maidan et al. ,2018). Age and visual conditions significantly affect locomotor timing and control, with older adults relying more on visual cues and showing longer total task completion times under occluded conditions. Obstacle height increases total task completion time (TTC), and older adults adopt wider step widths for stability (Kunimune & Okada ,2017)

8.2 How consistent are foot clearance measures for young adults when negotiating obstacles of different heights?

Chapter 4 aimed to evaluate the test-retest reliability (i.e. ICC) and minimum detectable change (MDC) of foot clearance metrics (leading and trailing limbs) when navigating obstacles of differing heights and under single/dual task conditions. It was important to establish as this has not been reported in the literature for obstacle clearance and since this is a fairly uncommon movement (in comparison to walking) its repeatability may not adequate.

The main results showed that all metrics were very reliable, even when obstacles were different heights or when people were doing two tasks at once. The step distance preceding the obstacle exhibited the greatest MDC (10.5–13.1 cm), suggesting that a change of at least 13 cm is needed to see any real change, underscoring diversity in approach modifications. Dual-task situations did not markedly influence repeatability, with ICCs similar to those in non-dual-task settings.

This was the first study to report the repeatability of foot clearance parameters when crossing an obstacle under bit single and dual task conditions. The results suggest that this methodology can consistently assess foot clearance parameters, establishing a standard for subsequent research and clinical use. It is not clear if this can be said for other foot clearance methods reported in the literature. However, this work does only apply to the current methodology and subsequent research should assess reliability across clinical groups, analyze the influence of cognitive dual tasks on foot clearance reliability, and examine motor planning modifications occurring several steps prior to and following obstacle clearance. Subsequent research should encompass longitudinal studies across varied demographics, analysis of distinct types of dual tasks, and bigger sample sizes to enhance the generalizability of findings.

8.3 What is the level of symmetry in foot clearance when stepping over an obstacle with four walking tasks?

Chapter 5 aimed to determine if foot clearance parameters were symmetrical when stepping over an obstacle. Symmetry is often assumed but this was the first study to employ a number of symmetry indices to establish if, for example, when the right/left leg are is the leading limb was this symmetrical in toe-clearance parameters. Four commonly used gait symmetry indices were employed: symmetry ratio (RI), symmetry index (SI), gait asymmetry (GA), and symmetry angle

(SA). The investigation was motivated by the critical role of gait symmetry in identifying deviations from normal walking, which are indicative of musculoskeletal, neurological, or functional impairments (Verghese et al., 2007; Beauchet et al., 2009). Obstacle clearance, being more demanding than level walking, presents a unique context to explore gait asymmetry, especially since previous research has focused mainly on level walking (Gillain et al., 2019)

The findings indicated that obstacle clearance was predominantly symmetrical in young, healthy individuals; however, asymmetry was observed in several parameters, including toe height above the front of the barrier and heel height above the back of the obstruction for the trailing limb. Symmetry indices such as SI and GA exhibited analogous asymmetry patterns (13/16 and 11/16 parameters for leading and trailing limbs, respectively), although RI indicated a reduced number of asymmetries (6/16 parameters). All indices exhibited a strong correlation ($r = 0.974–1.000$, $p < 0.001$), indicating that they were all in essence reporting similar results to each other.

In younger adults, obstacle clearance was seen as being symmetrical. However, assessing gait symmetry during obstacle clearance may reveal functional disparities in limb performance that may remain obscured in level walking (or detected earlier than normal walking), especially for clinical populations. This has ramifications for the early detection of fall risk and therapies targeting gait anomalies in clinical groups.

8.4 Are there any foot clearance parameters when stepping over obstacles that differ between genders?

Chapter 6 investigated the impact of obstacle height, dual-task conditions, and gender on foot clearance parameters during obstacle clearance. Both single-task and dual-task conditions were evaluated to examine cognitive load effects. Previous studies, such as those by Soma et al. (2010) and Schrodt et al. (2004), focused on various dual tasks, including counting backward while walking, to evaluate foot clearance parameters. In contrast, this study introduced a functional, manual, dual-task condition (holding a glass of water) and incorporated a gender comparison dimension, normalizing for anthropometric differences, such as (i.e. leg length), as proposed by Hof (1996).

Key results showed that obstacle height did not significantly alter approach distances but led to slightly increased departure distances for the leading limb. For the trailing limb, participants approached the HIGH obstacle significantly closer but departed farther compared to LOW conditions. Vertical clearance increased with obstacle height, showcasing adaptive kinematic strategies to ensure safe crossing. Under dual-task conditions, heel clearance reduced for the trailing limb, particularly in LOW obstacle scenarios, increasing tripping risk.

Gender-specific differences were evident, as females showed lower toe and heel heights over the obstacle and placed their limbs closer to the obstacle compared to males. However, this was mainly driven by differences in stature because these were removed when normalized for leg length, and only the leading limb's step distance away from the obstacle remained significantly different, suggesting a motor control adaptation unique to gender, as highlighted by Mengarelli et al. (2017).

The results from chapter 6 therefore suggest that normalizing to body dimensions is important to consider when testing gender differences – an approach not commonly used in obstacle clearance research.

Understanding foot clearance dynamics under varying obstacle heights and cognitive loads is crucial for designing safer living environments for populations at risk of falls and rehabilitation programs that address cognitive-motor interference. However, the importance of these findings lies in their clinical and functional relevance. Insights into dual-task impacts and gender differences enhance fall prevention and rehabilitation approaches, particularly for populations with motor control challenges. The results also show how important functional dual tasks are in the real world, as they are often more useful than lab-based tasks like counting backwards. Examples of these are holding objects. Gender-specific interventions can also be developed to improve gait stability and obstacle negotiation for both genders

8.5 Are there differences in foot clearance parameters between young and older people while stepping over an obstacle with four walking tasks?

Chapter 7 investigates whether older adults negotiate obstacles differently compared to younger adults, possibly due to differences in walking gait. The main effects with older adults mirrored those in Chapter 6, suggesting differences between obstacle height and DT. The focus therefore was on the differences between age groups. Older adults placed the trailing limb was further away from the obstacle than younger adults. This may have had the advantage of altering the high point of the foot trajectory, leading to foot height being higher for older adults at the front of the obstacle for the trailing limb - a potential advantage since this limb is crossing the obstacle without visual cues. However, the disadvantage for means that the leading and trailing limbs are placed closer to the obstacle when landing after crossing - a potential stumble scenario. This chapter also showed that, in relation to the wider literature, a mixed picture of how toe clearance of the leading limb is altered, or not, between young and older adults. There does not seem to be a pattern of why some studies have shown contradictory results (table 7.0), i.e. different obstacle dimensions.

