SmartSocks® Gait Analysis Report – V1

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BACKGROUND & AIM

Falls and mobility decline significantly affect health, independence, and quality of life in later life (e.g., Rubenstein, 2006). Gait characteristics such as walking speed, cadence, and stride length and duration are recognised as key indicators of gait performance and falls risk (Mazzà et al., 2021). Although laboratory-based gait assessment systems can measure these parameters with high accuracy, they require specialised equipment, trained personnel, and dedicated testing environments, limiting their utility for long-term monitoring in everyday settings.

SmartSocks (Milbotix Ltd., Bristol, UK) are wearable sensor socks that integrate physiological monitoring (e.g. pulse rate, skin temperature) with a lower-limb inertial measurement unit (IMU) embedded within an everyday garment. Compared with conventional wearable technologies, SmartSocks offer a discreet and potentially scalable approach to continuous monitoring of gait and balance without requiring users to wear an additional visible device. By embedding sensors within ordinary clothing, SmartSocks may help overcome often-reported barriers associated with adherence (e.g., Ma et al., 2025), including discomfort, aesthetics, and the stigma accompanying medical/assistive technologies.

While previous work has explored the comfort, safety, and acceptability of SmartSocks in different populations, including people living in care homes, it is not yet known how accurately the system can quantify clinically relevant gait characteristics. Establishing measurement validity in a controlled laboratory environment is an important first step before evaluating performance during everyday activities and in clinical populations. Although the present sample comprised relatively healthy community-dwelling older adults, participants varied considerably in age, functional capacity, and gait performance, providing a representative range of walking characteristics against which SmartSock-derived outcomes could be evaluated.

The aim of this proof-of-principle study was therefore to assess agreement between SmartSock-derived gait metrics and a gold-standard instrumented walkway system (Zeno Walkway) across a range of walking conditions varying in speed and cognitive demand in community-dwelling older adults.

METHODS

Participants: This initial validation study was approved by the research ethics committee of Brunel University of London's College of Health, Medicine and Life Sciences (ref: 51439-LR-Feb/2026-54991-2). We recruited 21 community-dwelling older adults (≥60 years) through the Brunel Older people's Reference Group. Eligible participants were healthy (free from neurological, musculoskeletal, vestibular, or uncorrected visual/hearing impairments).

Protocol: Participants attended a one-off laboratory visit at the Wolfson Health Sciences Laboratory in Mary Seacole. Following informed consent, they completed brief background questionnaires and a standardised screening battery assessing cognition (Montreal Cognitive Assessment), mobility (Timed Up and Go), concerns about falling (short FES-I), and perceived control over falling (UPCOF). Gait was assessed using an 8m long instrumented walkway (Zeno Walkway; the laboratory reference standard) and one pair of SmartSocks (worn on left foot). Participants completed four overground walking conditions manipulating speed and cognitive load: straight walking at preferred and fast speeds, and cognitive dual task walking at preferred and fast speeds, in this fixed order, with 2 min breaks in between. Each condition was repeated five times. During dual task trials, participants performed serial subtraction by seven while walking, with baseline seated cognitive performance recorded for comparison. After each block of walking trials, participants completed brief standardised self-report measures assessing confidence, fear of falling, and attentional focus. At the end of testing, participants completed a questionnaire evaluating comfort, acceptability, and experience with SmartSocks.

Data Processing: Custom-made Python scripts were used to segment continuous SmartSock recordings into individual walking bouts corresponding to passes recorded by the Zeno walkway. Three deliberate left-foot stamps performed immediately before and after each walking pass were used to identify bout boundaries within the IMU signal. Segmented bouts were subsequently processed using a custom Python-based gait analysis pipeline incorporating the *gaitmap* package, an open-source toolkit for analysis of foot-worn inertial measurement unit (IMU) data (Küderle et al., 2024; see Github for pipeline). Gait events and stride boundaries were identified automatically, and stride-level gait metrics were derived for each bout. Strides were classified as valid when stride time (0.3-2.5 s), stance time (0.2-1.2 s), swing time (0.2-0.8 s), and stride length (0.6-2.0 m) all fell within predefined physiological limits. Bout-level summary metrics were subsequently calculated using valid strides only. Reference gait outcomes were obtained from the Zeno Walkway using PKMAS (ProtoKinetics Movement Analysis Software) stepwise gait analysis outputs. Left-foot strides were extracted to match the SmartSock configuration, and comparable quality-control procedures were applied prior to calculation of bout-level summary metrics.

