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Changes in the control of obstacle crossing in middle age become evident as gait task difficulty increases

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ABSTRACT

Background: Age-associated physiological changes result in modified gait, such as slower speed, for older adults. Identifying the onset of age-related gait changes will provide insight into the role of aging on locomotor control. It is expected that a more challenging gait task (obstacle crossing) puts more demands on physiological systems, and may reveal gait modifications in a middle-aged group that are not evident in an easier gait task (level walking).
Research question: To identify the effect of advancing age on gait as a function of increasing locomotor challenge during an obstacle crossing task.
Methods: Three age groups (young, middle-aged, and older adults) stepped over an obstacle placed in a 15 m walkway. Task challenge ranged from low to high in four conditions: unobstructed gait, 3, 10, and 26 cm obstacles. Gait measures were calculated during the approach and crossing steps.
Results: Significant interactions were observed for gait speed (age by height by step, $p < 0.01$), foot placement variability (age by step, $p < 0.01$) and foot clearance (age by height, $p = 0.05$). Relative to young adults, older adults walked slower in all conditions and had higher foot clearances for the 10 and 26 cm obstacles. Middle-aged adults walked with speeds and foot clearances that were not different from young adults in the lower gait challenge conditions, and changed to values that were not different from older adults in the highest gait challenge conditions. Foot placement variability was greater for the middle-aged and older groups, but only in the last two steps before the obstacle.
Significance: Multiple gait changes were observed as early as middle-age, and changes in speed and foot clearance became more evident as task difficulty increased. The increased gait challenge placed more demands on the neuromuscular system, revealing age-related gait modifications that were not evident in the level walking gait task.

1. Introduction

Aging is characterized by progressive declines in neuromuscular, skeletal, and cognitive systems [1], which affect mobility and gait. The gait of younger and older adults has been compared extensively, but little is known about the onset of age-related changes. The progressive nature of these age-related changes leads to the expectation that gait changes observed in older adults will become evident during middle age. However, middle-aged adults do not walk differently from younger adults during unobstructed gait at natural cadences [2,3], which indicates that any age-related changes at middle-age are too mild to impair or modify gait in steady state. It is possible that unobstructed gait at a natural cadence may insufficiently task the neuromuscular and cognitive systems to reveal changes in middle age, and more challenging gait tasks are required to fully delineate the effect of aging on mobility. For example, manipulating gait speed revealed changes in the gait of middle-aged adults that were not evident when walking at self-selected speed [4].

Stepping over obstacles increases gait challenge, with the challenge systematically increasing with obstacle height, as evidenced by increasing contact rates with obstacle height [5]. During the approach the participant gathers visual information (e.g. obstacle height and

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position) to modify foot placement and successfully clear the obstacle [6,7]. A robust observation in previous studies is that the final foot placement before an obstacle is tightly controlled in young adults (20–35 years) [6] and older adults (65–90 years) [8–10], as foot placement closer to the obstacle increases trip risk [6,8,10–12]. Foot placement is also used to control trunk motion [13–15], and must be adjusted relative to the obstacle while concurrently maintaining trunk stability. If only the last step is adjusted to achieve the appropriate final foot placement, the abrupt change in step length may be detrimental to stability, especially in older adults as this population demonstrates compromised trunk control [4,16]. Thus, obstacle crossing task allows an assessment of gait adaptations as obstacle height increases. Adaptations to obstacle height as well as foot successive placements during the approach to the obstacle may reveal gait modifications in a middle-aged group that are not evident in the level walking gait task.

