A Kinematic Analysis of Gait during Obstacle Crossing in Middle-Aged Women

Sara Khoshjamal Fekri [a], Farhad Tabatabai Ghomsheh [b*], Ali Fatahi [a]

a Department of Sports Biomechanics, Central Tehran Branch, Islamic Azad University, Tehran, Iran; **b** Pediatric Neurorehabilitation Research Center, Department of Ergonomics, University of Social Welfare and Rehabilitation Sciences, Tehran, Iran

* ***Corresponding author***: Farhad Tabatabai Ghomsheh, Pediatric Neurorehabilitation Research Center, Department of Ergonomics, University of Social Welfare and Rehabilitation Sciences, Tehran, Iran, ***E-mail***: tabatabai@uswr.ac.ir

Submitted: 2022-12-23; **Accepted**: 2023-03-11; **Doi:** https: doi.org.10.22037.jcpr.v8i2.45402

Abstract

Introduction: Due to the significant risk of falls caused by overcoming obstacles, extensive research has focused on lower extremity movements to develop fall prevention strategies. So this study was conducted to identify kinematic analysis of gait during obstacle crossing in middle-aged women. **Materials and Methods**: The study population consisted of healthy middle-aged women aged 55 to 64 years old from the city of Tehran. The minimum sample size was determined to be 24 individuals using G-power software. Angles of lower limb joints were collected using movement analysis cameras during normal gait and obstacle crossing and F point was measured which is when big toe of one's left foot is at the greatest vertical distance from the ground. Paired-Sample T-Test was used with SPSS software version 22 at significant level of $P \leq 0.05$ for further statistical analysis. **Results**: At F point, the ankle and knee joint angles of both the right and left legs decreased significantly when crossing the obstacle compared to normal gait. In addition, Fpoint analysis showed a significant decrease in the hip joint angle of the right leg and a significant increase in the hip joint angle of the left leg. **Conclusion**: The observed kinematic changes indicate that obstacle navigation involves complex motor adjustments necessary to maintain balance and stability. Therefore, training and rehabilitation programs should address these adaptations by incorporating exercises to improve joint angles and minimize the risk of falls.

Keywords: Angle; Kinematic; Lower Limb; Middle-Aged; Obstacle, Woman.

***Please cite this paper as*:** Khoshjamal Fekri S, Tabatabai Ghomsheh F, Fatahi A. A Kinematic Analysis of Gait during Obstacle Crossing in Middle-Aged Women. J Clin Physio Res. 2023; 8(2): e87. Doi: *https:.doi.org.10.22037.jcpr.v8i2.45825*

Introduction

Upon entering the fourth decade of life, the function of joints and muscles undergo changes and people face a gradual decrease in muscle strength. In middle-aged people, like the elderly, falls mainly occur during walking, the main reasons are staggering, walking, and crossing obstacles (1, 2). Crossing obstacles during movement represents as a significant fall risk factor (3-5), and has led to extensive research into the kinematics of lower extremities movement in this activities (6-15). Understanding the mechanics of the locomotors system during obstacle-crossing is crucial for developing effective fall-prevention strategies and injury prevention programs tailored to different age groups and populations.

Earlier studies have primarily centered on young adults, offering foundational insights into the biomechanics of lower limb movement and control during obstacle crossing. These investigations have employed kinematic analyses to examine the movement patterns of both leading and trailing limbs when crossing obstacles of different heights (6, 8-11, 14-16). Key parameters such as foot clearance, foot-obstacle distances, and intersegment coordination have been explored to understand the precise control mechanisms involved in successful obstacle negotiation.

Middle-aged adults are increasingly recognized as a population at risk of falling, yet their specific gait dynamics and strategies during obstacle crossing have not been extensively studied. Stability during gait, particularly in challenging situations like obstacle crossing, depends on several factors including lower limb strength, the sense of proprioception, balance control, and the ability to coordinate movements effectively (17). Age-related declines in muscle strength, joint flexibility, and sensory feedback mechanisms can impair the mentioned factors, leading to an increased risk of instability and falls (18, 19). In elderly, falling can lead to serious problems like hip fractures, hospitalization, soft tissue injuries, and heightened disability (20). These risks highlight the importance of studying gait balance and obstacle negotiation in middle-aged adults to reduce future falls and injuries.

However, the applicability of these findings to middle-aged adults, who experience physiological changes that affect postural stability, remains uncertain. Falls are a major contributor to injuries and deaths in older adults, primarily due to the age-related decline in gait stability (21-23). Middle-aged adults are considered healthy compared to their older peers, but as they age, they gradually develop physiological changes that can compromise their ability to maintain balance during dynamic tasks such as obstacle crossing.(23-26).

