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1. Title

Continuous in-home walking speed monitoring in older people with a low-cost ambient sensor: Results of a feasibility study

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4. Abstract

BACKGROUND: Walking speed predicts important clinical outcomes in older adults and is one of the most significant indicators of frailty.

OBJECTIVE: To test whether it is feasible to measure walking speed frequently and unobtrusively in the home.

METHODS: A longitudinal feasibility study was conducted comprising the installation and monitoring of continuous measurement walking speed sensors in twenty frail older adults' homes for a period of twelve weeks. Manual walking speed, frailty level and health status were measured at four-weekly intervals. Qualitative interviews were conducted at the end of the study to assess participants' attitudes to the sensors and to the concept of continuous in-home walking speed measurement.

RESULTS: Eighteen participants completed the study. The number of walking speed measurements recorded by the sensors varied notably between participants (median 1942.39, range 2-3617). Participants indicated acceptability of both the sensor within the home and the concept of in-home walking speed measurement.

CONCLUSIONS: Where regular measurement was achieved, the results indicate that walking speed might be better viewed as a distribution rather than a single figure, taking into account the natural variation to walking speed in daily life. This study demonstrates the feasibility of continuous ambient in-home walking speed monitoring of older adults with a low-cost, easily deployed device.

5. Key words

Walking speed, digital health technology, health monitoring, frailty, older people

1. Introduction

The act of walking requires energy and relies on multiple organ systems [1]. The speed at which an older person walks is a predictor of many important outcomes, including mortality, hospitalisation, functional dependence and disability [2]. It has particular value as an indicator of frailty status [3, 4]. This has led to walking speed (also termed 'gait speed') being labelled the 'sixth vital sign' [5], with variations in speed associated with clinically meaningful changes in quality of life [6, 7]. Declining walking-speed predicts greater risk of falls [8] and indicates concurrent increase in activities of daily living dependence [9], with speeds lower than 0.8m/s indicating increased risk of adverse events [2].

Walking speed tests are well documented [1, 2, 10, 11] and prevalent as clinical and research instruments; however, the apparent simplicity of such tests belies the practical difficulties of administrating them accurately and consistently [12, 13], and it is common to see tests scheduled at only six-monthly or yearly intervals [12]. This limits opportunities for early detection since significant changes in the health of older people often occur within shorter periods [9]. In health services, this perpetuates a care model that reacts to crises (e.g. falls), rather than proactively avoids them. Also, the extent to which point measures of walking speed are reliable has been questioned due to their artificial nature and susceptibility to variance [12, 14–17]. A solution would be continuous, automatic monitoring of walking speed, able to detect functional decline and raise awareness of potential problems before they become more serious [1, 12]. The few studies that have attempted continuous, ambient measurement in the home have shown that the results can be correlated with, for example, cognitive decline [18]. However, the technology used in these studies does not lend itself to non-experimental deployment, as typically it involves

multiple devices and fixed installation [12, 16, 17, 19]. A wearable solution is a possibility, but among older people adherence to wearables can be low [20] or their use abandoned entirely [21]. This has led us to develop a passive, single-device walking-speed sensor.

2. Methods

The aim of this study was to test whether it is feasible and acceptable to measure walking speed of older people frequently and unobtrusively in the home using single-device low-cost technology.

2.1 Design and sample

A longitudinal feasibility study was conducted comprising the installation and monitoring of walking-speed sensors in the homes of older adults for a twelve-week period. Twenty older adults were recruited from two assisted-living housing facilities in the city of Sheffield (UK). This sample size was identified as it was deemed sufficient to meet the objectives of the study, whilst also being practicable within the economic and time restraints of the funding. With the support of the independent living coordinators (tenant-support staff within each facility), the project was advertised to residents, and a researcher attended 'coffee morning' community gatherings in each location to provide more information through an informal presentation. Recruitment was through self-selection, with participants included in the study if they a) lived alone (necessitated by the technology); and b) scored between four and six inclusive on the Clinical Frailty Scale [22], indicating vulnerability (4), mild frailty (5) or moderate frailty (6).