8.6 Limitation and further study

8.6.1 Chapter IV: Repeatability in young adults

8.6.1.1 Limitations:

There were some limitations associated with this chapter. The sample comprised solely healthy young males, constraining the generalizability of the findings to other demographics, including females, older adults, or individuals with disabilities. This omits varied populations, potentially obstructing comprehension of characteristics such as age, gender, or pathology that affect foot clearance. The research concentrated on manual dual tasks, excluding cognitive or intricate multitasking situations prevalent in real-life obstacle navigation. This may provide varying outcomes, especially in groups with compromised motor or cognitive abilities. The study did not look at changes in steps that happen a few strides before or after clearing an obstacle, so it may have missed important information about how to prepare for and recover from a walk. The study is in a controlled environment and may not accurately reflect real-world settings that present a greater diversity of challenges and distractions.

8.6.1.2 Recommendations:

In the future, researchers should include a wider range of participant types, use cognitive dual tasks, look at the steps and the biomechanics of these steps prior to the obstacle as it is possible that participants are making adjustments prior to the obstacle, look at longitudinal adaptations, find more real-world applications, and come up with and test new metrics. If these problems are fixed and these suggestions are put into action, future studies can build on the current ones to learn more about foot clearance and changes in gait, which will lead to better ways of assessing and treating patients.

8.6.2 Chapter V: Gait symmetry in young adults

8.6.2.1 Limitations:

The study has limitations, such as the employment of discrete symmetry indices that may oversimplify gait asymmetry evaluation, the small, homogeneous sample of young healthy participants that restricts generalizability to older or pathological populations, and the lack of standardized thresholds for asymmetry in healthy individuals, which complicates interpretation and applicability in clinical contexts.

8.6.2.2 Recommendations:

Future research should concentrate on evaluating the effectiveness of discrete versus continuous symmetry measures i.e. looking at foot clearance trajectory for obstacle clearance. Gait asymmetry may be looked at in terms of how it affects the risk of falling in older adults and people with certain disorders. This current work looked at toe-clearance parameters, yet the actual biomechanics which are causing these were not looked it. It is possible that asymmetries are seen here in the joint biomechanics yet symmetry is still maintained by for the toe-clearance parameters.

8.6.3 Chapter VI: Gender difference in young adults

8.6.3.1 Limitations:

The limitations of the study must be recognized. The findings may not generalize to older adults or clinical populations, as the study primarily involved younger adults. Additionally, the study tested a single obstacle depth, which limits the scope of depth-related insights. Finally, the dual task involved a motor-only secondary task, which may not fully represent the cognitive-motor demands of daily activities.

8.6.3.2 Recommendations:

This study has focused on a limited number of spatial parameters, providing outcome measures without explaining the underlying biomechanical causes of toe clearance. Typically, researchers analyze only the immediate steps before and after the obstacle, neglecting potential changes that may occur over a longer approach or departure phase. Further study may have the advantage of delving deeper into the biomechanics of foot clearance by examining both kinematic and kinetic factors. Additionally, this approach study will extend the analysis to multiple steps before and after obstacle clearance to identify any anticipatory or compensatory changes and provide a comprehensive view of gait adaptations

This chapter also focused on two height and one-depth of obstacle. However, there does not appear to be a consensus on the dimension of an obstacle should be when looking at obstacle clearance research. If there was a standardize obstacle then this would remove the potential confusion when comparing results to other studies.

Some ideas for further research may be to create training programs that teach people how to do two tasks simultaneously and get around obstacles better so they can move around more easily, to study how visual and proprioceptive feedback systems affect motor control processes that are different for men and women, and to do longitudinal studies to see how well interventions work across a variety of populations. For example, the dual-task in this study (holding a glass of water) may not fully replicate the complexity of real-world scenarios, such as navigating uneven surfaces or avoiding moving obstacles. Likewise, develop and evaluate training programs that simulate real-world conditions. For instance, the objective may be to design and evaluate training programs that enhance the ability of each individual to multitask while navigating obstacles. These programs should include simulated environments with tasks like walking through obstacle courses, responding to auditory cues, or engaging in cognitive tasks. The expected outcome is improved coordination and adaptability, leading to safer and more efficient mobility, especially for individuals with balance or mobility impairments.

8.6.4 Chapter VII: Stepping over an obstacle in young and older adults

8.6.4.1 Limitations:

Stepping over an obstacle in both young and older chapters have several limitations. First, there is sample homogeneity. The study predominantly included active older adults, which may not represent the broader population of older adults with varying levels of physical activity. This limits the generalizability of the findings to less active or frail older individuals (Chen et al., 1991). Secondly, the cross-sectional nature of the study only provides a snapshot of age-related differences in gait and obstacle clearance. Longitudinal studies of obstacle clearance will help show how this task changes over time (Maidan et al., 2018). Thirdly, the study focused on a single obstacle depth (35 cm). Examining a broader range of obstacle heights and depths could provide a more comprehensive understanding of how older adults navigate various environmental challenges (Lu et al., 2006). Fourth, the dual task in this study may not fully capture the complexity of real-world environments. Incorporating more complex and dynamic scenarios could yield insights that are more applicable to everyday life (Shumway-Cook and Wolcott, 2011). Finally, the study did not thoroughly assess the functional implications of the observed differences in gait parameters, such as the risk of falls or the impact on daily activities (Bautmans et al., 2011; Yogev et al., 2007).

8.6.4.2 Recommendation

Future study should focus on critical areas to enhance comprehension of barrier negotiation tactics and fall risk reduction in older persons. First, researchers should look into how obstacle-clearing metrics change in different dual-task situations, especially those that involve more complex cognitive tasks. Second, the effectiveness of specialized training programs aimed at enhancing dual-task walking and obstacle negotiating requires comprehensive examination. Research should investigate the impact of environmental elements, including lighting conditions and surface roughness, on foot clearance and related fall hazards. Finally, longitudinal research is essential to observe how techniques for surmounting difficulties evolve over time. These studies help us understand how age-related changes happen and help us come up with targeted interventions

8.7 Clinical Implications for Physiotherapy

The findings of this thesis have direct applications in clinical rehabilitation, particularly for populations at risk of falls, such as older adults. Key clinical takeaways include repeatability and diagnostics, symmetry gait, sex differences, dual-task and cognitive-motor training, and fall prevention strategies. Firstly, the high repeatability of foot clearance metrics allows for the precise tracking of gait impairments and recovery. Therapists can leverage these reliable measurements to tailor interventions for stability and step distance. Second, understanding asymmetries in gait aids in the early detection of risks and the development of targeted balance and strength training. Third, sex differences in obstacle clearance necessitate personalized exercises and protocols, ensuring equitable and effective treatment plans. Fourth, programs that focus on dual-task challenges can help with cognitive-motor interference, which makes it easier to get around obstacles in real life. Lastly, learning about the ways that people adjust as they get older helps with programs that aim to boost proprioception, strength, and balance, which will ultimately lower the risk of falling.