Despite the potential vulnerability of middle-aged adults for falling (24-26), there is a paucity of research focused specifically on their gait stability during obstacle crossing compared to older adults (27-30). Although preliminary comparisons may not show significant differences in gait stability between middle-aged and young adults (31), the effects of age and aging on neuromuscular coordination and balance modulation during complex activities such as obstacle crossing remain unknown.

This study aims to bridge this gap by conducting a detailed analysis of sagittal plane joint kinematics during both normal gait and obstacle crossing in middle-aged women. This study builds upon existing research methodologies used in younger adults and extends them to middle-aged women, who may face unique challenges due to age-related changes in muscle strength, joint flexibility, and balance control. Successful obstacle crossing requires coordinated efforts of the swing limb to clear obstacles and the stance limb to maintain stability, posing significant demands on neuromuscular coordination and joint mobility(6, 8-12, 14-16).Through comprehensive kinematic analyses, this research tries to clarify that how middle-aged women adapt their gait patterns and joint movements during obstacle crossing, compared to younger adults and potentially older adults. In conclusion, this study addresses a critical gap in current literature by focusing on the kinematic analysis of gait during obstacle crossing in middle-aged women. By enhancing our understanding of the biomechanical factors influencing gait stability in this demographic, this research aims to contribute valuable insights that can ultimately enhance quality of life and reduce the incidence of falls among middle-aged adults.

Materials and Methods

This research is a semi-experimental study using the impact evaluation model (causal-comparative) and pre-test-post-test design. The statistical population of this research comprised healthy middle-aged women aged 55 to 64 years from Tehran. The minimum sample size using G-power software, considering a statistical power of 0.8 and an effect size of 0.25 at a significance level of 0.05 was determined to be 24 individuals. The sampling method was randomly available.

All participants were coordinated a few days before the start of the research regarding the steps of implementing the training protocol and were comprehensively informed about the experimental methods, research objectives, and safety protocols. After they declared their consent to participate in the research, consent forms were completed by them. To prevent relative motion errors, the participants used special clothing designed to reduce these errors. Demographic characteristics of the participants, including age, time since surgery, the leg operated on, as well as height and weight, were recorded and analyzed. Then, passive markers were placed on the limbs based on the marker-based motion capture.38 passive markers and the Plug-in-Gait method are used to record the spatiotemporal data of markers and lower limb kinematics. According to Figure 1, 4 markers are used to determine the local coordinates of the pelvics. Two markers are placed on the posterior superior iliac crest and the other two markers are placed on the anterior superior iliac crest. Also, the spatial coordinates of these 4 markers and anthropometric data, according to the proposed model in Visual 3D software, are used to predict the hip joint center for both left and right joints. Two clusters, each with 4 markers, are used on the thighs to create the local coordinate system of the thigh organ. These markers are placed in the vertical direction and in the sagittal plane. Leg clusters are also used to create a local coordinate system for the leg. These clusters, like the leg cluster, are placed vertically and in the sagittal plane. Using the markers on the leg, the local coordinates of the leg were determined. These indicators include the indicator on the heel, the indicator in line with the fifth toe and the indicator between the big toe and the second toe. In this study, the data collection process included four stages: system setup, subject preparation, data recording method, and data processing.

To determine joint angle, ten-camera motion analysis systems from the UK (with a recording rate of 100 Hz) were used to track the motion of the lower limb segments while crossing obstacles. Given the significance of the dominant leg in obstacle crossing (31-33), and considering that all participants in this study were left-leg dominant an entry criterion for this test each subject's right leg was positioned before the obstacle, while the left leg was tasked with crossing a 40 cm barrier. This setup aimed to assess the joint angle data of both the leading (left) and supporting (right) legs at the critical stage of facing obstacles. Subjects were instructed to walk along the laboratory's longitudinal axis at a self-selected pace, maintaining a natural gait as they approached and crossed the barrier, which was set at a uniform height of 40 cm for all participants. To standardize the conditions affecting walking manner, all subjects walked barefoot (without shoes). This measure ensured that the results

Table 1. Mean (SD) of Demographic Characteristics of the Subjects

Variable	Mean (SD)
Age (year)	**59.31** (3.07)
Height (cm)	**157.91** (0.03)
Weight(kg)	**67.3** (8.66)
BMI (kg/m2)	**27.02** (3.65)