Statistical Analysis: Primary gait outcomes included stride time (s), stride length (m), stance time (s), swing time (s), cadence (strides/min), and stride speed (m/s). We evaluated the agreement between SmartSock-derived and Zeno-derived gait outcomes at both the walking-bout level and the condition level (using participant-condition averages). Agreement was quantified using intraclass correlation coefficients (ICC; two-way random effects, absolute agreement) and Bland-Altman analyses to evaluate systematic bias and limits of agreement. Participant-level agreement plots and Bland-Altman plots were generated to visualise agreement between systems and identify potential outlying observations.

RESULTS

Participants. Twenty-one participants completed the study. Participants had a mean age of 74.4 ± 7.9 years (range: 61-87), and most (n=14) were female. While they were overall relatively healthy and community-dwelling, the sample did show considerable heterogeneity in terms of their cognitive function, concerns about falling, motor symptoms, and mobility. Please see Table 1 for more detailed participant characteristics.

Table 1. Participant characteristics (N = 21).

Variable	Value
General	
Age in years (mean ± SD; range)	74.4 ± 7.9 (61-87)
Height (cm)	165 ± 9 (142-178)
Weight (kg)	72.5 ± 14.8 (47-100)
Sex (male/female)	7/14
Fall in past year (yes/no)	4/17
Taking >4 prescribed medications/day (yes/no)	2/19
Cognitive / Psychological	
MoCA (0-30) (mean ± SD; range)	28.5 ± 1.3 (26-30)
Short FES-I (mean ± SD; range)	20.9 ± 4.7 (16-39)
UPCOF (mean ± SD; range)	17.6 ± 2.0 (14-20)
Mobility	
TUG, s (mean ± SD; range)	8.0 ± 1.6 (5.2-11.6)

***NB**: MoCA = Montreal Cognitive Assessment; FES-I = Falls Efficacy Scale International; UPCOF = Updated Perceived Control Over Falling scale; TUG = Timed-up-and-Go;*

Gait outcomes: A total of 165 matched walking bouts were successfully processed and included in the agreement analyses.[1] Table 2 confirms initial face validity, as the SmartSock-derived gait metrics demonstrated the expected effects of the experimental manipulations: Fast-paced walking was characterised by shorter stride times, higher cadence, and greater stride speeds than normal-paced walking, while dual-task effects were comparatively modest.

As shown in Table 3, **temporal gait outcomes exhibited good-to-excellent agreement** with the Zeno-derived gait metrics, particularly for stride time, stance time, and cadence, with slightly lower values observed for swing time. In contrast, **spatial outcomes** (stride length and speed) **showed poor agreement**, and tended to be underestimated by the SmartSocks vs. the Zeno, as indicated by persistent negative bias.

[1] These interim analyses are based on n=13, as the first six participants were assessed prior to an IMU firmware update that improved the SmartSocks' IMU's measurement range, while two SmartSock recordings were not successfully stored. Data from these n=6 will be processed later as well.

Visual inspection of Bland-Altman plots (Figure 1) and absolute agreement (Figure 2) showed that, for temporal outcomes, differences between SmartSock-derived and Zeno-derived measurements were generally small and distributed evenly across the observed range of values, suggesting minimal systematic bias and heteroscedasticity. However, for stride length and stride speed, greater variability was evident together with a tendency for SmartSock-derived values to underestimate those obtained from the Zeno walkway. There was some suggestion that agreement for these spatial outcomes may have been stronger for shorter and slower strides; however, this pattern was not formally tested and caution is warranted with this interpretation.

