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Obstacle Crossing in Healthy Young and Older Individuals

An Honors Thesis submitted in partial fulfillment of the requirements of Honors Studies in
Exercise Science

by

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Abstract

Introduction: In the United States, the average population age is rising and will continue to increase in the coming years. With an older population comes increased risk of injury associated with falls. Falls are considered a leading cause of injury and death in older individuals, and many falls are caused by body imbalance or obstacle collision due to a clearly visible stationary object (e.g., rug, chair, branch). Older adults tend to cross obstacles with increased toe clearance in order to prevent tripping, but much of what is known about obstacle crossing in older adults is limited to artificial obstacles that are unique to the laboratory. Currently, there is little data about how older adults cross the varied types of obstacles that are likely encountered during community ambulation. Thus, this study compared measures of obstacle crossing between young and older adults.

Methods: Fifteen healthy, older adults (68 ± 6 years) and fifteen healthy, young adults (23 ± 2 years) completed a series of obstructed walking trials within the lab while barefoot. A 3D motion capture system tracked participants while they completed at least ten trials of walking for each obstacle along an 8-meter walkway. Obstacles were presented in a randomized order. Participants were instructed to “*walk at a comfortable pace, stepping over the obstacle along the way*”. The obstacles were a branch and a parking curb, representing natural obstacles, and a dowel rod, the traditional obstacle in laboratory studies. Vertical and horizontal toe clearance was measured to assess crossing strategies.

Results: Older individuals crossed the branch, the curb, and the dowel with increased margins of safety when compared to younger adults, which can be seen through the significantly higher foot clearance, specifically the lead toe clearance ($p = .013$), and trail toe clearance ($p = .001$). The curb had a smaller approach and landing distance due to the depth. Regardless of age, the dowel was crossed with a greater margin of safety than the branch and the curb, shown by higher leading and trailing limb toe clearances. The dowel also caused the greatest decrease in gait speed.

Discussion: These results show that older individuals increase foot clearance in both the leading and trailing limbs to prevent tripping, supporting the idea that the obstacle is perceived as a greater risk by older individuals. Interestingly, the branch and the curb appear to be less threatening than the dowel rod based on toe clearances. The smaller approach distance and landing distance for the curb, which can be attributed to its depth, suggest step length is maintained across obstacle types, regardless of the increased risk of obstacle contact.

Introduction

The average age of the United States population is increasing and will continue to increase in the coming years. According to the 2021 Census, 23.3% of United States residents are above the age of 60 (Census Bureau, 2021). Life expectancy is increasing due to medical advancements, such as vaccinations and prevention programs (Medina et al., 2020). The United States Census Bureau reported a 10-year increase in life expectancy from 1960 to 2015, and projects another 6 year increase in life expectancy by 2060, moving from 79.7 years old in 2017 to 85.6 years old in 2060 (Medina et al., 2020). With an increasing population of older individuals in the United States comes increased risk of injury associated with activities of daily living. Aging leads to muscle weakness and decreased balance, which can predispose older adults to fall (Lu et al., 2006). The average price of medical treatment for a fall injury in individuals aged 65-74 is \$6,128 (Burns et al., 2016). For individuals aged 75-84, the average cost of medical treatment for a fall injury is \$9,561 (Burns et al., 2016).

The combination of muscle weakness, decreased control of balance and coordination, and lack of stumble recovery ability are collectively referred to as dynamic stability (Lu et al., 2006). However, age-associated pathologies, such as various central nervous system diseases, may affect dynamic stability to a greater degree than the natural aging process (Hahn & Chou, 2004; Overstall et al., 1977). The majority of falls are caused by body imbalance or obstacle collision, and falls are considered a leading cause of injury and death in older individuals (Hahn & Chou, 2004; Hoyert et al., 2001; Overstall et al., 1977). Dysfunction within the locomotor system can lead to imbalances and instability in older adults, thus predisposing these individuals to trip over obstacles (Huang et al., 2008). According to a survey of individuals over the age of 65, 53% contributed their falls from the past year to tripping (Blake et al., 1988). Fife and Barancik

(1985) found 87% of fractures in adults aged 65 and older were due to a fall (Fife & Barancik, 1985). 32% of adults 75 years and older fell at least once within the previous 12 months and 24% experienced serious injuries (Tinetti et al., 1988). The majority of falls in older adults were due to a clearly visible stationary object (e.g., rug, chair, bag), with 15% of falls being related to a large object, such as the items listed (Muir et al., 2020; Timsina et al., 2017). In order to cross obstacles similar to the items listed previously, older individuals use greater hip flexion and hip adduction in the lead limb to clear the obstacle and increased ankle dorsiflexion in the trailing limb to stabilize themselves through the crossing motion (Lu et al., 2006).