3. Walking speed sensor

The walking-speed sensor used in this project was a custom-made device designed and manufactured by a UK electronic design company (GSPK Design Ltd) in collaboration with the research team. It is a discreet device based on lidar technology for monitoring walking speed whenever a person passes the sensor. Multiple distance and time measurements are converted into a measure of the walking speed using proprietary algorithms. The sensor uses low-power lasers and is classified as safe under normal use. The device is powered from the mains electricity supply, but consumption is low. Data are stored to an SD memory card. The device is designed so that the cost of manufacture is low, and we would expect the eventual purchase price of any product based on this design to be less than $300. It is easy to install in the home environment without expertise or training, enabling a range of future deployment options. However, the sensor is unable to differentiate individuals, and therefore in its current design it is intended for single-occupancy dwellings.

The sensor technology has been tested for accuracy in laboratory conditions using two different methods. First, in order to demonstrate that the device accurately records speeds of a moving body under 'ideal' conditions, an industrial robot arm was programmed to move a model human pelvis multiple times back and forth along a linear trajectory at each of a series of constant known speeds ranging from 0.4m/s to 1.2m/s inclusive in increments of 0.05m/s. Secondly, the accuracy of the sensor under more 'realistic' conditions was tested with human volunteers simulating the walking speeds of pre-frail and frail individuals within a VICON motion-capture system. Correlation was good between the sensor readings and the speed of the robot arm, and between sensor readings and speeds calculated from the VICON data.

3.1 Outcome measures

Quantitative measures comprise:

- *Walking speed sensor data*. Data points accessed from the memory cards of the sensors, each describing the raw measurements and derived speeds from a single pass of the sensor.
- *Timed walk test (manual).* For purposes of comparison, a clinical gold standard test for measuring walking speed [23] was conducted by the researcher at baseline (T1) and four-weekly intervals (T2; T3; T4) using a four-metre track and stopwatch. The time taken to cover the distance from a standing start is used to calculate walking speed.
- *Clinical Frailty Scale (CFS)* [22]. As a summary assessment of each participant's physical condition, this scale was completed at T1-T4 by the researcher following an informal discussion about the participant's current health. Higher numbers on the scale indicate greater frailty.

At the end of the study, semi-structured interviews were conducted with each participant to assess the acceptability of the device.

3.2 Procedure

The study took place between June and September 2018. With staggered recruitment, duration between the first and last participant starting the study was 13 days. After consent was gained the installation of the device was undertaken by the researcher. Once situated, the sensor was then turned on and participants were asked to not move it and to leave it running for the duration of the study.

The researcher visited the participants one week after installation to check that the sensors were operating as expected. Subsequent visits were scheduled at T2 and T3, to complete the quantitative outcome measures, to again check the sensor and to transfer data from SD card to secure drive, and finally at T4 to collect the sensors, to complete the final quantitative measures and to administer the semi-structured interviews.

3.3 Sensor installation

The sensors were placed where they would not create a trip hazard or inconvenience the participant, with advice from and approval of each participant. There were two further criteria for choosing the location of the sensors that the researcher attempted to fulfil in order to maximise the quality of the data collected: the placement should maximise the potential for regular walking traffic, and it should conform to the 'natural' flow of travel across the space to allow for a roughly perpendicular traversals of the sensor detection envelope. Hallways were considered the most likely locations within home environments that would satisfy these criteria. For the purposes of comparing sensor placement with performance, each location was graded subjectively by the researcher according to the extent to which the aforementioned criteria were achieved: A (both siting criteria were achieved; see example in Figure 1), B (only one criterion was achieved) or C (neither of the criteria were achieved).

3.4 Analysis

Given the duration of the data collection, we chose the week as a convenient temporal base for analysis. Walking speeds >1.5m/s were deemed to be outliers, as such speeds were

known to be beyond the ‘normal’ capabilities of all participants and so it could be said with near certainty that these readings either captured the motion of visitors or else were anomalies generated by incomplete traversals or interference from other sources registered by the sensor. Regardless of cause, these outlying readings were removed before analysis. The weekly mean of the daily median walking speed was used to visualise any week-to-week changes in the participant’s walking speed. Frequency distributions of speeds for each participant were also generated. Scatter plots and Spearman’s rank-order correlation test were used to compare walking speeds measured by the sensor and those calculated from the manually timed walk test.

Fig. 1 *A walking speed sensor (circled) placed in a participant's home and satisfying both placement criteria*

4. Results

4.1 Baseline characteristics of participants

There were slightly more female than male participants, the oldest age category (85+) was the most populous, and there was a tendency towards higher CFS categories (Table 1). The majority were of White British ethnicity. Manually measured walking speeds were between 0.2m/s and 1.0m/s, with the majority in the slower half of the range. Two participants (05 and 15) withdrew from the study, one due to admission to a care home, the other through personal choice.