The purpose of this study was to identify the effect of advancing age on gait as a function of increasing locomotor challenge during an obstacle crossing task. Three age groups included young (20–35 years), middle-aged (50–64 years), and older adults (65–79 years). Gait measures were calculated during the approach steps and the crossing steps and included gait speed, foot placement, foot placement variability, foot clearance, and foot clearance variability. Gait speed was selected as modifying speed is a robust strategy adopted in response to personal and environmental manipulations [8,17,18]. The placement and clearance measures were selected as they are related to successful obstacle crossing [6,11,12,19]. We predicted that middle-aged adults would be more like young adults in less challenging conditions (with no or low-height obstacles and/or in the steps farther away from the obstacle), and more like older adults in the harder conditions; as demonstrated by an interaction with age. For measures taken during the approach (speed, foot placement, and foot placement variability), we predicted one or more measures would demonstrate an interaction with age (age by obstacle height; age by step number; age by obstacle height by step number) as described above. For measures taken during crossing (foot clearance, and foot clearance variability), we predicted one or both measures would show an interaction (age by obstacle height) as described above. Finally, we hypothesized that all age groups will have a similar final foot placement before the obstacle, replicating previous research [6,8,10,20].

2. Methods

Participants were recruited through flyers posted on campus and in local senior centers, and through word of mouth. Three age groups were examined: young adults (N = 20, age: 23.8 ± 3.4 years, height: 1.77 ± 0.08 m, 10 females), middle-aged adults (N = 15, age: 55.5 ± 4.5 years, height: 1.71 ± 0.09 m, 11 females), and older adults (N = 19, age: 69.9 ± 4.9 years, height: 1.76 ± 0.09 m, 8 females). Height was not different across the three age groups ($F(2,51) = 3.18$, $p = 0.12$). All participants walked without an aid, had no orthopedic or neuromuscular disorders, and were independent in daily activities. All participants signed an informed consent approved by the Institutional Review Board.

Participants walked along a 15 m walkway and stepped over an obstacle when present (Fig. 1A). Four obstacle conditions were examined, representing increasing gait challenge: unobstructed, 3, 10, or 26 cm. Ten trials of each condition were presented in blocks with the order of the blocks randomized. A 5-minute rest break was provided every ten trials. If a participant contacted an obstacle, another trial was recorded.

Kinematic data were collected at 100 Hz using Qualysis Track Manager (Qualysis Inc., Gothenburg, Sweden). Eight clusters (four markers each cluster) were placed bilaterally on the shank, thigh, upper arm, and forearm segments, a cluster of five markers was placed on the head, a cluster of three markers was placed on the trunk as in [21], and markers were placed individually on landmark locations including the great toe, first and fifth metatarsal head, heel, greater trochanter, acromion process, ASIS, PSIS, radial and ulnar styloids, medial and lateral malleoli, femoral epicondyles, humeral epicondyles. One marker was placed on the top right corner of the obstacle. Kinetic data were collected at 1000 Hz from three embedded forceplates (AMTI, Watertown, MA), and then down-sampled to 100 Hz. A zero-lag, fourth-order, low-pass Butterworth filter was used, with cut-off frequencies of 8 Hz (kinematics) and 20 Hz (kinetics).

Gait events (heel contact and toe off) were selected using a threshold value (15 N) in the vertical ground reaction force. Four steps (step-2, step-1, step-obst, step + 1) and five foot placements (fp-3, fp-2, fp-1, fp + 1, fp + 2) were examined (Fig. 1A); these step and foot placement variables are defined relative to the obstacle location. In the unobstructed trials, the step terminology is consistent with the obstacle trials, even though an obstacle was not present (Fig. 1A). Gait speed was calculated by differentiating anterior-posterior displacement of the superior head marker; the resulting anterior-posterior velocity was averaged for each step to quantify gait speed. Foot placement was calculated as the anterior-posterior distance between the toe and obstacle in stance phase before crossing and the heel and obstacle after crossing (Fig. 1A). Foot clearance measures were only available for the crossing steps (Fig. 1B). Heel and toe clearances were defined as the vertical distance between the obstacle and heel or toe marker, respectively, at the frame where the heel or toe was directly above the obstacle. The smallest value of the heel and toe clearances was defined as minimal foot clearance [8,12]. Although step width, step width variability, and step length variability are not directly related to successful obstacle crossing like the foot clearance and placement measures [6,11,12,19], they were calculated as they are related to foot placement. Step width and length were calculated as the medial-lateral and anterior-posterior distances, respectively, between the two heel markers at subsequent heel contacts. Variability of each measure was defined as the standard deviation across the 10 trials of each condition.

