Short Title: *Gait Analysis: Zebris vs GaitRite Systems*

Agreement between Temporal and Spatial Gait Parameters from an Instrumented Walkway and Treadmill System at Matched Walking Speed

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ABSTRACT

Background: Commercially available instrumented treadmill systems that provide continuous measures of temporospatial gait parameters have recently become available for clinical gait analysis. This study evaluated the level of agreement between temporospatial gait parameters derived from a new instrumented treadmill, which incorporated a capacitance-based pressure array, with those measured by a conventional instrumented walkway (criterion standard).

Methods: Temporospatial gait parameters were estimated from 39 healthy adults while walking over an instrumented walkway (GAITRite®) and instrumented treadmill system (Zebris) at matched speed. Differences in temporospatial parameters derived from the two systems were evaluated using repeated measures ANOVA models. Pearson–product–moment correlations were used to investigate relationships between variables measured by each system. Agreement was assessed by calculating the bias and 95% limits of agreement.

Results: All temporospatial parameters measured via the instrumented walkway were significantly different from those obtained from the instrumented treadmill ($P < .01$). Temporospatial parameters derived from the two systems were highly correlated (r, 0.79–0.95). The 95% limits of agreement for temporal parameters were typically less than ±2% of gait cycle duration. However, 95% limits of agreement for spatial measures were as much as ±5cm.

Conclusions: Differences in temporospatial parameters between systems were small but statistically significant and of similar magnitude to changes reported between shod and unshod gait in healthy young adults. Temporospatial parameters derived from an instrumented treadmill, therefore, are not representative of those obtained from an instrumented walkway and should not be interpreted with reference to literature on overground walking.

Key words: Gait; Locomotion; Rehabilitation; Biomechanics.

INTRODUCTION

With the advent of modern instrumented walkway systems, basic temporospatial gait parameters have been increasingly used by clinicians to define the characteristics of normal and pathological gait and to assess interventions aimed at improving gait.[1] These portable devices typically permit rapid determination of temporospatial parameters during overground walking and have been shown to have good agreement with parameters derived from three-dimensional motional analysis systems.[2, 3] However, length restrictions of commercial instrumented walkways render them suboptimal for the investigation of long–distance locomotion and they are not suitable for use in locations with limited working space. Recently, instrumented treadmills that provide rapid measures of temporospatial gait parameters have become commercially available and overcome the spatial limitations of instrumented walkways. Moreover, treadmill walking is now considered a viable intervention for treating gait impairments following neurological disorders such as Parkinson's disease, though the duration of improvements is unclear.[4] Instrumented treadmills, therefore, provide the clinicians with a relatively simple method for monitoring the progress of training, and have recently been used as outcome measures in the evaluation of various clinical treatments, such as footwear [5] and ongoing neurorehabilitation trials.[6] However, no study to date has evaluated the concurrent validity of these new commercially available treadmill systems relative to a conventional instrumented walkway or criterion standard.

Protocols using instrumented treadmills have commonly matched treadmill speeds to comfortable self–selected walking speeds determined during independent overground walking trials.[7-9] Implicit to these studies, therefore, is the assumption that temporospatial parameters obtained during treadmill and overground walking at a common speed are comparable. While treadmill walking has been shown to alter neuromuscular control and co–ordination, and subsequent lower extremity joint moments and powers,[10, 11] the effect on basic temporospatial parameters is less clear. For instance, some studies have noted that treadmill walking in healthy individuals was associated with a higher cadence,[12, 13] decreased stance phase duration,[12, 13] shorter step/ stride length,[12, 14] and a shorter double support period [12, 15] when compared to overground walking at matched speeds. However, these parameters have not been consistently identified across studies and others have reported opposite effects, i.e. a decrease of the cadence and an increase of the stance phase duration [16] or found no significant change in temporospatial parameters between the two modes of walking.[17, 18]

The purpose of this study, therefore, was to compare temporospatial parameters measured during walking at preferred speed on an instrumented walkway system with those derived from a new instrumented treadmill system, which incorporated a capacitance–based foot pressure array .