Table 2. Comparison of F point angle of lower limb joints

Variable		Gait	Mean (SD)	Mean Difference	Degrees of freedom (df)	t	*P*-Value
Ankle	**Right**	Normal	91.950 (8.16)	5.415	23	14.01	0.01
		Obstacle	86.53 (8.03)				
	Left	Normal	85.37 (8.01)	-6.82	23	-6.189	0.01
		Obstacle	92.19 (10.07)				
Knee	**Right**	Normal	-1.083 (0.09	3.00	23	5.61	0.01
		Obstacle	-4.085 (0.35				
	Left	Normal	-24.038 (2.16	73.164	23	21.91	0.01
		Obstacle	-97.202 (10.05				
Hip	**Right**	Normal	0.882 (0.06	-2.069	23	-2.61	0.014
		Obstacle	2.951 (0.03				
	Left	Normal	32.668 (2.08	-47.795	23	-18.26	0.001
		Obstacle	80.463 (7.86				

were independent of the type of shoes or clothing, limiting the influence of these external factors in data analysis for angles of the lower limb joints. F point is the moment when the big toe of one's left foot is at the greatest vertical distance from the ground, which usually causes one to fall when crossing obstacles.

Descriptive and inferential statistical methods were used to analyze the data of this research. Descriptive statistics were used to analyze descriptive indices such as frequency, frequency percentage, mean, and standard deviation. To check the normality of data distribution, the Shapiro-Wilk test was used. In the inferential statistics section, to analyze the data, a Paired-Sample T–Test was used with SPSS software version 22 (IBM, New York, USA) at the significance level of $P \leq 0.05$.

Results

In Table 1, the demographic characteristics of the participants are shown. The independent t-test showed that there is no significant difference in age (59.31±3.07 year), height (157.91±0.03 cm), weight (67.3±8.66 kg), and body mass index (BMI) (27.02±3.65) among the subjects.

Also, according to Shapiro-Wilk test results, research variables had normal distribution. In order to investigate the changes in the range of motion of the lower limb joints when crossing the obstacle compared to normal gait in middle-aged women, the F point of the angle was compared in the three joints of the ankle, knee and thigh in the right leg.

Table 2 shows the comparison of F point ankle joint angle during normal gait and when crossing an obstacle. According to the results, a significant decrease in the F point of the ankle joint angle was observed in the right leg when crossing the obstacle compared to normal gait (*P*=0.01, t=14.01).A significant increase in the F point of the ankle joint angle was observed when crossing the obstacle in the left leg compared to normal gait (*P*=0.01, t=6.189) too.

According to the results, a significant decrease in the F point of the knee joint angle was observed when crossing the obstacle in the right leg compared to normal gait (*P*=0.01, t=5.61). A significant decrease in the F point angle of the knee joint angle was observed when crossing the obstacle in the right leg compared to normal gait (*P*=0.01, t=21.91).

According to the results, a significant decrease in the F point of the hip joint angle was observed when crossing the obstacle in the right leg compared to normal gait (*P*=0.014, t=5.61). A significant increase in the F point of the hip joint angle was observed when crossing the obstacle in the left leg compared to normal gait (*P*=0.014, t=-18.26).

The SPM (Statistical Parametric Mapping) diagram provides compares the right knee joint angles during normal gait (red line) and obstacle gait (black line).

SPM analysis shows that there are statistically significant differences (about 80-100%) between normal and resistance walking towards the end of the gait cycle regarding the angles of the right ankle joint (Figure 1).Around 80% (*P*=0.003) and 100% (*P*=0.001) of the gait cycle there is a significant difference