Gait variability, specifically greater step length variability and step time, is more apparent in older individuals with a history of falling (Pieruccini-Faria & Montero-Odasso, 2019). About 8% of older adults above the age of 65 who continue to live independently report difficulty walking (Leon & Lair, 1990; Chen et al., 1991). 56% of older individuals that reside in a nursing home require assistance to walk on a daily basis (Leon, J & Lair T, 1990; cited in Chen et al. article, 1991). Generally, older adults walk more slowly than younger adults with shorter, slower steps and more time spent with both feet on the ground during stance (Hollman et al., 2011).

Older adults are more conservative when approaching obstacles, shown by slower approach speeds, slower crossing speeds, and shorter step lengths (Chen et al., 1991; Hahn & Chou, 2004). This conservative strategy decreases the mechanical load that challenges older adults (Hahn & Chou, 2004) and reduces the likelihood of a fall. Most people modify their stride length before crossing an obstacle to maintain a natural stride through the obstacle crossing (Hahn & Chou, 2004; Sparrow et al., 1996). Older adults cross obstacles with increased toe clearance in order to prevent tripping and remain safe during obstacle crossing, suggesting they see the obstacle as a greater challenge with more severe consequences compared to healthy

young individuals (Lu et al., 2006). To account for decreased muscle strength due to aging, older individuals reduce the anteroposterior distance between their center of mass (COM) and center of pressure (COP) to decrease the load that joints experience when supporting themselves on a single leg, specifically during obstacle crossing (Hahn & Chou, 2004). The decrease in COM-COP separation allows for an increased ability to recover in the case of a collision by allowing extra time to correct foot placement; however, the delay in movement could cause a loss of balance posteriorly (Bhatt et al., 2005; Hak et al., 2013; Pijnappels et al., 2005). Thus, it is vital that older individuals continue progressing forward, albeit slowly, following a collision (Hak et al., 2019). This strategy, though aimed to prevent falls, could potentially amplify instability by increasing COM-COP separation if progression occurs too rapidly (Hahn & Chou, 2004; Moraes et al., 2007; Pieruccini-Faria & Montero-Odasso, 2019).

The increased risk of obstacle collision in older individuals is likely caused by restricted pelvic motion in the frontal plane, decreased stride length, and incorrect foot placement prior to obstacle crossing (Begg & Sparrow, 2000; McFadyen et al., 1993). When comparing older adults and younger adults, range of motion averaged 10 degrees less in older adults than in younger adults (Chen et al., 1991). Inadequate joint angles during obstacle crossing and inaccurate foot placement prior to crossing may result in poor foot elevation, causing obstacle collision (Chou & Draganich, 1998; Heijnen et al., 2012; Patla & Greig, 2006). Lead limb collisions are more common in older adults and require immediate correction, such as correcting foot placement, to prevent falling (Muir et al., 2020). Older adults may not be able to execute these corrections quickly and accurately, leading to falls (Muir et al., 2020). Conversely, trail leg collisions are less likely to result in a fall and more frequently observed in younger individuals (Muir et al., 2020). Avoiding collisions during obstacle crossing places substantial demand on

musculoskeletal, attention, navigation, and sensory functions, creating a test for stability (Brown et al., 2005; Haefeli et al., 2011; Patla & Greig, 2006).

The purpose of this study is to compare measures of obstacle crossing behavior between healthy, young and healthy, older adults in three different obstacles: a dowel, a branch, and a parking curb.

Methods

Participants

This study includes data from a total of 30 individuals. Fifteen healthy, young participants between 18-30 years of age previously participated in the study [age: 23 ± 2 years, mass: 72.5 ± 16.1 kg, height: 1.68 ± 0.97 m, 7 men, 8 women]. Fifteen healthy, older individuals between 60-80 years of age [age: 68 ± 6 years, mass: 79.5 ± 20.1 kg, height: 1.70 ± 0.95 m, 8 men, 7 women] were recruited to participate in this study. We chose this age range to target individuals that are likely experiencing age-related gait changes but are still living independently and community ambulators. Individuals with a history of neurological diseases, neuropathy, or vestibular issues were excluded from the study. Persons with unstable or uncontrolled psychiatric conditions, diabetes, cardiovascular/pulmonary diseases, or an orthopedic condition or musculoskeletal injury that prevented them from safely participating in the study tasks were also excluded. Participants were asked if they could walk unassisted for at least 15 minutes at a time without rest to ensure they will be able to complete the assessments safely. IRB approval was obtained for this research (IRB # 2105335358), and everybody involved acted with responsibility, integrity, and compassion throughout the research study.

