The effects of high cushioned versus minimal cushioned shoes on dynamic postural stability of older adults during obstacle crossing

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Abstract

Footwear can affect postural stability in individuals, particularly in elderly people. Aging-related decline in postural stability, particularly in the mediolateral (ML) direction, is a risk factor for falls and fall-related injuries among older adults. This study aimed to investigate the effects of high cushioned and minimal shoes on dynamic postural stability in ML during obstacle crossing in defined older and younger adults. Six healthy older adults (50–60 years old, body weight: 74.8 kg, body height: 168.0 cm) and six healthy younger adults (18–32 years old, body weight: 73.8 kg, body height: 174.8 cm) participated in the study. A Vicon motion analysis system with 10 optical cameras was used to capture the obstacle (20 cm height) crossing motion of the participants at 200 Hz, and ground reaction forces of obstacle crossing were collected at 1000 Hz. Motion data of obstacle crossing were collected at three shoe conditions, namely, minimal shoe, high cushioned shoe and barefoot (control). Data from five trials of obstacle crossing for each shoe condition were processed using Vicon Nexus software 2.11.0 and Matlab R2013b. Displacement and velocity of centre of mass (COM) in the ML direction, COM–centre of pressure (COP) ML separation, step length, step velocity, toe clearance, pre-horizontal distance, hip flexion angle and hip abduction angle during obstacle crossing were examined. One-way ANOVA with pairwise analysis showed that toe clearance was significantly larger in the high cushioned shoe conditions than in the minimal shoe and barefoot conditions in older adults (high cushioned shoes vs. barefoot: $p = 0.019$; cushioned shoes vs. minimal shoes: $p = 0.031$) and younger adults (high cushioned shoes vs. barefoot: $p = 0.016$; high cushioned shoes vs. minimal shoes: $p = 0.000$). No significant difference in the measures was found between the minimal shoe and barefoot conditions in each group. Compared with older adults, younger adults showed significantly larger step length in barefoot condition ($p = 0.000$) and minimal shoe ($p = 0.016$). Independent t-test for examination

of the significant difference of the means of each measure when the shoe condition was changed showed that only step length and step velocity were significantly different between older and younger adults. When the shoe condition was changed from minimal shoe or barefoot to high cushioned shoe, older adults showed significantly bigger change in step velocity (10.04 ± 4.39 cm/s for older; 1.87 ± 0.81 cm/s for younger; $p = 0.034$) and step length (14.26 ± 6.99 cm for older; 2.086 ± 1.13 cm for younger; $p = 0.041$) than younger adults. This result indicates that older adults had 23% greater total range of step length and 12% greater total range of step velocity compared with younger adults when shoe condition changed. Moreover, older adults showed 16% smaller total range in their maximal COM-COP ML separations than younger adults when shoe condition changed. It is concluded that high cushioned shoes can influence dynamic postural stability in the ML direction during obstacle crossing in younger and older adults. The minimal shoe and barefoot conditions did not show significant influence on postural stability in the ML direction during obstacle crossing in-older and younger adults. The minimal shoe on dynamic postural stability in the ML direction is not significant. Age differences in dynamic postural stability in the ML direction during obstacle crossing were found at the same shoe conditions. Moreover, when shoe condition was changed, shoe cushioning conditions affected postural stability to a larger extent in older adults compared with younger adults. The high cushioned shoe led to a more challenged postural stability in adults aged 50 to 60 than younger adults aged 18 to 32.

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List of Relevant Acronyms

COM: center of mass

COP: center of pressure

ML: mediolateral direction

COM-COP AP separation: the distance between COM and COP in anteroposterior direction

COM-COP ML separation: the distance between COM and COP in ML

BOS: Base of support

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Chapter 1: Introduction

1.1 Research background

Postural stability is essential to the safe and efficient performance of numerous daily living activities. Maintaining postural stability is achieved by integrating sensory inputs from the visual, vestibular and proprioception systems with adequate muscle strength, appropriate neuromuscular timing and joint mobility (Nashner & McCollum, 1985; Prince, Corriveau, Hébert, & Winter, 1997). Decreased postural stability is one of the risk factors leading to falls in older adults (Barbieri & Vitório, 2017). In Canada, fall and fall-related injuries are the number one reason resulting in older adults' hospitalisations and affect not only individuals but also their families, caregivers and the healthcare system (Stinchcombe, Kuran, & Powell, 2014). Various factors, such as age and aging, shoes and walking conditions (crossing an obstacle), can influence postural stability. Therefore, studying the influencing factors of postural stability will be helpful in the prevention of fall-related injuries.

Maintaining posture and balance during locomotion requires dynamic postural stability. Dynamic postural stability is the ability to shift and control the centre of mass (COM) within the fixed or moving base of support (BOS) (Nashner & McCollum, 1985; Pickerill & Harter, 2011; Winter, 1995). Subsequently velocity and displacement of COM have been used to examine dynamic postural stability (Hof, Gazendam, & Sinke, 2005). Given that BOS is the possible range of the centre of pressure (COP), which is the origin of ground reaction vector, COP measurement is studied in dynamic postural stability (Babič, Karčnik, & Bajd, 2001). Research demonstrated that the decline in dynamic postural stability in the mediolateral (ML) direction is closely associated with falls and re-occurrence of falls in elderly people (Lord, Rogers, Howland, &

Fitzpatrick, 1999). Thus, dynamic postural stability is thought to be a good predictor of future falls in elderly people (Piirtola & Era, 2006).

Gait analysis during obstacle crossing has been applied to research dynamic postural stability. Individuals encounter numerous obstacles in their daily lives (Chen, Ashton-Miller, Alexander, & Schultz, 1991). Studies on biomechanics showed that compared with ground walking, to safely cross obstacles, individuals should have a greater toe clearance, greater hip angles, greater COM displacement, faster COM velocity, and greater COM-COP ML separation (Hahn & Chou, 2004; Jian, Winter, Ishac, & Gilchrist, 1993; Li, 2016; Lugade, Lin, & Chou, 2011). This condition indicates that obstacle crossing exposes individuals to a great muscular demand (Hahn & Chou, 2004) and requires a greater muscular effort compared with ground walking. Healthy older adults have decreased muscle strength, and as a result, obstacle crossing can be a challenge for them (Hahn & Chou, 2004). Therefore, gait analysis of obstacle crossing had been applied in the examination of dynamic postural stability in healthy older people and older people with pathological conditions, such as stroke (Li, 2016; Said, Goldie, Patla, Sparrow, & Martin, 1999).

Aging leads to a decreased postural stability during obstacle crossing (Choy, Brauer, & Nitz, 2003; Hageman, Leibowitz, & Blanke, 1995). This condition is linked to the reduced musculoskeletal strength (Alcock, Vanicek, & O'Brien, 2013; Chamberlin, Fulwider, Sanders, & Medeiros, 2005). Poor postural stability in older adults during obstacle crossing is manifested by large COM displacements, fast COM velocities, and short COM-COP separations (Hahn & Chou, 2004). In addition, aging affects the temporospatial and kinematic parameters associated with postural stability, such as step velocity, step length, obstacle clearance distances and hip angles. Older adults show shorter step length, slower step velocity, more abducted and flexed hip joints

and larger obstacle clearance distances compared with younger adults (Espy, Yang, Bhatt, & Pai, 2010; Lu, Chen, & Chen, 2006; Maki, 1997). While crossing obstacles, compared with young people, older adults exhibit more conservativeness, indicating increased cautiousness, gait strategies to compensate for the reduced muscle strength and declined postural stability (Lu et al., 2006).

Shoes are interfaces between the sole of the foot and the ground, and they can influence postural stability (Menz & Lord, 1999). Footwear affects postural stability by altering foot position awareness, foot tactile sensation, plantar pressure distribution, lower extremity biomechanics and the level of fatigue (Brenton-Rule, Bassett, Walsh, & Rome, 2011). High cushioned shoes, also known as comfort shoes, decrease the cutaneous sensation and place the ankle in a plantar flexed position (Aboutorabi, Arazpour, Bahramizadeh, Hutchins, & Fadayevatan, 2016; Cudejko, Gardiner, Akpan, & D'Août, 2019). This condition changes the lower extremity biomechanics, especially by increasing the motion of COM and altering its location (Aboutorabi et al., 2016). Consequently, the individual's body will make additional adjustments to maintain its dynamic postural stability (Aboutorabi et al., 2016; Cudejko et al., 2019). Meanwhile, shoes with less or no cushioning, also known as minimal shoes, benefit postural stability by increasing foot position awareness and cutaneous sensation. Thus, these shoes can minimise the risk of falls in older adults (Cudejko et al., 2019; Iglesias, de Bengoa Vallejo, & Peña, 2012; Robbins, Gouw, & McClaran, 1992). Barefoot movement leads to the best dynamic postural stability by providing the best plantar information and foot position awareness (Cudejko, Gardiner, Akpan, & D'Août, 2020; Lord & MBBS, 1996; Menant, Steele, Menz, Munro, & Lord, 2008a).

The available research evidence on how shoes affect postural stability mostly focuses on static postural stability. A limited number of studies examined shoe effects on dynamic postural

stability during ground walking (Cudejko et al., 2020; Lord & MBBS, 1996). Knowledge about the effects of shoe cushioning on dynamic postural stability, especially in ML direction, during obstacle crossing is lacking. Thus, studying the influence of shoes on postural stability in ML during obstacle crossing will enable us to advance the understanding of this topic in the studied population.

1.2 Research Objectives

This study aimed to investigate the effects of high cushioned and minimal shoes on dynamic postural stability in ML during obstacle crossing in defined older and younger adults.

1.3 Variables

1.3.1 Independent Variables

1. Shoe cushioning: Two types of shoes with different cushioning were evaluated in this study: high cushioned and minimal shoes. Barefoot condition was considered the control variable in this study, and it was used as the baseline for two other shoe conditions (Aboutorabi et al., 2016).

2. Age: One group of younger adults (18–32 years old) and one group of older adults (50–60 years old) were recruited.

1.3.2 Dependent Variables

1. Step velocity and step length

One crossing stride was defined by the heel strike of the trailing limb before the obstacle to the heel strike of the same limb after the obstacle. A marker for motion analysis was placed on the shoe heel. The average velocity of the left and right heel markers was considered the step

velocity. Step length was defined as the horizontal distance between the trailing heel marker before the obstacle and the leading heel marker after the obstacle in the sagittal plane (Figure 1). Published research has shown that while crossing obstacles, older adults exhibit a slow step velocity and a short step length (Chen et al., 1991; Hahn & Chou, 2004). Slow step velocity and short step length indicate poor postural stability because of the prolonged time needed to monitor the steps and control limb trajectory when crossing an obstacle (McKenzie & Brown, 2004; Stegemöller et al., 2012).

2. Pre-horizontal and toe clearance distances

Pre-horizontal distance is defined as the horizontal distance between the toe marker on the trailing limb and the obstacle prior to crossing (Figure 1). Toe-clearance is defined as the vertical distance between the toe marker and the obstacle at the moment when the toe of the crossing foot (leading foot) is over the obstacle (Figure 2). Older adults exhibit a high obstacle toe clearance and great pre-horizontal distance during obstacle crossing (Patla, Prentice, & Gobbi, 1996). This process was thought to be a safe strategy for older adults during obstacle crossing (Chou & Draganich, 1998a). Such assumption was due to the reduced muscle strength demand caused by a considerable pre-horizontal distance, whereas a great toe clearance needs increased hip abduction and flexion angles that will help the COM to be closer to the BOS and COP.

3. Hip flexion and abduction angles

Hip angles were measured at the instance of obstacle crossing when the leading toe was above the obstacle. Research revealed that while crossing obstacles, older adults show increased flexion and abduction in their hip joints. This result is due to the correlation of the hip flexion angle with toe clearance, which influences the location of the COM (Lu et al., 2006). A more abducted and flexed hip joint draws the body COM closer to the BOS, which improves postural

stability and provides a safer strategy to cross an obstacle (Lu et al., 2006). Furthermore, hip abductor activities during the swing period determines the placement of foot in ML (Winter, 1995).