Table 1 *Baseline characteristics of participants*

Characteristics	Participant count (n=20)
Gender	
Female	11
Male	9
Ethnicity	
White British	19
Black Caribbean	1
Age range	
55-64	3
65-74	5
75-84	4
85+	8
CFS score	
4	5
5	8
6	7
Timed 4m walk test	
0.2 – 0.4m/s	6
0.4 – 0.6m/s	7
0.6 – 0.8m/s	5

0.8 – 1m/s	2

4.2 Sensor operation

The number of sensor readings varied notably among participants, as did the total number of days within the three-month period when sensor readings were recorded (Table 2). In terms of meeting placement criteria, the sensor placements were evenly spread across the three categories. For those who completed the study, the median number of total readings from sensors graded A for placement was 1301.5 (IQR 1045), B was 1386 (IQR 910), and C was 13 (IQR 202).

Table 2 *Individual sensor performance*

Participant ID	Total sensor readings	Sensor placement grading	Total days with data	Total days without data
01	211	C	50	34
02	1509	B	48	36
03	392	A	82	2
04	9	C	8	76
06	3617	A	79	5
07	1256	A	83	1
08	329	C	25	59
09	324	B	42	42
10	3439	B	38	46
11	2085	A	60	24
12	1005	B	20	64
13	722	A	71	13
14	13	C	3	81
16	2	C	2	82
17	134	B	23	61
18	1347	A	84	0
19	1640	B	45	39
20	1386	B	58	26

4.3 Walking speed data

There was a certain amount of noise in the data, due to the occasional presence of visitors and misreadings by the sensor, which, even with obvious outliers (>1.5m/s) removed, resulted in a degree of skew in the distributions for some participants. To illustrate the effects of placement on the data generated by the sensors, examples of the frequency distribution of speeds (Figure 2A-C) and the weekly mean of the daily median walking speed (Figure 2D-F) are included for three participants, those with the highest number of total sensor readings for each placement grade. The placement for participant 06 was graded A and the normal distribution evident in Figure 2A, centred around speeds between 0.7 and

0.8m/s is reflected in the weekly median speeds (Figure 2D). The distribution for participants 10 (B placement – Figure 2B) and 01 (C placement – Figure 2C) are less well defined; and there is insufficient data to compute median speeds for every week of the study (Figure 2E-F).