Table 2. SmartSock-derived gait characteristics by walking condition

Outcome	ST-NP	ST-FP	DT-NP	DT-FP
Stride time (s)	1.09 ± 0.07	0.85 ± 0.08	1.14 ± 0.19	0.96 ± 0.12
Stance time (s)	0.73 ± 0.05	0.55 ± 0.05	0.77 ± 0.14	0.63 ± 0.08
Swing time (s)	0.36 ± 0.03	0.30 ± 0.04	0.38 ± 0.06	0.33 ± 0.04
Stride length (m)	1.09 ± 0.18	1.19 ± 0.26	1.09 ± 0.18	1.09 ± 0.19
Stride speed (m/s)	1.00 ± 0.16	1.41 ± 0.27	0.99 ± 0.24	1.15 ± 0.23
Cadence (strides/min)	55.3 ± 3.8	71.7 ± 6.3	54.1 ± 8.3	63.8 ± 8.8

***NB**: ST = single-task; DT = dual-task; NP = normal pace; FP = fast pace;*

Table 3. Agreement between SmartSock-derived and Zeno-derived outcomes (n = 165 bouts)

Outcome	ICC	95% CI	Bias	MAE	Limits of Agreement	MRE (%)
Stride time (s)	**0.980**	0.971-0.987	-0.005	0.026	-0.079 to 0.069	2.6%
Stance time (s)	**0.959**	0.942-0.970	0.010	0.032	-0.065 to 0.084	4.9%
Swing time (s)	**0.816**	0.757-0.858	-0.015	0.031	-0.081 to 0.052	8.7%
Stride length (m)	0.173	0.069-0.290	-0.202	0.245	-0.689 to 0.285	18.3%
Stride speed (m/s)	0.472	0.343-0.601	-0.220	0.267	-0.833 to 0.393	19.2%
Cadence (strides/min)	**0.973**	0.957-0.984	0.335	1.658	-4.526 to 5.196	2.7%

***NB:** ICC = intraclass correlation coefficient; CI = confidence interval; MAE = mean absolute error; MRE = mean relative error; Positive bias values indicate higher SmartSock-derived values relative to Zeno; Bold ICC values indicate good/excellent agreement;*

