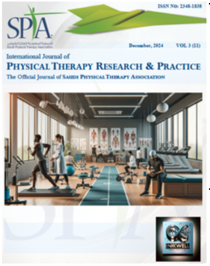

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Original Article

Reliability of Gait Analyst Pro for Measuring Spatial-Temporal Gait Parameters in Pilgrimages

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Abstract

Background: Accurate gait assessments are critical during events such as the Hajj pilgrimage, where participants walk long distances under challenging conditions, particularly elderly individuals with higher mobility risk. Reliable gait analysis tools are essential for determining whether mobility aids or wheelchairs are needed for support. The aim is to assess the intra-rater and inter-rater reliability of Gait Analyst Pro under both TM and OG walking conditions. **Methodology:** Seventy participants were recruited from a primary healthcare centre serving pilgrims. Fifty performed TM walking, and 20 completed OG walking. Gait Analyst Pro measured spatial-temporal gait parameters. Intra-rater and inter-rater reliability was analyzed using intraclass correlation coefficients (ICCs). **Results:** Higher intra-rater reliability was observed for TM walking (ICCs: 0.789–0.854) compared to OG walking (ICCs: 0.505–0.730). Similarly, inter-rater reliability was stronger for TM assessments (ICC = 0.784) than OG assessments (ICC = 0.503), highlighting the impact of environmental variability. A moderate positive correlation ($\rho = 0.368$, $p = 0.009$) was found between TM and OG walking speeds. ANOVA results indicated significant group differences for OG walking speeds ($p < 0.001$), while differences for TM walking speeds were not significant ($p = 0.086$). **Conclusion:** Gait Analyst Pro is highly reliable in controlled TM environments, but variability increases in OG conditions. These findings underscore the need for AI-driven validation of Gait Analyst Pro for both controlled and real-world applications, particularly during the Hajj pilgrimage.

Keywords: Gait Analyst Pro, Spatial-Temporal Gait, Hajj Pilgrimage, Reliability, Saudi Arabia.

Introduction

Walking proficiency, especially during the Hajj pilgrimage, is essential due to the physical demands on participants, who often walk long distances in crowded and challenging conditions (Aldossari et al., 2019). Standardized gait assessments are crucial in this context, particularly since many pilgrims are elderly and more vulnerable to mobility issues. Beauchet et al. (2017) provide reference values for spatiotemporal gait parameters in older adults, highlighting the importance of proper gait analysis to prevent falls and enhance mobility, ensuring the safety of participants. Key gait parameters, such as stride length, gait speed, and cadence, are vital for evaluating walking performance and managing potential mobility challenges during Hajj (Lindemann, 2020).

A recent meta-analysis provides insights into healthy adults' walking patterns and cadence across various paces. This research highlights how different walking speeds—ranging from slow to fast—relate to physical intensity and can inform health guidelines. It emphasises that walking pace is closely linked with cadence and physical effort, offering practical insights for public health by suggesting that pace-based instructions can be used to promote outdoor walking (Murtagh et al., 2021).

Advances in wearable and non-wearable technologies have made real-time gait monitoring possible, helping detect abnormalities and support timely interventions (Muro-de-la-Herran et al., 2014). While spatiotemporal gait parameters are commonly used in clinical settings, their application in the context of long-distance walking during Hajj has yet to be explored. Existing research on gait parameter reliability has mainly focused on wearable and non-wearable systems, with intra-observer reliability values ranging between 0.85 and 0.95 for stride length, 0.80 and 0.90 for gait speed, and 0.75 and 0.85 for cadence (Herssens et al., 2018; Lindemann, 2020).

Gait Analyst Pro is a mobile software tool that allows rehabilitation professionals to measure key spatiotemporal gait parameters, including walking speed, step duration, single and double support, swing phase, step asymmetry, and step length. While it has been used in rehabilitation, its reliability in pilgrimage settings, where mobility demands are high, has yet to be established (Stenum et al., 2024; Bonanno et al., 2023).

The Timed Up-and-Go (TUG) test is a widely used tool for assessing functional mobility and fall risk, particularly in older adults and individuals with movement disorders. It measures the time required to stand from a chair, walk three meters, turn, return, and sit down (CDC, 2017). The simplicity of the TUG test and its minimal equipment requirements make it suitable for use across clinical settings and populations (Ellis et al., 2015; Liu et al., 2021).