Repeated measures mixed model ANOVA with participant nested within age group were completed (SAS 9.3, SAS Institute, Cary, NC). For measures assessed across all steps (Obstacle approach; Fig. 1B) the three-way model included age group (3 levels: young, middle-aged, older adults) by obstacle condition (three levels: 3, 10, 26 cm or four levels: unobstructed, 3, 10, 26 cm; three levels were used for foot placement measures, four levels were used for speed, step width, and variability of step length and step width) by step number (4 levels: step-2, step-1, step-obst, step + 1 or 5 levels: fp-3, fp-2, fp-1, fp + 1, fp + 2; Fig. 1). For measures only available in the crossing steps (Obstacle crossing; Fig. 1B) the two-way model included age group (3 levels: young, middle-aged, older adults) and obstacle condition (3 levels: 3, 10, 26 cm). Significance was $p \leq 0.05$; only the significant effects are reported. Tukey post hoc pairwise comparisons were conducted to determine group differences.

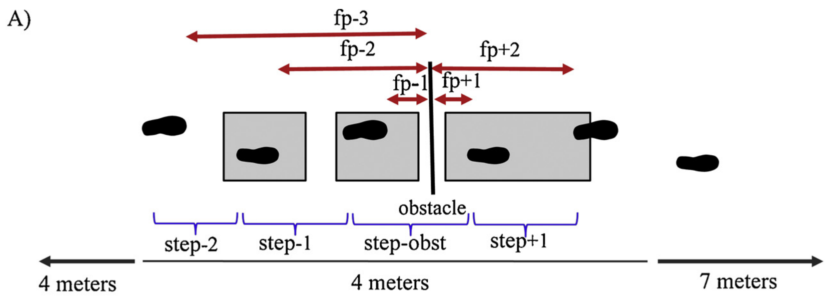
3. Results

3.1. Obstacle contacts

Twenty obstacle contacts were observed in 1620 (1.2%) obstructed gait trials. For the young, middle-aged, and older adults, contact rates were: 2.3%, 0.5%, and 0.7%. For 3 cm, 10 cm, and 26 cm obstacles, contact rates were: 0.2%, 1.3%, and 2%. Detailed description and analyses of gait parameters during inadvertent contacts are available [22].

Consistent with our hypothesis, significant interactions with age (where middle-aged adults were more similar to young adults in the less challenging conditions and more similar to older adults in the more challenging conditions) were observed for the following variables: gait speed, foot placement variability, and lead foot clearance. These predicted interactions are described first, followed by other significant findings.

A)



B)

Variables during Obstacle Approach		Variables during Obstacle Crossing
Step Number	**Foot Placement Number**	
Gait speed Step width Step length variability Step width variability	Foot placement variability Foot placement	Lead minimum foot clearance Trail minimum foot clearance Lead minimum foot clearance variability Trail minimum foot clearance variability
age x step x obstacle	age x fp x obstacle	age x obstacle
Obstacle – 4 levels	Obstacle – 3 levels	Obstacle – 3 levels

Fig. 1. Depiction of the walkway and the terminology for each foot placement (fp) and each step (a). The five foot placements (fp-3, fp-2, fp-1, fp + 1, fp + 2) and four steps (step-2, step-1, step-obst, step + 1) are depicted. The gray boxes are the force plates. The dependent variables measured at each step, at each foot placement, and at crossing step only (b). In the bottom two rows, the statistical interactions examined for each set of measures are noted, and the number of levels within obstacle height.