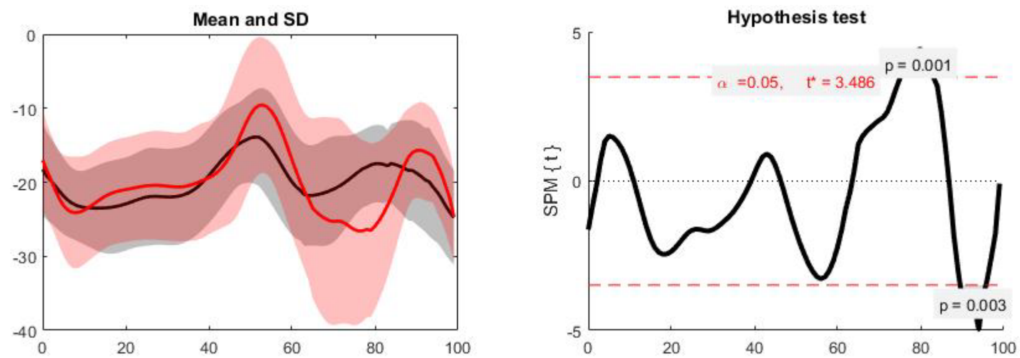

Figure 1. SPM diagram of right ankle joint angle

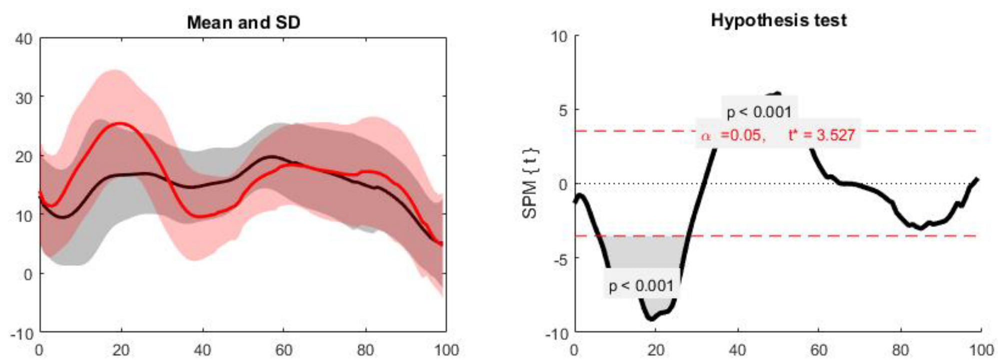

Figure 2. SPM diagram of left ankle joint angle

between ankle angles during obstacle and normal gait. These findings suggest that during obstacle navigation, the angle of the right ankle in the latter part of the gait cycle is significantly different from its normal gait pattern. This may reflect the adaptations or compensations of ankle motion required to navigate the obstacle.

In Figure 2 the SPM analysis indicates that there are statistically significant differences in left ankle joint angles between normal gait and obstacle gait at two key points in the gait cycle. Around 20% (P<0.001) and 50% (P<0.001) of the Gait Cycle, there is a significant difference in ankle angles during obstacle and normal gait. These findings suggest that when navigating an obstacle, the left ankle joint angle significantly deviates from its normal gait pattern at these specific points in the gait cycle. This could reflect different phases of the gait cycle where the ankle's movement is adjusted to accommodate the presence of an obstacle. Significant differences between normal and obstacle gait at approximately 20% and 50% of the gait cycle. Indicates biomechanical adjustments or functional adaptations in left ankle joint behavior during obstacle navigation. Understanding these differences could be crucial for designing interventions or assistive devices aimed at improving gait safety and efficiency in environments with obstacles.

In Figure 3 the SPM analysis indicates that there are statistically significant differences in right knee joint angles between normal gait and obstacle gait at two key points in the gait cycle. Around 10% (P=0.0003) and 80% (P<0.001) of the Gait Cycle, there is a significant difference in knee angles during obstacle and normal gait. These findings suggest that when navigating an obstacle, the right knee joint angle significantly deviates from its normal gait pattern at these specific points in the gait cycle. This could reflect different phases of the gait cycle where the knee's movement is adjusted to accommodate the presence of an obstacle. Significant differences between normal and obstacle gait at approximately 10% and 80% of the gait cycle. Indicates biomechanical adjustments or functional adaptations in right knee joint behavior during obstacle navigation.

In Figure 4 the SPM analysis indicates that there are statistically significant differences in left knee joint angles between normal gait and obstacle gait at two key points in the gait cycle. Around 10% (P=0.0001) and 45% (P<0.001) of the Gait Cycle, there is a significant difference in knee angles during obstacle and normal gait. These findings suggest that when navigating an obstacle, the left knee joint angle significantly deviates from its normal gait pattern at these specific points in the gait cycle. This could reflect different phases of the gait cycle

