Int J Physiother. Vol 12(3), 308-313, September (2025) ISSN (P): 2349-5987, ISSN (O): 2348-8336

ORIGINAL ARTICLE

IJPHY

Impact of Eye-Leg Coordination in Volitional Stepping on a Moving Target Compared Between Young and Middle-Aged Adults

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ABSTRACT

Background: Coordinating vision with movement is essential for precise foot placement during volitional stepping, especially in dynamic conditions. Visual feedback enables preplanning and real-time corrections to ensure accuracy. This study aimed to determine the effect of age on eye-leg coordination by comparing stepping performance between younger and middle-aged adults.

Methods: This observational study included 60 healthy participants: 30 young adults (17 females, 13 males) and 30 middle-aged adults (15 females, 15 males). A 157-inch tape line guided a lightweight ball synchronized with metronome beats at 35, 45, and 55 beats per minute (BPM). Participants performed voluntary stepping onto a moving ball with both legs. Key spatiotemporal parameters assessed were reaction time, response time, movement time, foot placement error, and missed steps.

Results: Movement time significantly decreased with increasing tempo. For both legs, movement time at 35 BPM was significantly longer than at 55 BPM (right leg: $p = .004$; left leg: $p = .012$). Across all tempos, middle-aged adults demonstrated longer movement times than younger adults (35 BPM: right $p = 0.003$, left $p < 0.001$; 45 BPM: right $p < 0.001$, left $p = 0.003$; 55 BPM: right $p < 0.001$, left $p < 0.001$). Middle-aged adults also showed greater foot placement errors. They missed steps increased with tempo in both groups, with greater inaccuracies, particularly in the non-dominant leg of middle-aged adults.

Conclusion: Eye-leg coordination declines with age, affecting stepping accuracy and speed. Findings highlight the need for targeted balance training and fall prevention strategies to maintain mobility and reduce the risk of falls in aging populations.

Keywords: Eye-leg coordination, voluntary stepping, visual feedback, aging, balance, visuo-motor integration.

Received 30th April 2025, accepted 17th July 2025, published 09th September 2025

www.ijphy.com

10.15621/ijphy/2025/v12i3/1866

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INTRODUCTION

Coordinating vision with movement is crucial in executing precise movements, particularly in volitional stepping tasks, where accurate foot placement is essential in dynamic situations. Coordination of sensory input and motor output enables individuals to move through their environment, especially in tasks involving volitional stepping onto moving surfaces. Eye-leg coordination is crucial for achieving accurate foot placement in stepping tasks. However, the effectiveness of this coordination does vary across ages and may influence reaction time, movement accuracy, and overall motor functioning. These aspects are critical not only for individual mobility but also for broader considerations in health care, well-being, and global health, as they impact fall prevention, rehabilitation outcomes, and mobility across populations.

Visual feedback plays a crucial role in modulating foot trajectory, particularly in response to unexpected changes that disrupt planned foot placement. Although the extent to which vision actively affects foot placement during the swing phase of an unperturbed step is unclear, it is believed that vision improves accuracy but does not significantly alter final position [1], which highlights that the gaze behavior is closely associated with motor execution, especially in tasks that involve accurate foot placement. This suggests that vision not only aids in preplanning movement but also remains active during the step cycle, contributing to ongoing motor coordination [2]. Under normal locomotion, the gaze is directed forward to examine the environment and predict impending obstacles [3]. When precise foot placement is required, such as when stepping onto a moving target, the gaze drops down to track the foot-fall area, making the adjustments necessary for proper foot placement.

Eye-leg coordination has also been investigated in more detail in visually guided stepping tasks, and it is shown that vision operates in a feedforward control mode. In precision stepping tasks, participants use visual information to pre-plan foot placement before movement initiation. Preplanning is necessary to enable the locomotor and oculomotor control centres to communicate effectively and generate synchronized stepping movements [4].