Conclusion

This thesis aimed to investigate the repeatability of foot clearance parameters during obstacle crossing, if they were symmetrical, if there were differences in foot clearance parameters for different height obstacles and dual tasks, if there were differences between genders, and if older individuals stepped over obstacles differently compared to younger adults based on obstacle clearance criteria. However, the findings of this thesis have significant implications for clinical rehabilitation, particularly for populations at risk of falls, such as older adults.

The first finding from chapter IV (Repeatability in young adults) highlights the repeatability test. This study looked into how reliable measurements of foot clearance were in young adults who were navigating obstacles of different heights while also doing other tasks. The results showed that the measurements were strong-to-excellent across all obstacle heights and task conditions. The step distance exhibited the highest variability, and the methodology was validated for future clinical and research applications. However, the high repeatability of foot clearance data makes it possible to look for problems in the characteristics of gait in individuals and keep track of how they change over time. This lets therapists create personalized treatments that improve stability and predictability, with a focus on step distance.

The second finding from chapter V (Gait symmetry in young adults) analyzed foot clearance parameters during obstacle navigation using four gait symmetry indices: symmetry ratio (RI), symmetry index (SI), gait asymmetry (GA), and symmetry angle (SA). Results showed a largely symmetrical obstacle clearance, but asymmetries were observed in specific parameters. SI and GA showed similar asymmetry patterns across leading and trailing limbs, while RI identified fewer asymmetries. These findings highlight the importance of understanding gait symmetry during obstacle clearance for early detection of fall risks and targeted therapies. However, limitations include discrete symmetry indices and a homogeneous sample. Additionally, gait symmetry analysis offers valuable insights into subtle asymmetries that may indicate underlying impairments or fall risks. By utilizing indices such as the symmetry index (SI) and gait asymmetry (GA), clinicians can identify asymmetrical patterns and address these through interventions focused on balance, strength, and task-specific training

The third finding from chapter VI (Gender differences in foot clearance) investigated the impact of obstacle height, dual-task conditions, and gender on foot clearance parameters during obstacle navigation. This study found that obstacle height did not significantly affect approach distances but increased departure distances for the leading limb. Participants approached higher obstacles closer and departed farther for the trailing limb. Vertical clearance increased with obstacle height, demonstrating adaptive strategies. Dual-task conditions reduced trailing limb heel clearance, particularly for lower obstacles, increasing the risk of tripping. Gender-specific differences were evident, with females placing limbs closer to obstacles. However, when normalized for leg length, only leading limb departure distances remained significantly different. Comprehending gender-specific gait alterations and the influence of dual-tasking on obstacle navigation is essential for developing solutions. Additionally, the observed gender-specific differences in foot clearance parameters underscore the importance of personalized rehabilitation strategies. For instance, the tendency for females to place their limbs closer to obstacles may inform tailored exercises aimed at optimizing approach distances and reducing tripping risks. Normalizing foot clearance metrics for leg length further ensures equitable and individualized rehabilitation protocols.

The final finding from chapter VII (Foot clearance in younger and older adults) looked at how older people get around obstacles with their feet, with a focus on cognitive-motor interference. The compensatory strategies demonstrated by older adults, such as positioning the leading limb closer to obstacles and increasing trailing toe clearance, highlight critical areas for intervention. Likewise, dual-task training programs that address cognitive-motor interference can improve strength, balance, and proprioception, enhancing obstacle navigation under real-world conditions. These insights are particularly relevant for fall prevention strategies, as reduced trailing limb heel clearance and dual-task challenges are associated with increased fall risk.

Future research should emphasize the development of dual-task walking programs, proprioceptive enhancement exercises, and gender-specific therapies to address the various obstacles caused by biomechanical and anatomical differences. Adding contextual variables and doing longitudinal research on how people get around obstacles would also make rehabilitation therapies more useful in the real world and have longer-lasting effects. These findings collectively establish a strong framework for enhancing treatment procedures to improve functional independence and mitigate fall risks in various populations.

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Appendix 1

Participant information sheet

Research Project: Repeatability of minimum foot clearance and speed during crossing over obstacle and stepping with and without dual task in healthy young adult

Name of Researcher: Sirirat Tohpreecha

Supervisors: Prof. Jo Jackson and Dr. Matthew Taylor

Thank you for taking the time to read this participant information sheet,

We would like to invite you to participate in a research study at the University of Essex if you are healthy individuals. Before you decide you need to understand why the research is being done and what it would involve for you. So, please take time to read the following information carefully. You can ask questions about anything you read if this is not clear for you or would like more information.

What is the project about?

The aim of study is to determine the reliability of minimum toe clearance and speed during crossing over an obstacle and stepping with and without holding a glass in healthy adults.

Tripping is a common cause of falls in older persons. There are several issues that investigate the style of walking for preventing the risk of falling. For example, ageing and/or history of fall in older adults influences minimum foot clearance (MFC) characteristics during level walking.

MFC is strategies in biomechanics model investigating the risk of for falling. In term of definition, it is the smallest distance between forefoot and the ground during the mid-swing phase. By understanding this, researchers will be able to take this measure forward into a group of older individuals to establish the clinical utility of any biomechanical measurement. It is the first necessary to establish how repeatable measurements are.

This study will investigate the repeatability of minimum foot clearance in healthy adults and provide a basis for future work on older individuals. The long-term aim of our research is to understand the mechanism of controlling height or clearance of trailing leg over obstacles and stepping in older adults for tripping prevention.

What does participating involve?

First, you will be asked to fulfil the inclusion and exclusion criteria. If so, you will attend for the same tests on three occasions approximately a week apart. The first occasion your mass, height, and leg length will be measured and passive length of key muscles assessed. Then the participants will be asked to wear shorts, t-shirts and their own foot wears. Thirty-nine markers will be placed on the participant's body for motion analysis and measurements. Next, the participants will be asked to calibrate the model on a force plate with weight distributed equally on both lower limbs. Finally, all participants will perform a series of tasks such as walking at their natural speed, crossing over an obstacle, and stepping. The duration of the trial is expected to last two hours. All data collected will be individually assigned a subject ID number ensuring the anonymity of the participants. None of the procedures should cause any pain.

Do I have to take part?

No, it is up to you to decide whether you would like to take part or not. We will describe the study and go through the participant information sheet, which we will give to you. We will then ask you to sign a consent form to show you agreed to take part. You are free to withdraw at any time, without giving a reason.

What will happen to any information I give?

All data collected will be anonymous and remain confidential. The data will be stored in a password protected file on a personal computer and will be held in accordance with university regulations and then destroyed after use. Informed consent forms will be stored safely in a locked cabinet in School of Health. If you withdraw from the study all the information and data collected from you, to date, will be destroyed and you ID code removed from all the study files.

What will be done with the results of the project?

The results of the study will be submitted for publication to medical journals and at conferences. In addition, the results will help to inform a future study investigating these issues over an extended period. If you wish, we can send you a summary of the findings when the study has been completed. You will not be identified in any report/publication unless you have given your consent.

