Gait & Posture 86 (2021) 27–32

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

A mobile app to transparently distinguish single- from dual-task walking for the ecological monitoring of age-related changes in daily-life gait

Francesca Lunardini [a,*], Milad Malavolti [a], Alessandra Laura Giulia Pedrocchi [a], N. Alberto Borghese [b], Simona Ferrante [a]

[a] NearLab, Department of Electronics, Information and Bioengineering, Politecnico di Milano, Via Ponzio 34/5, 20133, Milano, MI, Italy
[b] AIS Lab, Department of Computer Science, University of Milano, Via Celoria 18, 20133, Milano, MI, Italy

ARTICLE INFO

Keywords:
Ageing
Dual tasking
Gait alterations
Instrumented insoles
m-health

ABSTRACT

Background: Early detection of gait impairments in older adults allows the early uncovering of fall risk and/or cognitive deficits, resulting in timely interventions. Dual-task paradigms have been shown to be more sensitive than single-task conditions for the detection of subtle yet relevant gait impairments.
Research question: Can a system - encompassing a pair of instrumented insoles and a customized mobile app - transparently and accurately study ecological walking activities in single- and dual-task conditions, with the aim of detecting early and subtle age-related alterations of gait?
Methods: The system was tested on 19 older adults during outdoor walking (two identical single-task trials and two motor-cognitive dual-task trials with the user engaged in a simple phone call and in a cognitive-demanding phone call). A single-task cognitive trial was included. Relative reliability of the gait parameters provided by the insoles during single-task walking was investigated (Intraclass Correlation Coefficient). The effect of dual tasking on both motor (Friedman test) and cognitive (Wilcoxon signed-rank test) domains was studied.
To study usability, the system was tested on 5 older adults in real-life environment over 3 months.
Results: Most of the parameters showed excellent reliability. Independently from the cognitive demand, walking while talking resulted in increased gait cycle and step time, with a prolonged stance phase due to an augmented double-support. Variability of gait cycle and stance phase increased only during the most demanding dual-task. Dual tasking resulted in a reduced cognitive score.
Usability feedback were excellent, with users reporting to understand the usefulness of the devised system and to feel at ease when using the system and the insoles.
Significance: This work paves the way toward fruitful applications of the devised system to achieve accurate and ecological monitoring of daily-life walking activities, with the final aim of detecting early and subtle alterations of gait.

1. Introduction

The ageing population is a well-documented phenomenon that goes hand in hand with an increasing concern over its impact on public costs, because of both physical and cognitive age-related decline [1]. As for physical decline, fall-related episodes in people over 65 represent the 46 % of total costs of injury-related hospital admissions [2]. On the other hand, the fast growing of people with dementia is imposing a huge economic burden, with an estimated US$ 604 billion worldwide cost in 2010 [3].

These figures suggest the strong need of moving from a reactive and curative approach, towards a proactive care based on health promotion and prevention. Age-related decline is typically diagnosed at a relatively late stage [4], after a fall or in an advanced stage of dementia. Against this background, tools able to detect early signs of decline become crucial to promote an active and healthy ageing.

When it comes to age-related decline, gait should be kept under close surveillance. It is well documented that the prevalence of gait disorders increases with age [5], and that a substantial decrease in walking speed represents a key element of frailty [6]. In addition, studies show that older adults with gait alterations have an increased risk of developing cognitive deficits [7]. Importantly, gait and cognitive impairments are

---

* Corresponding author.
E-mail address: francesca.lunardini@polimi.it (F. Lunardini).

https://doi.org/10.1016/j.gaitpost.2021.02.028
Received 7 October 2020; Received in revised form 3 February 2021; Accepted 24 February 2021

both risk factors for falls [6], which may in turn result in a reduction of the individual's quality of life.

Early detection of gait deficits allows the early uncovering not only of fall risk but also of cognitive impairments, giving the chance to implement timely interventions to improve gait and/or to maintain cognition [8]. In this framework, dual-task paradigms (e.g., walking while simultaneously performing a second task) are key to facilitate the detection of even subtle dysfunctions that may remain undetected under a traditional single-task condition. The assumption underlying these paradigms is that each person possesses a maximum capacity of attentional reserves. As more attentional resources are needed for safe walking during dual-task conditions, walking occurs with less automaticity. Resource competition is more pronounced in older adults, as part of their attention is needed to compensate for age-related deficits in muscle strength, sensory inputs or executive functions [8]. The result in seniors is typically slowed walking speed and increased gait variability [9]. Lundin and colleagues [10] showed that 80 % of seniors not able to perform dual-task walking while talking fell at least once in the following six months.