Procedures

Participants arrived at the Neuromechanics of Human Movement Laboratory (“the MOVE lab”) in the University of Arkansas Health, Physical Education and Recreation (HPER) building for a single study visit. We discussed their informed consent form to verify their understanding of risks and benefits as well as answer any questions that they may have. After obtaining informed consent, they were asked to complete a few questionnaires (Health History – encompasses neurological or physical injury, a Godin Exercise Questionnaire – describes exercise habits, and the Activity-Specific Balance Confidence Scale – a rating of perceived safety for completing a variety of tasks) to assess their general health, activity levels, and confidence concerning obstacle crossing. The questionnaires were used for descriptive purposes and were not included in the statistical analysis. They were also asked to complete the Short Physical Performance Battery (a functional test of balance, strength, and general mobility) to ensure they are able to safely complete the obstacle crossing tasks. A score of 10 was required to continue data collection; a score lower than 10 may indicate at least one mobility disability (Halaweh et al., 2016). We then placed 39 retroreflective markers on various anatomical landmarks on the participant, in accordance with Vicon Plug-in-Gait© full body marker set. The laboratory contains a 3D motion capture system (Vicon Motion Systems, Oxford, UK) with 16 cameras installed lining the edge of the ceiling to capture 360° movement, and the system includes three hidden force plates in the center of the laboratory to measure ground reaction forces (AMTI, Watertown, MA). The motion capture system tracks the participant’s movement within the laboratory. The first 10 trials consisted of the participant walking unobstructed at a self-selected pace from one side of the laboratory to the other (~8 meters) at a natural, steady pace as a baseline assessment. Following the unobstructed walking trials, an obstacle was placed

across to the walkway on the floor in the middle of the laboratory, and the participant was instructed to walk to the other side of the room “*at a comfortable pace, stepping over the obstacle along the way*”. We included three obstacles presented in a randomized order: 1) a dowel rod, 2) a curb, and 3) a branch. We manually recorded the leading leg each time.

Immediately following the walking trials, the retroreflective markers were removed from the participant, and they were asked to complete two cognitive assessments: the Montreal Cognitive Assessment and the Trails Making Test. Cognitive assessments were used to identify any cognitive impairment, but they were not included in the statistical analysis. The results of the questionnaires and cognitive assessments are presented below in Table 1.

Data Analysis

The data was processed and analyzed using the Vicon Nexus software to generate joint angles and information about the obstacle crossings. We used a custom MATLAB code to pick out discrete variables of interest, including toe clearance and change in walking velocity. Vertical toe clearance over each obstacle was measured in millimeters when the toe marker was directly above the obstacle, for both the leading and trailing legs. Horizontal toe clearance was also measured as the horizontal distance between the toe and the obstacle when the trailing leg is planted prior to crossing (approach distance) and between the leading heel and the obstacle after crossing (landing distance). Change in walking velocity was calculated as the difference between self-selected walking velocity and obstacle crossing velocity using center of mass velocity. Trials were cropped to exclude acceleration and deceleration. Greater toe clearance indicates increasing caution associated with crossing, as does decreased gait speed during crossing. We used a series of 2×3 repeated measures analysis of variance tests to explore how the two groups (younger adults and older adults) cross the three different obstacles (dowel, curb, and branch).