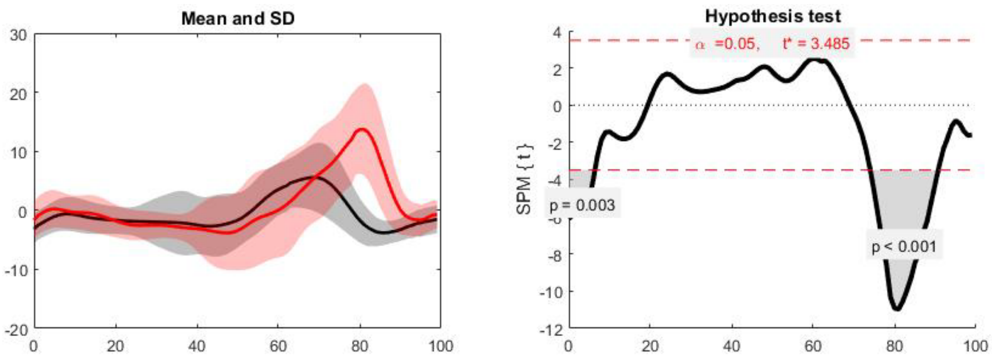

Figure 3. SPM diagram of right knee joint angle

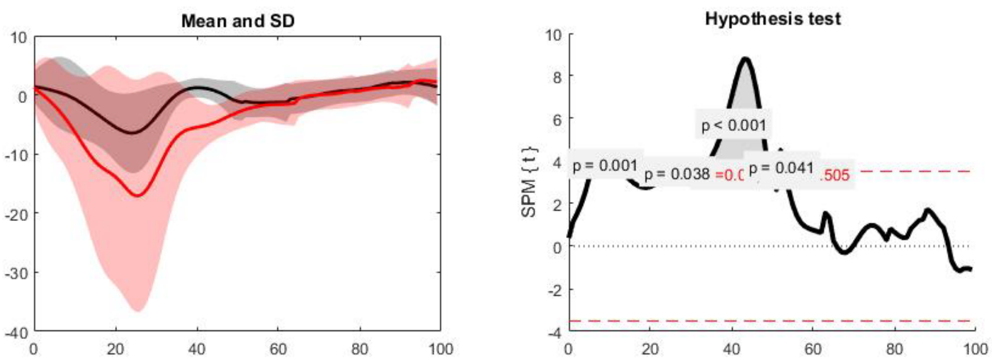

Figure 4. SPM diagram of left knee joint angle

where the knee's movement is adjusted to accommodate the presence of an obstacle. Significant differences between normal and obstacle gait at approximately 10% and 45% of the gait cycle.

In Figure 5 the SPM analysis indicates that there are statistically significant differences in right hip joint angles between normal gait and obstacle gait at two key points in the gait cycle. Around 20% (P=0.001) and 70% (P<0.016) of the Gait Cycle, there is a significant difference in hip angles during obstacle and normal gait. These findings suggest that when navigating an obstacle, the right hip joint angle significantly deviates from its normal gait pattern at these specific points in the gait cycle. This could reflect different phases of the gait cycle where the hip's movement is adjusted to accommodate the presence of an obstacle. Significant differences between normal and obstacle gait at approximately 20% and 70% of the gait cycle.

In Figure 6 the SPM analysis indicates that there are statistically significant differences in left hip joint angles between normal gait and obstacle gait at two key points in the gait cycle. Around 20% (P=0.001) and 70% (P<0.001) of the Gait Cycle, there is a significant difference in hip angles during obstacle and normal gait. These findings suggest that when navigating an obstacle, the left hip joint angle significantly deviates from its normal gait pattern at these specific points in the gait cycle. This could reflect different phases of the gait cycle where the hip's movement is adjusted to accommodate the presence of an obstacle. Significant differences between normal and obstacle gait at around 15% and 55% of the gait cycle.

Discussion

Due to the limited focus on lower limb joint angles during both unhindered and obstacle walking in existing research, we aimed to investigate the movement strategies of elderly women using lower limb joint angle kinematics during obstacle walking at the F point time. Our findings showed a significant decrease in the angles of the ankle and knee joints in both the right and left legs while crossing the obstacle. Specifically, the hip joint angle showed a significant decrease in the right leg and a significant increase in the left leg.

These results show that crossing the obstacle affects the range of motion of the lower limb joints. Decreased ankle and knee joint angles during obstacle walking and natural conditions may be due to changes in muscle strength and endurance, while increased hip joint angles in the left leg could be due to greater muscle effort. Thus, middle-aged women adopt distinct kinematic strategies to successfully cross obstacles. Various