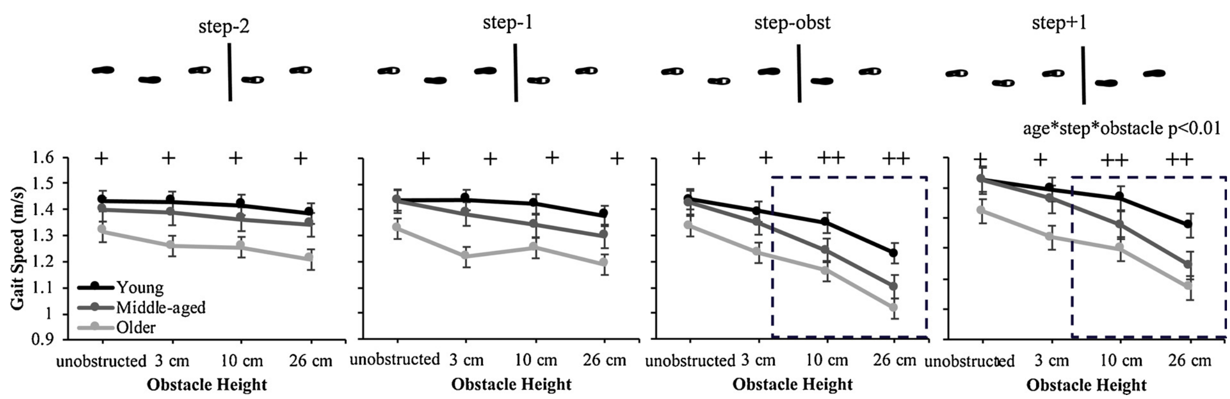


Fig. 2. Gait speed expressed as function of step, obstacle height, and age group. Successive steps are shown from left panel to right panel: step-2, step-1, step-obst, and step + 1. Young adults (black), middle-aged adults (dark gray), older adults (light gray). Error bars represent the standard error. A three-way interaction was observed, age by step by obstacle height ($p < 0.01$). Post hoc analyses revealed that gait speed was faster in young adults versus older adults in all steps and for all obstacles; for simplicity, this statistical difference is not indicated in the figure as it was the same for all conditions. + indicates conditions where middle-aged adults were not different from young adults. + + indicates conditions where middle-aged adults were not different from older adults (dashed box).

As hypothesized, a significant interaction (age by step by obstacle) was observed for gait speed ($F(18,468) = 2.84$, $p < 0.01$, Fig. 2). Post hoc analyses revealed that across all four steps in all obstacle conditions, young adults had a faster gait speed than older adults. In step-2 and step-1 the gait speed of young and middle-aged adults was not different for all obstacle heights, while in step-obst and step + 1, middle-aged adults had a slower gait speed than young adults, but only for the 10 and 26 cm obstacles (Fig. 2, dashed boxes).

As hypothesized, a significant interaction (age by foot placement) was observed for foot placement variability ($F(8,204) = 3.65$, $p < 0.01$, Fig. 3B). All age groups demonstrated a decrease in foot placement variability during approach to the obstacle and an increase after crossing the obstacle. Post hoc analyses revealed that in fp-1, fp + 1, and fp + 2 there was no difference between the age groups. In fp-3 and fp-2, young adults had less variability than middle-aged and older adults across all obstacle heights, with no differences between older and middle-aged groups.

As hypothesized, a significant interaction (age by obstacle height) was observed for lead minimum foot clearance ($F(4,84) = 2.40$, $p = 0.05$, Fig. 4). Post hoc analyses revealed that for the 3 cm obstacle no difference between age groups was observed, for the 10 cm obstacle older adults have a higher minimum foot clearance than young adults, and for the 26 cm obstacle both middle-aged and older adults have a higher minimum foot clearance compared to young adults.