Sensorimotor systems work together to complete motor activities. For instance, one needs to know the target's position in relation to the body to guide the hand towards a visual target. This requires gaze corrections through eye-head synchronization to bring the target's picture to the fovea, a portion of the retina that has the most acute vision [1]. When an unexpected visual cue occurs, a motor response sequence begins, regulating the movements of eyes, head, and limbs [5]. This can be extended to eye-leg coordination, as gaze behaviour influences foot positioning techniques [14]. For stepping tasks, fixating gaze on a target provides the spatial information needed to correct foot trajectory during movement, thereby maintaining accuracy, even in the presence of possible perturbations [6].

Eye-hand coordination (EHC) has been extensively studied as a model for visual-motor integration. It requires the coordination of the visual and motor systems to perform precise actions, like reaching and grasping small objects. According to one previous study, accurate eye-hand coordination requires exact visual input from the surroundings as well as precise motor control [7]. The basic concepts of EHC apply to eye-leg coordination, where visual feedback leads to changes in lower-limb actions in response to changing environmental conditions.

The study highlighted that older individuals tend to fixate their gaze on the footfall area, suggesting a greater reliance on visual cues for step planning and performance [8]. Similarly, the importance of anticipatory and compensating postural modifications is emphasized in maintaining stability when exposed to external perturbations [9, 13]. These adaptations become more important as people get older, as reduced reaction time and muscular coordination might impair a person's capacity to adjust to imbalances [10].

In natural environments, controlling the gaze is crucial for regulating foot placement. Research on gaze behaviour during locomotion over irregular terrain suggests that people employ predictive visual strategies to detect future stepping targets and modulate their gait accordingly [6].

Aging impairs one's capacity to react quickly to shifting stepping targets, which leads to slower reaction times and less precise foot placement [15]. Evidence on age-related changes in stepping performance indicates that older individuals require more visual feedback to compensate for proprioceptive and motor deterioration [8].

This study aims to examine how age influences eye-leg coordination by comparing the timing, accuracy, and execution of stepping performance in young and middle-aged adults during voluntary stepping on a moving target. Specifically, it seeks to evaluate how varying ball movement speeds (35, 45, and 55 beats per minute) affect stepping performance and eye-leg synchronization across age groups. By exploring age-related differences in visual-motor integration during dynamic balance tasks, this study further aims to generate insights that inform the development of age-appropriate training and fall prevention strategies.

By comparing the stepping accuracy, reaction time, and movement control of young and middle-aged individuals, this study provides insight into eye-leg synchronization in volitional stepping onto a moving target. Walking, climbing stairs, and stepping onto moving platforms like escalators or buses all require good visual-motor coordination [11,16]. Understanding these changes will help to explain age-related differences in motor performance and stability under dynamic conditions.

METHODS

The Institutional Ethics Committee for students' projects approved the study with reference. No: **REF: CSP-III/25/JAN/15/27**

SAMPLE CALCULATION:

The sample size for this study was determined based on a pilot study conducted at the faculty of physiotherapy, Sri Ramachandra Institute of Higher Education and Research. Based on the pilot data, the standard deviation for group I (younger adults) was 110, and for group II (middle-aged adults) was 243, with a mean difference of 150 between the groups. Using these values, the effect size was calculated to be approximately 0.85. With a significance level (α) of 5% and a statistical power (1-β) of 90% and considering a two-sided hypothesis test, the estimated total sample size required was 60 participants.

Selection and description of participants:

A cross-sectional study conducted in 2024-2025 examined eye-leg coordination during voluntary stepping on a moving target, comparing young and middle-aged adults. A total of 60 healthy individual participated in the study, consisting of 30 young adults (aged 19 – 35 years; 17 females and 13 males) were selected from the faculty of physiotherapy student population and 30 middle- aged adults (aged 36- 57 years; 15 females and 15 males) were recruited from the physiotherapy outpatient department (OPD) at Sri Ramachandra Institute of Higher Education and Research (Deemed to be university).