4. COM ML velocity, COM ML displacement and COM-COP ML separation

The COM ML displacement and velocity are measures for postural stability (Winter, 1995). A faster and greater motion of COM in ML can be observed in older adults and patient with poor postural stability, which reflects the difficulty in maintaining postural stability (Hahn & Chou, 2003). The COM and its interaction with COP and COM-COP separation was evaluated to improve the understanding of postural stability (Yu et al., 2008). COM-COP separation is defined as the distance between the COM and the corresponding COP during obstacle crossing. A small COM-COP separation had been reported for older adults, and this result was associated with a decreased muscular strength and linked to a poor postural stability (Hahn & Chou, 2004; Jian et al., 1993; Li, 2016; Lugade et al., 2011). COM-COP separation had been shown to be a sensitive measure of postural stability (Moudy, Patterson, & Bugnariu, 2020).

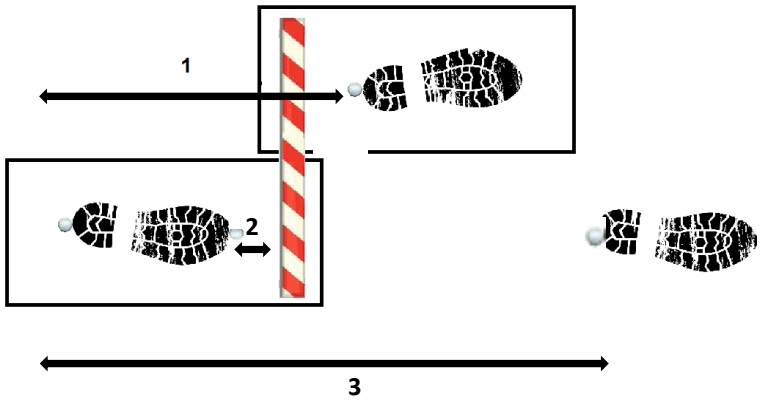


Figure 1. Illustration of crossing step, pre-horizontal distance, and crossing stride during obstacle walking. Note: 1. Crossing step length; 2. Pre-horizontal distance; 3. Crossing stride.

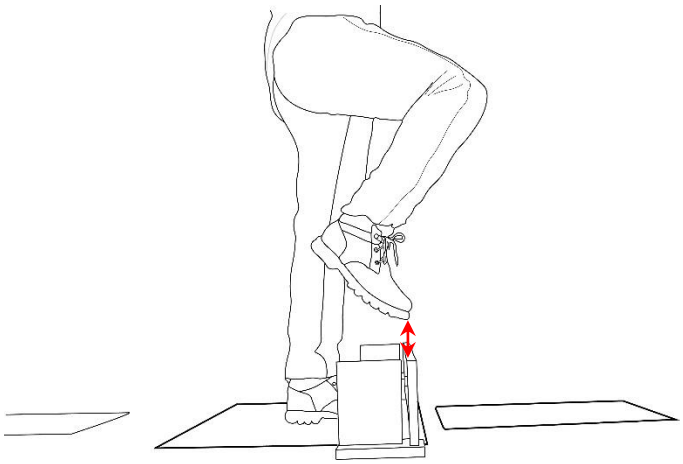


Figure 2. Illustration of vertical toe clearance

1.4 Hypothesis

We hypothesised that 1) the participants will show improved dynamic postural stability measures when wearing minimal shoes during obstacle crossing in comparison with high cushioned shoes. Furthermore, the participants will show the best postural stability measures while being barefoot. Finally, the dynamic postural stability measures while wearing minimal shoes will be close to the barefoot condition; 2) the younger adults will show better postural stability measures in all shoe conditions compared with older adults; 3) shoe cushioning conditions will affect postural stability to a larger extent in older adults compared with younger adults.

Wearing of minimal shoes compared with the high cushioned shoe will lead to the following performances:

1. Greater step velocity and longer step length;
2. Smaller pre-horizontal distance and smaller toe clearance;
3. Smaller crossing hip flexion and abduction angles;
4. Decreased average COM ML velocity and maximal COM ML displacement;

5. Increased maximal and average COM-COP ML separation.

1.5 Delimitations

In this study, four delimitations were applied as follows.

1. Older adults of the participants referred to the people aged 50–60 years old. The results of this study are only applicable to this population.

2. Younger adults of the participants referred to the people aged 18–32 years old. The results of this study are only applicable to this population.

3. Cushioned shoes refer to Hoka One One (Bondi 6) with EVA (ethylvinylacetate) midsoles that attenuate impact forces and help shock absorption. The results of this study are only applicable to this kind of shoes.

4. Minimal shoes refer to Xero Shoes Prio with no midsoles and the least cushioning feature. The results of study are only applicable to this kind of shoes.

1.6 Relevance

The findings of the study may further the understanding of the effects of shoes on dynamic postural stability of older and younger adults during obstacle crossing. The results can also provide scientific evidence that may help older adults in the selection of shoes and fall prevention.

Chapter 2: Literature review

Postural stability is an essential factor affecting the risk of falls amongst older adults (Barbieri & Vitório, 2017). Postural stability is the ability of individuals to maintain their centre of mass (COM) position within the stability limits (Tiedemann, Sherrington, & Lord, 2007). Stability limits are boundaries in which the body can maintain its position without changing the base of support (BOS) (Tiedemann et al., 2007). Postural stability requires a complex interaction of musculoskeletal system, sensory system and nervous system (Tiedemann et al., 2007). It can be classified into static and dynamic postural stability. Static postural stability is defined as the ability to limit the movement of COM when the BOS remains fixed (Nashner & McCollum, 1985). Dynamic postural stability is the ability to shift and control COM within the fixed or moving BOS (Nashner & McCollum, 1985; Pickerill & Harter, 2011; Winter, 1995). Age-related changes in the functions of musculoskeletal and sensory systems result in decreased postural stability (Borah, Singh, Wadhwa, & Bhattacharjee, 2007; Tiedemann et al., 2007). External factors, such as shoes, challenged walking conditions or obstacle crossing, can also influence postural stability (Galna, Peters, Murphy, & Morris, 2009; Menz & Lord, 1999). This literature review discusses the research in postural stability during walking and obstacle crossing as well as the influence of shoes and age on postural stability.

2.1 Gait and postural stability of older adults

Maintaining postural stability whilst walking is a complicated task, particularly for older adults, because the COM departs from the BOS during walking (Menz, Lord, & Fitzpatrick, 2003). During a major period of walking, the body is supported by a single limb, and the COM is located outside of the boundaries of BOS (Menz et al., 2003). Older adults may experience decreased postural stability, thereby increasing fall risks (Qiu et al., 2012). Gait analysis has been applied to

examine gait and posture; changes in temporospatial and kinematic parameters can indicate an alteration in postural stability (Winter, 1995). Age-related changes in musculoskeletal function and diminished somatosensory function, such as declined cutaneous sensation, are amongst the factors influencing gait and posture. In the following section, the dynamic postural stability studies in normal walking and obstacle crossing in older adults are reviewed.

2.1.1 Aging and gait

Slow gait velocity and short step length in older adults are well documented in the literature (Beijersbergen, Granacher, Gäbler, DeVita, & Hortobágyi, 2017; Boyer, Johnson, Banks, Jewell, & Hafer, 2017; Bus, 2003; Chamberlin et al., 2005). Changes in gait velocity and step length are associated with decreased postural stability in older adults (Espy et al., 2010; Maki, 1997). Ageing causes biomechanical alterations in the temporospatial changes in the gait of older adults (Alcock et al., 2013; Chamberlin et al., 2005). Reduced muscle strength and reduced joint range of motion resulting from musculoskeletal, physiological and neuromuscular changes due to ageing are attributed to biomechanical alterations (Alcock et al., 2013). Thus, older adults tend to adopt different gait strategies, such as altering the temporospatial gait parameters, to make up for the changes mentioned (Alcock et al., 2013; Espy et al., 2010). Maki (1997) investigated the relationship between temporospatial parameters and risk of falls in 14 healthy older adults during ground walking. He found that short step length and slow gait velocity are associated with decreased postural stability and falls in older adults. Moreover, the changes in these two variables are adaptation to stabilize their bodies. Shkuratova et al. (2004) further supported Maki's finding by examining the effects of ageing on postural stability and balance control during normal walking (Shkuratova, Morris, & Huxham, 2004).

Older adults spend much time during the stance phase of the gait, and they have short step length, leading to a slow gait velocity (Alcock et al., 2013). Changes in temporospatial gait characteristics, including gait velocity, are associated with poor postural stability and falls in older adults (Topp, Mikesky, Dayhoff, & Holt, 1996; Whipple, Wolfson, & Amerman, 1987). The conclusion indicating that the gait velocities of older adults are slower than those of younger adults is the most consistent finding amongst the studies (Prince et al., 1997; Winter, 2009). Step velocity has a strong correlation with postural stability (Espy et al., 2010). Individuals lose 1.2% of their gait velocity through ageing every year (Alcock et al., 2013; Kirkwood et al., 2011). Physical limitations, such as musculoskeletal, neural and biological declines, account for the slow gait velocity in older adults (Alcock et al., 2013; Kirkwood et al., 2011). Alcock et al. studied gait velocity and changes in gait associated with ageing in 39 healthy older women. They concluded that deterioration in gait velocity represents the loss of musculoskeletal function, namely, declines in muscle and neural functions and biological declines in older adults. These declines include diminished leg strength and range of motion (Alcock et al., 2013). Fear of falls can also affect gait velocity (Maki, 1997). Older adults with the fear of falls adopt cautious gait strategies to improve their postural stability (Chamberlin et al., 2005; Maki, 1997).

The step length of older adults is shorter than that of young adults, and step length is associated with postural stability (Espy et al., 2010). Schulz et al. conducted gait analysis in young and older adults and reported that the maximum step length of younger adults is 40% greater than that of the older adults (Schulz, Ashton-Miller, & Alexander, 2008). Individuals adjust the boundaries of their BOS by changing their step length and step width depending on the motion of their COM (Young & Dingwell, 2012). Short step length alters the postural stability in ML direction by placing the COM closely to the BOS. This conservative strategy can improve stability,

and it can be considered a modification for a slow gait velocity (Espy et al., 2010; Young & Dingwell, 2012). Chamberlin et al. studied the association of fear of falls with the reduced step length in older adults during walking. They stated that fear of falls is associated with reduced step velocity and step length (Chamberlin et al., 2005). Prince et al. conducted a comprehensive review on ageing and its effects on mobility. They mentioned neurological and physiological changes as factors associated with ageing affecting gait parameters, such as step length and step velocity; neurological changes include loss of motor units and sensitivity, peripheral troubles, increased reaction time and increased rate of brain loss, whereas physiological changes include decreased muscle strength (Prince et al., 1997). In conclusion, the age-related biomechanical changes in older adults and fear of falls can lead to postural instability, which can be represented in short step length and slow step velocity.

2.1.2 Dynamic postural stability and obstacle crossing

Obstacle crossing can be highly demanding for dynamic postural stability particularly in older adults (Blake et al., 1988). Obstacles such as floorings, carpet edges, sidewalk curbs and electrical cords can be found indoors and outdoors (Chen et al., 1991). Compared with level walking, stepping over an obstacle can be a considerable challenge to the dynamic postural stability, particularly in older adults, because of two main reasons. Firstly, an individual experiences a long swing period whilst crossing an obstacle, indicating a long single-stance phase. The instability caused by COM being outside the BOS for a long time can cause a high chance of dynamic postural instability and tripping (Austin, Garrett, & Bohannon, 1999; Li, 2016). Secondly, a chance exists that either the trailing or the leading limb makes contact with the obstacle, possibly leading to tripping and losing balance (Benedetti, Berti, Maselli, Mariani, & Giannini, 2007; Pan, Hsu, Chang, Renn, & Wu, 2016). During obstacle crossing, the individual experiences a long

swing period, and the BOS is limited to a single foot for a long time. Thus, the chance of experiencing postural instability on the unsupported side is high (Chou, Kaufman, Hahn, & Brey, 2003; Lord, Rogers, Howland, & Fitzpatrick, 1999; Rogers, Hedman, Johnson, Cain, & Hanke, 2001). Therefore, obstacle crossing has been used as an approach to assess dynamic postural stability in ML direction.