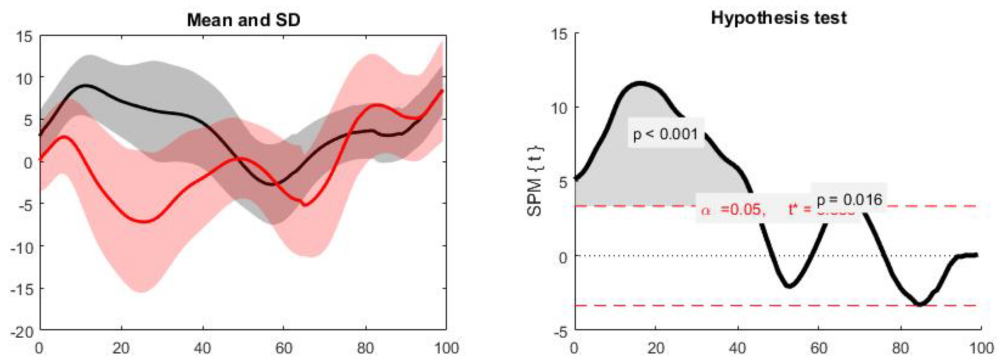

Figure 5. SPM diagram of right hip joint angle

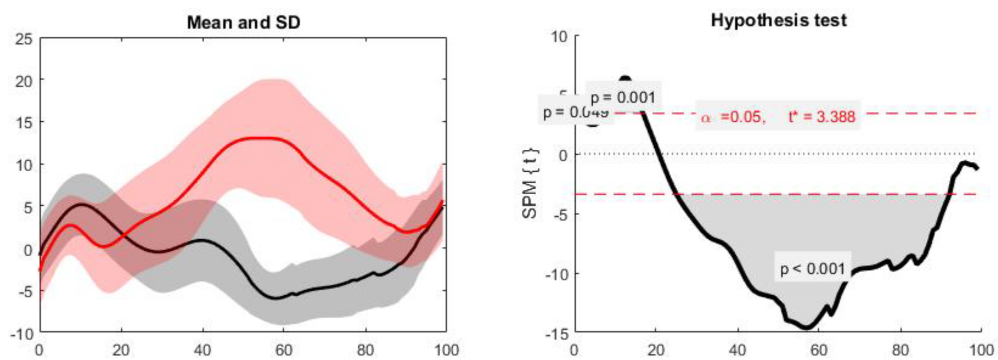

Figure 6. SPM diagram of the left hip joint angle

factors can cause changes in the range of motion of lower limb joints in middle-aged women when crossing an obstacle. These changes may result from decreased flexibility, reduced muscle strength, alterations in balance and stability, and physiological and biomechanical changes due to aging (27, 34, 35). Research indicated that aging decreases the flexibility of the ankle joint, leading to movement limitations and reduced motor ability (36, 37). The significant decrease in the hip joint angle in the right leg and its increase in the left leg suggest different movement strategies between the two legs. These differences may arise from compensatory mechanisms and the body's effort to maintain stability (38). Essentially, the increased hip joint angle in the left leg may compensate for the decreased angle in the right leg. These findings are align with previous studies showing that each leg can adopt different strategies in the face of obstacles (39).

Muir *et al.* (40) found that the ankle and knee joint angles significantly change in both the right and left legs when crossing an obstacle compared to normal gait. Additionally, they reported a notable decrease in the hip joint angle in the right leg and a significant increase in the left leg. Supporting this, Chuyi *et al.* (41) examined the range of motion of lower limb joints in middle-aged women during obstacle crossing. Their study showed significant changes in the range of motion of these joints, demonstrating that crossing an obstacle can substantially impact the range of motion of lower limb joints in middle-aged women.

These findings suggest that obstacle crossing induces distinct biomechanical adaptations in the lower limbs. Decreasing the ankle and knee joint angles in both legs may be a self-made strategy to reduce the risk of falling, as the reduced angle can contribute to a more stable and controlled movement pattern. Contrasting behavior of the hip joint between the right and left legs indicates asymmetric adjustments, possibly due to changes in muscle strength, coordination, or preference for use of the dominant leg. The decrease in ankle and knee joint angles observed during obstacle crossing is consistent with previous research. Studies showed that people decrease their joint angles to achieve a more conservative walking pattern, thereby increasing stability and control when crossing obstacles (42). These adaptations are believed to be protective mechanisms aimed at preventing falls and ensuring safe passage over obstacles. However, the changes in hip joint angles between the right and left legs offer new insights. Although some studies have noted asymmetric limb behavior during walking (42, 43), the significant increase in the left thigh angle compared to the right side represents a unique adaptive strategy in response to obstacle crossing. This finding may be attributed to individual variations in motor control, limb dominance, or compensatory mechanisms due to previous injuries or inherent biomechanical differences.

Previous research with similar findings and high validity can support these results, though some studies may present different outcomes. Such discrepancies might be due to variations in sampling, methodology, tools used, or differences in the age and conditions of the participants, which can lead to diverse results across studies. It is important to note that this research was conducted with only 24 samples of middle-aged women, so its findings cannot be generalized to the entire population of middle-aged women. To confirm or reject the proposed hypothesis, further and more extensive research is needed with appropriate sampling and consideration of other factors such as test conditions and the population under investigation.

Understanding these biomechanical changes is crucial for developing effective rehabilitation protocols, exercise training programs, and fall prevention strategies. For instance, targeted exercises aimed at enhancing the strength and flexibility of the ankle and knee joints can improve stability during obstacle crossing and lower the risk of falls in older adults. In sports training, recognizing the asymmetry in hip joint angles between the right and left legs can aid in creating balanced training programs that address these imbalances, enhance overall performance, and reduce the risk of injuries.