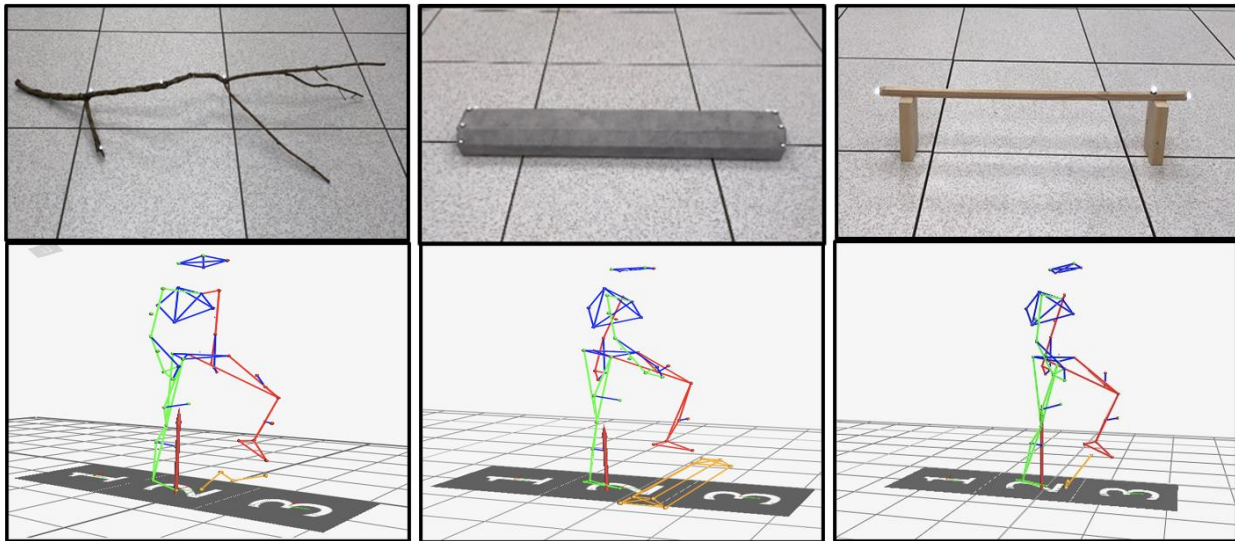


Figure 1: Branch (A), curb (B), and dowel (C) used in walking trials.

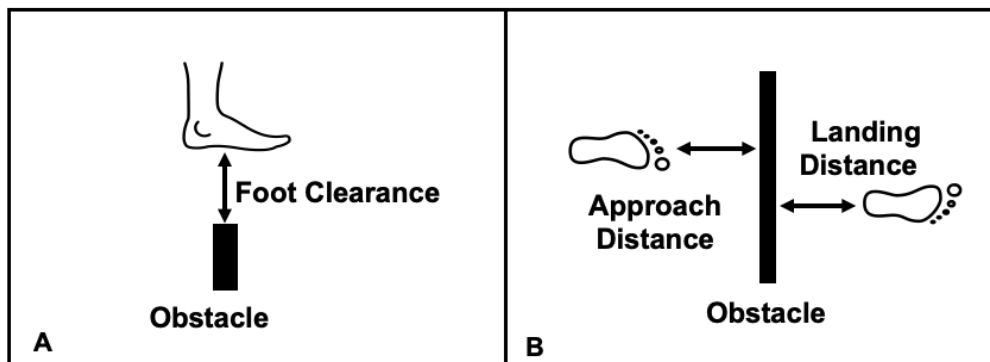


Figure 2: Schematic of foot clearance (A), approach and landing distance (B) measures.

Results

General demographic information from all 30 participants can be found in Table 1. Older adults crossed the obstacles with their dominant leg 51% of the time whereas young individuals crossed the obstacles with their dominant leg 45% of the time. Older individuals crossed the branch, curb, and dowel with increased margins of safety when compared to younger adults, which can be seen through the significantly increased leading vertical toe clearance ($p = .013$) and trailing vertical toe clearance ($p = .001$).

Table 1: Demographic information of participants.

	Older Adults <i>n</i> = 15	Younger Adults <i>n</i> = 15
Height (m)	1.7 ± 0.9	1.7 ± 0.9
Weight (kg)	79.5 ± 19.5	72.5 ± 15.6
Age (years)	68 ± 6	23 ± 2
Gender (men:women)	7:8	8:7
Limb dominance (right:left)	14:1	13:2
Falls in the last 12 months	0.6 ± 1.4	0.067 ± 0.3
SPPB score	11.7 ± 0.6	12 ± 0
MOCA score	26.1 ± 2.6	27.3 ± 1.9
Trails A Time (seconds)	89.8 ± 31.9	66.5 ± 19.3
Trails A Errors	1.2 ± 1.4	1.8 ± 1.5
Trails B Time (seconds)	129.4 ± 39.3	89.2 ± 31.2
Trails B Errors	1.1 ± 1.2	0.5 ± 0.5

Table 2: Mean ± SD of measures of obstacle crossing in mm.

		Approach Distance (TL)	Landing Distance (LL)	Lead Toe Clearance	Trail Toe Clearance
Older Adults	Branch	271 ± 62	232 ± 68	166 ± 43	202 ± 48
	Curb	191 ± 47	127 ± 52	129 ± 24	134 ± 29
	Dowel	276 ± 58	210 ± 67	195 ± 42	240 ± 50
Younger Adults	Branch	270 ± 59	258 ± 47	130 ± 22	154 ± 46
	Curb	184 ± 46	161 ± 39	117 ± 25	105 ± 20
	Dowel	272 ± 61	263 ± 48	159 ± 31	186 ± 36

Each obstacle was crossed differently, regardless of age. There was a significant difference for approach distance between the branch and the curb ($p < .001$) and for the curb and the dowel ($p < .001$). Significant differences in landing distance were also observed between the curb and both other obstacles ($p < .001$) as well as between the branch and the dowel ($p = .048$). The curb had significantly smaller approach and landing distances than the branch and the

dowel. Finally, both leading vertical toe clearance and trailing vertical toe clearance were different for each obstacle comparison ($p < .001$).