What are the possible benefits of taking part?

There are no benefits with undertaking this study but this information will help to understand the style of walking focusing MFC and provide a basis for future work on older individuals

Are there any risks?

No, there is an inherent risk with any type of testing, however the testing for this study will be in a controlled laboratory environment and are tasks that are performed frequently so the risk is very minimal.

Contact details

The study is being led by Sirirat Tohpreecha. This is research project of PhD student under the supervision of Prof. Jo Jackson, School of Health and Human Science and Dr. Matthew Taylor, School of Biological Sciences, University of Essex. If you have any questions about the project, please don't hesitate to ask. My contact details are:

Sirirat Tohpreecha
Email: st16490@essex.ac.uk
Tel: 07542337701
School of Health and Human Science, University of Essex, Wivenhoe Park, Colchester, CO43SQ

If you wish to contact a senior member of the University about the research or make a complaint please contact:

Professor Jo Jackson
Email: jo.jackson@essex.ac.uk
School of Health and Human Science, University of Essex, Wivenhoe Park, Colchester, CO43SQ

<u>Thank you for reading this information sheet and considering taking part in the study</u>

Appendix 2

Consent form

Title of the Project: Repeatability of minimum foot clearance and speed during crossing over an obstacle and stepping with and without dual task in healthy young adults
Researchers: Miss Sirirat Tohpreecha
Faculty: School of Health and Human Science
Supervisors Prof. Jo Jackson and Dr. Matthew Taylor

Please initial box

1. **I confirm that I** have read and understand the Information Sheet 3/07/2017 for the above study. I have had the opportunity to consider the information, ask questions and have had these questions answered satisfactorily. ☐
2. I understand that my participation is voluntary and that I am free to withdraw from the project at any time without giving any reason and without penalty. ☐
3. *Example of a risk statement:* I understand that, due to the nature of the stimulation used, entrainment sessions may not be suitable to individuals who suffer, or have suffered, from epileptic seizures, that I am aware of the potential risks associated with that, and I confirm that, to the best of my knowledge, I have never had epileptic seizures. ☐
4. I understand that the identifiable data provided will be securely stored and accessible only to the members of the research team directly involved in the project, and that confidentiality will be maintained. ☐
5. I understand that data collected in this project might be shared as appropriate and for publication of findings, in which case data will remain completely anonymous. ☐
6. I agree to take part in the above study. ☐

Participant Name	Date	Participant Signature
____________________	______________	___________________________
Researcher Name	Date	Researcher Signature
____________________	______________	___________________________

Appendix 3

Letter of ethic approval

University of Essex

03 August 2017

MISS S. TOHPREECHA
WILLIAM MORRIS TOWER
WM / 0 / 11 / 1
UNIVERSITY OF ESSEX
WIVENHOE PARK
COLCHESTER
ESSEX
CO4 3SQ

Dear Sirirat,

Re: Ethical Approval Application (Ref 16087)

Further to your application for ethical approval, please find enclosed a copy of your application which has now been approved by the School Ethics Representative on behalf of the Faculty Ethics Committee.

Yours sincerely,

Lisa McKee
Ethics Administrator
School of Health and Human Sciences

cc. Research Governance and Planning Manager, REO
Supervisor

Colchester Campus
Wivenhoe Park
Colchester CO4 3SQ
United Kingdom

School of Health and Social Care
T 01206 872854
E hsc@essex.ac.uk

www.essex.ac.uk
@Uni_of_Essex /uniofessex /uniofessex

Ethics Approval: Amendment Request

Name: Jo Jackson

Date: 1June 2017

Signature: J Jackson,

Description of Amendment:

Change to part of the protocol (new protocol below) This will add 5 additional trials (repetitions) to be recorded using the VICON system.

1 Walking in natural speed on the walkway 10 meters. (6 trials)
2 Walking in natural speed with dual task (holding a glass of water whilst walking) on the walkway 10 meters. (6 trials)
3 Crossing over low obstacle on the walkway 10 meters. (6 trials)
4 Crossing over low obstacle with dual task on the walkway 10 meters. (6 trials)
5 Crossing over high obstacle on the walkway 10 meters. (6 trials)
6 Crossing over high obstacle with dual task on the walkway 10 meters. (6 trials)
7 Stepping on low obstacle on the walkway 10 meters. (6 trials)
8 Stepping on low obstacle with dual task on the walkway 10 meters. (6 trials)
9 Stepping on high obstacle on the walkway 10 meters. (6 trials)
10 Stepping on high obstacle with dual task on the walkway 10 meters. (6 trials)

Low obstacle is 15 cm high

High obstacle is 20cm high

Reason for Amendment:

The focus for the study is currently on minimum foot clearance rather than turning so the turning trials have been removed and additional stepping trials included.

(For office use only)

The amendment has been approved. ☑

The amendment has not been approved ☐

Resubmission required ☐

Signature:

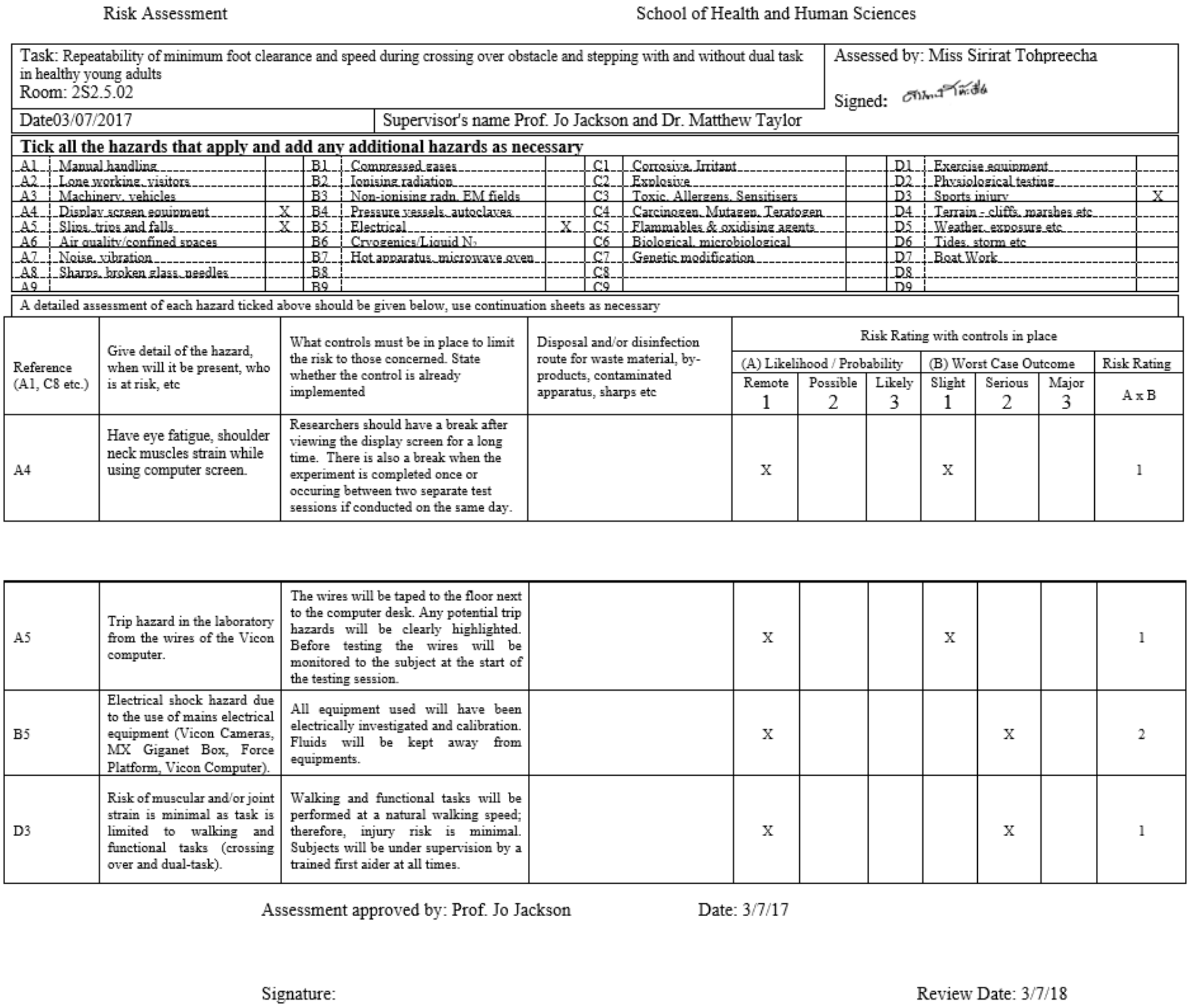
Name (in block capitals): W. Wilson

Department: S.HHS

Date: 9/06/17

Appendix 4

Risk Assessment Form



Risk Assessment — School of Health and Human Sciences

Task: Repeatability of minimum foot clearance and speed during crossing over obstacle and stepping with and without dual task in healthy young adults
Room: 2S2.5.02

Assessed by: Miss Sirirat Tohpreecha

Signed:

Date03/07/2017

Supervisor's name Prof. Jo Jackson and Dr. Matthew Taylor

Tick all the hazards that apply and add any additional hazards as necessary

A1	Manual handling		B1	Compressed gases		C1	Corrosive, Irritant		D1	Exercise equipment	
A2	Lone working, visitors		B2	Ionising radiation		C2	Explosive		D2	Physiological testing	
A3	Machinery, vehicles		B3	Non-ionising radn, EM fields		C3	Toxic, Allergens, Sensitisers		D3	Sports injury	X
A4	Display screen equipment	X	B4	Pressure vessels, autoclaves		C4	Carcinogen, Mutagen, Teratogen		D4	Terrain - cliffs, marshes etc	
A5	Slips, trips and falls	X	B5	Electrical	X	C5	Flammables & oxidising agents		D5	Weather, exposure etc	
A6	Air quality/confined spaces		B6	Cryogenics/Liquid N_2		C6	Biological, microbiological		D6	Tides, storm etc	
A7	Noise, vibration		B7	Hot apparatus, microwave oven		C7	Genetic modification		D7	Boat Work	
A8	Sharps, broken glass, needles		B8			C8			D8		
A9			B9			C9			D9		

A detailed assessment of each hazard ticked above should be given below, use continuation sheets as necessary

Reference (A1, C8 etc.)	Give detail of the hazard, when will it be present, who is at risk, etc	What controls must be in place to limit the risk to those concerned. State whether the control is already implemented	Disposal and/or disinfection route for waste material, by-products, contaminated apparatus, sharps etc	Risk Rating with controls in place						
				(A) Likelihood / Probability			(B) Worst Case Outcome			Risk Rating
				Remote 1	Possible 2	Likely 3	Slight 1	Serious 2	Major 3	A x B
A4	Have eye fatigue, shoulder neck muscles strain while using computer screen.	Researchers should have a break after viewing the display screen for a long time. There is also a break when the experiment is completed once or occuring between two separate test sessions if conducted on the same day.		X			X			1
A5	Trip hazard in the laboratory from the wires of the Vicon computer.	The wires will be taped to the floor next to the computer desk. Any potential trip hazards will be clearly highlighted. Before testing the wires will be monitored to the subject at the start of the testing session.		X			X			1
B5	Electrical shock hazard due to the use of mains electrical equipment (Vicon Cameras, MX Giganet Box, Force Platform, Vicon Computer).	All equipment used will have been electrically investigated and calibration. Fluids will be kept away from equipments.		X				X		2
D3	Risk of muscular and/or joint strain is minimal as task is limited to walking and functional tasks (crossing over and dual-task).	Walking and functional tasks will be performed at a natural walking speed; therefore, injury risk is minimal. Subjects will be under supervision by a trained first aider at all times.		X				X		1

Assessment approved by: Prof. Jo Jackson Date: 3/7/17

Signature: Review Date: 3/7/18

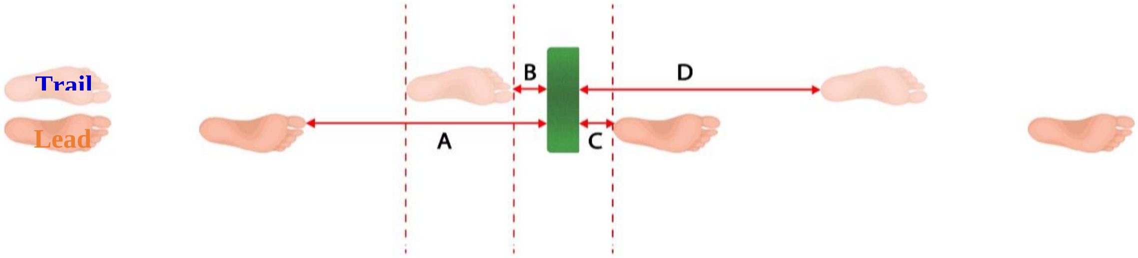
Appendix 5

Toe clearance measurement

The trials are labelled as Left and Right. Subjects were free to choose which limb they went over the obstacle with first. Therefore, it will not be Right leg first for all subjects and may even change for the same subject. Because of this we will use the terms LEADING and TRIALING LIMBS.