Research has shown that fatigue can significantly impact gait performance. A study reported that while fatigued participants maintained their walking speed and step length, they exhibited increased step width and greater trunk acceleration in the mediolateral direction. Fatigue also increased variability in step length and trunk acceleration in the vertical direction, resembling patterns observed in older adults at risk of falls (Jorunn L, 2007). Similarly, Barbieri et al. (2013) found that fatigue affected gait parameters in both active and inactive young adults, increasing step width and stride speed in both normal walking and obstacle-crossing tasks. Inactive participants demonstrated lower endurance and adjusted their obstacle-crossing strategies differently from active participants, suggesting subtle differences in fatigue adaptation.

Hamacher et al. (2016) explored how fatigue influences gait stability across different age groups. They found that young participants became more stable after intense exercise, while older participants experienced reduced stability even with moderate fatigue, increasing their risk of falls. These findings emphasise the importance of understanding how fatigue affects gait performance, especially for events like the Hajj pilgrimage, where participants must walk long distances under physically demanding conditions.

The Hajj pilgrimage presents unique physical challenges, requiring participants to walk long distances under crowded and demanding conditions. These circumstances can result in significant fatigue, increasing the risk of falls, particularly among elderly pilgrims or those with mobility impairments (Aldossari et al., 2019). Fatigue has been shown to alter gait parameters, reduce stability, and heighten walking variability, especially in older adults (Hamacher et al., 2016; Barbieri et al., 2013). However, conventional mobility assessments like the Timed Up and Go (TUG) test focus primarily on short-distance mobility, offering limited insight into performance over prolonged walking, such as that required during Hajj. This underscores the need for reliable gait assessments tailored to real-world, high-demand scenarios to better understand functional mobility and the effects of fatigue over time.

Incorporating fatigue assessments into gait analysis is crucial for developing targeted interventions, such as recommending mobility aids or wheelchairs for individuals requiring support. Tools like the Gait Analyst Pro software offer potential for accurate and detailed spatiotemporal gait analysis, enabling healthcare providers to identify risks and tailor interventions to enhance safety and reduce injury among pilgrims. By ensuring the reliability and applicability of gait analysis methods across controlled and real-world settings, this study aims to provide practical solutions for large-scale events like Hajj, ultimately improving participant mobility and safety.

Methods

This study employed a cross-sectional reliability design to evaluate the intra-rater and inter-rater reliability of the Gait Analyst Pro software, as well as to explore correlations between Timed Up and Go (TUG) test results, cadence, walking speed, and spatiotemporal gait parameters during treadmill (TM) and overground (OG) walking.

Study Design and Variables

The independent variables included walking conditions (TM and OG) and rater sessions. Dependent variables were spatiotemporal gait parameters (e.g., stride length, step width, and stance time), TUG test results, cadence, and walking speed. The primary outcomes focused on the reliability of Gait Analyst Pro software and the relationships between:

- TUG test results and walking speed (OG and TM).
- Walking speeds during OG and TM conditions.

Population and Sampling

The study population comprised Hajj pilgrims visiting seasonal Primary Healthcare Centers (PHCs) in Madinah. Convenience sampling was initially used, followed by random selection to ensure a representative sample. A total of 50 participants were recruited for TM walking analysis, and 20 were included for OG walking. Sample size calculations were based on an alpha (α) of 0.05, a statistical power of 0.8, and an expected intraclass correlation coefficient (ICC) of 0.7, which accounted for potential variability and ensured the study's reliability.

Inclusion and Exclusion Criteria

Adults aged 18 years or older who were able to walk and provided informed consent were included in the study. Individuals under 18 years of age or those unable to walk short distances due to physical limitations were excluded.

Data Collection Procedures

Participants underwent walking sessions under both TM and OG conditions. During TM walking, participants walked on a motorized treadmill at a self-selected comfortable speed. For OG walking, participants walked a predefined distance in a controlled environment. Walking sessions were video recorded and analyzed using Gait Analyst Pro software to extract spatiotemporal gait parameters. The TUG test was conducted by measuring the time taken for participants to rise from a chair, walk 3 meters, turn, and return to the chair.