METHODS

Participants

A convenience sample of 39 (11 female and 28 male) healthy adults was recruited from University faculty to participate in the study. The mean (± SD) age, height, weight and body mass index of participants was 21.6 ± 3.0 years, 168.6 ± 9.6 cm, 67.4 ± 17.7 kg, and 23.7 ± 5.7 $kg.m^{-2}$, respectively. No participant reported a medical history of medical or balance disorders or musculoskeletal conditions likely to affect their ability to walk on a treadmill. All participants gave written informed consent prior to participation in the research. The study received approval from the university human research ethics committee and was undertaken according to the principles outlined in the Declaration of Helsinki.

Equipment

Temporospatial gait data were collected via two commercially available systems; A GAITRite® instrumented mat (CIR Systems Inc., 60 Garlor Drive Havertown, PA 19083), and a Zebris instrumented gait analysis system (Zebris Medical GmbH, Max-Eyth-Weg 43, D-88316, Isny, Germany).

The GAITRite instrumented mat possessed a sensing area of 4.8 x 0.6 m and incorporated 18,432 sensors, each approximately 1 cm^2, with a spatial resolution of 1.27 cm. The GAITRite system derives measures of step and stride length, duration, velocity and cadence from the timing of sensor activation and the distance between activated sensors. Previous research has established the test–retest reliability of temporospatial parameters derived from the GAITRite system, with reports of good to excellent reliability, both within and between–days, in healthy adults.[19] The system has also been reported to have 'excellent' agreement with temporospatial parameters determined derived from 3–D motion analysis systems and have been shown to be accurate to within 1.5 cm and 0.02 s for individual step parameters on the majority (80–94%) of occasions.[2, 3]

The Zebris instrumented gait analysis system (FDM–THM–S, Zebris Medical GmbH) is comprised a capacitance–based foot pressure platform housed within a treadmill. The pressure platform had a sensing area of 108.4 x 47.4 cm and incorporated 7168 sensors, each approximately 0.85 x 0.85 cm. The treadmill has a contact surface of 150 x 50 cm and its speed could be adjusted between 0.2 and 22 kmh^{-1}, at intervals of 0.1 kmh^{-1}. Although the grade of the contact surface of the treadmill is adjustable in 1% increments up to 25%, it was maintained in a horizontal position (0%) throughout testing. High levels of between- and within-day reliability have been reported for the majority of temporospatial gait parameters recorded by the Zebris system during walking in healthy seniors, with coefficients of variation typically below 5% and 7%, respectively.[20]

Protocol

Participants reported to the gait laboratory (thermoneutral environment) wearing lightweight, comfortable clothing and having abstained from vigorous physical activity. Following anthropometric assessment, participants were instructed to walk barefoot at their 'preferred' walking speed over a 10–m walkway in which the GAITRite instrumented mat was mounted at its midpoint. Temporospatial data were collected once the between–trial walking speed of each subject varied by less ±10%. For each gait trial, temporospatial data for the first stride onto and off the mat were excluded from further analysis. In total, ten gait trials were recorded for each participant, equating to approximately 45 steps.

As outlined by Van de Putte *et al*.[21] participants were then afforded a treadmill acclimatisation session, in which they were briefed regarding the safety procedures for treadmill walking, and undertook a minimum of 10 minutes practice. Following acclimatisation, participants were requested to walk barefoot on the Zebris treadmill system. Treadmill speed was adjusted to match the self–selected walking speed determined during overground walking on the GAITRite system. Once participants were comfortable, a 30 second data capture period was used; equating to approximately 55 steps. Data for each system were sampled at 120 Hz and proprietary software was used to calculate temporospatial variables including cadence, step, stance and swing phase duration, and the duration of single and double limb support.