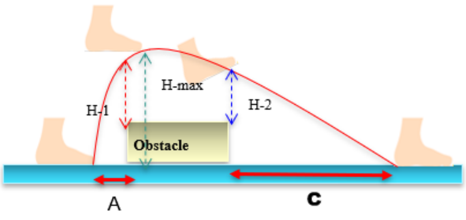
Leading limb – first limb to go over the obstacle

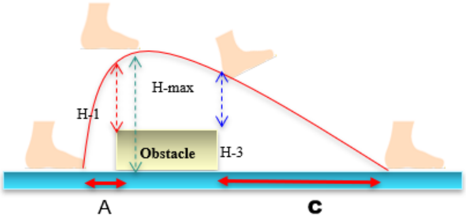
Trailing limb – the second limb to go over

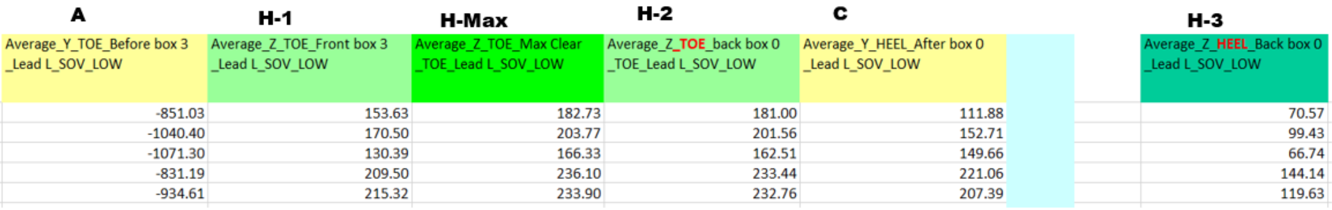


How can you identify these?

Leading Limb

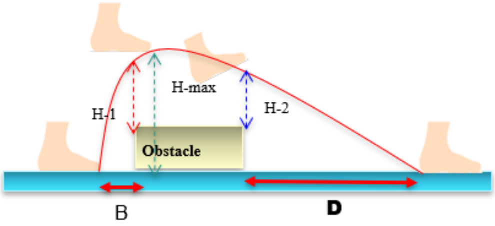


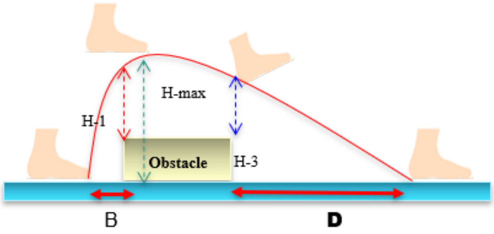


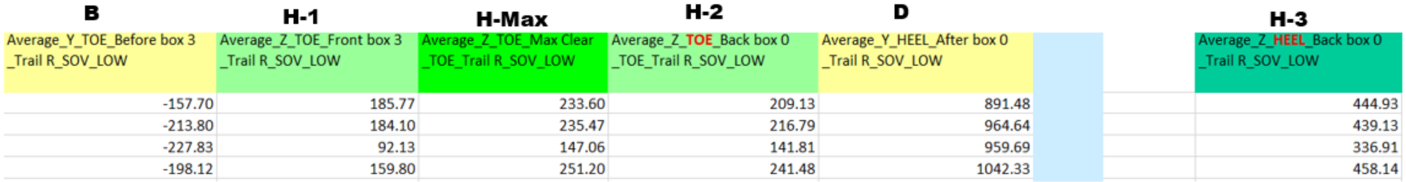


A	H-1	H-Max	H-2	C			H-3
Average_Y_TOE_Before box 3 _Lead L_SOV_LOW	Average_Z_TOE_Front box 3 _Lead L_SOV_LOW	Average_Z_TOE_Max Clear _TOE_Lead L_SOV_LOW	Average_Z_TOE_back box 0 _TOE_Lead L_SOV_LOW	Average_Y_HEEL_After box 0 _Lead L_SOV_LOW			Average_Z_HEEL_Back box 0 _Lead L_SOV_LOW
-851.03	153.63	182.73	181.00	111.88			70.57
-1040.40	170.50	203.77	201.56	152.71			99.43
-1071.30	130.39	166.33	162.51	149.66			66.74
-831.19	209.50	236.10	233.44	221.06			144.14
-934.61	215.32	233.90	232.76	207.39			119.63

Trailing limb







B	H-1	H-Max	H-2	D			H-3
Average_Y_TOE_Before box 3 _Trail R_SOV_LOW	Average_Z_TOE_Front box 3 _Trail R_SOV_LOW	Average_Z_TOE_Max Clear _TOE_Trail R_SOV_LOW	Average_Z_TOE_Back box 0 _TOE_Trail R_SOV_LOW	Average_Y_HEEL_After box 0 _Trail R_SOV_LOW			Average_Z_HEEL_Back box 0 _Trail R_SOV_LOW
-157.70	185.77	233.60	209.13	891.48			444.93
-213.80	184.10	235.47	216.79	964.64			439.13
-227.83	92.13	147.06	141.81	959.69			336.91
-198.12	159.80	251.20	241.48	1042.33			458.14

A = Step distance in front of box of Leading limb (cm)

B = Step distance in front of box of Trailing limb (cm)

C= Step distance away from box of Leading limb (cm)

D = Step distance in front of box of Trailing limb (cm)

H-1 = the vertical distance of the front edge of Z_TOE above BOX 3

H-2 = the vertical distance of the back edge of Z_TOE above BOX 3

H-3= the vertical distance of the back edge of Z_HEEL above BOX 3

H-max = the maximum vertical distance between Z_TOE and floor

Appendix 6

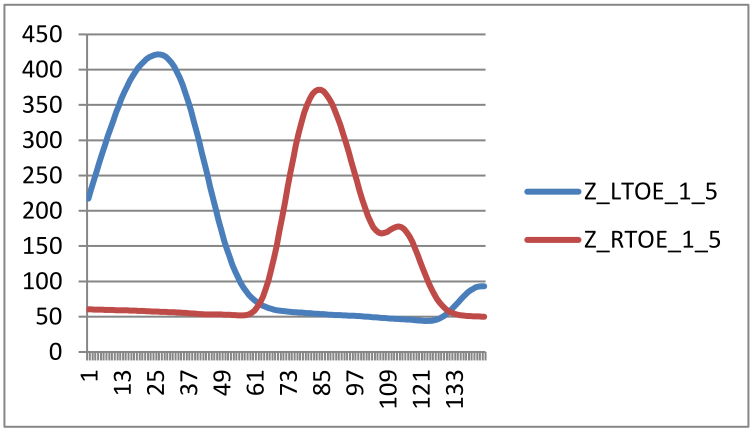
Example of MFC data calculation

report 1_SOV_5

1 Leading limb

1.1 Leading limb going over the front edge of the obstacle (Box0)

		Y_mm	Z_mm	Height above the box (toe or heel marker Z-box Z)
Leading limb	**BOX_0**	**670**	**171.6**	
	LTOE	685.56	407.38	235.78
	LHEE	684.48	303.37	131.77