Data Analysis

ntra-rater (ICC1,1) and inter-rater reliability (ICC2,1) were evaluated. Spearman's rank correlation examined relationships between walking speeds, TUG results, and TM and OG speeds. Non-normal distribution was confirmed by the Shapiro-Wilk test ($p < 0.001$). Group differences were analyzed using ANOVA, with effect sizes calculated (eta-squared, epsilon-squared, omega-squared).

Ethical Considerations

This study received IRB approval from (Prince Sultan Armed Forces Hospital - Madinah

Research & Ethics Committee) (Appendix 1). Data were anonymized and stored securely on a password-protected computer, with physical documents locked in a cabinet. Video recordings will be destroyed after project completion. Written informed consent was obtained from all participants and raters. To minimize eye strain, raters followed the 20-20-20 rule during analysis sessions.

Results

Descriptive Statistics

Participants on the treadmill (TM) had a mean age of 41.52 years, weighed 78.72 kg, and had an average height of 169.18 cm. TUG results averaged 7.48 seconds (Table 1). Overground (OG) participants had similar age profiles (mean = 41.15 years) but weighed slightly more (83.45 kg). The average TUG time for OG participants was 7.40 seconds, with a mean walking distance of 17.1 meters (Table 2).

Table 1: Descriptive Statistics for Participants in the treadmill walking group.

Measure	Mean	SD	Variance	Skewness	Kurtosis
Age	41.52	11.6	134.42	0.136	-0.056
Weight	78.72	16.7	279.85	0.882	1.377
Height	169.2	6.64	44.01	0.287	-0.428
TUG	7.48	2.03	4.132	0.053	-0.892

Table 2: Descriptive Statistics for Participants in the overground walking group

Measure	Mean	SD	Variance	Skewness	Kurtosis
Age	41.15	10.36	107.29	0.706	1.168
Weight	83.45	11.03	121.74	-0.023	-0.278
Height	171.65	7.22	52.13	0.131	-0.534
TUG	7.40	1.54	2.36	-0.178	-1.069
Distance	17.10	2.97	8.83	-0.028	-0.143

Intra-rater reliability was higher for TM participants, with ICC values ranging from 0.789 to 0.854 across raters, indicating good to excellent consistency (Table 3). For OG participants, reliability ranged from moderate (ICC = 0.611) to lower consistency (ICC = 0.505), with one rater achieving better reliability (ICC = 0.730) (Table 4). Inter-rater reliability was stronger for TM participants (ICC = 0.784) compared to OG participants (ICC = 0.503), highlighting increased variability in OG assessments (Table 5). Step Asymmetry and Cycle Duration showed significant agreement for TM participants (Kappa = 0.048 and 0.033, respectively, $p < 0.001$). In contrast, OG assessments exhibited lower reliability with near-zero Kappa values for parameters like Step Frequency (Kappa = -0.015, p = 0.205) and Step Length (Kappa = 0.001, p = 0.789). TM assessments demonstrated overall stronger consistency compared to OG (Table 6).

Table 3: Intra-rater reliability for treadmill walking group participants

Rater	Type	Point Estimate	95% CI	
			Lower	Upper
Rater 1	ICC1,1	0.813	0.765	0.859
Rater 2	ICC1,1	0.789	0.737	0.84
Rater 3	ICC1,1	0.854	0.815	0.891

Table 4: Intra-rater reliability for overground walking group participants

Rater	Type	Point Estimate	95% CI	
			Lower	Upper
Rater 1	ICC1,1	0.611	0.54	0.688
Rater 2	ICC1,1	0.505	0.432	0.589
Rater 3	ICC1,1	0.73	0.669	0.791

Table 5: Inter-rater reliability between groups

Group	Type	Point Estimate	95% CI	
			Lower	Upper
TM	ICC2,1	0.784	0.731	0.835
OG	ICC2,1	0.503	0.431	0.586

Key: Treadmill (TM) and overground (OG) walking.

Table 6: Inter-rater reliability of various gait parameters measured across the Treadmill (TM) and overground (OG) walking.