Statistical Analysis

The SPSS™ statistical package (SPSS, Chicago, IL) was used for all statistical procedures. Kolmogorov-Smirnov tests were used to evaluate data for underlying assumptions of normality. Because outcome variables were determined to be normally distributed, means and SD have been used as summary statistics. Differences between measurements systems with respect to global gait parameters (cadence, and gait cycle duration) were evaluated using paired t–tests. For all other variables, differences between systems were assessed using repeated measures ANOVA within a generalized linear modeling framework. In each case, system (GAITRite and Zebris) and limb (left and right) were treated as within–subject factors. Underlying assumptions regarding the uniformity of the variance–covariance matrix were assessed using Mauchly's test of sphericity. When the assumption of uniformity was violated, an adjustment to the degrees of freedom of the F–ratio was made using Greenhouse–Geisser Epsilon, thereby making the F–test more conservative. Relationships between variables measured by each measurement system were investigated using Pearson–product–moment correlations, while agreement was assessed by calculating the bias and 95% limits of agreement.

RESULTS

Despite walking at a common gait speed (1.3 ± 0.1 m.s^{-1}), participants assumed a significantly faster cadence and shorter gait cycle duration when walking on the Zebris system compared to the GaitRite walkway (Table 1).

< Table 1 >

The mean stance phase duration recorded by the Zebris system during walking was on average 12 ms shorter ($F_{1,38}$ = 34.3, P <.001) than that of the GAITRite system (Figure 1). When expressed as a percentage of the gait cycle, however, the stance phase duration recorded by the Zebris system was significantly longer ($F_{1,38}$ = 103.0, *P* <.001) and the swing phase significantly shorter ($F_{1,38}$ = 102.8, *P* <.001) than that of the GAITRite system (Table 2). Furthermore, the period of single limb support was significantly shorter with the Zebris system ($F_{1,38}$ = 102.9, *P* <.001), while double limb support was significantly greater compared to that measured by GAITRite system ($F_{1,38}$ = 95.2, *P* <.001).

< Figure 1 >

As demonstrated in Table 2, step length was significantly shorter on the Zebris (≈1.75 cm) compared to the GAITRite system ($F_{1,38}$ = 21.0, *P* <.001). Similarly, the foot progression angle was significantly smaller when measured by the Zebris system ($F_{1,38}$ = 497.2, *P* <.001). However, average step width recorded by the Zebris (8.4 ± 2.6 cm) was not significantly different to that measured by the GAITRite system (8.8 ± 2.7 cm).

< Table 2 >

As illustrated in Figure 2, strong positive correlations were noted between temporospatial gait parameters measured by the two systems (*P* < .001), with correlation coefficients ranging from 0.79 to 0.95 for the left foot and 0.81 to 0.95 for the right foot.

< Figure 2 >

Although the cadence measured by the Zebris system was 3 steps per minute greater than that measured by the GAITRite, the 95% limits of agreement between the two systems was ± 5 steps per minute. For all temporal gait parameters, the bias and limits of agreement between the two systems were less than 2%, except for the duration of double support. However, there was a lower level of agreement between systems for spatial parameters (Table 3). For instance, the bias and 95% limits of agreement for step width was 0.3 ± 4 cm.

< Table 3 >

DISCUSSION

This study compared the agreement between temporospatial gait parameters measured with a new instrumented treadmill system (Zebris Medical GmbH) to those derived from a conventional instrumented walkway system (GAITRite®) at a matched speed. We noted small but statistically significant differences in all of the measured spatial and temporal gait parameters recorded by the systems. The discrepancies in temporospatial parameters likely reflect differences in the spatial resolution of the two systems, disparities in calculation of some temporospatial parameters and changes in gait patterns associated with treadmill walking.