A significant interaction (age by step by obstacle) was observed for foot placement ($F(16,410) = 1.88$, $p = 0.02$, Fig. 3A). Although a three-way interaction was observed, only the 26 cm results are plotted for simplicity (Fig. 3A); the results for the 3 and 10 cm obstacle conditions were markedly similar despite the three-way interaction. Post hoc analyses revealed that the changes in foot placement at each stance phase demonstrate that both older groups placed the foot closer to the obstacle at fp-3, fp + 1 and fp + 2, consistent with a shorter step length for both older groups. No differences between middle-aged and older adults were observed. Thus, although a three-way interaction was observed, it did not follow the predicted trend; rather, the middle-aged group was not different from older adults in all conditions, not only in the difficult conditions. All groups maintained a similar final foot placement in fp-2 and in fp-1, the final foot placement before the obstacle, as predicted.

A main effect of age was observed for step width variability ($F(2,51) = 4.96$, $p = 0.01$), where step width variability was progressively larger with advancing age: 25 ± 3, 30 ± 3, 34 ± 3 mm, for young, middle-aged and older, respectively. Step length variability and step width did not demonstrate any main effects or interactions with age ($F(2,51) = 2.96$, $p = 0.06$, $F(2,51) = 133$, $p = 0.27$, respectively).

Trail foot minimum clearance demonstrated main effects of age and

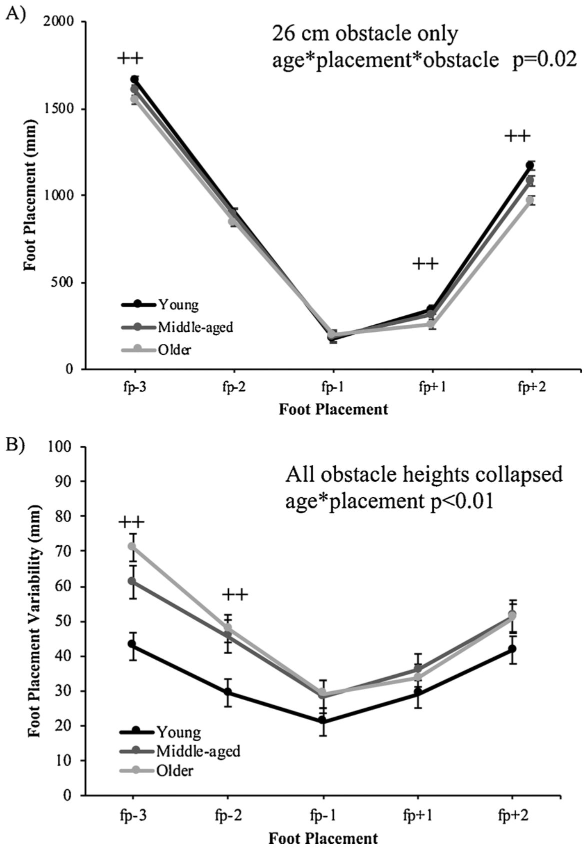


Fig. 3. Foot placement (a) for the 26 cm obstacle expressed as a function of step and age group. A three-way interaction was observed, age by step by obstacle height (p = 0.02), but only the 26 cm is plotted here for simplicity since the other two heights demonstrated markedly similar results. Foot placement variability (b) across all obstacle heights expressed as a function of foot placement and age group. Young adults (black), middle-aged adults (dark gray), older adults (light gray). Error bars represent the standard error. A two-way interaction was observed, age by step ($p < 0.01$). Data were collapsed across obstacle height, as there was no main effect or interactions with obstacle height. Post hoc analyses revealed that in fp-1, fp + 1, and fp + 2 there was no difference between the age groups. In fp-3 and fp-2, young adults had less variability than middle-aged and older adults across all obstacle heights. + + indicates conditions where middle-aged adults were not different from older adults.