1.2 Leading limb going over the back edge of the obstacle (Box1)

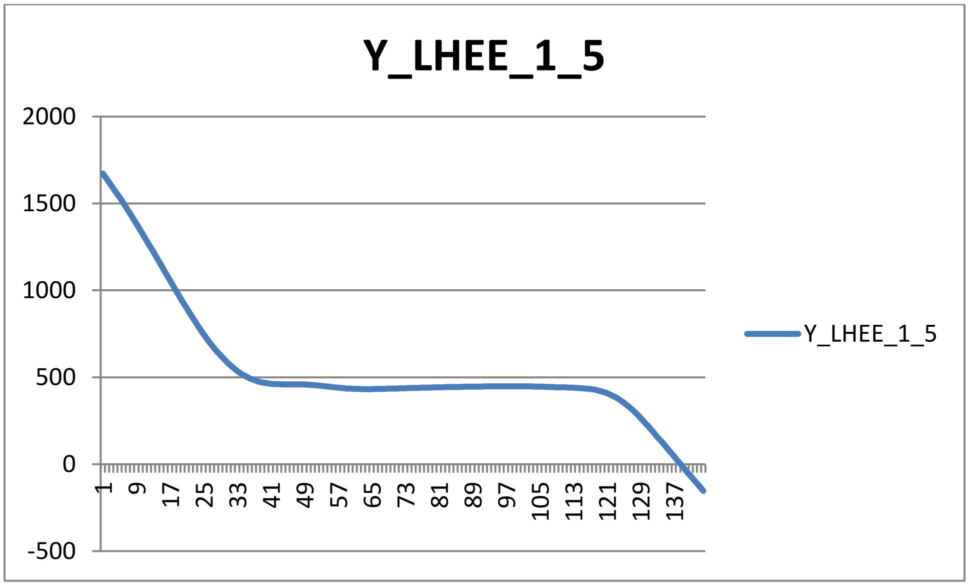
		Y_mm	Z_mm	Height above the box (toe or heel marker Z-box Z)
Leading limb	**BOX_1**	**936**	**171.6**	
	LTOE	929.77	368.12	196.52
	LHEE	935.90	350.95	179.35

1.3 Maximum Toe clearance ofLeading limb= 421.72mm (250.2 mm above the box)

1.4 Step length after obstacle of Leading limb (Y_HEEl)

step length away from BOX1 = BOX1_Y-LHEE_Y at the foot flat

step length away from BOX1 = 936-448 = 488mm



2 Trailing limb

2.1Trailing limb going over the front edge of the obstacle (Box0)

		Y_mm	Z_mm	Height above the box (toe or heel marker Z-box Z)
Trailing limb	BOX_0	670	171.6	
	RTOE	684.09	369.64	198.04
	RHEE	661.73	609.84	438.24

2.2 Trailing limb going over the back edge of the obstacle (Box1)

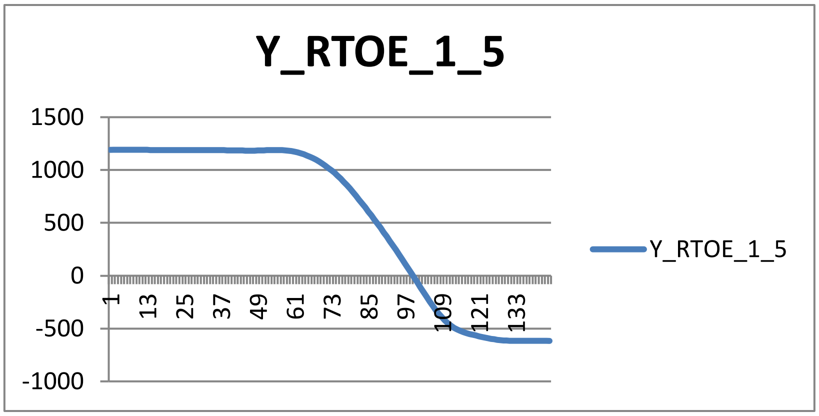
		Y_mm	Z_mm	Height above the box (toe or heel marker Z-box Z)
Trailing limb	BOX_1	936	171.6	
	RTOE	946.01	274.53	102.93
	RHEE	930.42	504.75	333.15

2.3 Maximum Toe clearance ofLeading limb = 371.54mm (199.94mm above from box)

2.4 Step length before obstacle of trailing limb (Y_TOE)

step length before obstacle BOX0 = -RTOE_Y at the foot flat-BOX0_Y

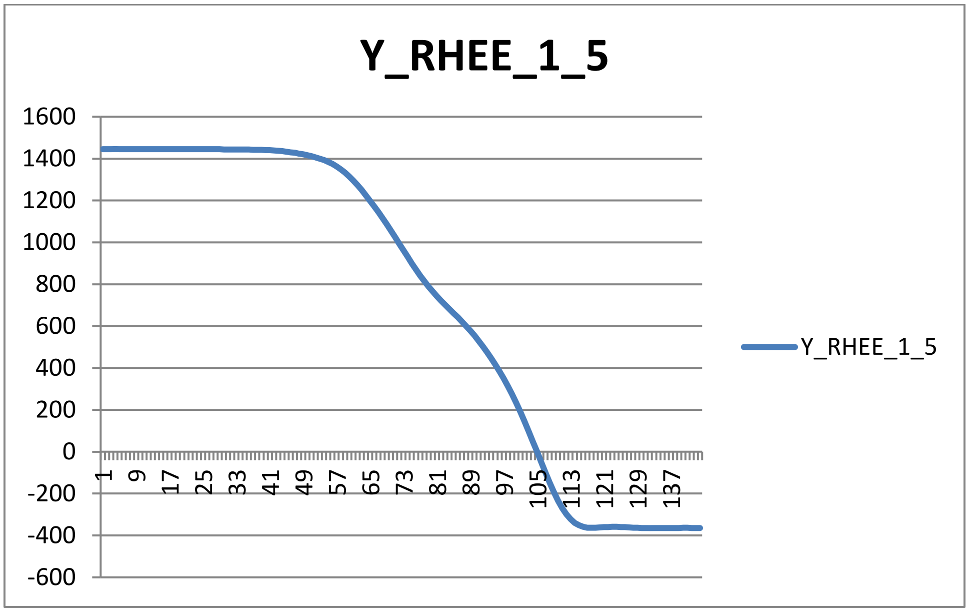
step length before obstacle BOX0 = 1188-670= 518mm



2.5Step length after obstacle of trailing(Y_TOE)

step length away from BOX1 = BOX1_Y-RHEE_Y at the foot flat

step length away from BOX1 = -364-936 = 1300mm



Example of data analysis of MFC in elderly adults

1 The height of toe and heel during BOX 0 and BOX1

	Box 0					Box 0				
	Left_Box0	Left_Box0	Right_Box0	Right_Box0	Max.Toe clear_ Left	Left_Box0	Left_Box0	Right_Box0	Right_Box0	Max.Toe clear_ Left
	Toe	Heel	Toe	Heel		Toe	Heel	Toe	Heel	
Number	136	137	122	123	206	131	131	123	124	209
Average	446.27	339.59	205.58	329.45	188.82	154.58	328.77	152.68	316.24	195.13
Max	483.12	541.31	310.20	519.94	352.12	476.37	495.12	287.30	505.77	353.99
Min	387.24	38.78	106.80	36.90		46.90	134.42	31.26	133.53	