Age affects the success rates in obstacle crossing (Weerdesteyn, Nienhuis, & Duysens, 2005). Chou and coworkers (1997) compared the postural stability of older adults with that of younger adults whilst crossing obstacles with different heights. They stated that regardless of obstacle height, obstacle crossing for older adults can be more demanding than that for younger adults (Chou & Draganich, 1997; Chou et al., 2003). Galna et al. made a comprehensive review on obstacle crossing in older adults. They mentioned that age-related deterioration of locomotion skills is associated with falling over obstacles in older adults (Galna et al., 2009). Dynamic postural stability measures associated with obstacle crossing include crossing step length, step velocity, foot clearance distance, COM displacement and velocity and COM–centre of pressure (COP) ML separation distances (Li, 2016; Said et al., 1999). Dynamic postural stability in ML direction is more important than anteroposterior direction because it is closely associated with falls and recurrence of falls in older people (Lord, Rogers, Howland, & Fitzpatrick, 1999). Dynamic postural stability is a good predictor of future falls in elderly people (Piirtola & Era, 2006).

2.1.2.1 Step velocity and step length

Step length and step velocity have been used in studying dynamic postural stability during obstacle crossing amongst older adults. The crossing velocity and step length of older adults are slower and shorter than those of younger adults whilst crossing obstacles (Alcock, Galna, Perkins, Lord, & Rochester, 2018; Chen et al., 1991; Menz et al., 2003; Tiedemann et al., 2007). Short step

length and slow gait, which are associated with ageing, can be a strategy to respond to postural instability (Alcock et al., 2013; Chamberlin et al., 2005; Menz et al., 2003). When individuals are asked to increase their gait velocity, older adults tend to increase their cadence and still walk with a short step length. However, younger adults tend to adopt the opposite approach (Skelton, 2001). Chen et al. (1991) examined the strategies of crossing obstacles by measuring the temporospatial measures in younger adults and older adults during obstacle crossing. They found that the strategies adopted by older adults during obstacle crossing, presented by short step lengths and slow gait velocities, are more conservative than those by younger adults (Chen et al., 1991; Tiedemann et al., 2007). Menz et al. evaluated acceleration patterns, velocity, step length and postural stability in older adults whilst walking over obstacles. They determined short step length as a strategy to improve postural stability in older adults (Menz et al., 2003). McKenzie and Brown compared the gait kinematics of older adults with those of younger adults whilst initiating an obstacle. They mentioned fear of falls as a key factor influencing step velocity and step length whilst crossing an obstacle (McKenzie & Brown, 2004). During obstacle crossing, older adults tend to adopt a conservative gait; in particular, they adopt short step length and a slow gait velocity as a response to their fear of falls (McKenzie & Brown, 2004). According to Pan et al., the slow gait velocity whilst crossing predicted obstacles may benefit older adults' postural stability. Furthermore, they stated that the slow gait velocity in older adults is a safe strategy; it also provides them a long time to adjust their limbs and allows them to cross the obstacle safely (Pan et al., 2016). These findings in step length and step velocity from obstacle crossing studies are quite consistent with the previous research evidence (Di Fabio, Greany, & Zampieri, 2003; Paquette & Vallis, 2010).

2.1.2.2 Toe clearance, pre-horizontal distance, and hip angles

Pre-horizontal distances, toe clearance, hip flexion angle and hip abduction angle are associated with postural stability during obstacle crossing (Patla et al., 1996; Weerdesteyn et al., 2005). Pre-horizontal distance is defined by the distance between the toe of the trailing limb and obstacle prior to crossing over the obstacle. Toe clearance is defined as the distance between the toe marker and the obstacle at the instance when the crossing foot is above the obstacle. Hip flexion and abduction angles are measured when the leading toe is above the obstacle (Li, 2016). These variables, which have been commonly used in examining postural stability and predicting falls during obstacle crossing (Galna et al., 2009; McKenzie & Brown, 2004; Patla et al., 1996), influence one another (Chen et al., 1991). Trailing foot placement before the obstacle (pre-horizontal distance) affects the vertical toe clearance (Chen et al., 1991). Chen et al. (1991) reported that a short pre-horizontal distance leads to a small toe clearance (Chen et al., 1991). Moreover, reducing pre-horizontal distance lessens hip flexion and abduction angle, leading to a small toe clearance (Chou & Draganich, 1998b; Li, 2016).

Pre-horizontal distance has been used to predict falls (Patla et al., 1996; Stegemöller et al., 2012). Patla et al. studied how locomotion can be affected by ageing. They stated that older adults attempt to maintain large pre-horizontal distance during obstacle crossing. This crossing pattern is associated with the fear of falling, leading to a safe crossing strategy in older adults (Patla et al., 1996). Chou et al. (1998) studied the relationship amongst pre-horizontal distance, toe clearance and hip flexion angle during crossing obstacles with different heights. They concluded that short pre-horizontal distances lead to small trailing toe clearance and small hip angles. The short pre-horizontal distance and a small toe clearance lead to a high chance that the trailing limb makes contact with the obstacle. The possible reason behind this evidence is that when the trailing pre-

horizontal distance is short, the individual has a minimal swing time from toe off to clear the obstacle successfully (Chou & Draganich, 1998b). McKenzie and Brown studied the effects of fear of fall on postural stability in older adults and younger adults whilst crossing obstacles. Although they mentioned that horizontal distances are affected by fear of falls, older adults do not have a great pre-horizontal distance, as they had hypothesized in their study. The experiment design of McKenzie and Brown possibly did not expose older adults to any postural threat. As a result of not experiencing any fear of falls, they did not show any changes in their horizontal distances (McKenzie & Brown, 2004). Chen et al. compared the kinematics of 24 healthy older adults with those of 24 healthy younger adults whilst stepping over an obstacle. They also mentioned that the pre-horizontal distance of older adults is larger than that of younger adults (Chen et al., 1991). A safe strategy for obstacle crossing consists of an increased pre-horizontal distance in older adults compared with that in younger adults. This strategy makes an appropriate positioning which is not too close to the obstacle (Chen et al., 1991; McKenzie & Brown, 2004; Patla et al., 1996). In addition, older adults can have sufficient time to monitor their leading limb trajectory and make modifications. Gathering visual information during obstacle crossing is an important factor. Older individuals have slow gait when crossing obstacles. This scenario suggests that a long time is needed to gather visual information in older adults. Thus, a substantial pre-horizontal distance provides an individual a long time to gather visual information (McKenzie & Brown, 2004; Muir, Haddad, van Emmerik, & Rietdyk, 2019; Muir, Rietdyk, & Haddad, 2014). Another possible reason leading to large pre-horizontal distance could be that lower extremity strength in older adults is a major factor in balance and postural stablity. A reduced pre-horizontal distance leads to an increase in abduction and rotation moments of the ankle joint, leading to an increased muscle strength demand in the ankle adductors and rotartors. The increased muscle

strength demand can be a risk factor for postural stability for older adults who naturally have decreased muscle strength caused by ageing (Chou & Draganich, 1998a; Galna et al., 2009).

Toe clearance is a key factor in obstacle avoidance (Patla et al., 1996). Research found that toe clearance is high in older adults (Chen et al., 1991; Li, 2016). The average toe clearance in healthy young adults is 3 cm (Patla et al., 1996). However, this number increases to 10–15 cm for older adults regardless of obstacle height (Patla et al., 1996). Chen et al. studied the association between falls and obstacle crossing. They examined the gait of 24 healthy older adults whilst stepping over obstacles with different heights. The toe clearance values of older adults are higher than those of the control group consisting of younger adults (Chen et al., 1991). Pan et al. studied the biomechanics of obstacle crossing in older adults with high and low risk of falls. They declared that older adults with a high risk of falls show high toe clearances. They further concluded that a high toe clearance is associated with a high risk of falls (Pan et al., 2016). Lu et al. (2006) studied foot clearance variables and hip abduction and flexion. They also agreed that older adults increase their toe clearance to cross the obstacles with different heights safely (Lu et al., 2006). Increased toe clearance distance represents a conservative and safe crossing strategy in older adults (Li, 2016; Patla et al., 1996).

Hip angles in both ML (adduction/abduction) and anteroposterior (flexion/extension) planes can affect toe clearance because individuals try to reach the safe toe clearance by altering their hip angles (Chou & Draganich, 1998b). Moreover, the foot placement in ML direction is determined by the activity of hip abductors (Winter, 1995). Whilst crossing an obstacle, older adults exhibit appropriately flexed and abducted hip joints, which are associated with toe clearance (Lu et al., 2006). Lu et al. (2006) compared joint angles of older adults with those of younger adults whilst crossing obstacles with heights of 10%, 20% and 30% of the participants' leg lengths.

Older adults tend to increase their hip abduction and flexion in swing (crossing) and stance limb. Older adults achieve their desired toe clearance in the same limb's toe by increasing the flexion and abduction in their crossing limb hip joint to cross the obstacle safely. In addition, the increased hip abduction and flexion in the stance limb aims to lower the body COM and draw it close to the BOS to provide a stable landing (Lu et al., 2006). This approach is a safe crossing strategy in healthy older adults. However, the decreased flexor strength in older adults makes them unable to increase hip flexion during obstacle crossing, resulting in a risk of falls (Lu et al., 2006; Patla et al., 1996).

2.1.2.3 COM and COP associated variables

COM is a point representing the weighted average of each body segment. In particular, the body mass is presumably concentrated in the COM point (Lugade et al., 2011; Yu et al., 2008). COP is the combination of all the inertial forces that individuals use to maintain their balance (Lugade et al., 2011; Yu et al., 2008). Responding to extrinsic risk factors by appropriate responses and adjustments of the sensory and neuromuscular systems is known as dynamic postural stability (Hahn & Chou, 2003). When the balance is perturbed, the balance control system sends corrective feedbacks to the musculoskeletal system to control the COM motion by altering COP location (Chou et al., 2003; Hahn & Chou, 2004). The forces that bring COM back to its state of balance are defined by COP motion (Martin et al., 2002). COM must fall within the BOS to stand balanced. COM and COP remain in the BOS boundaries during the double support phase of gait. However, COM moves outside of the BOS and COP remains inside the BOS during the single-limb support (swing phase of gait) (Lugade et al., 2011). Winter (1995) described this system of balance as dynamic postural stability (Winter, 1995). The COM should move in relation to the BOS and COP (Lugade et al., 2011). The ML and anteroposterior placements of COP are determined by the

previous step length and step width (Winter, 1995). COM- and COP-associated variables, including displacement and velocity, have been used to examine postural stability.

The inability of an individual to control the COM motion in the frontal plane leads to a loss of postural stability in ML direction and falling to the side, which is an independent factor of hip fractures (Hahn & Chou, 2003). Chou et al. (2001) studied the COM motion in adults aged 30 ± 3.4 whilst initiating obstacles with different heights. They found that adults show high COM velocities when crossing high obstacles (Chou, Kaufman, Brey, & Draganich, 2001). Hahn and Chou investigated the possibility of distinguishing healthy older adults from older adults with postural stability problems by measuring the motion of their COM. They reported that the maximal displacement of COM and the COM motion in ML direction of older adults with postural stability problems during obstacle crossing are greater and faster than those of healthy older adults; thus, older adults showed difficulty in maintaining postural stability in frontal plane (Hahn & Chou, 2003). Therefore, the ML motion of COM can be used as an identifier of postural instability and risk of falls (Hahn & Chou, 2003). It can also be used to examine postural stability in healthy and people with disorders (Chen, Chang, & Chou, 2013; Chou et al., 2001; Li, 2016).