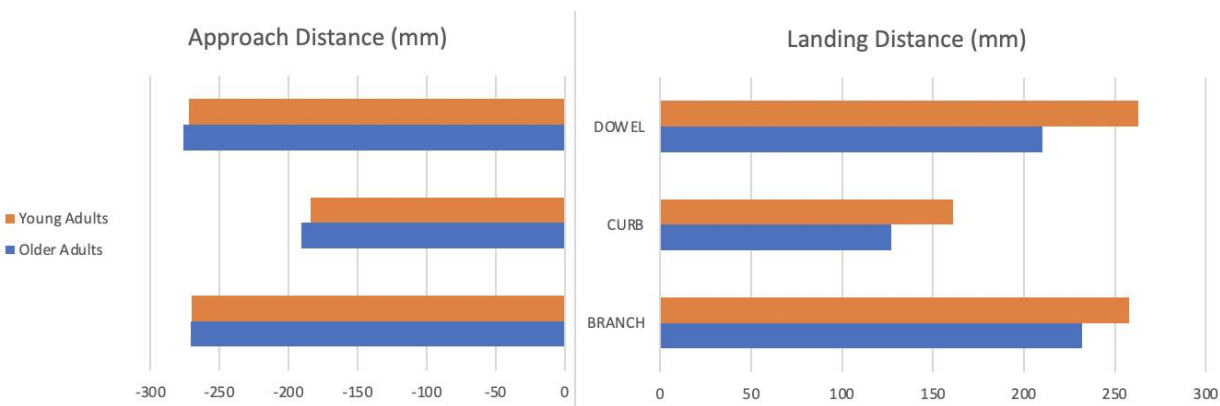


Figure 3: Approach and Landing Distance in mm.

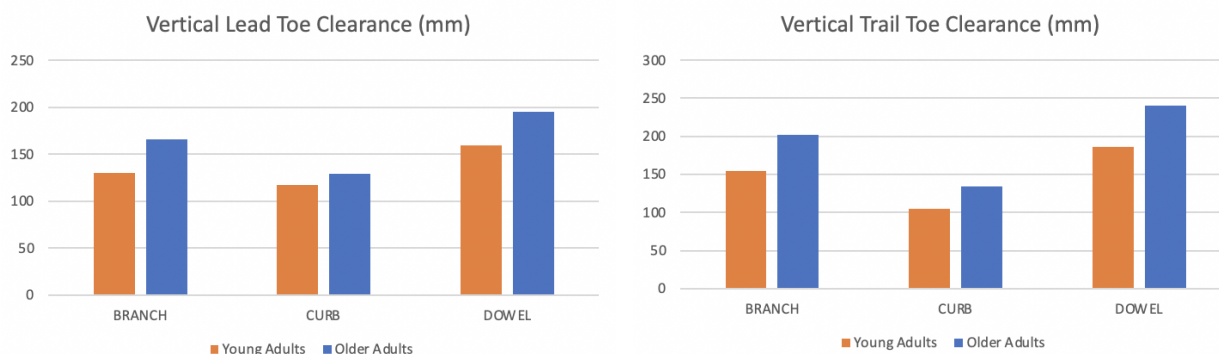


Figure 4: Vertical Toe Clearance for both the Lead and Trail limbs in mm.

Although older adults crossed obstacles more slowly than younger individuals, there was no difference in the percent change observed between groups ($p = .135$). Regardless of age, participants decreased their speed when crossing the dowel compared to either the branch or the curb (both $p < .001$). The greatest difference between young and older individuals occurred during branch crossing trials (4% difference).

Table 2: Speed during unobstructed and obstructed walking trials in m/s.