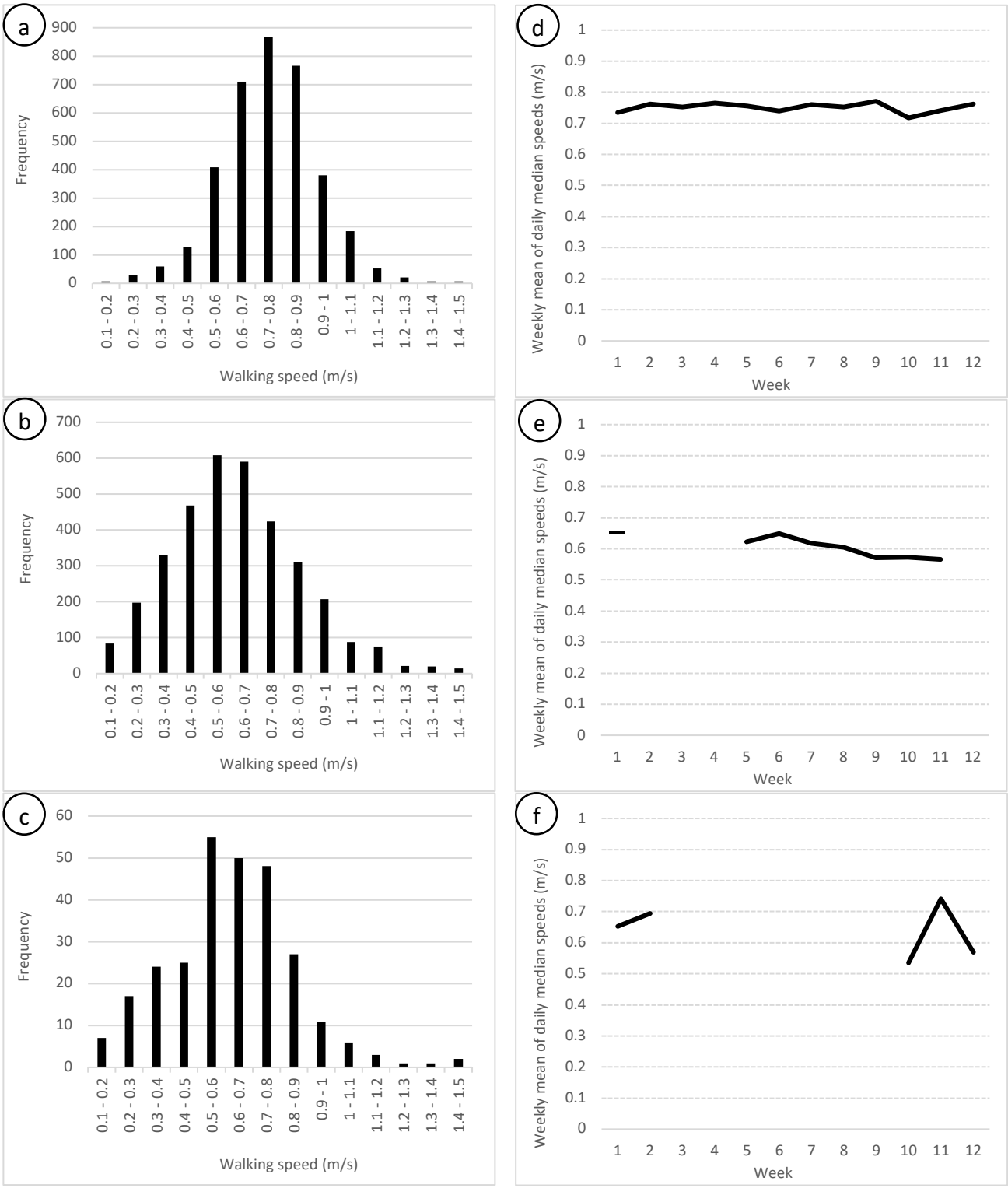

Fig. 2 *Frequency distribution graphs of the walking speeds for participants 06 (a), 10 (b) and 01 (c), and graphs depicting the weekly mean of the daily median walking speeds for participants 06 (d), 10 (e) and 01 (f), during the 12-week study*

For the purposes of the following analysis, participants with fewer than 100 recorded walking speed measurements were excluded (n=5 exclusions): for these participants, with so few readings (fewer than 2 a day on average, distributed unevenly across the 12-week period), any statistical analysis based on weekly means of daily medians would be unreliable. The average walking speeds as measured by the sensors for participants rated (at the end of the study) 4 (the least frail in the study) on the CFS was 0.72m/s, for those rated 5 it was 0.58m/s, and for those rated 6 (the most frail) it was 0.47m/s. Figure 3 depicts a comparison between walking speeds measured by the sensor and those calculated from a manually timed walk test, by plotting (where data exist) the monthly manually timed walk speeds (at T2, T3 and T4) against the mean of the preceding week's daily median sensor walking speeds for each participant. A Spearman's rank-order correlation was carried out to assess this relationship. Preliminary analysis showed the relationship to be monotonic, as assessed by visual inspection of the scatterplot (Figure 3). There was a statistically significant, weak positive correlation between the sensor measurements and the manually timed walk test measurements ($r_s(28) = .323$, $p < .05$).