Despite employing matched walking speeds, we observed a significantly greater cadence, shorter gait cycle, reduced step length and shorter stance phase (≈12 ms) during walking on an instrumented treadmill compared to an instrumented walkway. While similar observations have been made in elderly adults walking at matched speeds,[22] when expressed as a percentage of the gait cycle, the stance phase recorded by the Zebris system was significantly longer and the swing phase significantly shorter than that of the GAITRite system, indicating that walking on an instrumented treadmill was associated with a change in the relative timing of gait events. Moreover, the period of double limb support was significantly greater (and single limb support shorter) during walking on the Zebris system compared to the GAITRite system. While such changes have been suggested to reflect balance–control mechanisms associated with a fear of falling,[23] Zijlstra *et al.*[24] demonstrated that changes in the timing of support and swing phases only occur with changes in step length. In the current study, the step length determined by the Zebris treadmill was on average 3% shorter than GaitRite walkway system. Hence, it can be questioned whether the longer duration of double support with walking on the instrumented treadmill reflects an adaptive phenomenon related to balance control, true measurement error, or a consequence of regulating stride length.

Agreement between the two systems was greater for temporal rather than spatial gait measures. The limits of agreement for the majority of temporal parameters between systems were within ±2% of the gait cycle duration and equated to approximately twice the temporal resolution of each system (≈1% of the gait cycle duration). Similarly, the average difference between systems for spatial measures of step length (≈1.8 cm) was about twice the spatial resolution of the Zebris treadmill system (0.85 cm). Given the spatial resolution of the GAITRite walkway (1.27 cm) is about 1.5 times that of the Zebris system, it is possible that the relatively wide limits of agreement between systems for spatial measures of step width (±4 cm) and step length (±5 cm) reflect, in part, the lower spatial resolution of the GAITRite system. It is interesting to note, however, that similar limits of agreement in step length have been observed with repeated measurements (both within and between days) using the Zebris system in healthy adults.[20] Hence, the wide limits of agreement in spatial measures may reflect a greater variability associated with treadmill walking.[25] Similarly, we estimate that differences in spatial resolution of the two systems would result in only about a one degree (1º) difference in the foot progression angle determined by the two systems. While this parameter had the largest measurement bias (systematic error, 6º) of all gait variables, it is noteworthy that in comparison to all other temporospatial parameters, the foot progression angle was defined differently between the two measurement systems. The GAITRite software estimates foot progression angle with respect to the intermittent direction of travel determined from three sequential footfalls, rather than an assumed direction of travel as is the case for the Zebris system. Thus, it should be recognized that these two parameters cannot be used interchangeably.

Given that temporospatial parameters from the two systems were highly correlated and that differences in these measures were small relative to the minimal detectable change reported for the GAITRite at self–selected walking speeds,[26] it may be argued that the differences in temporospatial parameters are not clinically meaningful. However, it is noteworthy that the 95% limits of agreement for measures from the two systems are similar to the magnitude of change reported in these parameters during shod and unshod walking in young adults.[27] Consequently, temporospatial parameters derived from an instrumented treadmill system are not interchangeable with those obtained from an instrumented walkway and, as such, should not be interpreted with reference to literature on overground walking.