The study was explained to individuals meeting the inclusion criteria, and informed consent was obtained. All participants were selected based on the inclusion criteria: adequate vision and hearing (either naturally or with correction) to perceive movement, cognitive ability to comprehend and follow instructions, and voluntary willingness to participate in the study. Participants with any history of neurological, musculoskeletal, vestibular, or visual impairments that could affect stepping performance were excluded.

Data collection and Measurements:

INSTRUMENTATION

- TAPE LINE: A 157-inch measuring tape was securely affixed to the floor to serve as a straight path for the ball's movement
- LIGHTWEIGHT BALL: placed on the tape line, designed to move freely along the path.
- DIGITAL METRONOME: used to provide auditory cues at three distinct tempos – 35, 45, and 55 beats per minute (BPM)
- Tripod to stabilize the camera frame angle
- a mobile phone camera to record the video of the stepping performance.

STUDY PROCEDURE:

Study participants will be recruited based on specific criteria and provided with a detailed explanation of the procedure, and their consent will be obtained before proceeding.

TESTING OF SPATIOTEMPORAL PARAMETERS OF VOLITIONAL STEPPING ON A MOVING TARGET:

A 157cm tape was affixed to the floor to serve as the path for the ball's motion, and a lightweight ball was manually moved back and forth along the tape by the researcher. Set up a metronome to control the ball's movement at tempos of 35, 45, and 55 BPM for different trials. Participants were instructed to stand at the centre of the tapeline and asked to perform voluntary stepping on the moving ball in synchrony with the metronome beats. Emphasize the importance of timing and accuracy, aiming for precise foot placement on the ball with each beat. Inform them that both legs will be tested separately during the trials. Allow participants a short practice session at the slowest tempo (35 BPM) to familiarize themselves with the task. Each participant will then perform the stepping task at three tempos: 35, 45, and 55 BPM. Three trials will be conducted for each tempo, with each trial lasting 15 seconds. Trials will alternate between the right and left legs. After completing the trials, allow participants to rest and ensure they are comfortable before thanking them for their involvement. The entire procedure was recorded using a mobile phone camera, and videos were analysed using software called "TRACKER SOFTWARE Version 6.1.3", which can be used to ensure precision in stepping performances. These data were taken for analysis.

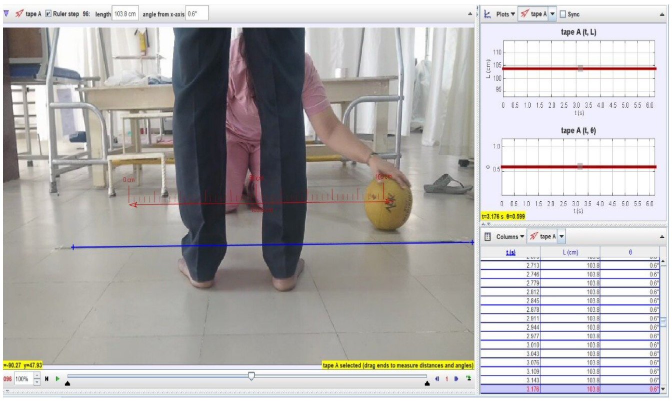
PARAMETERS:

The following spatial-temporal parameters (quantifying data) are calculated in the tracker:

- **REACTION TIME:** time interval from the metronome beat to the moment the foot lifts off the floor
- **RESPONSE TIME:** time interval from the metronome beat to the moment the foot contacts the moving ball
- **MOVEMENT TIME:** the difference between response and reaction time, which represents the duration the foot remained airborne.
- **FOOT PLACEMENT ERROR:** deviation from the midpoint of the ball.
- **MISSED STEPS:** number of unsuccessful attempts to contact the moving ball.