Parameter	Group	Kappa	SE	z	p-value	95% CI	
						Lower	Upper
Step Duration	TM	-0.001	0.004	-0.271	0.786	-0.009	0.007
	OG	-0.007	0.006	-1.095	0.274	-0.018	0.005
Step Asymmetry	TM	0.048	0.005	9.29	<0.001	0.038	0.058
	OG	0.002	0.007	0.339	0.735	-0.011	0.016
Double Support Duration	TM	0.046	0.005	8.616	<0.001	0.035	0.056
	OG	0.026	0.011	2.265	0.024	0.003	0.048
Single Support Duration	TM	0.026	0.005	5.834	<0.001	0.018	0.035
	OG	0.005	0.006	0.822	0.411	-0.007	0.016
Swing Phase Duration	TM	0.026	0.005	5.838	<0.001	0.018	0.035
	OG	0.005	0.006	0.822	0.411	-0.007	0.016
Stance Duration	TM	0.009	0.004	2.571	0.01	0.002	0.017
	OG	0.005	0.006	0.921	0.357	-0.006	0.016
Step Frequency	TM	0.018	0.007	2.507	0.012	0.004	0.032
	OG	-0.015	0.012	-1.267	0.205	-0.039	0.008
Step Length	TM	0.034	0.005	6.49	<0.001	0.024	0.045
	OG	0.001	0.005	0.267	0.789	-0.008	0.011
Cycle Duration	TM	0.033	0.003	9.779	<0.001	0.026	0.039
	OG	0.001	0.005	0.109	0.913	-0.01	0.011