This study has a number of limitations which should be considered within the discussion of the results. Firstly, we compared common temporospatial parameters in healthy young adults at a self–selected ‘comfortable’ walking speed using an instrumented walkway (criterion standard) and a new commercially available instrumented treadmill that incorporated a capacitance–based pressure platform. While walking speed was matched between the two systems, it is possible that individuals may have adopted a gait pattern that was more representative of overground walking if they had been allowed to select their preferred walking speed on the treadmill system. However, previous research has shown that preferred walking speeds determined on a treadmill are slower than those in overground walking (≈21% relative difference) and result in a relatively shorter stride/step length (≈12%) and lower cadence (≈6%).[28, 29] Secondly, this study evaluated temporospatial gait parameters in healthy young adults and the findings may not be applicable to children, older cohorts, or individuals with gait abnormalities in which temporospatial parameters may vary markedly and faster or slower gait speeds are common.[12, 23] Thirdly, while the current study afforded all participants with a standard 10-minute familiarization period prior to measurement, learning effects associated with treadmill walking were not quantified and study participants were not assessed for their level of previous treadmill walking experience. However, habituation to treadmill walking has been shown to occur in a similarly aged cohort with as little as 10 minutes practice.[21] Hence we believe that any learning effects associated with treadmill walking would be minimal. Finally, both systems apply spatial and, in the case of the treadmill system, temporal constraints on the gait of participants and as such data may not be representative of unconstrained walking outside of the laboratory setting. We attempted to limit our comparison to steady state walking by excluding temporospatial data for the first stride on and off the instrumented walkway. While some research has indicated that five or more steps may be required to achieve steady state walking,[30] the weight of literature has demonstrated that the initiation and termination of overground walking typically involves fewer than three steps at preferred gait speeds, with the majority of gait adjustments occurring in the first and final steps.[31] Consequently, effects associated with the initiation and termination of walking trials with the GAITRite system were likely minimal. None–the–less, the findings of the current study indicate that temporospatial parameters derived from an instrumented treadmill system are not representative of those obtained from an instrumented walkway. Further research, therefore, is required to develop a normative database for temporospatial parameters derived from these new instrumented treadmill systems.

In conclusion, this study is the first to establish the agreement between temporospatial gait parameters obtained from a Zebris instrumented treadmill relative to a conventional GAITRite electronic walkway. Small but statistically significant differences were observed between systems for all temporospatial gait parameters despite employing matched walking speeds. Although parameters from the two systems were highly correlated, agreement was greater for temporal rather than spatial measures. The limits of agreement for temporal measures where typically within ±2% of the gait cycle duration, while spatial measures, such as step length agreed to within ±5 cm. Temporospatial gait parameters determined using an instrumented treadmill system should not be interpreted with reference to literature on overground walking at comfortable self–selected speeds.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest directly related to the contents of the manuscript.

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Table 1. Mean (SD) general gait parameters recorded during walking

	GaitRite®	**Zebris**
n	39	39
Speed (m/s)	1.3 (0.1)	1.3 (0.1)
Cadence (steps/min)	115.6 (6.4)	118.2 * (5.9)
Gait Cycle (sec)	1.04 (0.06)	1.02 * (0.05)

* Indicates a statistically significant difference between systems ($P < .001$)

Table 2. Mean (SD) temporospatial parameters recorded for left and right limbs during walking

	GaitRite®		Zebris	
	Left	**Right**	**Left**	**Right**
Stance Phase Duration (%)	60.5 (1.2)	60.4 (1.1)	61.5 (1.4)	61.4 * (1.4)
Swing Phase Duration (%)	39.5 (1.2)	39.6 (1.1)	38.5 (1.4)	38.6 * (1.4)
Single Support (%)	39.6 (1.2)	39.6 (1.1)	38.5 (1.4)	38.6 * (1.4)
Double Support (%)	20.8 (2.3)	20.8 (2.3)	22.8 (2.8)	22.8 * (2.8)
Step Length (cm)	70.0 (6.8)	69.9 (6.1)	68.2 (7.5)	68.2 * (6.7)
Foot Progression Angle (º)	1 (6)	3 (6)	7 (4)	9 * (5)

* Indicates a statistically significant difference between systems ($P < .001$)

Table 3. Bias and 95% limits of agreement between systems for temporospatial parameters recorded for the left and right limb.