STATISTICAL ANALYSIS:

IBM SPSS Statistics was used for data analysis. The effects of age group (young and middle-aged), stepping frequency (35, 45, and 55 BPM), and lower limb (left and right) on movement duration were evaluated using a One-way ANOVA. For each leg, the effect of ball speed on eye-leg coordination was investigated independently.



t (s)	L (cm)	θ
2.713	103.8	0.6°
2.746	103.8	0.6°
2.779	103.8	0.6°
2.812	103.8	0.6°
2.845	103.8	0.6°
2.878	103.8	0.6°
2.911	103.8	0.6°
2.944	103.8	0.6°
2.977	103.8	0.6°
3.010	103.8	0.6°
3.043	103.8	0.6°
3.076	103.8	0.6°
3.109	103.8	0.6°
3.143	103.8	0.6°
3.176	103.8	0.6°

Figure 1: Calibration of ball position using a tape measure and a stepping task

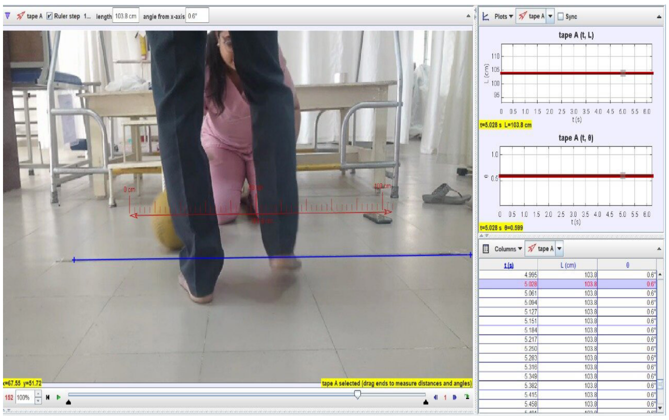


Figure 2: Initial Foot Lift-off (Reaction Time) During Voluntary Stepping Task

Figure 3: Foot Placement on Moving Ball (Response Time) During Voluntary Stepping Task

RESULTS

Table 1: Demographic data

VARIABLE	YOUNG ADULTS (n = 30) (Mean ± SD)	MIDDLE-AGED ADULTS (n = 30) (Mean ± SD)
AGE	23.50 ± 2.03	46.76 ± 6.73
GENDER	17F / 13M	15F / 15M
HEIGHT	164.3 ± 9.55	160.4 ± 8.85
WEIGHT	63.50 ± 12.65	70.43 ± 17.95

Table 1 summarizes participant demographics. Young adults (n = 30) had a mean age of 23.5 ± 2.0 years, with 17 females and 13 males; middle-aged adults (n = 30) had a mean age of 46.8 ± 6.7 years, with 15 females and 15 males. The average height and weight were 164.3 ± 9.6 cm and 63.5 ± 12.7 kg for young adults, and 160.4 ± 8.9 cm and 70.4 ± 18.0 kg for middle-aged adults.

Table 2: Descriptive Statistics for Movement Time across BPMs by right and left leg:

VARIABLE	BPM	N	MEAN (ms)	SD (ms)	F-VALUE	P- VALUE
RT	35	60	490.30	159.74	5.286	.006
	45	60	458.68	130.59		
	55	60	411.15	107.11		
LT	35	60	502.77	127.33	4.335	.015
	45	60	454.20	145.37		
	55	60	430.43	138.68		

ANOVA * Significant at p value < 0.05

Table 2: A One-way ANOVA revealed a significant effect of metronome beats per minute (BPM) on movement time for both legs. For the right side, there was a statistically significant difference among the 35, 45, 55 BPM conditions [F(2,177) = 5.286, p = .006]. Similarly, for the left side, a significant effect was observed [F(2,117) = 4.335, p = .015].

Table 3: Post Hoc Comparison for movement time between BPMs for right and left legs

VARIABLE	GROUP 1(BPM)	GROUP 2(BPM)	P- VALUE
RT	35	45	.403
RT	35	55	.004
RT	45	55	.131
LT	35	45	.131
LT	35	55	.012
LT	45	55	.610

ANOVA * Significant at p value < 0.05

Table 3 shows Post hoc comparison using Bonferroni correction indicated that, for the right side, movement time at 35 BPM was significantly longer than at 55 BPM (p = .004). No significant difference was found between 35 and 45 BPM (p = .403) or 45 and 55 BPM (p = .131). For the left side, movement time at 35 BPM was significantly longer than at 55 BPM (p =.012). difference between 35 vs. 45 BPM (P = .131) and 45 vs. 55 BPM (p = .610) were not significant.