COM ML displacement and COM ML velocity are well-documented measures for dynamic postural stability (Chen et al., 2013; Chou et al., 2001; Chou et al., 2003). However, evaluating COM and COP separately may be insufficient for dynamic postural stability assessment (Hahn & Chou, 2004; Yu et al., 2008). The interaction of COM and COP is an important measurement in understanding dynamic postural stability because it demonstrates how COP moves in relation to COM motion (Yu et al., 2008). The COM-COP separation is the distance between the COM and the corresponding COP (Li, 2016). Healthy older adults have decreased muscle strength (Hernandez, Goldberg, & Alexander, 2010). Thus, they maintain their COM in close

boundaries of the BOS, thereby demonstrating a small COM-COP separation (Li, 2016; Martin et al., 2002). Chou et al. (2004) studied the relationship between COM and COP. A substantial COM-COP separation distance increases the moment of arm of body weight about joints. In addition, healthy older adults reduce the COM-COP separation to decrease the muscular effort for counterbalance (Hahn & Chou, 2004; Jian et al., 1993; Li, 2016). Lugade et al. also studied COM-COP separation in healthy older adults, older adult fallers and young adults. They found that older adults have small COM-COP separations. They mentioned fear of sideway falls and reduced muscle strength as the reasons leading to COM-COP separation of older adults that is smaller than that of younger adults (Lugade et al., 2011). Wright et al. (2015) investigated the relationship of COM and COP in faller old adults versus nonfaller old adults. They reported that the COM-COP separation observed in nonfaller older adults is greater than that in faller older adults. Research evidence suggested that COM-COP separation, particularly ML direction, can be an appropriate measure of dynamic postural stability and risk of falls and is a sensitive measure for examining postural instability and risk of falls (Yu et al., 2008).

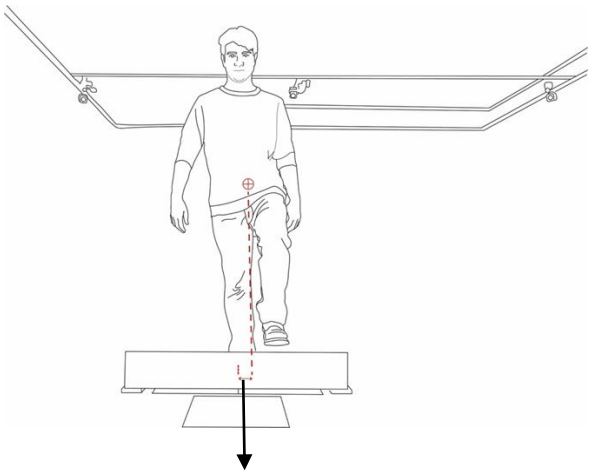


Figure 3. The sketch map of the COM-COP in ML direction.

2.2 Foot, shoes, and postural stability in older adults

Ageing can affect somatosensory information and consequently postural stability (Ridge et al., 2018; Rinkel et al., 2017). The central nervous system (CNS) must receive inputs from somatosensory system, visual system and vestibular system for an individual to maintain a posture (Horak, 2006). In a well-lit environment and on a firm support base, individuals tend to rely highly on somatosensory information to maintain their postural stability (Horak, 2006). Somatosensory system comprises peripheral nerve fibres, receptors, proprioceptive (joint, muscle) and cutaneous sensitivity (McGlone & Reilly, 2010). Somatosensory information, which is negatively affected by advanced ageing, is associated with a decreased postural stability and increased risks of falls. Diminished somatosensation in older adults is a risk factor for poor postural stability and falls (Rinkel et al., 2017). The study from Hafström further supported a relationship between somatosensation and several measures of static postural stability and balance control in relatively healthy older adults (Hafström, 2018). One of the vital input signals to CNS for maintaining postural stability in humans is from plantar surface cutaneous sensation (Kenshalo Sr, 1986; Maki, Perry, Norrie, & McIlroy, 1999; Perry, 2006). Somatosensory system includes tactile and prospective systems. Tactile sensation is associated with cutaneous mechanoreceptors (Kars, Hijmans, Geertzen, & Zijlstra, 2009). The cutaneous receptors are stimulated by plantar pressure. Then, the receptors send the plantar pressure information to the CNS. Finally, CNS modifies the plantar pressure (Kenshalo Sr, 1986; Maki et al., 1999; Perry, 2006; Zhang & Li, 2013). Nurse and Nigg mentioned that muscles and cutaneous receptors send information to the CNS to create good posture and locomotion patterns. These receptors receive feedbacks from joint kinematics and pressure distribution on the plantar foot surface (Nurse & Nigg, 2001). According to the mentioned studies, reduced foot tactile sensation can lead to instability in gait and decreased postural stability.

A study comparing the effects of facilitation of sensation from plantar foot surface boundaries on postural stabilization in young and older adults demonstrated that compared with young adults, older adults had reduced cutaneous sensation (Maki et al., 1999). The change in foot plantar sensation leads to decreased postural stability (Maki et al., 1999). Machado et al. compared the sensitivity and plantar pressure of older adults with those of younger adults. They further proved that compared with younger adults, older adults had reduced foot sensation (Machado, Bombach, Duysens, & Carpes, 2016). The altered mechanical properties of older adult skin, including decreased density, change in the receptor morphology and the increasing frequencies of neuropathies with age, account for the frequent loss of sensitivity in foot soles (Kenshalo Sr, 1986). The changed quality and quantity of sensory information related to cutaneous sensation as ageing are major contributors to the postural stability decline in older adults.

Footwear, as the interface between feet and the floor, can influence the somatosensory feedbacks (Clark, Christou, Ring, Williamson, & Doty, 2014) and can subsequently affect dynamic postural stability (Menz & Lord, 1999; Ridge et al., 2018). Appropriate footwear improves postural stability, decreases sway and prevents falls by improving the BOS and somatosensation (Brenton-Rule et al., 2011; Federolf, Roos, & Nigg, 2012; Lindemann et al., 2003).

Shoe cushioning, associated with decreased somatosensation and poor postural stability, has a positive correlation with risk of falls (Chander, Knight, & Carruth, 2019a, 2019b; Iglesias et al., 2012; Tencer et al., 2004). Shoes with soft soles attenuate impact force, thereby helping shock absorption (Shorten & Mientjes, 2011). The ability of a material to attenuate peak forces between two colliding bodies is called cushioning (Clarke, Frederick, & Cooper, 1983). Compared with shoes with hard soles, shoes with soft soles substantially decrease the peak forces (Chander et al., 2019b). Different studies showed that shoes with thick and soft heels, namely, shoes with high

cushioning features, decrease plantar information, such as plantar pressure and somatosensory information, during interactions with the environment, possibly leading to poor postural stability and high risk of falls (Chander et al., 2019a, 2019b; Cudejko et al., 2020). On the contrary, shoes with less or no cushioning, such as minimal shoes, improve the quality of tactile information (Cudejko et al., 2020; Ridge et al., 2018). Shoes with thin and hard soles and shoes with minimal cushioning can provide a correct position awareness, stimulate cutaneous receptors and improve the somatosensory information, leading to enhanced postural stability due to appropriate responses (Cudejko et al., 2020; Robbins, Waked, Allard, McClaran, & Krouglicof, 1997).

Shoe cushioning can influence the biomechanics of body and postural stability. Shoes with extra cushioning usually have elevated (thick) heels, and they place the foot and ankle in a plantar flexed position, leading to changes in lower extremity biomechanics. Thus, the individual's body must make additional adjustments to maintain postural stability (Chander et al., 2019a, 2019b). Menant et al. studied static postural stability and sway. They stated that shoes with 4.5 cm heel height or more can affect postural stability negatively (Menant et al., 2008a). They further mentioned that shoes with heels higher than 2.5 cm increase the risk of falls in older adults (Menant, Steele, Menz, Munro, & Lord, 2008b). Elevated heels result in an elevation and a shift forward in the COM location and close to the slipping areas of BOS. Moreover, the individual's body must make additional biomechanical adjustments, which require extra effort (Menant et al., 2008b). Perry et al. investigated the effects of cushioning on dynamic postural stability during normal walking. They concluded that soft-heeled shoes result in a small maximum COM-COP separation, which reflects considerable muscular challenges in maintaining postural stability. This scenario leads to low postural stability, given that older adults naturally have low muscular strength (Perry, Radtke, & Goodwin, 2007). Iglesias et al. investigated the static postural stability in older

adults wearing shoes with different types of soles and cushioning, and they demonstrated that wearing shoes with hard soles lead to good postural stability indicated by a small range of COP displacement (Iglesias et al., 2012). Cudejko et al. compared postural stability of older adults whilst wearing minimal shoes and cushioned shoes during normal walking. They concluded that the dynamic postural stability provided by minimal shoes in both anteroposterior and ML direction is better than that by cushioned shoes. The COM velocity whilst wearing cushioned shoes is considerably higher than that whilst wearing minimal shoes. The reason is that cushioned shoes shift the location of the body COM (Cudejko et al., 2019).

Most of the current research on the effects of age and shoes on postural stability is limited to static postural stability. In addition, few studies investigating dynamic postural stability analysed dynamic postural stability during normal walking. Therefore, the effects of shoe cushioning on dynamic postural stability in ML direction in older adults and younger adults during obstacle crossing must be examined. Moreover, the available research mainly focuses on dynamic postural stability assessment by examining COM and COP motions separately. The relationship of COM and COP, such as COM-COP separation, must be studied to understand the effect of shoe cushioning and ageing on dynamic postural stability. COM and COP relationship is a considerably sensitive measure of postural stability.

Barefoot condition provides good proprioception and plantar sensitivity, which are optimal postural stability inputs (Menant et al., 2008b). Considerable research studied the postural stability in barefoot condition. Lord and Bashford (1996) examined the effects of shoe characteristics on the postural stability capacity in older women by testing static postural stability (body sway) and dynamic postural stability indicated by maximal balance range and coordinated stability in four conditions. The tested conditions included barefoot, standard low-heeled shoes (walking shoes),

standard high-heeled shoes and their own shoes. Their results showed that compared with low- and high-heeled shoes, barefoot condition provided a considerably improved postural stability (Lord & MBBS, 1996). Cudejko et al. (2020) found that the postural stability in ML and anteroposterior directions of older adults in barefoot condition is better than that of older adults in cushioned shoes (Cudejko et al., 2020). Therefore, the study in postural stability in barefoot condition is often used as a baseline for other shoe conditions because it provides the best somatosensory signals and, consequently, the optimal postural stability.

2.3 Summary

The postural stability of older adults is poorer than that of younger adults. Decreased muscle strength, flexibility and proprioception are linked to declined postural stability. Poor postural stability leads to a high risk of falls. Obstacle crossing can present a high demand for older people's postural stability. Thus, obstacle crossing can be used in examining dynamic postural stability. Dynamic postural stability during obstacle crossing can be studied by measuring crossing step velocity, step length, toe clearance, hip flexion and abduction angles, COM displacement, COM velocity and COM-COP ML separation.

Footwear can also affect postural stability. Shoes with thick and soft heels lead to a decreased postural stability. However, minimal shoes have slight influences on postural stability. The current available research evidence about the effects of shoes on both static and dynamic postural stability is mainly from gait analysis during ground walking. To our knowledge, research on the effects of shoe cushioning on postural stability in ML direction in older adults whilst performing challenging locomotion, namely, obstacle crossing, is lacking. Therefore, this research gap must be filled to increase our understanding of the effects of shoe cushioning on the dynamic postural stability in ML direction in older adults and younger adults.

Chapter 3: Methodology

3.1 Participants

This research aimed to study the dynamic postural stability in the ML direction of older adult population (50–60 years old) compared with younger adults (18–32 years old) in different shoe cushioning conditions. Six older and six younger adults were recruited through online advertisements and posters. The sample size was calculated using the equation adopted from the study of Eng (Eng, 2003).

$$N = \frac{4\sigma^2(z_{crit} + z_{pwr})^2}{D^2}$$

Equation. ***N****: Total sample size (two groups);* σ *: Standard deviation of each group;* ***Zcrit****: Associated with the desired significance criterion;* ***Zpwr****: Value associated with the standard power;* ***D****: minimum expected difference between the two means.*

To calculate the sample size, we conducted a pilot study on one older and one younger individual. Data from five trials for each participant were analysed. The standard deviation and the minimum expected difference of mean COM-COP ML separation values between trials and between older and younger individuals was adopted. The power was set to 0.90 in accordance with the power analysis conducted using the G*power software. The significance criterion was set to $p \leq 0.05$. As a result, six participants were selected for each age category.