Conventional gait analysis studies are conducted in specific labs through objective and accurate measurements obtained from systems like motion trackers and force platforms. However, elements like the controlled environment and protocol, and the cumbersome apparatus undermine the ecological validity of these studies. A key work about dual-task in ageing highlights the importance of studying ecologically valid dual-task situations to emphasize the study of resource allocation, especially in older adults [11]. To this end, the use of smartphones is becoming more and more popular to monitor gait in everyday life. However, the available mobile apps, which exploit the device embedded sensors (e.g., accelerometer and gyroscope), usually return basic information about walking activities (e.g. the number of steps and the covered distance), which is not accurate enough to detect fine changes in the gait pattern. To overcome the limitations of the state-of-the-art solutions for ecological gait monitoring, recent research has developed unobtrusive solutions for home-based monitoring of gait in older adults, composed by a pair of electronic insoles transferring data to smartphones [12].

Driven by the successful results of such solutions [13], we developed a system encompassing a pair of instrumented insoles and a customized mobile app with the aim of transparently and accurately studying ecological outdoor walking activities in single- and dual-task conditions. The system was developed within the European MoveCare Project [14], specifically targeting older adults at risk of frailty and cognitive decline. To achieve transparent monitoring and minimize user interaction, the mobile app was designed to work in background, with the final aim of boosting users' acceptance, particularly critical in the elder population [15]. The use in combination with instrumented insoles allows obtaining fine and accurate gait parameters. Importantly, the app was designed to exploit the phone registry to automatically label the gait data when the subject is engaged in a phone call; such functionality allows studying walking during single-task or motor-cognitive dual-task modalities.

The current work presents the system together with reliability and usability studies. The system was first tested on 19 older adults during outdoor walking tasks mimicking daily-life, with the aim of testing the reliability of the extracted gait parameters, and of studying the ability of the system to detect the effect of dual-task conditions on both motor (gait) and cognitive domains. To study usability in real-life environment, the mobile app was installed on the smartphone of 5 older adults and was tested over 3 months in uncontrolled conditions.

2. Materials and methods

2.1. *The system*

We devised a novel system composed by a pair of instrumented insoles and a customized mobile application.

2.1.1. *Instrumented insoles*

The FeetMe insoles® were selected: they combine pressure and motion sensors and embed calculation power to allow real time gait parameters assessment. Each insole is instrumented with a 6-axis IMU unit (150 Hz) and 19 pressure sensors (100 Hz). Wireless charging allows charging the battery without removing the insoles from the shoes, thus increasing usability. Wireless communication is achieved through Bluetooth Low Energy (BLE). SDK are provided to allow the development of a customized mobile app. The FeetMe insoles® do not provide sensors raw data, but a series of metrics for each stride. The FeetMe insoles® come with a validation against a gold standard instrumented mat (GAITRite©) [16].

2.1.2. *The mobile app*

We designed and developed an Android-based mobile app running on version 8 or higher. The app was designed to be intuitive and allow easy interaction with the user. The app achieves two main functionalities (Fig. 1):

i) Gait monitoring: FeetMe® APIs were used to achieve pairing, connection, calibration and BLE data streaming from the insoles during walking. The app was designed to activate and deactivate gait recordings in two different modalities: a) manual start and stop; b) automatic GPS-triggered start and stop. The first modality was envisaged for technology-prone users, allowing them to manually start the recording when preferred, without the need to keep GPS and BLE modules always on, thus reducing battery discharge. The second modality was designed to work in background without requiring an interaction with the user: when a specific distance from the user's home is reached and detected through GPS, the app automatically connects to the insoles and starts recording gait data. Likewise, when the user returns towards the home location (GPS), recording is stopped.
ii) Phone registry monitoring: the app stores information about both incoming and outgoing calls (timing and duration), thus allowing labeling the gait data when the subject is engaged in a phone call.

Gait and phone registry measurements are uploaded to the cloud once WiFi connection is detected, to avoid wasting the user's mobile data. Data upload can be done in two modalities: automatically once a day, or manually by pressing a button.

2.2. *Participants and protocol*

2.2.1. *System controlled testing*

The system was devised for a daily-life use, to achieve continuous ecological and accurate monitoring of walking activities. Before deployment of the system, a controlled validation study on potential users was conducted.

The study protocol was approved by the Politecnico di Milano Ethical Committee (n. 04/2018) in compliance with the Declaration of Helsinki, with the following inclusion criteria: i) age ≥65 years old; ii) good perceived health status; iii) no fall in the previous year; iv) lack of neurological, vascular of musculoskeletal pathologies affecting gait.