Table 4: Descriptive statistics for movement time across BPMs in right and left legs for young and middle-aged adults

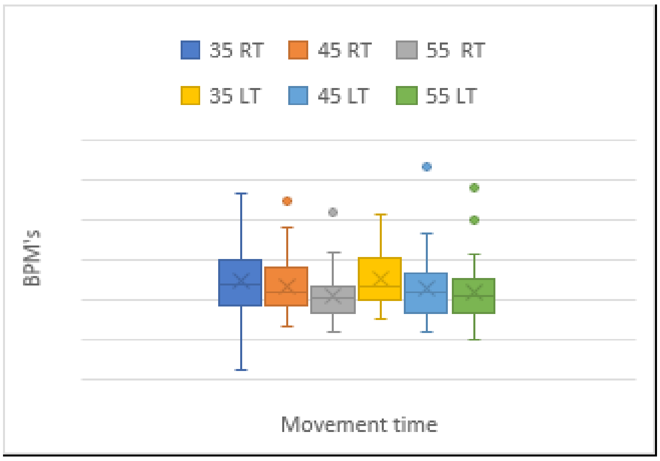
CONDITION	GROUP	MEAN (ms)	SD (ms)	F-VALUE	P-VALUE
35 RT	YOUNG	431.43	113.33	9.293	.003
	MIDDLE-AGED	549.17	178.61		
45 RT	YOUNG	404.80	95.93	12.143	<.001
	MIDDLE-AGED	512.57	139.60		
55 RT	YOUNG	365.47	94.66	13.165	<.001
	MIDDLE-AGED	456.83	100.30		
35 LT	YOUNG	424.23	77.42	36.593	<.001
	MIDDLE-AGED	581.30	119.29		

45 LT	YOUNG	399.90	117.29	9.589	.003
	MIDDLE-AGED	508.50	152.11		
55 LT	YOUNG	361.83	96.32	19.407	<.001
	MIDDLE-AGED	499.03	140.78		

ANOVA * Significant at p value < 0.05

Table 4 shows a comparison between young and middle-aged adults, revealing significant age-related differences in movement time across all BPM conditions for both the right and left legs. At 35 BPM, middle-aged adults showed significantly longer movement times compared to young adults for both the right leg (F = 9.293, p = .003) and the left leg (F = 36.593, p <.001). This continued at 45 BPM, with middle-aged participants demonstrating slower movement times than younger adults for the right leg (F = 12.143, p < .001) and the left leg (F = 9.589, p = .003). Similarly, at 55 BPM, movement time remained significantly higher in the middle-aged group for the right leg (F = 13.165, p<.001) and the left leg (F 19.407, p<.001).

FIG (1) shows the comparison of movement time across stepping frequencies and legs (Right and Left) at 35,45,55 BPMs



DISCUSSION

Key Findings:

This study aimed to determine age-related changes in eye-leg coordination by comparing younger and middle-aged adults under varying stepping speeds. The main findings were: stepping speed significantly affected movement time, with faster tempos resulting in quicker stepping on the moving target; However, middle-aged adults consistently exhibited slower reaction and movement times compared to younger adults across all conditions, indicating age-related declines in motor response efficiency; Both groups showed an increase in missed steps as stepping speed increased, but this effect was more pronounced at 55 BPM, especially among younger adults. Middle-aged adults exhibited a higher incidence of missed steps and significantly more foot placement errors, particularly on the left (non-dominant) leg. These results suggest age-related asymmetries in motor control and a reduced capacity to synchronize motor actions with visual information under time constraints.