	Left	**Right**
Temporal Parameters		
Stance Phase Duration (%)	1.0 ± 1.2	1.0 ± 1.6
Swing Phase Duration (%)	-1.0 ± 1.2	-1.0 ± 1.6
Single Support (%)	-1.0 ± 1.7	-1.0 ± 1.2
Double Support (%)	2.0 ± 2.6	2.0 ± 2.5
Spatial Parameters		
Step Length (cm)	-1.8 ± 5.0	-1.7 ± 4.9
Foot Progression Angle (º)	6 ± 3	6 ± 4

FIGURE LEGENDS

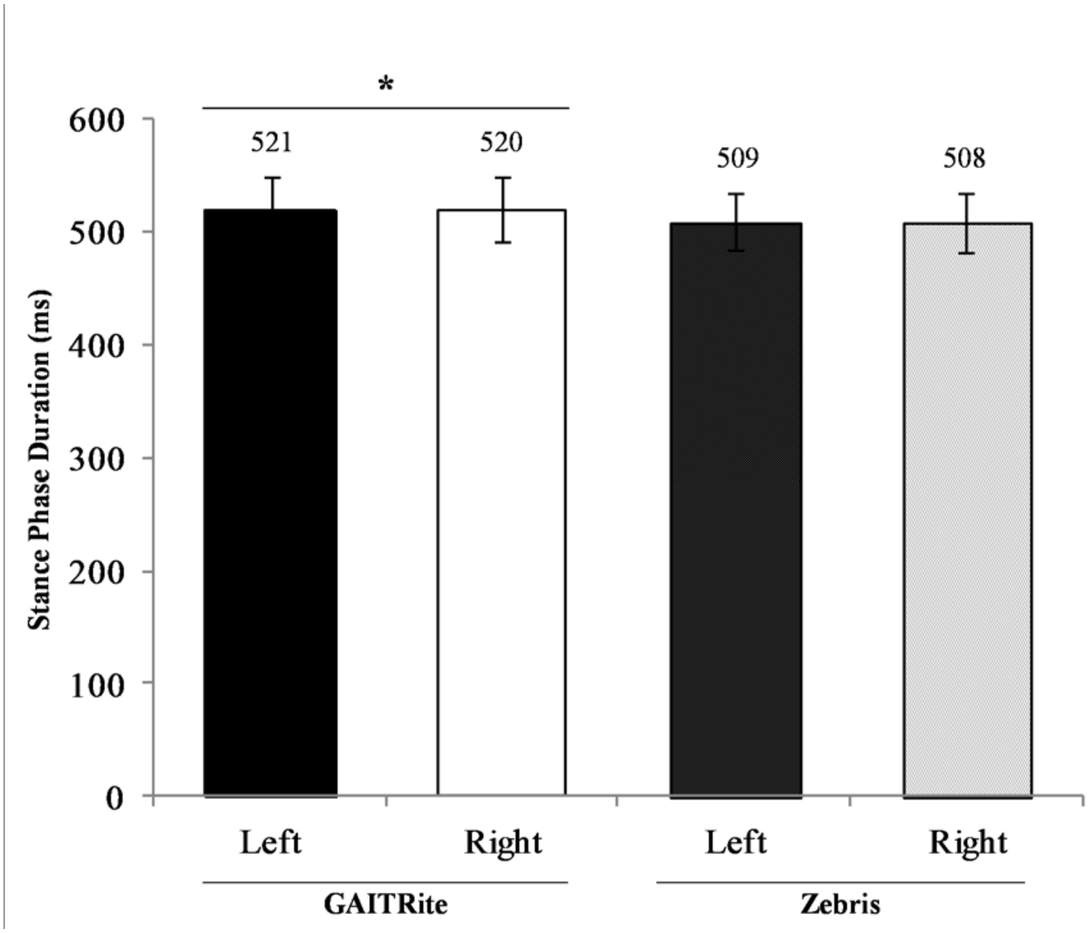

Figure 1. Mean stance phase duration for left and right feet recorded by the GAITRite and Zebris treadmill system while participants (n=39) walked at their preferred speed. Error bars represent standard deviations. * indicates a statistically significant difference (*P* < .001) between measurement GAITRite and Zebris measurement systems.