	Unobstructed	Branch	Curb	Dowel
Older Adults	1.26 ± 0.14	1.22 ± 0.15	1.24 ± 0.17	1.19 ± 0.14
Young Adults	1.26 ± 0.13	1.26 ± 0.1	1.25 ± 0.13	1.21 ± 0.12

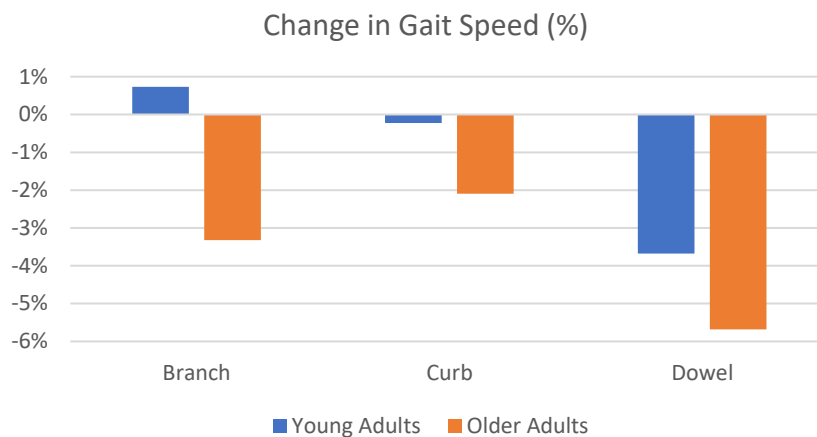


Figure 5: Percent change in Gait Speed from unobstructed walking. Negative values indicate slowing down during the obstacle crossing trials.

Discussion

The purpose of this study was to compare measures of obstacle crossing behavior between young and older adults for three different obstacles: a dowel, a branch, and a parking curb. Our results are consistent with previous literature showing that older individuals increase foot clearance in both the leading and trailing limbs to prevent tripping, supporting the idea that the obstacle is perceived as a greater risk by older individuals (Lu et al., 2006). By increasing toe clearance of both legs, older individuals exhibit a greater margin of safety, decreasing the likelihood of contacting the obstacle and potentially falling.

Although there were no significant differences observed in gait speed change between young and older individuals, all of the participants in this study were fairly healthy and walked

with similar preferred walking paces. The participants' SPPB scores indicate that both young and older individuals were relatively healthy and did not demonstrate marked functional deficits. Previous studies found that older individuals decrease their speed much more than younger individuals; however, the dowel was the only obstacle that was evaluated in those studies (Chen et al., 1991). The populations included in aforementioned studies were older than our population, so greater aging deficits were likely experienced in their population. In older populations, it is likely that results are magnified, and balance deficits are more pronounced. Our results show that the dowel had the greatest percent decrease in gait speed in both young and older individuals, so the participants hesitated more and took more caution when crossing the dowel, regardless of age. Although there was no significant gait speed differences between younger and older individuals, maintenance of COM-COP is vital for balance in older individuals, and the slower crossing speed allows older individuals to maintain balance, especially throughout obstacle crossing (Hahn & Chou, 2004).

There were, however, pronounced differences in measures of obstacle crossing among the three different obstacles. The significant difference between the curb and the other two obstacles, the branch and the dowel, regarding approach distance and landing distance can be attributed to the depth of the curb. The branch and dowel had very little depth (< 25mm) whereas the curb was 200 mm wide. When accounting for the depth of the curb, we can see that the step length of the crossing step is similar for all the obstacles. When encountering obstacles with more depth, such as bags or boxes, there may be an increased risk of falling due to the lack of change in step length. Real-world obstacles vary in dimension, thus increasing the likelihood of a fall if the crossing step is not adjusted to account for an obstacle's shape. Due to its depth, the curb simulates reality more closely and had significantly decreased approach distance and

landing distance in comparison to the other two obstacles. It is vital to adjust step length in order to make it over an obstacle, so a lack of adjustment could indicate an increased risk of obstacle contact and a subsequent fall.

The ability to cross an obstacle with both legs has benefits. Crossing with the non-dominant leg allows increased stability in the first half of obstacle crossing because the dominant leg is stable on the ground. Because most collisions in older adults occur by obstacle contact with the leading leg, increased stability during the first half of crossing is of more importance (Muir et al., 2020). Crossing with the dominant leg allows stability when the trailing leg is crossing the obstacle because the dominant leg is stable on the ground for the final half of crossing. The majority of collisions in younger individuals occur with the trailing leg, so increased stability during the second half of obstacle crossing is more useful (Muir et al., 2020). Our participants successfully crossed the obstacles with both legs, demonstrating they could switch leading limb selection smoothly to cross obstacles and maintain a regular gait pattern rather than dramatically altering their gait, which could lead to instability and unsafe obstacle crossing. In individuals with balance problems, having a preferred lead limb increases confidence and stability throughout obstacle crossing; however, the participants in our study had good balance, indicated by the SPPB scores, and, thus, were able to switch their leading limb.