In this study, male and female participants were recruited given the absence of sex differences in static and dynamic postural stability demonstrated by published research (Hageman et al., 1995; Melam, Buragadda, Alhusaini, Ibrahim, & Kachanathu, 2014).

Inclusion and exclusion criteria:

Healthy participants were recruited in Ottawa, Ontario. A series of questions was asked to the potential participants for screening during recruitment. The participants were required to have an average physical activity of at least 150 min of moderate-intensity aerobic physical activity per week (Piercy et al., 2018). The exclusion criteria were any of the following conditions in the past six months: balance impairments, macro-vascular conditions such as stroke, peripheral vascular disease, diabetes, musculoskeletal disorders, and presence of any neurological disorders; a surgery either in ankle, knee, or hip; fall or dizziness history; use of walking aids. Moreover, the shoe size was limited to 9 and 10 men. The outlined protocol of this study has been approved by the University of Ottawa Health Science and Science Research Ethics Board.

3.2 Instruments

Shoes: Two types of shoes with different cushioning were used: a cushioned shoe (Hoka One One (Bondi6)) and a minimal shoe (Xero Shoes Prio). In the Runners' World website, Hoka One One (Bondi 6) shoes were stated to have the most cushioning (Figure 5(A)). Hoka One One is considered a maximalist running shoe with a 29–33 mm (toe to heel) cushioning feature which provides a cushioned and light feeling while wearing the shoes. According to the information provided by the shoe manufacturer, Hoka One One (Bondi 6) has a full EVA midsole that provides the cushioning function. EVA materials are made of thousands of bubbles that cluster together to hold the air (closed cell foam material) and can provide a high level of cushioning and shock absorption (James, 2000).

Xero Shoes Prio had the least cushioning (Figure 5 (B)). Xero Shoes Prio have three parts: an outsole (sole), a removable insole, and the upper part. Xero Shoes Prio lack a midsole that is the shoe's part that provides a cushioning function. Xero Shoes Prio's sole material is Vibram

Cherry Rubber which has a woven texture that prevents the airy and light shoe effect. The dimension and material information of the shoes are listed in Table

Motion analysis system and force plates: A Vicon motion analysis system, with 10 infrared, high-velocity, optical cameras (Vicon MX-13, Oxford Metrics, Oxford, UK), was used to capture obstacle crossing motion in three dimensions and recorded at 200 Hz. All cameras were either hung from the ceiling or mounted on individual tripods. The ground reaction forces generated during obstacle crossing were recorded using three force plates (models 9286AA, Kistler Instruments Corp, Winterthur, Swtz; FP 4060-08, Bertec Corporation, Columbus, OH, USA) at 1000 Hz. The arrangement of two force plates allowed participants to step on them before and after obstacle crossing (Figure 6).

Table 1. Footwear information

	Hoka one one Bondi 6	**Xero shoes prio**
Weight/shoe	10.9 oz	7.6 oz
Heel Drop	4 mm	0
Stack height (heel/toe)	33/29 mm	5.5mm
Material	Ethylene-vinyl acetate	vibram cherry rubber

Figure 4. Types of shoes. A) Hoka one one (Bondi 6) from Hoka one one; B) Xero shoes prior from xero shoes

Walking path and obstacle: The walkway was 8 m long, and the middle 3 m of the walking path was used as the motion capture area. The obstacle was composed of two upright upholders and one crossing plank which was collapsible and connected to two upholders by magnets. This setup allowed the obstacle to be easily dislodged with any contact and thus prevented participants from falling if they did not clear the obstacle. The obstacle was 20 cm high, which is similar to that might be encountered in daily activities (Chou et al., 2003). The obstacle was placed in the centre of the two force plates and was easily visible to the participants (Figure 5).

3.3 Testing Protocol and Data Collection

The participants were given a detailed explanation of the nature of the study and the exact test procedure. The participants signed a consent form after the consent form and the anonymity of the information were explained to them. The participants were asked to remove all their accessories and to change into laboratory-provided, fit black T-shirts and shorts. Anthropometric measurements of body height, body mass, leg length, knee width, ankle width, elbow width, wrist width, shoulder offset and hand thickness were recorded. For each shoe condition, the participants

were asked to walk along the walking pathway for 2–3 min to familiarise themselves with the shoe and practice their walking before motion capture.

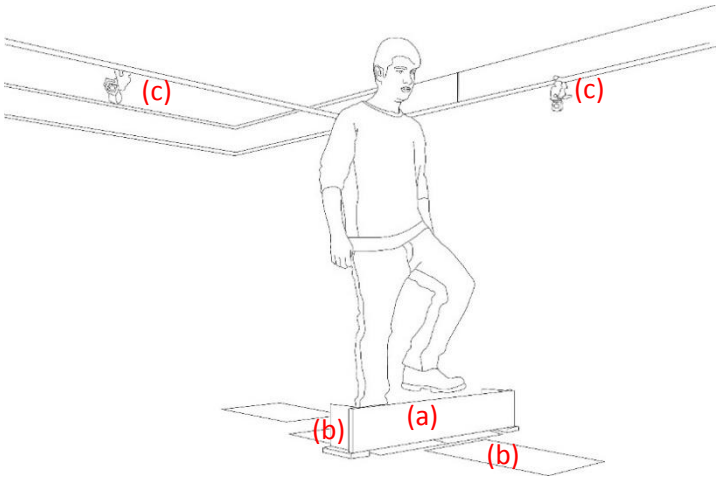


Figure 5: The laboratory set up. a. The obstacle. b. Force plates. c. Part of the cameras.

The plug-in-gait model was adopted, and 43 reflective markers were positioned on the participants' bodies accordingly. For dynamic calibration, a T-shaped wand (240 mm) was used to calibrate the system. For static calibration, the wand was placed on the floor to assign the centre of global coordinate system. Then, the participants were asked to undergo a static trial first, in which they stood quietly with their arm in the T-position in the middle of the testing pathway. The cameras captured the positions of the markers that were attached to their bodies for 5 s. This condition allowed the system to create a three-dimensional model of the participants. Then, the participants were asked to complete the following tasks in their own preferred speed:

1) Obstacle crossing while wearing high cushioned shoes;

2) Obstacle crossing while wearing minimal shoes;

3) Obstacle crossing while wearing no shoes (barefoot).

The participants were asked to use their dominant limb (kicking leg) as their supporting limb during obstacle crossing. Data from five successful trials were collected for each condition. A successful trial was defined as participants walked naturally, and no markers were missed. Participants were allowed to take breaks at any time during the data collection session. To prevent fatigue, the participants went into 5 min breaks between each condition.

3.4 Data Processing

The motion capture data were reconstructed and labelled using the Vicon Nexus software 2.11.0 (Oxford, UK). All data were cropped to one crossing stride. Once all the missing trajectories were filled, the data were filtered using a 4th-order Butterworth filter with a cut-off frequency of 6 Hz. After filtering, the events were determined using Vicon pipelines. Afterward, full body plug-in-gait was used to create the models. The data were exported as CSV. and C3d. files. The biomechanical measures were obtained using Matlab R2013b (MathWorks, Natick, MA, USA), and Excel 2013 (Microsoft, Washington, USA) was used to determine the measures.

COM ML velocity, COM ML displacement, and COM-COP ML separation: The average and maximal COM ML velocity and displacement and COM-COP ML separation were analysed during one crossing stride. One crossing stride is defined by the heel strike (initial contact) of the trailing limb before the obstacle to the heel strike of the trailing limb after the obstacle. Ground reaction forces data recorded in stance foot were used to locate COP prior and after the obstacle crossing. Vicon Nexus and Matlab program were used to calculate the velocity and displacement of COM and the average and maximal COM-COP ML separation during the crossing stride.

Step velocity, step length, pre-horizontal distance, toe clearance, hip flexion and abduction angles: Step velocity was calculated in one crossing stride. Step length was defined as the length of one crossing step. Crossing step is defined by the heel strike (initial contact) of the trailing limb

before the obstacle to the heel strike of the leading limb (crossing limb) after the obstacle. Step length and step velocity were calculated by the position of heel markers on the leading and trailing limbs. A marker was put on the obstacle to create a rigid body by Nexus Vicon. Toe clearance was defined by the vertical distance the crossing toe marker and markers on the obstacle at the moment when crossing toe passed over the obstacle (Chen et al., 1991). Pre-horizontal distance was defined by the horizontal distance between trailing toe marker and the obstacle in the anteroposterior direction prior to crossing. Hip angles of the leading limb were calculated in anteroposterior (flexion/ extension) and ML (abduction/ abduction) directions at the moment the leading toe was above the obstacle.

The extent of impact of shoe cushioning conditions on postural stability: The following approaches were adopted to examine how much each of the measures from older and younger adults were affected by different shoe conditions. 1) Examining the difference between the means of each measure obtained when the shoe condition shifted from one to other in older and younger adults. The absolute differences between the means of each measure in between shoe conditions were calculated. The calculation was performed by subtracting the measures as the following conditions for older adults and younger adults: absolute difference in the means of each measure between a) cushioned shoe and barefoot condition; b) minimal shoe and cushioned shoe; c) barefoot condition and cushioned shoe. This procedure enabled us to determine the study groups (older or younger), and measurement was affected substantially when the shoe condition was changed. 2) The percentage of the total changes in the value of each measure was obtained from three shoe testing conditions in older adults and younger adults. The lowest value of each of the measures was subtracted from the highest value of the same measure in older and younger adults. The total range of change for each measure was presented as a percentage.

3.5 Statistical analysis

SPSS 22.0 (SPSS Inc. Chicago, IL, USA) was used in statistical analysis. The normal distribution of data was assessed by Shapiro–Wilk's test of normality ($p > 0.05$). A two-way (shoes and age) analysis of variance (ANOVA) was used to examine the significance and interaction of shoe cushioning and age on the measures. If an interaction was not found, two one-way ANOVAs are conducted to examine the effects of shoe cushioning and age on the measures separately. Mauchly's test of sphericity was used to test the sphericity for two-way interactions. Levene's test of equality revealed the homogeneity of variances. If a significant main effect was present, Bonferroni post hoc test was conducted to determine where these differences occurred. The significance level was set at $p \leq 0.05$. In addition, multiple student t-tests (independent sample t-tests) were used to examine the significance of the differences between the means of measures when the shoe condition shifted in older and younger adults. The significance level was set at $p \leq 0.05$.

Chapter 4: Results

This study investigated the effects of high cushioned and minimal shoes on dynamic postural stability in ML during obstacle crossing in defined older and younger adults. All participants successfully completed the tests. Participant demographics are presented in Table 2. Independent t-tests showed no significant differences in body height and weight between the two groups. All data are expressed by mean and standard deviation (SD).

Table 2. Participants' demographics (Mean ± SD)

	Young (n = 6)	**Older (n = 6)**	**P-value**
Female	2	2	-
Male	4	4	-
Age (year)	27.0 ± 2.6	54.0± 3.1	-
Body weight (kg)	73.8 ± 15.5	74.8 ± 6.0	0.9
Body height (cm)	174.8 ± 7.9	168.0 ± 8.0	0.2

4.1 Impacts of shoe conditions: barefoot, cushioned, and minimal

Two-way ANOVA did not reveal any significant interaction of age and shoe cushioning on the measures. One-way ANOVA for the main effects showed significantly greater toe clearance in the cushioned shoe condition compared with the minimal shoe and barefoot conditions in older adults (cushioned shoes vs. barefoot: $p = 0.019$; cushioned shoes vs. minimal shoes: $p = 0.031$). Significances in toe clearance among the three shoe conditions were also found in younger adults (cushioned shoes vs. barefoot: $p = 0.016$; cushioned shoes vs. minimal shoes: $p = 0.000$). No significant difference in toe clearance was found between the barefoot and minimal shoe conditions. Figure 8C shows the toe clearance measured in three shoe conditions in both groups.