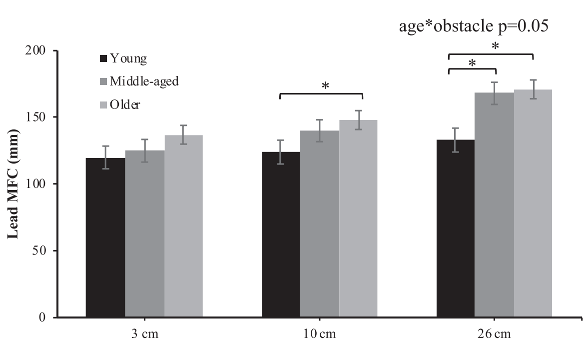


Fig. 4. Lead minimum foot clearance expressed as a function of age group and obstacle height. Young adults (black), middle-aged adults (dark gray), older adults (light gray). Error bars represent the standard error. A two-way interaction was observed, age by obstacle (p = 0.05) Post hoc analyses revealed that for the 3 cm obstacle no difference between age groups was observed, for the 10 cm obstacle older adults have a higher foot clearance than young adults, and for the 26 cm obstacle both middle-aged and older adults have a higher foot clearance compared to young adults. * indicates a significant difference between conditions.

obstacle height ($F(2,52) = 8.24$, $p < 0.01$, $F(2,104) = 52.22$, $p < 0.01$, respectively, Table 1), where minimum foot clearance progressively increased with advancing age, and a higher clearance was adopted by all age groups for the 26 cm obstacle compared to the smaller obstacles. Only obstacle height effects were observed for lead and trail foot minimum clearance variability ($F(2,80) = 7.34$, $p < 0.01$, $F(2,104) = 45.53$, $p < 0.01$, respectively, Table 1). Post hoc analysis revealed that the 26 cm obstacle had greater minimum foot clearance variability compared to the 3 and 10 cm obstacles.

4. Discussion

The goal of this research was to assess the role of advancing age on gait adaptability as a function of task difficulty. The locomotor task challenge was examined based on increasing difficulty due to obstacle height manipulations, while also assessing the nature of the approach to the obstacle. Significant interactions were observed for gait speed and lead foot clearance. In general, when crossing lower obstacles, middle-aged adults were not different from young adults. However, as obstacle height increased, the gait of middle-aged adults more closely resembled that of the older adults. Therefore, as predicted, differences in the control of adaptive locomotion at middle-age were generally observed in the more challenging conditions.

The progressive decrease in speed as a function of obstacle height in all age groups (Fig. 2) reflects that the ability to recognize and scale behavior to the level of task challenge is maintained with healthy aging. Older adults were always slower than young adults, likely indicating longer time needed to gather visual information during the approach and greater caution during the approach and crossing steps [7,10,17,23,24]. The speed of the middle-aged adults revealed the expected effect: the middle-aged group was not different from young adults at the low task challenge (i.e, steps preceding the obstacle and smaller obstacles), but at the higher task challenge (i.e., steps over the obstacle and taller obstacles) middle-aged adults were not different from older adults (dashed box, Fig. 2). In other words, the easier conditions were insufficiently demanding to reveal age-related changes in speed at middle age. Therefore, middle-aged adults modified gait speed in response to lower challenges – such as those observed in a typical urban community – in a similar manner as young adults, but were more affected by environments with greater challenge – such as hiking. However, changes were observed not only for the 26 cm obstacle, but also the 10 cm obstacle, which is similar to curb height and may be relevant for behaviors such as crossing a street safely within the allotted crossing time.

The changes to lead foot clearances reinforce the preceding observation that middle-aged adults adopt foot clearance strategies that are similar to young adults in low challenge locomotor tasks, and similar to older adults in the high challenge locomotor tasks (Fig. 4). Middle-aged adults had lead foot clearances similar to the young adults for the 3 and 10 cm obstacles, but lead foot clearances similar to the older adults for the 26 cm obstacle. Stepping over larger obstacles is more demanding physiologically, and thus provides a window into physiological changes that affect mobility during middle-age.

All age groups controlled the foot placement as expected, such that in the final trail foot placement before the obstacle, the foot placement position and foot placement variability were not different as a function of age (Fig. 3A,B), consistent with previous findings [8,10,20]. However, the foot placement variability was greater for the middle-aged and older groups in the third and second foot placements before the obstacle (Fig. 3B). Higher variability can be interpreted as detrimental or functional. From a detrimental perspective, higher foot placement variability in the older groups may reflect a reduced ability to gather and/or transform the visual information in the earlier steps [6]. Conversely, higher foot placement variability in the steps preceding the final foot placement may be functional, as the older groups may require more variability in the earlier steps to ensure that the final foot

Table 1
Dependent variables during crossing expressed as a function of age group and obstacle height.