Subjects were asked to wear a pair of instrumented insoles in their sneakers and keep the mobile phone with the installed app with them. Each subject performed four outdoor walking trials in a quiet space in which they were asked to walk back-and-forth along a 30-meter rectilinear path at their self-selected speed for 3 min. The beginning and the end of the path were marked by two small obstacles to be circumvented. The following trials were executed:

1 3-minute walking test Single Task trial 1 (3MWT-ST1)
2 3-minute walking test Single Task trial 2 (3MWT-ST2)
3 3-minute walking test Ecological Dual Task (3MWT-DTEco)
4 3-minute walking test Motor Cognitive Dual Task (3MWT-DTCog)

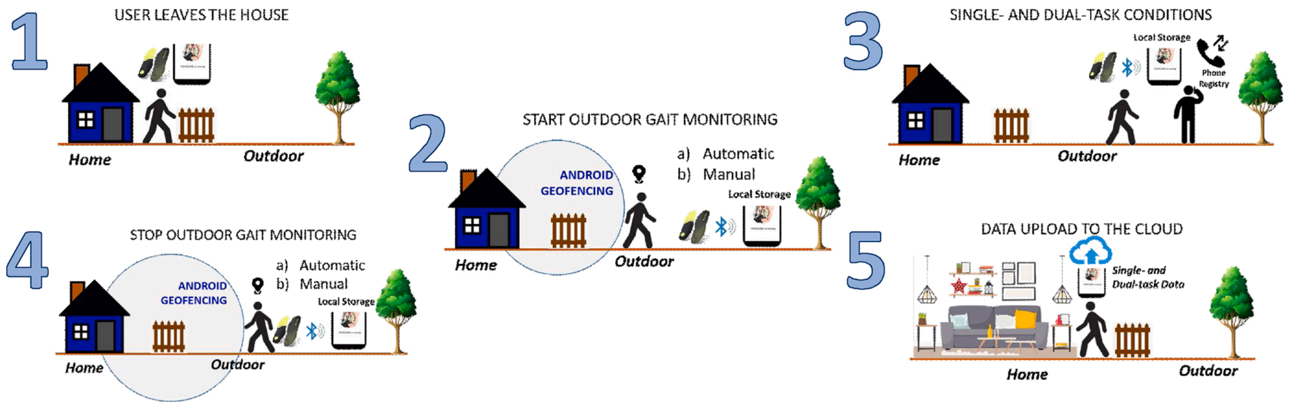

Fig. 1. Mobile App functioning. 1: The user leaves the house with the smartphone and wearing the insoles. 2: When a specific distance from the user's home is reached and detected through GPS, the app automatically connects to the insoles and starts recording gait data; otherwise, manual start can be used. 3: The app stores gait indicators and information recorded from the phone registry. 4: When the user returns towards the home location (detected through GPS), recording is stopped; otherwise, manual stop can be used. 5: Gait and phone registry measurements are uploaded to the cloud once WiFi connection is detected; otherwise, manual upload can be triggered.

In 3MWT-ST1 and 3MWT-ST2, subjects performed the 3MWT twice to verify whether the obtained indicators are representative and stable over time. In 3MWT-DTEco, subjects performed the 3MWT while engaged in a simple phone call; in 3MWT-DTCog, subjects performed the 3MWT while engaged in a cognitive demanding phone call in which they were asked to respond to the following requests in a specific time: count from 1 to 50 while discarding the multiples of 3 (4 s); subtract 7 from 100 and keep subtracting 7 from the result till reaching 30 (45 s); list the names of a specific category (e.g.: animals, cities) starting with a specific letter (45 s); repeat the 3 objects named by the examiner at the beginning of the trial (15 s); backward spell a word (20 s).

In a fifth trial, subjects were asked to respond to the same requests while simply seating at a table:

5 Cognitive Single Task (STCog)

The order of the five trials was randomized and at least 1 min of break was given between trials.

For the experimental protocol, data recording from the app was initiated manually.

2.2.2. System usability in everyday life

The system was developed within the European MoveCare Project [14], a modular platform that leverages a net of heterogeneous sensors to achieve ecological monitoring of frailty through quantitative measurements transparently recorded during different daily-life activities. The gait monitoring app was tested, during the project pilot, on senior participants willing to try it.