No significant differences in other measures were observed among the three shoe conditions in the older and younger groups.

4.2 Impact of age: older versus younger adults

Two-way ANOVA revealed no significant interaction of age and shoe cushioning on the measures. One-way AONVA showed significant age difference only in step length. Step length was significantly greater in younger adults than older adults in the barefoot (p = 0.000) and minimal shoe (p = 0.016) conditions. Figures 7 to 9 illustrate the results of the measures in the three shoe conditions in both groups. Tables 3 and 4 present the mean and SD for the measures in the three shoe conditions in both groups.

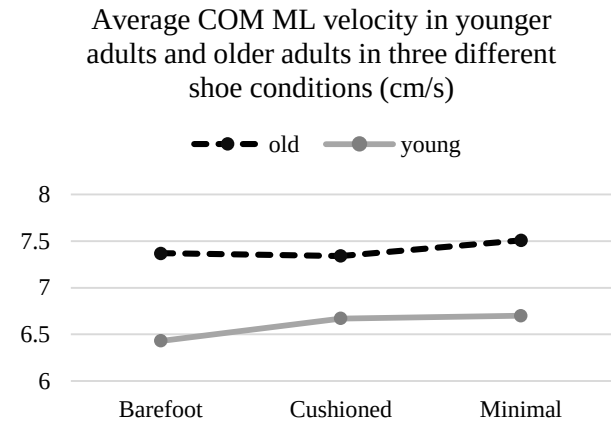
Table 3. COM-COP ML separation, COM ML velocity, COM ML displacement measures for older and younger adults in three shoe conditions during obstacle crossing (Mean ± SD)

	Barefoot		**Cushioned shoe**		**Minimal shoe**	
	Old	Young	Old	Young	Old	Young
Maximal COM-COP ML separation (cm)	7.38 ± 3.10	7.45 ± 1.63	7.67 ± 2.86	9.22 ± 2.42	7.33 ± 2.27	7.36 ± 2.15
Average COM-COP ML separation (cm)	4.12 ± 1.37	4.52 ± 1.31	4.50± 2.32	5.52 ± 0.98	3.76 ± 1.27	4.35 ± 0.95
Average COM velocity (cm/s)	7.37 ± 1.85	6.43 ± 1.16	7.34 ± 1.45	6.67 ± 0.23	7.51 ± 1.91	6.70 ± 0.511
Maximal COM ML displacement (cm)	6.90 ± 2.39	6.14 ± 1.52	6.39 ± 1.38	6.20± 1.39	7.11 ± 1.95	6.56 ± 1.78

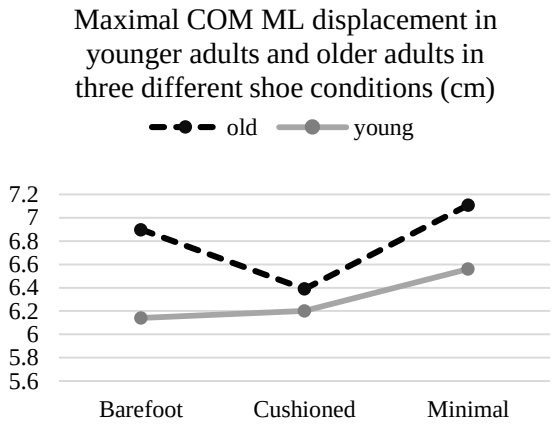
Table 4. Temporospatial and kinematics measures for older and younger adults in three shoe conditions during obstacle crossing (Mean ± SD)

	Barefoot		**Cushioned shoe**		**Minimal shoe**	
	Old	Young	Old	Young	Old	Young
Average Step Velocity (cm/s)	88.13 ± 18.88	116.92 ± 18.46	103.19± 18.36	118.23 ± 21.96	95.00± 20.46	115.42 ± 15.82
Step Length (cm)	58.63 ± 5.99*	73.89 ± 2.98*	80.00 ± 16.06	77.02 ± 3.04	66.02 ± 7.03*	74.77 ± 2.43*
Pre-horizontal distance (cm)	19.96 ± 6.93	23.05 ± 6.15	21.83 ± 5.67	17.97 ± 4.83	22.37 ± 5.21	21.96 ± 3.38
Toe Clearance (cm)	12.27 ± 3.18[a]	13.94 ± 1.43[a]	16.35 ± 2.51[b, c]	17.57 ± 2.24[b, c]	14.42 ± 3.45[a]	14.38 ± 1.97[a]
Hip Flexion Angle (°)	68.41 ± 11.67	61.61 ± 11.23	70.51 ± 10.68	63.56 ± 10.63	69.13 ± 10.58	60.46 ± 11.08
Hip Abduction Angle (°)	10.43 ± 8.75	3.66 ± 3.66	9.66 ± 9.70	3.66 ± 2.63	10.33 ± 9.70	4.00 ± 2.64

$p \leq 0.05$, [a], significantly different from the cushioned shoe in the same group; [b], significantly different from the minimal shoe in the same group; [c], significantly different from the barefoot condition in the same group. *, represents significant differences between two groups (older versus younger) at the same shoes condition.



A



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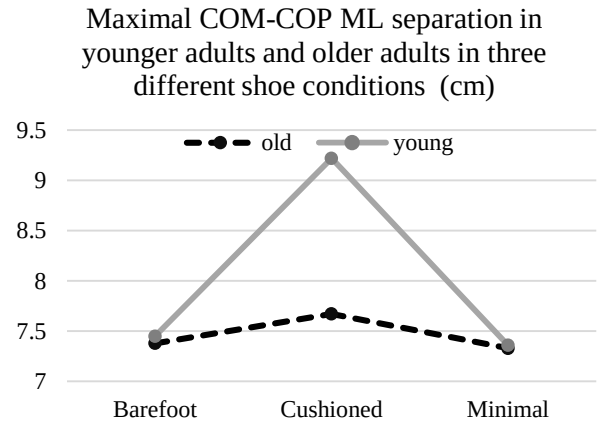

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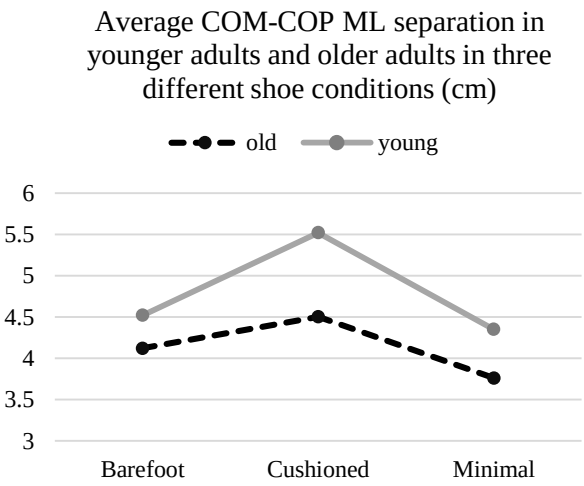

D

Figure 6. The results from statistical analysis for COM and COP measures of older adults and younger adults in three different shoe conditions during obstacle crossing.

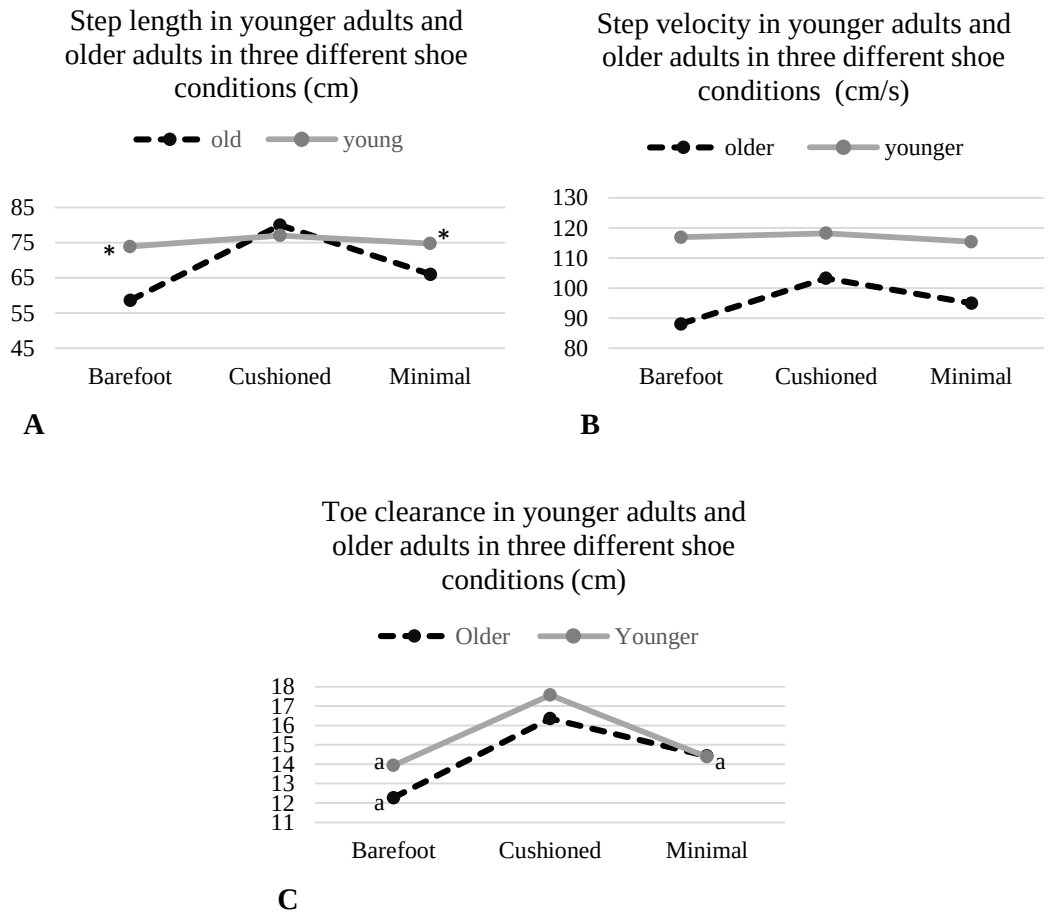

Figure 7. The temporospatial measures in older adults and younger adults in three different shoe conditions during obstacle crossing.

$p \leq 0.05$, [a], significantly different from the cushioned shoe in the same group; *, represents significant differences between two groups (older versus younger) at the same shoes condition.

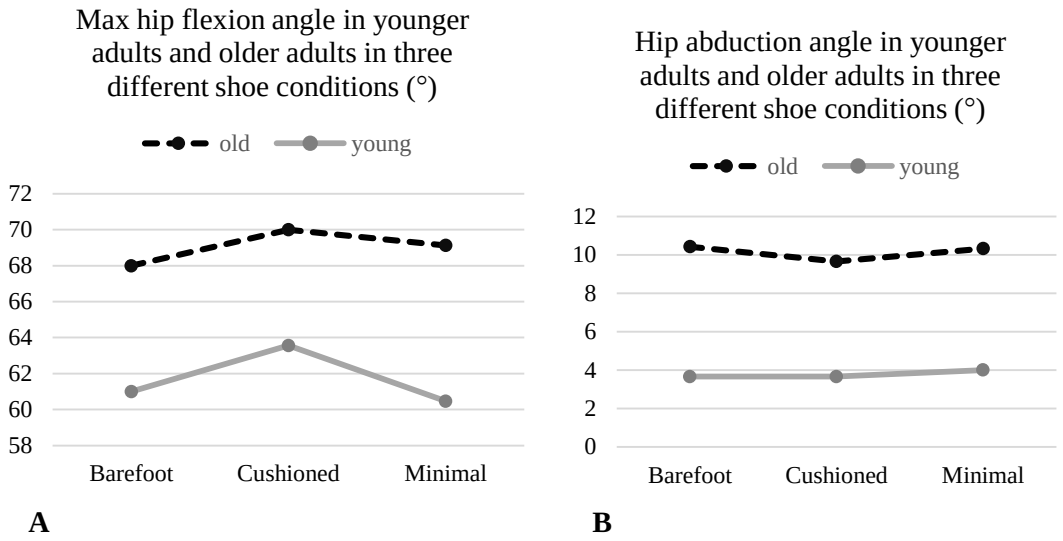

Figure 8. Hip angles in older adults and younger adults in three different shoe conditions during obstacle crossing.