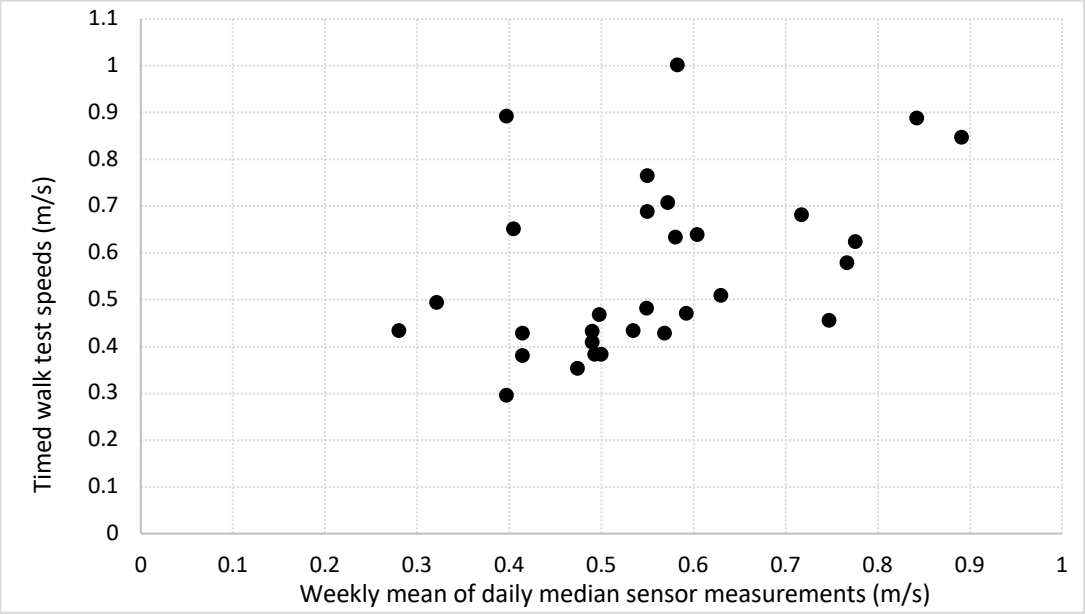

Fig. 3 *The mean of the preceding week's daily median walking speeds measured by the sensor plotted against those derived from a manually timed walk test for eligible participants (n=15; note number of walk tests recorded varies among participants).*

4.4 Acceptability of the sensors

The 18 participants who completed the study also completed a semi-structured interview. When asked for their impressions of the sensor, participants described it as small and/or discreet (11 participants). The only negative comments about the design were that a light could be noticed in darkness (2; this refers to an internal LED that from certain angles can be seen through the apertures in the sensor casing) and that the mains lead was an inconvenience (1). Ten participants reported being aware of the sensor on a day-to-day basis, with the other 8 not aware of it.

With regards to the purpose of the device, 14 participants responded positively to the idea of finding out about their walking speed (1 negatively, 3 unsure/neutral); 11 responded positively to the concept of being informed regularly about their walking speed (4

negatively, 3 unsure/neutral); but only 6 responded positively to the idea of having a walking speed sensor in their home for longer (11 negatively, 1 unsure). Reasons for not wanting the sensor for a longer period included not having received any benefit from it and the device being "in the way".

Ten participants responded positively to the possibility of walking speed information being shared with others (3 negatively, 5 unsure/neutral), with family members being most commonly suggested as the recipients of this information (8), as well as the on-site independent living coordinators (7), GPs (7), unspecified health professionals (6), carers (3), friends (3), physiotherapists (1) and holistic therapists (1). One person raised concerns over privacy.

Common themes around the concept of measuring walking speed included the fact that the participants were getting old and "slowing down" was to be expected (10); there isn't anything that can be done about it (10); they already know how fast they walk (5); it could inform them about their health status (5); and they could act on the information or use it to measure progress (3).

Finally, groups who the participants suggested might benefit from measuring their walking speed were either older people (8) or people with disabilities or long-term conditions (4).

5. Discussion

This study aimed to test the feasibility of continuous, ambient in-home walking speed measurement using an unobtrusive and easily installed sensor. Despite placement issues

within some homes, the data generated by the sensors (when placed according to identified criteria), as well as the qualitative feedback from the target-user population, support the feasibility of continuous walking speed measurement with this device.

The results highlight both the challenge and the necessity of testing innovative health technologies in real-world settings with environmental and human factors that cannot always be anticipated. This is most evident in the inconsistencies experienced with sensor placement. The researchers had set criteria that should ideally be met in order for the sensor to capture regular and accurate measurements of walking speed (placement in a frequently visited location, and in conformance with the natural path taken when traversing the space). As residents of assisted living housing facilities operated by the same organisation, participants' homes had similar layouts. Typical layouts had been shared with the research team in advance, and a hallway area had been identified as the most suitable location to satisfy the above criteria. However, in practice there was a lack of consistency regarding the presence of mains sockets within the participants' hallways, with some having no sockets at all and others having none in reach of a suitable flat surface. Also, the preferences of individual participants did occasionally conflict with the researcher's suggested location, with reasons cited including wanting to keep sockets available for other uses and not wanting certain surface space occupied by the sensor. In these circumstances, alternative locations were sought. Whilst it could be argued that including participants in the study for whom sensor placement did not meet the identified criteria was counterproductive, this is only evident with hindsight, as the grading was based on assumptions about optimal environmental siting and the subjective opinion of the researcher at the time of installation. The results relating to placement suitability are in fact

an important finding of this feasibility study. Learning from this experience, future research involving the walking speed sensor will include the environmental compatibility for siting sensors as part of the inclusion criteria.