Conclusion

Older individuals cross obstacles with increased margins of safety when compared to younger individuals, shown in increased toe clearance in all three obstacles. The curb had significantly decreased approach and landing distances due to the depth of the obstacle. Real-world obstacles vary in depth, so changing step length to adapt to obstacles is a vital

modification to decrease the likelihood of a fall. Our results better our understanding of how obstacle crossing changes with age and support the notion that balance is a priority during safe obstacle crossings. The differences in obstacle crossing strategies between the two age groups could help inform future fall prevention strategies during obstacle crossing in real-world situations. By evaluating real-world obstacles, more realistic strategies can be implemented to decrease falls in the aging population

References

- Census Bureau (2021). *age predictions—Census Bureau Tables*. (2021).
<https://data.census.gov/cedsci/table?q=age%20predictions>
- Begg, R. K., & Sparrow, W. A. (2000). Gait Characteristics of Young and Older Individuals Negotiating a Raised Surface: Implications for the Prevention of Falls. *The Journals of Gerontology: Series A*, *55*(3), M147–M154. <https://doi.org/10.1093/gerona/55.3.M147>
- Bhatt, T., Wening, J. D., & Pai, Y.-C. (2005). Influence of gait speed on stability: Recovery from anterior slips and compensatory stepping. *Gait & Posture*, *21*(2), 146–156.
<https://doi.org/10.1016/j.gaitpost.2004.01.008>
- Blake, A. J., Morgan, K., Bendall, M. J., Dallosso, H., Ebrahim, S. B., Arie, T. H., Fentem, P. H., & Bassey, E. J. (1988). Falls by elderly people at home: Prevalence and associated factors. *Age and Ageing*, *17*(6), 365–372. <https://doi.org/10.1093/ageing/17.6.365>
- Brown, L. A., McKenzie, N. C., & Doan, J. B. (2005). Age-Dependent Differences in the Attentional Demands of Obstacle Negotiation. *The Journals of Gerontology: Series A*, *60*(7), 924–927. <https://doi.org/10.1093/gerona/60.7.924>
- Burns, E. R., Stevens, J. A., & Lee, R. (2016). The direct costs of fatal and non-fatal falls among older adults—United States. *Journal of Safety Research*, *58*, 99–103.
<https://doi.org/10.1016/j.jsr.2016.05.001>
- Chen, H.-C., Ashton-Miller, J. A., Alexander, N. B., & Schultz, A. B. (1991). *Stepping over obstacles: Gait patterns of healthy young and old adults*. *46*(6), 196–203.
<https://doi.org/10.1093/geronj/46.6.m196>

- Chou, L.-S., & Draganich, L. F. (1998). Placing the trailing foot closer to an obstacle reduces flexion of the hip, knee, and ankle to increase the risk of tripping. *Journal of Biomechanics*, *31*(8), 685–691. [https://doi.org/10.1016/S0021-9290\(98\)00081-5](https://doi.org/10.1016/S0021-9290(98)00081-5)
- Fife, D., & Barancik, J. I. (1985). Northeastern Ohio Trauma Study III: Incidence of fractures. *Annals of Emergency Medicine*, *14*(3), 244–248. [https://doi.org/10.1016/s0196-0644\(85\)80448-0](https://doi.org/10.1016/s0196-0644(85)80448-0)
- Haefeli, J., Vögeli, S., Michel, J., & Dietz, V. (2011). Preparation and performance of obstacle steps: Interaction between brain and spinal neuronal activity. *European Journal of Neuroscience*, *33*(2), 338–348. <https://doi.org/10.1111/j.1460-9568.2010.07494.x>
- Hahn, M. E., & Chou, L.-S. (2004). Age-related reduction in sagittal plane center of mass motion during obstacle crossing. *Journal of Biomechanics*, *37*(6), 837–844. <https://doi.org/10.1016/j.jbiomech.2003.11.010>
- Hak, L., Houdijk, H., Beek, P. J., & Dieën, J. H. van. (2013). Steps to Take to Enhance Gait Stability: The Effect of Stride Frequency, Stride Length, and Walking Speed on Local Dynamic Stability and Margins of Stability. *PLOS ONE*, *8*(12), e82842. <https://doi.org/10.1371/journal.pone.0082842>
- Halaweh, H., Willen, C., Grimby-Ekman, A., & Svantesson, U. (2016). Physical functioning and fall-related efficacy among community-dwelling elderly people. *European Journal of Physiotherapy*, *18*(1), 11–17. <https://doi.org/10.3109/21679169.2015.1087591>
- Heijnen, M. J. H., Muir, B. C., & Rietdyk, S. (2012). Factors leading to obstacle contact during adaptive locomotion. *Experimental Brain Research*, *223*(2), 219–231. <https://doi.org/10.1007/s00221-012-3253-y>