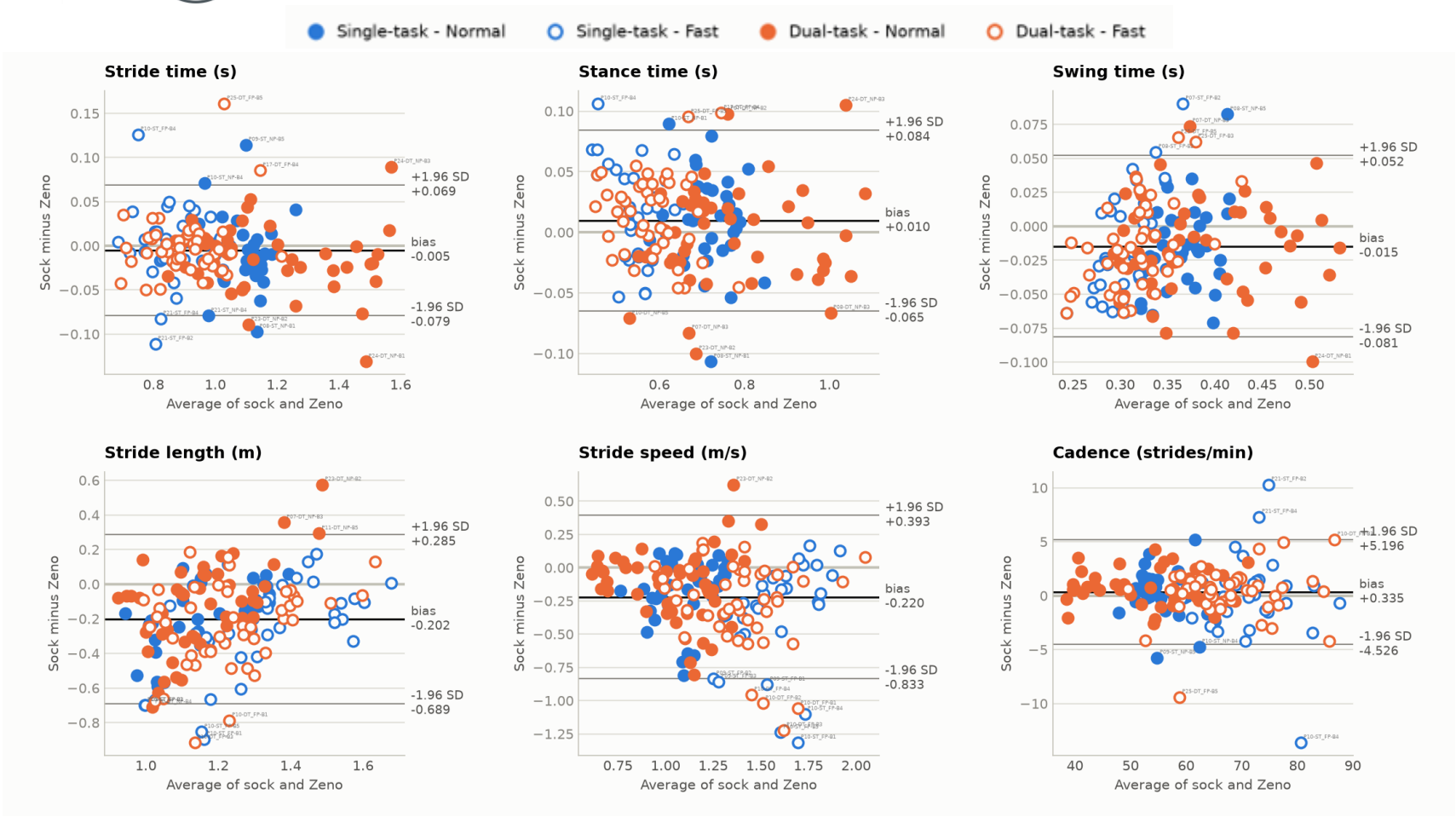


Figure 1. Bland-Altman plots indicating agreement for each of the six outcome measures. Each dot represents one bout. Potential outlying variables are highlighted.