4.3 The extent of impact of shoe cushioning conditions on postural stability

Independent t-test was used to examine the significant difference in the means of each measure when shoe changed. Significance differences in step length and step velocity were found. When the shoe condition was changed, older adults showed significantly greater changes in step length (14.26 ± 6.99 cm for older; 2.086 ± 1.13 cm for younger) and step velocity (10.04 ± 4.39 cm/s for older; 1.87 ± 0.81 cm/s for younger) compared with younger adults. Table 5 presents the statistical analysis results of comparison of the differences in the means of the measures between older and younger adults in the different shoe conditions.

Table 6 lists the percentage of the total changes in each measure obtained from the three shoe testing conditions in older and younger adults. Compared with younger adults, older adults showed greater percentages of changes in step velocity (15% vs. 2%), step length (26% vs. 4%) and toe clearance (23% vs. 21%; Figure 9). Older adults demonstrated smaller percentages of

change associated with shoe conditions in maximal (4% vs. 20%) and average COM-COP ML separation (16% vs. 26%), as well as pre-horizontal distance (11% vs. 22%; Figure 10).

Table 5. Comparison of the differences of the mean in the measures between older and younger adults in different shoe conditions

	Cushioned - Barefoot		**Minimal - Cushioned**		**Barefoot - Minimal**		***p* value**
	old	young	old	young	old	young	
Maximal COM-COP ML separation (cm)	0.29	1.77	0.34	1.86	0.05	0.09	0.157
Average COM-COP ML separation (cm)	0.38	1	0.74	1.17	0.36	0.17	0.437
Average COM velocity (cm/s)	0.03	0.24	0.17	0.03	0.14	0.27	0.485
Maximal COM ML displacement (cm)	0.51	0.06	0.72	0.36	0.21	0.42	0.341
Average Step Velocity (cm/s)	15.06	1.31	8.19	2.81	6.87	1.5	0.034*
Step Length (cm)	21.37	3.13	13.98	2.25	7.39	0.88	0.041*
Pre-horizontal distance (cm)	1.87	5.08	0.54	3.99	2.41	1.09	0.247
Toe Clearance (cm)	4.08	3.63	1.93	3.19	2.15	0.44	0.816
Hip Flexion Angle (°)	2.1	1.95	1.38	3.1	0.72	1.15	0.390
Hip Abduction Angle (°)	0.77	0	0.67	0.34	0.1	0.34	0.294

P< 0.05, *, significantly different between two groups (younger adults versus older adults).

Table 6. The total change range of the measures associated with shoe condition on younger adults and older adults.

	Old (%)	**Young (%)**
Maximal COM-COP ML separation	4	20
Average COM-COP ML separation	16	26
Average COM velocity	2	4
Maximal COM ML displacement	10	6
Average Step Velocity	15	2
Step Length	26	4
Pre-horizontal distance	11	22
Toe Clearance	23	21
Hip Flexion Angle	3	5
Hip Abduction Angle	7	9

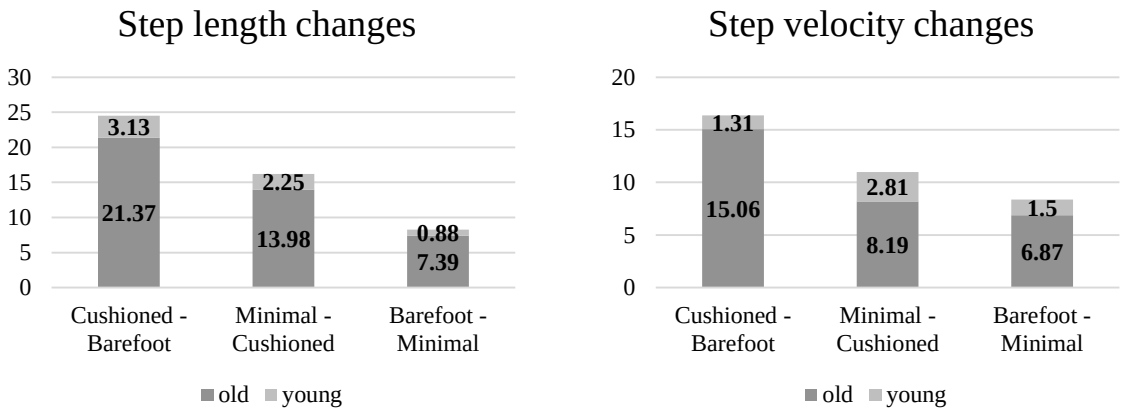

Figure 9. Changes in step length (left) and step velocity (right) when shoe condition changes from one to another in older adults and younger adults

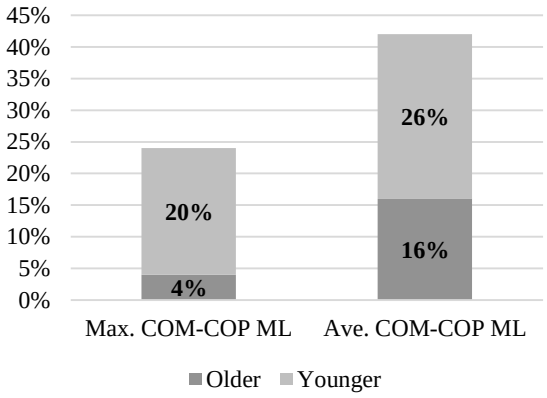

Figure 10. Changed percentage in maximal and average COM-COP ML separation when shoe condition changes from one to another in younger adults and older adults.

Chapter 5: Discussion

This study examined the impact of high cushioned and minimal shoes on postural stability in ML during obstacle crossing in older and younger adults. Results indicated that high cushioned shoes significantly influenced postural stability during obstacle crossing. No significant difference in postural stability was found between the minimal shoe and barefoot conditions. Moreover, significant age differences were found in postural stability measures during obstacle crossing. Furthermore, significant differences in the change extent of measures when the shoe condition shifted were found between the two groups. Older adults showed more conservative gait patterns compared with younger adults. To the best of our knowledge, this study is the first to investigate the impact of shoes on dynamic postural stability in ML during a challenging locomotion (i.e. obstacle crossing) in older and younger adults.

5.1 Impacts of shoe conditions: barefoot, cushioned, and minimal

Significantly higher toe clearance during obstacle crossing was observed in the cushioned shoe condition than in the minimal shoe and barefoot conditions in both groups. Younger and older groups showed the lowest toe clearance in barefoot. In addition, both groups showed larger hip flexion angles in the cushioned shoe condition during obstacle crossing than in the minimal shoe and barefoot conditions. High toe clearance has been observed in individuals with poor postural stability (Pan et al., 2016). The higher toe clearance presented in high cushioned shoes in this study demonstrates the diminishing effect of high cushioned shoes on postural stability. Shoes reportedly affect postural stability by changing gait characteristics, altering base of support (BOS) and the ability to sense the floor (Brenton-Rule et al., 2011; Federolf et al., 2012; Lindemann et al., 2003). Cushioned shoes have been associated with decreased postural stability, whereas minimal shoes have been associated with improved postural stability and lower risk of falls (Tencer et al., 2004).

Barefoot condition provides the best postural stability and lower risk of falls, especially in older adults (Cudejko et al., 2020). The impact of cushioned shoes on decreasing postural stability is associated with altering the location of COM and decreasing somatosensation (Chander et al., 2019a, 2019b; Cudejko et al., 2020; Maki & McIlroy, 2006; Menant et al., 2008b; Menz & Lord, 1999; Tencer et al., 2004). Shoes with thinner soles, such as minimal shoes, can improve postural stability by increasing tactile sensation and improving foot position awareness (Cudejko et al., 2020; Robbins et al., 1997).

High toe clearance is associated with large hip flexion. In this study, large hip flexion angles were shown with high cushioned shoes. The evidence is consistent with previous obstacle crossing studies in which large hip flexion angles have been linked to wide toe clearance (Lu et al., 2006). The high toe clearance and large hip flexion angle may be related to changes in somatosensation and shoe sole thickness. The participants attempted to increase their toe clearance to succeed the crossing. Individuals need great hip flexor forces (to elevate the entire limb) to maintain a high toe clearance (Lu et al., 2006). The postural stability of individuals without sufficient flexor muscle strength can be exposed to a greater threat (Lu et al., 2006). Thus, postural stability might be challenged while wearing cushioned shoes during obstacle crossing. Decreased somatosensation associated with cushioned shoes might have led to a more challenged postural stability than minimal shoe or barefoot condition, especially during obstacle crossing.

5.2 Impact of age: older versus younger adults

Some measures of postural stability in this study showed age differences from the two groups. Compared with younger adults, older adults showed significantly shorter step length in the barefoot and minimal shoe conditions. Step length in cushioned shoes was very close in both groups. Older adults showed slower step velocity than younger adults in all shoe cushioning

conditions, but the difference was not significant. Step length during obstacle crossing had been applied to identify fall risk in older adults (Alcock et al., 2018; Galna et al., 2009; Maidan et al., 2018; Menz et al., 2003). Galna et al. (2009) systemically reviewed studies on obstacle crossing in older adults. They summarised that older adults adopt more conservative strategies in obstacle crossing than younger adults to compensate for age-associated changes, and short step length can be considered a conservative strategy (Galna et al., 2009). A recent study has further provided support to the conservative strategies adopted by older adults during obstacle crossing (Maidan et al., 2018). Short step length provides more time for older adults to adjust their steps and reduce the risk of tripping (Maidan et al., 2018). McKenzie et al. (2004) compared the kinematics of obstacle crossing between older and younger adults and found some age differences. They suggested that short step length in older people is a sign of a more conservative gait possibly because of fear of falls (McKenzie & Brown, 2004).

Different from the minimal shoe and barefoot conditions, high cushioned shoes showed no age difference in step length. Unexpectedly, the step length of older adults was close to that of younger adults in cushioned shoes during obstacle crossing. Possible reason leading to the greater step length in cushioned shoes in older adults compared with younger adults might be related to the shoe designs. The midsole of the shoe provides its cushioning feature. Hoka One One Bondi 6, the cushioned shoe used in this study, is a running shoe with a full ethylene vinyl acetate (EVA) midsole made of closed cell foam material (thousands of bubbles come together to hold the air), which provides cushioning and shock absorption (James, 2000). Most designed running cushioned shoes are designed to improve athletic performances, such as step length and step velocity (Monaghan, 2018; Shorten, 1993). Shoes with EVA midsole material (such as Hoka one one bondi 6) have viscoelastic and spring-like properties. They are designed to improve gait economy in

athletes, increasing step velocity and step length (Monaghan, 2018; Shorten, 1993). Research demonstrated that altering midsole materials can lead to changes in gait kinematics, such as step length (Wunsch, Kröll, Stöggl, & Schwameder, 2017). Results of the present study showed that the high cushioned shoe condition increased the step length of older adults compared with the minimal shoe and barefoot conditions. This evidence suggests that older adults could not adopt a cautious and safe strategy while wearing the cushioned shoe.

Step length measured in the minimal shoe and barefoot conditions in older adults was very close. The minimal shoe sole is made of Vibram cherry rubber, which prevents the cushioned and light shoe effect. The absence cushioning function affects step length (Monaghan, 2018; Shorten, 1993, Law et al., 2019). As expected, minimal shoe without cushioning function led to a similar step length during obstacle crossing to barefoot condition. The findings of this study suggest that high cushioned shoes could influence postural stability in older and younger adults. Compared with the high cushioned shoe condition, the minimal shoe and barefoot conditions might provide safer postural stability strategies for older adults. However, further studies are needed to investigate postural stability and shoe condition in different age ranges.