2 Step length after an obstacle of leading limb

	Step length of Leading limb After_HEEL
Number	213
Average	136.83
Max	298.18
Min	20.62

3 Step length before after an obstacle of leading limb

	Step length of Trailing limb After_HEEL	Step length of Trailing limb Before_TOE
Number	213	212
Average	872.23	174.18
Max	1222.26	469.60
Min	656.81	57.93

Appendix 7

Vicon lab guide

1 Turn on the PC, Vicon system and force plate PC

2 Open nexus on Vicon PC and Bioware on Force plate PC.

In Bioware, go to ‘Tools’ and then ‘Bodyweight’ to link force plate to nexus

Prepare a data storage location

- Go to the communications pane, and click ‘Data Management’
- Click the ‘Main Eclipse menu’ button and then ‘Create’ (unless you want to use an existing database)
- Name your folder
- Click the green, ‘New Patient Classification’. Generally, this classifies a group of subjects such as Men/Women, Old/Young.
- Click the yellow, ‘New Patient’ button to add a new patient folder.
- Add a session to the patient folder, by clicking the grey ‘New Session’ button.
- Ensure the new session folder remains selected on the ‘Data Management’ tab.

Calibrate the Vicon cameras

- Make sure you are in LIVE mode. Go to camera view, and select all of the cameras
- Click ‘System Preparation Tools’ pane. Mask any unwanted reflections – Make sure the wand isn’t anywhere near the volume.
- Expand the ‘Calibrate Cameras’ and from the drop down, select which calibration device you are using.
- Click ‘Start’ in calibrate cameras and wave the calibration wand throughout the capture volume, ensuring that the markers on the calibration object are visible to the cameras.
- Continue to wave the wand until the process is completed and check the wand count (should be about 1000 frames).

Set the volume origin

- Display in 3D perspective
- In Systems Preparation, expand the ‘Set Volume Origin’ tab and make sure you have selected the correct calibration device from the drop down

- In the capture volume (over the force plate) place the calibration device down. Click ‘Start’ and then ‘Set origin’.

Create a new subject

- In the ‘Subjects’ pane, click ‘Create new subject from a labelling skeleton’ (middle of the 3) – Select Full body Plug in gait.
- Take and enter subject measurements.

Attach markers to subject

- See Plug in gait marker document.

Perform a static trial

- In the Communications pane, on the Data Management tab, ensure that you have created or opened the required database in which to store the data you will be capturing.
- Make sure nexus is in LIVE mode and display in 3D perspective
- Stand on force plate in the ‘motorbike’ position
- Capture the static trial
- Click reconstruct (grey bubbles button) or run the pipeline
- In the Subjects Resources tree, right-click on the subject node and attach the required PlugInGait Ai (Auto Initialise) labelling skeleton template.
- Run the Auto-initialise labelling pipeline.
- If this doesn’t work, manually label skeleton using Label/Edit tab
- Run static plug in gait pipeline
- Assess the results in 3D perspective. Ensure the markers are correctly labelled and connected.
- Save the trial and the labelling skeleton.

Perform a dynamic trial

- Make sure nexus is in LIVE mode
- Display in 3D perspective
- In the ‘Capture Tools’ pane, choose your trial type.
- In the System Resources tree, select Local Vicon System. In the Properties pane, in the General section, set Processing Output Level to Labels.
- Make sure the participant walks from the blue tank towards the fire exit to make ensure best coverage form the cameras
- Capture dynamic trials (If labelling error is obvious or persistent, restart the labeller with CTRL+R)
- Crop file to only include good quality data
- Run pipeline after capture - select the Reconstruct and Label and Plug-in Gait Dynamic pipelines.

Review trials and fill gaps

- Review data quality by playing through the trial using the Time Bar and/or looking at the information on the data Quality tab
- Ensure Nexus is Offline
- Display in 3D perspective view and optionally a graph view.
- In the nexus tool bar, click auto gap fill.

To use the Auto Intelligent Gap Fill pipeline:

- On the tools pane, click the Pipelines button
- Select Auto Intelligent Gap Fill from the drop-down list
- From the list of operations, select which gap-filling operations you would like to use. In the properties pane, you can modify the relevant settings to suit your trial.
- Either click ‘Run’ or you can use the ‘Auto Gap Fill’ button.
- Save the trial

To manually fill gaps:

- Ensure Nexus is in offline mode, and display in 3D perspective view and optionally a graph view.
- Set the region of interest of the trial that you wish to analyse. For example, if the capture includes the subject entering and leaving the capture volume, Vicon recommends that you set the range of frames to exclude these parts of the capture, as they are likely to include large gaps. To do this, on the time bar, move the blue range indicator triangles to select a range of frames and then right-click and click ‘Zoom to region of interest’.
- In the subject’s tree, make sure the correct subject is selected.
- In the Label/Edit tools pane, in the Gap Filling section, any markers whose trajectories contain gaps within the selected range of frames are listed in the Trajectory column, with the number of gaps for each trajectory identified in the #Gaps column and the largest gap length in the Max Gap Length column.
- In the Trajectory column, click on the trajectory whose gaps you want to fill. Nexus will automatically show you where the gap is by placing blue cones at the start and end of the gap. A red dotted line will run between the cones to display the shape of the trajectory if a spline fill editing operation is run.
- In the Range section, view the range values to identify the size of the gap and use the buttons to navigate between the gaps in the selected trajectory.
- You can edit the gap range in 3D perspective view by dragging the blue cones.
- Choose appropriate fill tool and click ‘Fill’ or to have nexus fill all the gaps in the selected trajectory with the currently chosen type of gap filling, click ‘All’. The options are:
- *Spline fill*: Performs a cubic spline interpolation operation to fill the currently selected gaps. Use it when you have suitable frames with no gaps on either side of the gap.
- *Pattern fill:* Uses the shape of another trajectory without a gap to fill the selected gap. Use this tool only if there is a suitable marker with a trajectory like the one whose gap you wish to fill.

- *Rigid body fill:* Use this option when a rigid or semi-rigid relationship exists between markers.
- *Kinematic fill:* This option uses information about the connection of markers to segments in the labelling skeleton template (VST). For this option to be available, you may first need to run the Kinematic Fit pipeline.
- *Cyclic Fill:* For trials that contain captured data that is cyclic in nature. This option uses patterns from a missing marker from earlier or later gait cycles to fill gaps.
- Nexus will reduce the entry in the #Gaps column by one and move onto the next gap. Repeat steps for all trajectories.
- Save the trial.