		Young	Middle-aged	Older	age	obstacle	age *obstacle
Lead MFC	**3 cm**	120 ± 9	125 ± 7	137 ± 8			
(mm)	**10 cm**	124 ± 9	140 ± 7	148 ± 8	0.03	< 0.01	**0.05**
	26 cm	133 ± 9	168 ± 7	171 ± 8			
Trail MFC	**3 cm**	80 ± 12	103 ± 12	137 ± 14			
(mm)	**10 cm**	74 ± 12	115 ± 12	139 ± 14	< **0.01**	< **0.01**	0.15
	26 cm	117 ± 12	181 ± 12	183 ± 14			
Lead MFC	**3 cm**	11 ± 2	15 ± 2	15 ± 2			
Variabilty (mm)	**10 cm**	13 ± 2	16 ± 2	18 ± 2	0.06	< **0.01**	0.06
	26 cm	18 ± 2	22 ± 2	17 ± 2			
Trail MFC	**3 cm**	12 ± 3	17 ± 3	22 ± 3			
Variabilty (mm)	**10 cm**	19 ± 3	23 ± 3	25 ± 3	**0.2**	< **0.01**	0.32
	26 cm	37 ± 3	32 ± 3	41 ± 3			

Mean ± standard error. Minimum foot clearance (MFC).

placement is achieved. With the protocol employed here, we cannot determine if the higher foot placement variability in the earlier steps of the older groups reflects a decrease in control or a compensatory adaptation. However, it is evident that the middle-aged group was more similar to the older group in foot placement variability.

The age-related progressive increase in step width variability may indicate a reduction in medial-lateral control of the center of mass during the obstacle crossing task, as higher step width variability may reflect increased errors in medial-lateral foot placement or reactive adjustments to control the center of mass [10,18,25–27]. The lack of change in step length variability with age may indicate that the decline is limited to the medial-lateral control for this locomotor task. As increases in step width and foot placement variability occurred in the middle-age group, it would appear that a decline in balance control has occurred by age 50 years. If this population were aware of the decline, a decrease in gait speed may be adopted as a cautious strategy. However, changes to gait speed in the middle-aged group were only observed in the most challenging tasks, which may indicate that this age group may not be aware of the age-related gait decrements.

In summary, declines in neuromuscular and cognitive systems at middle age were too mild to modify unobstructed gait. Greater gait task challenge was required to reveal the impact of these age-related changes at middle-age. These findings reinforce the importance of sufficiently challenging patients in the clinical setting to fully reveal mobility impairments, such as the obstacle crossing component of the BESTest [28]. Further, future studies should examine if middle-aged adults who are active in physically demanding environments, such as hiking in challenging terrain, maintain their adaptive locomotor skills.

There are two main limitations to this study. First, reliable measures of variability require a large numbers of steps [29], which was not possible in the current paradigm. Therefore, variability measures should be viewed with caution. Second, other gait measures not included in this analysis may reveal different interactions, perhaps where changes in middle-age are not observed as a function of task difficulty. However, we did observe the predicted differences in speed, foot placement, and foot clearance, which are critical measures that reflect strategies to successfully cross the obstacle, and our results are consistent with others [4].

5. Conclusion

Gait changes were observed as early as middle-age, and changes in speed and foot clearance became more evident as task difficulty increased. Middle-aged adults demonstrated age-related gait changes that were not different from young adults in the easy task, and not different from older adults in the more challenging tasks. Manipulating locomotor task challenge with obstacles provides a window into the physiological changes that affect mobility during middle-age that are not evident during unobstructed gait.

Conflict of interest statement

The authors declare that there are no conflicts of interest.

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