5.3 The extent of impact of shoe cushioning conditions on postural stability in older and younger adults

Comparison of the differences between the means of each measure from older and younger group led to the following results. Compared with younger adults, older adults presented significantly greater changes in step length and step velocity when shoe condition was changed (Table 5). Older adults also showed higher percentages in total change ranges in step length and step velocity when compared with younger adults. When the shoe conditions were changed, older adults showed 22% larger change in step length and 13% larger change in step velocity compared

with younger adults (Table 6). Li et al. (2016) compared the temporospatial and kinematics measures of healthy older regular Tai Chi practitioners and older participants matched in age, sex and exercise habits during obstacle crossing. The difference in step length between two groups was 6.5% of difference. Chen et al. (1991) studied the gait patterns of healthy younger and older adults during obstacle crossing. The difference of 8.7% in step velocity and 5.7% of difference in step length between older and younger adults was found and considered significant (Chen et al., 1991). In this study, 22% of change in step length and 12% of change in step velocity between older and younger adults could be very remarkable. An individual adjusts the boundaries of their BOS by changing their step length and step width depending on the motion of their COM (Young & Dingwell, 2012). To maintain their postural stability, the older adults in the present study had to alter their step velocity and step length to make up for the large changes in COM ML displacements. These remarkable alterations in step velocity and length when the shoe condition was changed between the minimal shoe, barefoot and high cushioned shoe conditions could have been demanding for the postural stability of older adults.

Among the measures obtained from the three shoe conditions, the total change percentage from the lowest to the highest COM-COP ML separation value in older adults showed 16% less change compared with younger adults. Older adults showed 10% less total change in their average COM-COP ML separation compared with younger adults. Fujimoto et al. (2015) investigated the distance between COM and BOS during first step lift-off in lateral perturbations in older adult fallers and non-fallers. They found a significant difference in COM and BOS separation between faller and non-faller older adults. Their results generated a difference of 15% in the measure between older adult fallers and non-fallers. Fujimoto et al. defined functional BOS as the effectively utilised area for COP movement (Fujimoto, Bair, & Rogers, 2015). Although COP can

move within the boundaries of BOS, COM can be controled within the areas of functional BOS. Older adults have diminished BOS, which diminishes the limits of stability for COM control (Fujimoto et al., 2015; Winter, 1995). Smaller functional BOS leads to smaller COM-COP ML separation (Fujimoto et al., 2015). The present study showed that older adults had less change in COM-COP ML separation across the shoe cushioning conditions compared with younger adults. The less change in COM-COP ML separation would be attributed to the age related decline in functional BOS as stated by Fujimoto et al. Decline in functional BOS limits one's capacity to maintain their postural stability (Fujimoto et al., 2015; Winter, Patla, Prince, Ishac, & Gielo-Perczak, 1998). This finding suggests that older adults were less capable and flexible in maintaining postural stability and adapting to the shoe condition changes, whereas younger adults presented much larger change percentage in maximal and average COM-COP ML separation in shoe shifting. This result suggests that younger adults were more capable to maintain postural stability by adjusting their COM and COP positions.

Decreased hip muscle performance capacity, ankle muscles and/ or hip muscles are related to small functional BOS and consequently a small COM-COP ML separation in elderly people (Fujimoto et al., 2015). A great COM-COP separation creates a high moment around joints, which consequently requires strong muscle strength to maintain body counterbalance. When crossing higher obstacles, older adults use 38%–50% of their muscular capacity; however, younger adults use 25%–36% of their lower extremity muscular capacity (Hahn & Chou, 2004). Compared with younger adults, older adults have decreased muscle strength (Goodpaster et al., 2006; Hughes et al., 2001). A ten-year longitudinal study in 120 subjects initially 46 to 78 years old found that the rates of decline in isokinetic strength averaged 14% per decade for knee extensors and 16% per decade for knee flexors in men and women (Hughes et al., 2001). Later, Goodpaster and co-

workers (2006) reported the study findings from three-year changes in muscle mass and strength in 1880 older healthy adults. The annualized rates of leg strength decline were 2.6% to 4.1% in men and women (Goodpaster et al., 2006). With small COM-COP ML separation, older individuals could minimise the effort to maintain their counterbalance (Hahn & Chou, 2004; Jian et al., 1993; Lugade et al., 2011). Therefore, the smaller COM-COP ML separation presented in older adults than younger adults in this study across the different shoe conditions indicates they used a more conservative strategy in obstacle crossing. With this approach, older adults tried to avoid the mechanical challenge caused by a larger separation distance (Hahn & Chou, 2004; Jian et al., 1993; Li, 2016; Lugade et al., 2011).

Impaired (diminished) cutaneous sensation is an important influencing factor of detecting COM to the stability boundaries (Fujimoto et al., 2015). High cushioned shoe, minimal shoe and barefoot affect cutaneous sensation differently (Cudejko et al., 2019; Iglesias et al., 2012; Robbins et al., 1992). Older people have experienced decline in their cutaneous sensation. If shoe influences their cutaneous sensation the combined effects of shoe and aging might intensify the alteration in postural stability.

Results of one-way ANOVA showed no significant age difference in average and maximal COM-COP ML separation between older and younger adults in the three shoe conditions. However, the measure in both groups at the three shoe conditions showed interesting age different trends (Figures 6C and 6D). The extent of changed percentage of the measure revealed a remarkable difference. If the sample size in both groups was larger, the difference in COM-COP ML separation between the two groups might be significant. Using the means and standard deviation obtained from this study sample size the number of participants to achieve a significant result was calculated. If the sample size could be increased to 11 people in each group, significant

differences could be shown based on the shoe factor; and further if the sample size could be increased to 18 people in each group significant differences could be shown based on the age factor. Significant difference in COM-COP ML separation could be shown on the basis of age and shoe factors with 18 participants in each group.

5.4 Limitations

Several limitations exist in our study. Due to the COVID-19 pandemic, we were unable to recruit older adults over the age of 60 because of health and safety concerns. The older population of this study were recruited from adults aged 50 to 60 years old. For future studies, an older population might provide more information.

Another possible limitation might be the uncomfortable feeling that some participants experienced when walking barefoot. We asked participants to walk for 5 min in each shoe condition to become familiar and comfortable with the condition. Regardless, we received feedback from some participants that they were not feeling comfortable in barefoot.

Chapter 6: Conclusion

This study investigated the effects of high cushioned and minimal shoes on dynamic postural stability in ML during obstacle crossing in defined older and younger adults. The study demonstrated that shoe cushioning can influence dynamic postural stability in the ML direction during obstacle crossing in younger and older adults. High cushioned shoes led to a challenged postural stability, especially in older adults. The minimal shoe and barefoot conditions did not show significant influence on postural stability in the ML direction during obstacle crossing in older and younger adults. This result suggests that the influence of minimal shoe on dynamic postural stability in the ML direction is not significant. Age differences in dynamic postural

stability in the ML direction during obstacle crossing existed at same shoe conditions. When the shoe condition was changed, shoe cushioning conditions affected postural stability to a larger extent in older adults than younger adults. Older adults (50–60 years old) seemed to have less capacity to adapt to the changes in shoe condition than younger adults (18–32 years old).

This study findings could elucidate the effects of shoe cushioning conditions on dynamic postural stability in the ML direction during obstacle crossing, a challenged locomotion, in older and younger adults. Minimal shoes might be a better choice for older adults to wear on a daily basis because it has less influence on altering dynamic postural stability, which could help older adults maintain their balance. The findings of the study showed that adults aged 50–60 have significant postural stability differences than younger adults. Thus, changes in the dynamic postural stability of the ML direction could start in earlier ages. Future studies should examine older adults over the age of 65 to gain further information. Moreover, electromyography signal analysis of lower limb and trunk muscles during obstacle crossing from older adults might provide useful information about neuromuscular activity. Whether or not wearing the shoes for longer time would make a difference in the dynamic postural stability of individuals is unclear. Examining the adaptive effects of shoes could be beneficial for understanding shoe effects on dynamic postural stability.

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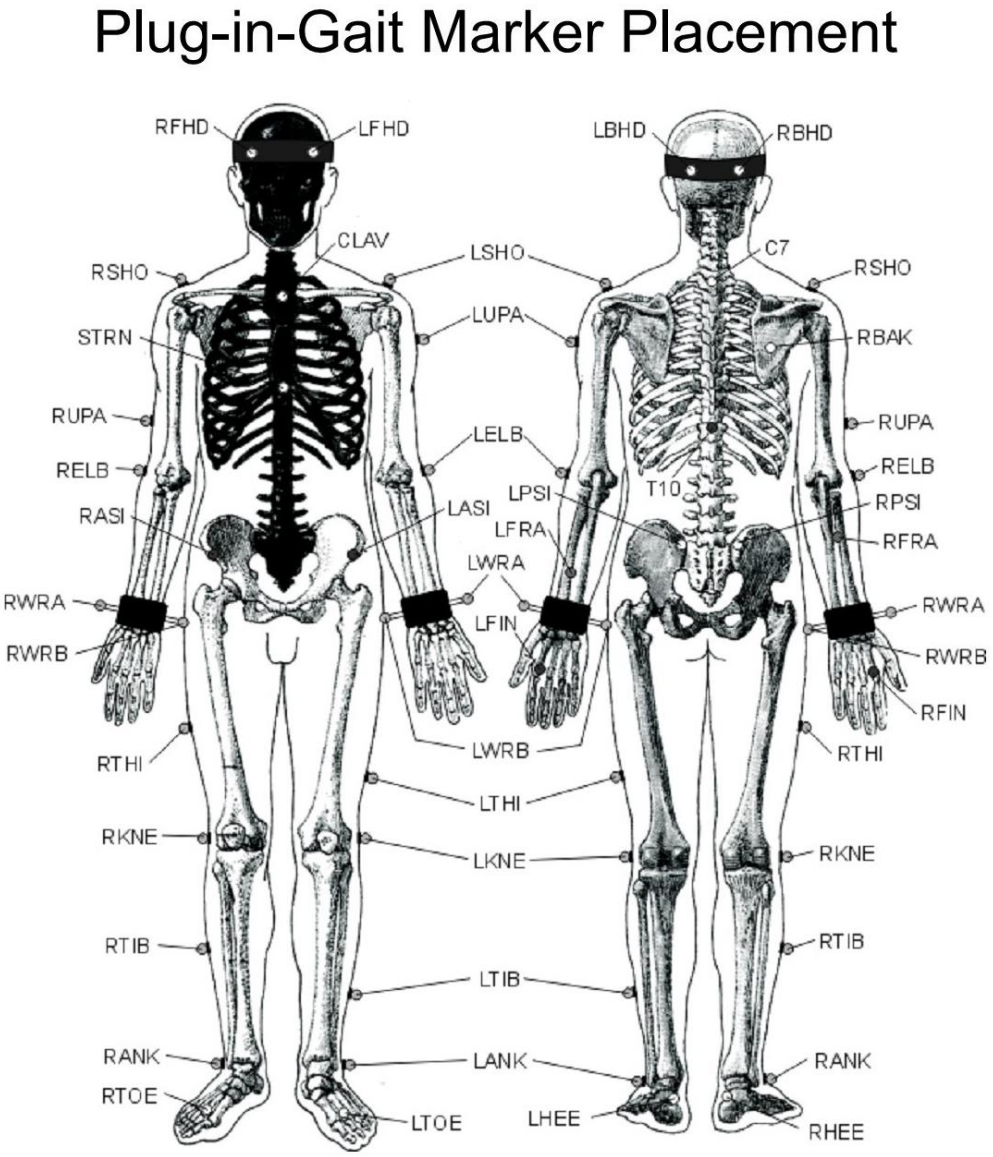
Appendix: Plug-in-Gait marker set



The following describes in detail where the Plug-in-Gait markers should be placed on the subject. Where left side markers only are listed, the positioning is identical for the right side.