- Hollman, J. H., McDade, E. M., & Petersen, R. C. (2011). Normative spatiotemporal gait parameters in older adults. *Gait & Posture*, *34*(1), 111–118.
<https://doi.org/10.1016/j.gaitpost.2011.03.024>
- Hoyert, D. L., Arias, E., Smith, B. L., Murphy, S. L., & Kochanek, K. D. (2001). Deaths: Final data for 1999. *National Vital Statistics Reports: From the Centers for Disease Control and Prevention, National Center for Health Statistics, National Vital Statistics System*, *49*(8), 1–113.
- Huang, S.-C., Lu, T.-W., Chen, H.-L., Wang, T.-M., & Chou, L.-S. (2008). Age and height effects on the center of mass and center of pressure inclination angles during obstacle-crossing. *30*(8), 968–975. <https://doi.org/10.1016/j.medengphy.2007.12.005>
- Lu, T.-W., Chen, H.-L., & Chen, S.-C. (2006). Comparisons of the lower limb kinematics between young and older adults when crossing obstacles of different heights. *Gait & Posture*, *23*(4), 471–479. <https://doi.org/10.1016/j.gaitpost.2005.06.005>
- McFadyen, B. J., Magnan, G. A., & Boucher, J. P. (1993). Anticipatory locomotor adjustments for avoiding visible, fixed obstacles of varying proximity. *Human Movement Science*, *12*(3), 259–272. [https://doi.org/10.1016/0167-9457\(93\)90019-L](https://doi.org/10.1016/0167-9457(93)90019-L)
- Medina, L., Sabo, S., & Vespa, J. (2020). *Living Longer: Historical and Projected Life Expectancy in the United States, 1960 to 2060*. 25–1145.
- Moraes, R., Allard, F., & Patla, A. E. (2007). Validating determinants for an alternate foot placement selection algorithm during human locomotion in cluttered terrain. *Journal of Neurophysiology*, *98*(4), 1928–1940. <https://doi.org/10.1152/jn.00044.2006>
- Muir, B. C., Bodratti, L. A., Morris, C. E., Haddad, J. M., van Emmerik, R. E. A., & Rietdyk, S. (2020). Gait characteristics during inadvertent obstacle contacts in young, middle-aged

and older adults. *Gait & Posture*, 77, 100–104.

<https://doi.org/10.1016/j.gaitpost.2020.01.020>

Overstall, P. W., Exton-Smith, A. N., Imms, F. J., & Johnson, A. L. (1977). Falls in the elderly related to postural imbalance. *British Medical Journal*, 1(6056), 261–264.

<https://doi.org/10.1136/bmj.1.6056.261>

Patla, A. E., & Greig, M. (2006). Any way you look at it, successful obstacle negotiation needs visually guided on-line foot placement regulation during the approach phase.

Neuroscience Letters, 397(1–2), 110–114. <https://doi.org/10.1016/j.neulet.2005.12.016>

Pieruccini-Faria, F., & Montero-Odasso, M. (2019). Obstacle Negotiation, Gait Variability, and Risk of Falling: Results From the “Gait and Brain Study.” *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences*, 74(9), 1422–1428.

<https://doi.org/10.1093/gerona/gly254>

Pijnappels, M., Bobbert, M. F., & Dieën, J. H. van. (2005). Push-off reactions in recovery after tripping discriminate young subjects, older non-fallers and older fallers. *Gait & Posture*,

21(4), 388–394. <https://doi.org/10.1016/j.gaitpost.2004.04.009>

Sparrow, W. A., Shinkfield, A. J., Chow, S., & Begg, R. K. (1996). Characteristics of gait in stepping over obstacles. *Human Movement Science*, 15(4), 605–622.

[https://doi.org/10.1016/0167-9457\(96\)00022-X](https://doi.org/10.1016/0167-9457(96)00022-X)

Timsina, L. R., Willetts, J. L., Brennan, M. J., Marucci-Wellman, H., Lombardi, D. A.,

Courtney, T. K., & Verma, S. K. (2017). Circumstances of fall-related injuries by age and gender among community-dwelling adults in the United States. *PLOS ONE*, 12(5),

e0176561. <https://doi.org/10.1371/journal.pone.0176561>

Tinetti, M. E., Speechley, M., & Ginter, S. F. (1988). Risk Factors for Falls among Elderly Persons Living in the Community. *New England Journal of Medicine*, 319(26), 1701–1707. <https://doi.org/10.1056/NEJM198812293192604>