The extent to which placement affected the ability of the sensors to record measurements is discernible in the data. Whilst the volume of data generated by sensors whose placement met at least one of the identified criteria (placements graded A or B) does vary, those that met neither criterion (graded C) generated fewer readings overall. However, this is only one among several factors that could help explain the variance in the number of days without measurements (see Table 2). Other factors include time spent away from home and the sensor being turned off or obstructed, as occasionally discovered during the researcher's visits. Another possible factor is that of the sensor not working as expected; the next version of the sensor firmware includes more comprehensive error logging to confirm or discount this.

The weak correlation between walking speeds as measured by the sensor in participants' homes and by the four-metre timed walk test observed in Figure 3 is consistent with previous research where measurements of walking speed in the 'real world' have been compared with test measurements [12, 14–17, 24]. Contrary to existing evidence [16, 24], however, our results do not agree with the finding that walking speeds measured according to clinical protocols are (on average) higher than those measured in the home, although it has been noted that this effect decreases with advancing age [24], and participants of the present study tended to be those in the older categories.

The examples presented in Figures 2A-C suggest that 'walking speed' might be better thought of as a *distribution* rather than a single figure, taking into account the natural variation in walking speeds that occur in daily life. Adopting this perspective, whilst isolated measures of walking speed may be useful indicators of health [1], it is questionable whether they are useful for detecting *changes* in health (and the rate of any such change), and hence for enabling timely and effective intervention [12]. The continuous monitoring of walking speed presents this opportunity, and algorithms for identifying 'clinically meaningful' (rates of) changes need to be developed. Existing evidence derived from manual tests suggests reductions of 0.15m/s or greater could be meaningful [25], but further work is needed to determine whether this value can be translated to a rate of change under continuous monitoring. Further trials with the device are required, with more participants measured over a longer period of time to increase the likelihood that some will experience health-related changes in walking speed. Nonetheless, this initial study suggests the sensor can generate data comparable with that of continuous home-based walking speed systems [12, 16, 17, 19], but with a device of much smaller physical size, fewer operating constraints, greater ease of installation, and likely lower cost, all of which increase its potential to constitute part of a widely applicable and cost-effective service for the health and care sector in the near future.

There was good acceptance of the design and purpose of the sensor, as reported by participants who had the device in their homes for 12 weeks. Of some concern was the negative reaction to the idea of long-term placement of the sensor; however, since at this preliminary stage the device is not integrated into systems of care (nor, indeed, does it provide the user with any direct feedback whatsoever), this is perhaps understandable.

Future assessments of an integrated system are expected to give a more accurate indication of the potential for sustained adoption.

A tangential theme arising from the interviews was the belief of many participants that 'slowing down' was to be expected in old age and about which there is nothing to be done. This suggests an opportunity to provide education and advice, as evidence suggests that 'general' physical decline in older age can be slowed and in some cases reversed [26].

The initial study suggests some modifications of the sensor design. Firstly, wireless data transmission to a cloud-based database would simplify the research process and move the sensor closer to being a practical component of a viable healthcare service. Secondly, converting the sensor to battery power would remove the need for an accessible mains supply socket, opening up greater possibilities for locating the sensor in the home. However, given the current state of battery technology, this is not a straightforward adaptation, and the need for frequent battery recharging or replacement is a recognised barrier to health technology adoption [27]. A low-powered sensor transmitting data a short distance to a mains-powered transmission hub conveniently sited elsewhere in the house is one possible solution.

Conclusions and Implications

This study has demonstrated the feasibility of continuous, ambient in-home walking speed monitoring for older adults, using a discreet, low-cost and easily installed device. Although further development is required to integrate data collection and increase usability, there are strong indications from this initial feasibility study that the results are comparable to more

complex (and more expensive) systems, something which promises to make wide-scale walking speed monitoring for older people a viable proposition.

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Author contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Phil Joddrell, Stephen Potter and Mark Hawley. The first draft of the manuscript was written by Phil Joddrell and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Conflicts of interest

The authors declare that they have no conflict of interest.

Ethical considerations

This study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by the School of Health and Related Research Ethics Committee at The University of Sheffield (December 2018, REC reference number 017762). Informed consent was obtained from all individual participants included in the study.

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