Conclusion

This study showed significant biomechanical adaptations in the lower extremities during obstacle crossing, including notable reductions in ankle and knee joint angles and asymmetrical changes in hip joint angles. These findings enhance our understanding of human movement strategies and have practical implications for improving safety and functions across different populations. Future research should investigate the factors contributing to these asymmetrical adaptations and their effects on overall movement efficiency and injury prevention. The observed kinematic changes suggest that navigating obstacles involves complex motor adjustments crucial for maintaining balance and stability. Therefore, training and rehabilitation programs should consider these changes, incorporating exercises that improve joint angles and reduce the risk of falling. Enhancing mobility strategies can effectively reduce the risk of falling and improve overall quality of life in people.

Acknowledgment
None.

Ethical consideration
None.

Funding support
None.

Conflict of Interest
None.

Author Contribution
All authors made substantial contributions to the conceptions, design, analysis, and interpretation of data.

References

1. Stolt LROG, Kolish DV, Cardoso MRA, Tanaka C, Vasconcelos EFS, Pereira EC, et al. Accidental falls in middle-aged women. Revista de saude publica. 2020;54:141.
2. Sparrow W, Tirosh O. Gait termination: a review of experimental methods and the effects of ageing and gait pathologies. Gait & posture. 2005;22(4):362-71.
3. Tinetti ME, Speechley M. Prevention of falls among the elderly. New England journal of medicine. 1989;320(16):1055-9.
4. Wang Y. Angular movements of the trunk and pelvis when stepping over obstacles of different heights. Research in Sports Medicine. 2003;11(4):219-34.
5. Campbell AJ, Spears G. Fallers and non-fallers. Age and ageing. 1990;19(5):345-6.
6. Patla AE, Prentice SD, Robinson C, Neufeld J. Visual control of locomotion: strategies for changing direction and for going over obstacles. Journal of Experimental Psychology: Human Perception and Performance. 1991;17(3):603.
7. Chen H-C, Ashton-Miller JA, Alexander NB, Schultz AB. Stepping over obstacles: gait patterns of healthy young and old adults. Journal of gerontology. 1991;46(6):M196-M203.
8. Patla AE, Prentice SD. The role of active forces and intersegmental dynamics in the control of limb trajectory over obstacles during locomotion in humans. Experimental Brain Research. 1995;106:499-504.
9. Sparrow W, Shinkfield AJ, Chow S, Begg R. Characteristics of gait in stepping over obstacles. Human Movement Science. 1996;15(4):605-22.
10. Chou L-S, Draganich LF. Stepping over an obstacle increases the motions and moments of the joints of the trailing limb in young adults. Journal of biomechanics. 1997;30(4):331-7.
11. Begg R, Sparrow W, Lythgo N. Time-domain analysis of foot–ground reaction forces in negotiating obstacles. Gait & posture. 1998;7(2):99-109.
12. Chou L-S, Draganich LF. Increasing obstacle height and decreasing toe-obstacle distance affect the joint moments of the stance limb differently when stepping over an obstacle. Gait & posture. 1998;8(3):186-204.