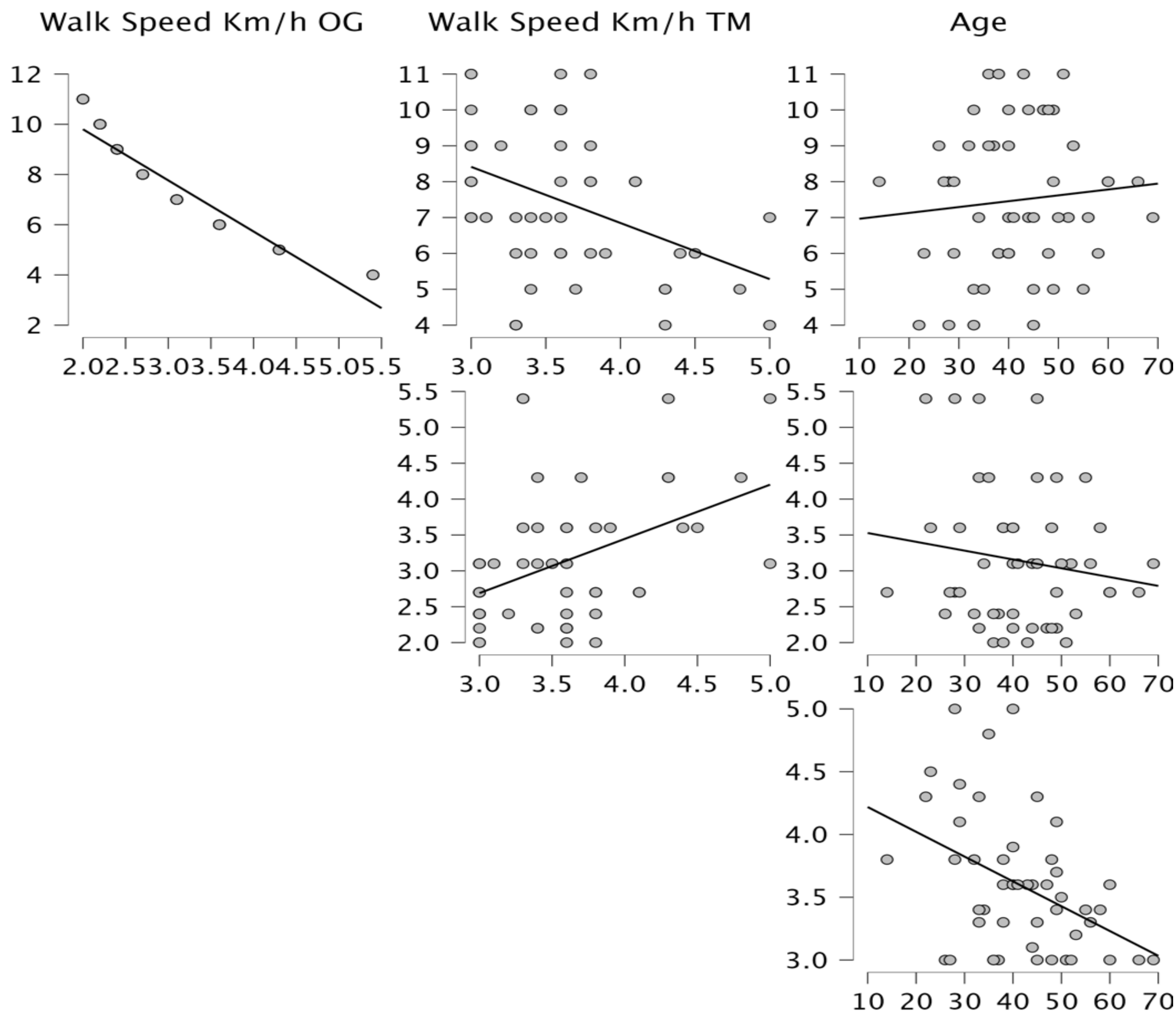

Figure 1: Shows scatter plot for correlation analysis between age, walking speed, TUG

Strong negative correlations were observed between TUG and OG walking speed (ρ = -1.00, p < 0.001), suggesting that faster walkers performed better on the TUG test. A moderate negative correlation was found between TUG and TM speed (ρ = -0.368, p = 0.009). OG and TM walking speeds showed a moderate positive correlation (ρ = 0.368, p = 0.009). Age was weakly correlated with TUG (ρ = 0.087, p = 0.550) and showed a significant negative correlation with TM speed (ρ = -0.395, p = 0.005) (Table 7, Figure 1).

The Shapiro-Wilk test confirmed that the data were not normally distributed (p < 0.001), justifying the use of non-parametric methods (Table 8). ANOVA revealed significant group differences for OG walking speed (F = 1.656, p < 0.001), but not for TM walking speed (F = 1.949, p = 0.086). Effect sizes for TM speed showed moderate effect sizes (eta-squared = 0.245, epsilon-squared = 0.119) (Tables 9–10).

Table 7: Spearman's Correlation Between Walking Speed and TUG Test Results

Variable	TUG Spearman's rho	Walk Speed Km/h OG	Walk Speed Km/h TM	Age
TUG	—	-1	-0.368	0.087
p-value	—	0	0.009	0.55
Walk Speed Km/h OG	-1	—	0.368	-0.087
p-value	0	—	0.009	0.55
Walk Speed Km/h TM	-0.368	0.368	—	-0.395
p-value	0.009	0.009	—	0.005
Age	0.087	-0.087	-0.395	—
p-value	0.55	0.55	0.005	—

Table 8: Shapiro-Wilk Test for Multivariate Normality

Test	Statistic	p-value
Shapiro-Wilk	0.922	<0.001

Table 9: ANOVA for Walk Speed Km/h readmill (TM) and overground (OG) walking.

Variable	Sum of Squares	df	Mean Square	F	Sig.
Walk Speed Km/h OG	44.200	7	6.314	1.656	<0.001
Walk Speed Km/h TM	3.526	7	0.504	1.949	0.086
Within Groups TM	10.853	42	0.258		

Table 10: ANOVA Effect Sizes for Walk Speed Km/h readmill (TM) and overground (OG) walking.

Measure	Point Estimate	95% CI	
		Lower	Upper
Eta-squared	0.245	0.000	0.344
Epsilon-squared	0.119	-0.167	0.234
Omega-squared Fixed-effect	0.117	-0.163	0.231
Omega-squared Random-effect	0.019	-0.020	0.041

Discussion

TM assessments demonstrated higher intra-rater reliability than OG walking, where environmental factors contributed to significant variability. Inter-rater reliability for both conditions was moderate, with TM showing more consistency between raters. A moderate positive correlation between TUG scores and walking speed indicates that participants with better functional mobility walked faster in both conditions.