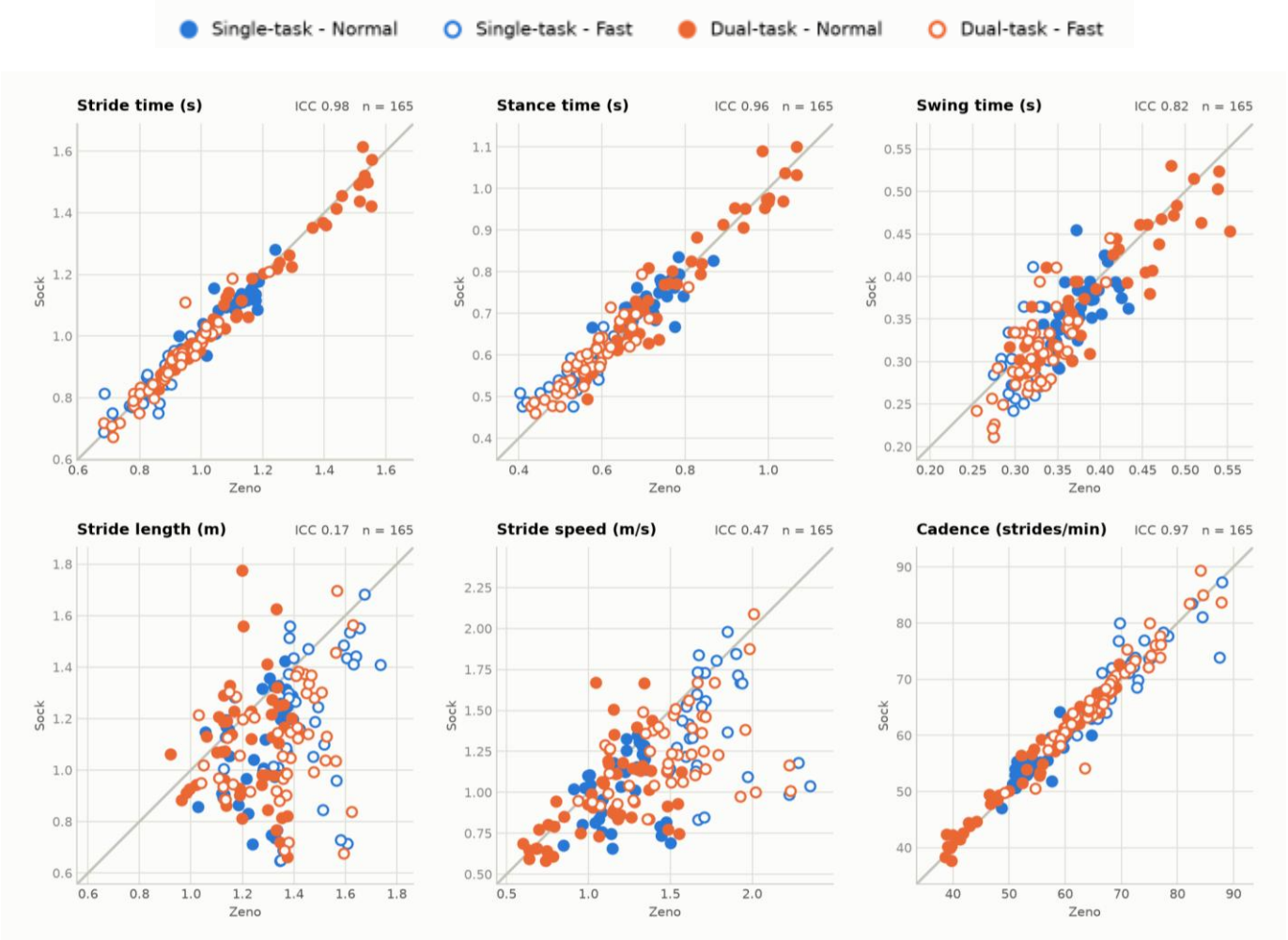


Figure 2. Absolute agreement between Zeno and SmartSocks-derived gait metrics. Each dot represents one bout. Potential outlying variables are highlighted.

CONCLUSION

This proof-of-principle validation study suggests that SmartSocks can accurately quantify several key temporal gait characteristics in older adults. Specifically, excellent agreement was found for stride time, stance time, and cadence when compared against the Zeno Walkway. Agreement was good for swing time, albeit lower. This may in part be explained by the inherent challenges of using a single IMU only for the identification of exact transition between stance and swing phases, as small errors in timing will have a proportionally larger effect on estimates of swing time vs stance time.

Spatial/spatiotemporal measures, i.e., stride length and stride speed, demonstrated poor agreement and tended to be systematically underestimated relative to the Zeno Walkway-derived metrics. This may reflect the greater difficulty of estimating displacement from a single foot-mounted IMU, where estimated are necessarily indirect, and hence more sensitive to potential errors that occur downstream, e.g., in trajectory reconstruction and estimation of the IMU's orientation. One recommendation is to further test and refine the algorithms used for spatial(-temporal) parameters, and explore the potential effects of wearing two SmartSocks and higher sampling frequencies (e.g. 50-100 Hz).

It is worth noting that the sample consisted of healthy community-dwelling older adults with considerable variation in motor and cognitive functioning. Agreement results also seemed consistent across task conditions (e.g. normal vs fast pace, single- vs dual-task), which suggests that SmartSock performance is not substantially affected by changes in walking speed or cognitive load. Note, however, that Bland-Altman analyses did suggest trends toward greater underestimation of especially stride length and speed *longer* stride lengths and *higher* stride speeds, respectively. This requires further formal testing in a larger sample, e.g. across greater range of speeds and in more dynamic tasks and/or environments that require more adaptive stepping responses and adjustments.

Finally, a key practical issue was that one-third of walking bouts could not be analysed using the current gait-processing pipeline. Approximately ~66% of these were attributable to failure to identify a sufficient stationary calibration period prior to gait analysis. Inspection of raw data suggested that, in some cases, participants transitioned too rapidly from the start marker into walking for a suitable stationary period to be detected. Yet, when walking bouts were successfully processed, SmartSock-derived gait metrics demonstrated good-to-excellent agreement for key gait outcomes. Future work should therefore investigate alternative processing approaches that are less dependent on explicit stationary calibration periods and evaluate SmartSock performance during more ecologically valid activities involving turning, transfers, obstacle negotiation, and everyday mobility – where similar issues are likely to present.

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