13. Austin GP, Garrett GE, Bohannon RW. Kinematic analysis of obstacle clearance during locomotion. Gait & posture. 1999;10(2):109-20.
14. CHEN H-L, LU T-W, Lin H. Three-dimensional kinematic analysis of stepping over obstacles in young subjects. Biomedical Engineering: Applications, Basis and Communications. 2004;16(03):157-64.
15. Yogev-Seligmann G, Rotem-Galili Y, Mirelman A, Dickstein R, Giladi N, Hausdorff JM. How does explicit prioritization alter walking during dual-task performance? Effects of age and sex on gait speed and variability. Physical therapy. 2010;90(2):177-86.
16. Patla A, Rietdyk S. Visual control of limb trajectory over obstacles during locomotion: effect of obstacle height and width. Gait & Posture. 1993;1(1):45-60.
17. Hollman JH, Kovash FM, Kubik JJ, Linbo RA. Age-related differences in spatiotemporal markers of gait stability during dual task walking. Gait & posture. 2007;26(1):113-9.
18. Fukagawa NK, Wolfson L, Judge J, Whipple R, King M. Strength is a major factor in balance, gait, and the occurrence of falls. The Journals of Gerontology Series A: Biological Sciences and Medical Sciences. 1995;50(Special_Issue):64-7.
19. Chen N, Xiao X, Hu H, Chen Y, Song R, Li L. Identify the alteration of balance control and risk of falling in stroke survivors during obstacle crossing based on kinematic analysis. frontiers in Neurology. 2019;10:436580.
20. Sattin RW. Falls among older persons: a public health perspective. Annual review of public health. 1992;13(1):489-508.
21. Prince F, Corriveau H, Hébert R, Winter DA. Gait in the elderly. Gait & posture. 1997;5(2):128-35.
22. Kang HG, Dingwell JB. Effects of walking speed, strength and range of motion on gait stability in healthy older adults. Journal of biomechanics. 2008;41(14):2899-905.
23. Talbot LA, Musiol RJ, Witham EK, Metter EJ. Falls in young, middle-aged and older community dwelling adults: perceived cause, environmental factors and injury. BMC public health. 2005;5:1-9.
24. Elliott S, Painter J, Hudson S. Living alone and fall risk factors in community-dwelling middle age and older adults. Journal of community health. 2009;34:301-10.
25. Ziere G, Dieleman J, Hofman A, Pols HA, Van Der Cammen T, Stricker BC. Polypharmacy and falls in the middle age and elderly population. British journal of clinical pharmacology. 2006;61(2):218-23.
26. Gill J, Allum J, Carpenter M, Held-Ziolkowska M, Adkin A, Honegger F, et al. Trunk sway measures of postural stability during clinical balance tests: effects of age. The Journals of Gerontology Series A: Biological Sciences and Medical Sciences. 2001;56(7):M438-M47.
27. Menz HB, Lord SR, Fitzpatrick RC. Age-related differences in walking stability. Age and ageing. 2003;32(2):137-42.
28. Helbostad JL, Moe-Nilssen R. The effect of gait speed on lateral balance control during walking in healthy elderly. Gait & posture. 2003;18(2):27-36.
29. Grabiner PC, Biswas ST, Grabiner MD. Age-related changes in spatial and temporal gait variables. Archives of physical medicine and rehabilitation. 2001;82(1):31-5.
30. Lee H-J, Chou L-S. Detection of gait instability using the center of mass and center of pressure inclination angles. Archives of physical medicine and rehabilitation. 2006;87(4):569-75.
31. Schorderet C, Hilfiker R, Allet L. The role of the dominant leg while assessing balance performance. A systematic review and meta-analysis. Gait & posture. 2021;84:66-78.
32. Byrne JM, Prentice SD. Swing phase kinetics and kinematics of knee replacement patients during obstacle avoidance. Gait & posture. 2003;18(1):95-104.
33. Petrarca M, Di Rosa G, Cappa P, Patanè F. Stepping over obstacles of different heights: kinematic and kinetic strategies of leading limb in hemiplegic children. Gait & posture. 2006;24(3):331-41.
34. Michalska J, Kamieniarz A, Sobota G, Stania M, Juras G, Słomka KJ. Age-related changes in postural control in older women: Transitional tasks in step initiation. BMC geriatrics. 2021;21:1-9.
35. Sipilä S, Törmäkangas T, Sillanpää E, Aukee P, Kujala UM, Kovanen V, et al. Muscle and bone mass in middle-aged women: role of menopausal status and physical activity. Journal of cachexia, sarcopenia and muscle. 2020;11(3):698-709.
36. Hunter SK, Pereira HM, Keenan KG. The aging neuromuscular system and motor performance. Journal of applied physiology. 2016.
37. Vandervoort AA, McCOMAS AJ. Contractile changes in opposing muscles of the human ankle joint with aging. Journal of Applied Physiology. 1986;61(1):361-7.
38. Yun J-E, Park J-H. Effects of multi-obstacle contexts on obstacle negotiation strategies in healthy older adults under dual-task conditions. Gait & Posture. 2022;94:198-202.
39. Park SY, Lee YS. Kinematics of the Lower Limbs during Obstacle Crossings Performed by Young Adultsand the Elderly. Journal of Physical Therapy Science. 2012;24(10):941-4.
40. Muir B, Bodratti L, Morris C, Haddad JM, Van Emmerik R, Rietdyk S. Gait characteristics during inadvertent obstacle contacts in young, middle-aged and older adults. Gait & Posture. 2020;77:100-4.
41. Cui C, Muir B, Rietdyk S, Haddad J, van Emmerik R, Ambike S. Sensitivity of the toe height to multijoint angular changes in the lower limbs during unobstructed and obstructed gait. Journal of Applied Biomechanics. 2021;37(3):224-32.
42. Sadeghi H, Allard P, Prince F, Labelle H. Symmetry and limb dominance in able-bodied gait: a review. Gait & posture. 2000;12(1):34-45.
43. Robinson JL, Smidt GL, Arora JS. Accelerographic, temporal, and distance gait: factors in below-knee amputees. Physical therapy. 1977;57(8):898-904.