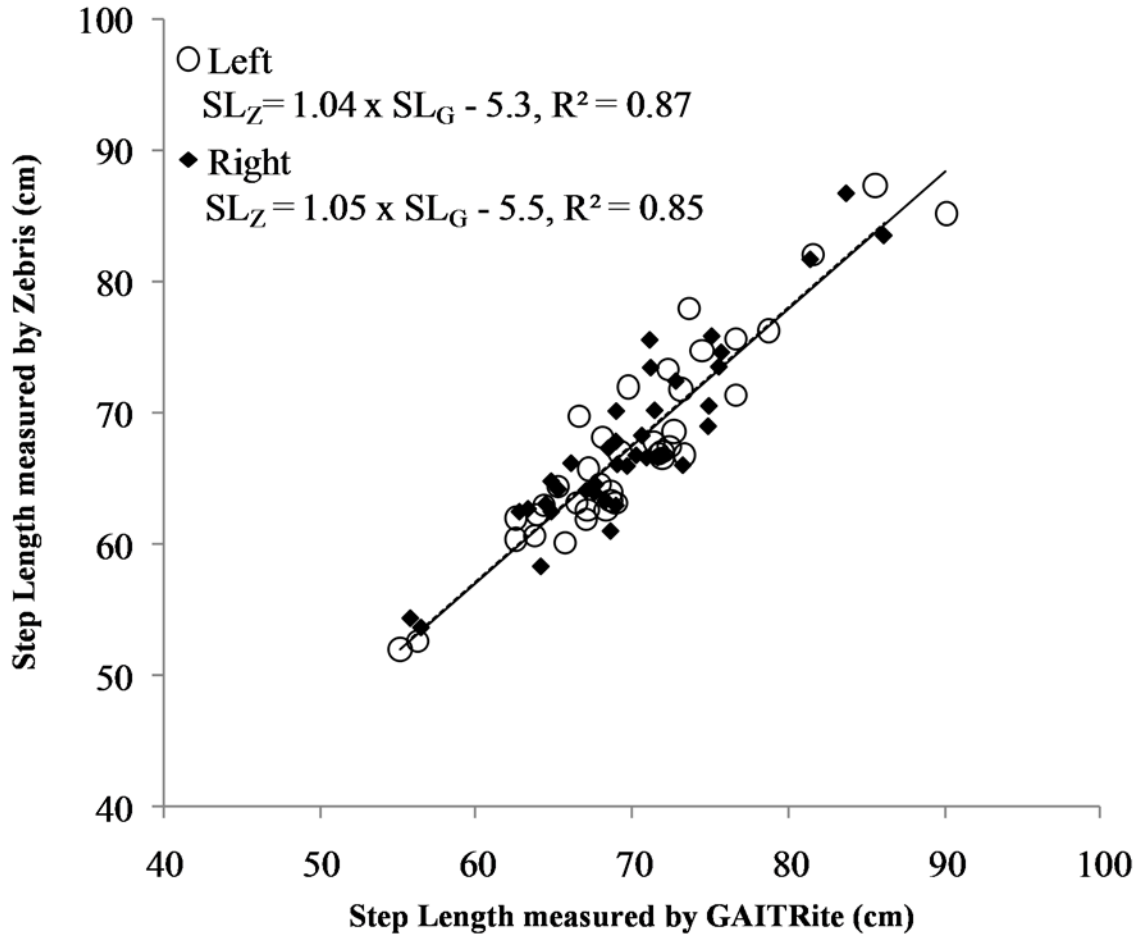

Figure 2. Relationship between mean participant step length recorded by the GAITRite mat and Zebris treadmill systems while participants (n=39) walked at a common gait speed (1.3 m/s). Note that although measures of step length are highly correlated between systems, the bias and limits of agreement are 1.8 ± 5.0 cm for the left and -1.7 ± 4.9 cm for the right limb.