Both McGinley et al. (2009) and this study found that reliability varies by the type of movement. Sagittal plane movements, such as hip and knee flexion, were more consistent, while transverse plane movements, like hip rotation, had higher error rates. This aligns with the lower inter-rater reliability for OG assessments, where environmental factors introduced variability. Kainz et al. (2017) reported better reliability in controlled environments, which corresponds with the higher reliability of TM assessments in this study.

Krebs et al. (1985) highlighted that measurement error is unavoidable, as observed in the variability of OG inter-rater reliability. Their recommendation for repeated ratings and rater training aligns with this study's use of trained raters for Gait Analyst Pro assessments. Additionally, Artificial Intelligence (AI) enhances predictive accuracy for gait-related tasks, reducing variability (Harris et al., 2022; Ben Chaabane et al., 2023).

McCalmont et al. (2018) introduced a framework for continuous monitoring using smart insoles, indicating that technology reduces human error. This is consistent with the findings of higher TM reliability across parameters such as Step Frequency, Double Support Duration, and Step Duration.

Semaan et al. (2022) also highlighted the differences between TM and OG walking. Their findings that kinematic and kinetic measures vary between these settings align with this study's results, where TM assessments showed higher reliability than OG conditions.

The analysis of TUG components aligns with Syczewska et al. (2012), showing that tracking specific mobility components, such as walking, turning, and sitting, provides insights into functional issues. Berkner et al. (2017) emphasize monitoring TUG components over time to measure intervention effectiveness, similar to the potential applications of this study's findings in settings like the Hajj. Personalized mobility solutions, as noted by Howell et al. (2019), can address unique challenges during long-distance walking.

Hollman et al. (2016) corroborated the study's findings by demonstrating that TM walking reduces variability, aligning with this study's higher intra-rater reliability for TM assessments. TM assessments demonstrated higher intra-rater reliability than OG walking, where environmental factors contributed to significant variability. Inter-rater reliability for both conditions was moderate, with TM showing more consistency between raters. A moderate positive correlation between TUG scores and walking speed indicates that participants with better functional mobility walked faster in both conditions.

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Hollman et al. (2016) corroborated the study's findings by demonstrating that TM walking reduces variability, aligning with this study's higher intra-

rater reliability for TM assessments. Their observation of increased variability in OG walking also aligns with the lower inter-rater reliability observed in real-world conditions.

This study has several limitations. The sample size was relatively small, limiting the generalizability of findings to larger and more diverse populations. Environmental factors contributed to variability in OG assessments, which may not fully reflect the controlled nature of TM walking. Although raters were trained, inter-rater reliability variability indicates a need for further standardization of protocols. Finally, the study primarily focused on gait parameters without accounting for potential physiological factors, such as fatigue, that could influence real-world walking performance.

Conclusion

This study demonstrates that TM gait assessments have higher reliability than OG assessments, where environmental factors contribute to variability. Moderate inter-rater reliability across both settings indicates that while Gait Analyst Pro is valuable, consistent rater training and standardized protocols are crucial for accurate results. The positive correlation between TUG scores and walking speed underscores the importance of functional mobility assessments in predicting performance. These findings highlight the need for validating gait analysis tools in controlled and real-world settings to support practical applications, such as ensuring safe and effective mobility during events like the Hajj. Future research should involve more diverse populations to strengthen these findings and improve gait assessment protocols.

Recommendations

Future research should include larger and more diverse participant groups to improve generalizability and statistical power. Validation of Gait Analyst Pro in real-world settings, particularly during physically demanding events like the Hajj pilgrimage, is essential for its practical application. Studies should explore the effects of fatigue on gait and combine TUG tests with other mobility assessments for a comprehensive evaluation of functional abilities. Additionally, assessing the intra- and inter-rater reliability of Gait Analyst Pro before and after using walking aids would provide valuable insights into its performance and clinical relevance.

Author Contributions

All authors significantly contributed to the work reported, including conception, study design, execution, data acquisition, analysis, and interpretation. They actively participated in drafting, revising, or critically reviewing the manuscript, provided final approval of the version to be published, agreed on the journal submission, and accepted accountability for all aspects of the work.

Data Availability Statement

The authors will transparently provide the primary data underpinning the findings or conclusions of this article, without any unjustified reluctance. If need from editorial team.

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Conflicts of Interest

The authors declare no potential conflicts of interest related to the research, writing, or publication of this work.

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