The pilot study was approved by the Junta de Extremadura and the Policlinico di Milano (127_2018bis) Ethical Committees. The following inclusion criteria were defined: age $\geq$ 65; ii) living alone; iii) Mini-Mental State Examination [17] (MMSE) $\geq$ 26; iv) pre-frailty (Fried Scale [6] = 1–2) or non-frailty (Fried Scale = 0) individuals. During the Movecare system deployment, an operator instructed participants about the use of the devised outdoor gait monitoring system and the maintenance of the instrumented insoles. At the end of the 3-month pilot study, participants were asked to fill out a usability questionnaire, which included 5-point Likert scale questions related to the outdoor gait monitoring app (Table 1).

2.3. Data analysis and statistics

2.3.1. System controlled testing

For each walking condition, we pre-processed the parameters provided by the FeetMe insoles® to obtain the mean (*M*) over the trial of the following gait indicators: *Gait Cycle*, *Step Time*, *Single-Support Time*, *Double-Support Time*, *Stance Time*, *Stance Percentage*, *Swing Time*, *Swing Percentage*. In addition, for the same indicators, to investigate gait variability, we computed the coefficient of variation (*CV*). Finally, for each trial, the *Cadence* was retained.

Table 1
System Usability Results. For each 5-point Likert scale question (1: totally disagree; 5: totally agree), we report the answers of the 5 senior participants to the Movecare pilot, together with their age.

Question	User 1 (75 yo)	User 2 (79 yo)	User 3 (85 yo)	User 4 (68 yo)	User 5 (80 yo)
1. I felt at ease when using the mobile app	4	1	5	5	5
2. I found it easy to charge the insoles	5	2	5	5	5
3. I think the insoles were comfortable	5	1	5	3	5
4. I think tracking outdoor gait through insoles and mobile app is useful	5	–	5	5	3
5. If I have the possibility, I would use the smart insoles in the future	5	4	4	5	5

For the cognitive test, we calculated overall indicators of the total number of errors (*Error*), the total number of correct answers (*Correct*), and the overall score (*Score*), computed by subtracting *Error* from *Correct*.

Statistical analysis (RStudio version 1.3.1056; significance at 5 %) was conducted with multiple aims:

- To investigate the relative reliability of the gait parameters extracted using our system during outdoor walking activities: first, we verified the gaussian distribution of the mean gait indicators (Lilliefors test). A one-way repeated measures ANOVA was used to compare the gait indicators extracted during 3MWT-ST1 and 3MWT-ST2 to ensure the absence of systematic error [18]. The relative reliability between the two single-task trials was assessed computing the Intraclass Correlation Coefficients (ICC 2-way mixed-effects model, absolute agreement). ICC values of 0.5, 0.75, and 0.9 indicate moderate, good and excellent reliability, respectively [19].
- To investigate whether the devised system is suitable for extracting parameters of gait able to discriminate between different walking conditions: between-condition (3MWT-ST1, 3MWT-ST2, 3MWT-DTEco, 3MWT-DTCog) differences in gait parameters were

investigated with the Friedman test and, in case of significance, post-hoc multiple comparisons were conducted with the Wilcoxon signed-rank test with Bonferroni adjustment. Nonparametric statistics were adopted after verifying that not all indicators were normally-distributed (Lilliefors test).
- To conduct a complete cognitive-motor dual-task study [11], we investigated the performance changes also in the cognitive domain: between-condition differences were investigated by comparing the results of the cognitive test (*Error*, *Correct*, *Score*) in the 3MWT-DTCog and STCog conditions with the Wilcoxon signed-rank test.

3. Results

3.1. System controlled testing

This section presents the results from 19 recruited seniors (age: 74.53 ± 7.28 years old). To validate test-retest reliability of the extracted parameters, a sample size of at least 10 subjects was estimated considering an ICC of 0.7 [16], a statistical power of 80 %, with a 5 % significance [20].

3.1.1. Relative reliability of the mean gait parameters

Results of the relative reliability of the gait parameters are presented in Table 2. The analysis on all parameters revealed the absence of systematic error and a significant excellent to good relative reliability between the two single-task walking trials.

3.1.2. Between-condition differences in gait parameters

The results investigating between-condition differences in gait parameters are presented in Table 3.

3.1.3. Between-condition differences in cognitive test

As for the cognitive tasks, differences between the single and dual-task conditions were found for the *Correct* [3MWT-DTCog: median 28 (IQR 14.5); STCog: 37 (20); p-value = 0.006] and the *Score* [3MWT-DTCog: 25 (17); STCog: 32 (22.5); p-value = 0.004] parameters.