The progressive increase in missed steps at higher tempos reflects the impact of reduced processing time on visual-motor coordination. Middle-aged adults showed slower responses and greater error rates, especially on the non-dominant leg, may indicate age-related declines in anticipatory control and limb coordination.

Comparison with previous studies:

These findings are consistent with Chapman and Hollands et al. (2006), who reported that older adults rely heavily on visual information for accurate foot placement, resulting in increased stepping errors when visual feedback is removed [7]. Similarly, Hollands and Marple-Horvat et al. (1996) demonstrated that visual input during late stance is crucial for precise stepping; when vision is denied, delays in movement initiation and compensatory adjustments occur[2i.e. towards the end of that limb's stance phase. When negotiating the same walkway without ambient lighting, and with each stone's location indicated by a central light spot (LED]. This aligns with our observation that middle-aged adults showed longer reaction and movement times, indicating a reduced ability to use visual cues efficiently for anticipatory control.

Furthermore, the pronounced left-leg errors suggest reduced non-dominant limb control under time pressure, echoing Hollands and Marple-Horvat et al. (2001), who emphasized that saccadic eye movements are tightly coupled with leg movements during visually guided stepping [1]. Rizzo et al. (2020) also support the broader relevance of visual-motor integration, showing that cortico-cerebellar networks underpinning eye-hand coordination are equally essential for eye-leg tasks[6]. Our results correspond with Ramachandran et al. (2024), who highlighted the importance of proactive visual-motor planning for accurate stepping [11], Robins et al. (2017), who supported the use of visually guided stepping tasks to evaluate age-related declines in coordination [12].

Theoretical and Clinical Implications:

The observed age-related differences highlight the crucial role of visual-motor integration in maintaining stepping accuracy under dynamic conditions. Middle-aged adults' slower responses and higher foot placement errors may indicate early declines in visuomotor processing efficiency, potentially increasing the risk of missteps in real-world environments. The left-leg asymmetries observed suggest that the non-dominant limb is more vulnerable to performance deterioration under time pressure, which may reflect age-related neural and motor control changes. These findings support the theories of Chapman and Hollands, 2006 and Hollands and Marple-Horvat et al. (2001), emphasizing the dependence of stepping accuracy on timely visual guidance and the close coordination of eye and leg movements[1, 7].

Given that faster stepping tempos increased errors even in younger adults, there is a critical threshold where available processing time is insufficient for accurate visual-motor integration. The results underscore the importance of training interventions that enhance visuomotor coordination and stepping efficiency, particularly in populations at risk of age-related motor decline.

Limitations:

This study was limited by the inclusion of only two groups (young and middle-aged adults), which restricts the understanding of age-related progression in eye-leg coordination. Declines may be more noticeable if older persons are included. The testing environment was controlled, which may not accurately simulate real-world stepping challenges such as distractions, uneven terrain, or spontaneous movements. Visual strategies were not measured, limiting insight into gaze behaviour during stepping. The brief duration of the task may not capture fatigue effects or sustained coordination performance.

Future studies should include older adults to capture the full spectrum of age-related changes in eye-leg coordination. conducting similar tasks in more dynamic, unpredictable environments. Incorporating eye-tracking to assess visual strategies and including dual-task conditions could assess how cognitive demand impacts eye-leg coordination, especially in the aging population.

CONCLUSION

This study demonstrates notable age-related variations in voluntary stepping tasks in eye-leg coordination. Middle-aged adults demonstrated slower movement times, increased foot placement errors, and more missed steps compared to younger adults, particularly under higher stepping frequency (55 BPM). These findings suggest a decline in visuomotor integration and motor response, potentially affecting stepping precision and timing. Understanding these changes can inform the need for early interventions to maintain mobility and prevent falls, especially as individuals age.

ACKNOWLEDGMENT:

The authors acknowledge the valuable contribution of all participants involved in this study.

FUNDING:

No external funding was received in this research.

CONFLICTS OF INTEREST:

The authors declare no conflict of interest.

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