3.2. System usability in everyday life

Feedback about system usability were collected from 5 senior participants (age: 77.4 ± 6.35 years old) to the Movecare Project pilot study. Results are summarized in Table 1.

Table 2

Relative Reliability results on 19 older adults. For each gait indicator, we report: the p-value of the one-way repeated measures ANOVA (p-value > 0.05 indicates absence of systematic error); the p-value of the relative reliability (p-value < 0.05 indicates significance) and the related ICC (0.9-1: excellent, 0.75-0.9: good, 0.5-0.75: moderate, < 0.5: poor reliability), with confidence intervals expressed as lower and upper bounds.

Gait Indicator	Systematic Error ANOVA p-value	Relative Reliability on 19 subjects	
		p-value	ICC (lower bound-upper bound)
Cadence	0.638	<0.001	0.932 (0.822–0.974)
Gait Cycle M	0.633	<0.001	0.934 (0.824–0.975)
Step Time M	0.648	<0.001	0.934 (0.829–0.975)
Single-Support Time M	0.488	<0.001	0.898 (0.712–0.962)
Double-Support Time M	0.862	<0.001	0.960 (0.901–0.984)
Stance Time M	0.709	<0.001	0.944 (0.859–0.978)
Stance Percentage M	0.874	<0.001	0.936 (0.844–0.975)
Swing Time M	0.488	<0.001	0.898 (0.712–0.962)
Swing Percentage M	0.874	<0.001	0.936 (0.844–0.975)

4. Discussion

We devised and developed a novel system consisting of a pair of instrumented insoles and a customized mobile app to achieve accurate and at the same time ecological monitoring of daily-life walking activities, with the final aim of detecting early and subtle age-related alterations of gait. Achieving monitoring of everyday activities to detect early signs of age-related decline is nontrivial and presents two main challenges: the ability to detect subtle yet relevant changes, and the users' low acceptance of the system intrusiveness. To face the first challenge, we leverage dual-task test paradigms, which are known to be more sensitive for detecting impairment than single-task conditions [8]. To do so, the key feature of this system is the ability to automatically distinguish gait parameters extracted during single-task walking from those computed while the user is engaged in a phone call. To face the second challenge, the app was devised for non-expert users: it works in background, and automatically manages start/stop recording and data upload to the cloud, thus maximizing transparency and ease of use.

Controlled testing of the devised system on 19 older adults was conducted during outdoor walking tasks mimicking daily-life, with the aim of testing the relative reliability of the extracted gait parameters, and of studying the ability of the devised system to detect the effect of dual-task conditions on both motor (gait) and cognitive domains. As for reliability, we obtained successful results, with almost all parameters showing excellent reliability.

As for the second aim, most of the gait parameters extracted with our system showed a clear effect of both dual-task conditions, compared to single-task walking. Indeed, independently from the cognitive task demand, the fact of being engaged in a phone call while walking modifies the gait pattern of our subjects, resulting in increased gait cycle and step time durations, and consequent reduced cadence, confirming previous work on both young [21,22] and older healthy adults [9]. Importantly, our results suggest that the gait cycle was not just increased in duration, but that the proportion between stance and swing percentage was significantly modified: while the swing time duration was kept constant, the stance phase was increased due to a prolonged double-support aimed at enhancing gait stability during dual-task walking. Although significant, the alteration of the proportion between stance and swing phases does not reach the levels found in pathological conditions, such as Parkinson's disease (PD) [23] and Huntington's disease [24]. Previous studies on dual-task walking in ageing reported an enhanced gait variability [9]; this is true also for our work, however the variability of the gait cycle and the stance durations increased only for the most demanding dual-task condition, similarly to what was reported on young healthy adults [22].

Although the daily-life use of the system does not allow investigating performance changes in the cognitive domain, we leveraged this supervised experimental session to investigate the effect of dual tasking on the cognitive test outcome. Our results, which report a decreased cognitive performance during dual-task, show how dual tasking in older adults has an effect on both motor and cognitive domains, causing a decreased performance for both.

Controlled testing was followed by a 3-month field-testing of the system in daily-life during the MoveCare Project [14] pilot. Usability feedback collected from 5 older adults show excellent results for almost all users, who reported to understand the usefulness of the devised system and to feel at ease when using the system and the insoles.

The devised app, which allows studying ecological single- and dual-task walking in a transparent and user-friendly way, was specifically envisaged for older adults at risk of frailty and cognitive decline. However, for its ease-of-use and its ability to investigate dual-task paradigms, the system has potential fruitful applications in diverse target populations, particularly in the field of neurological diseases affecting gait (e.g. PD [23] and Huntington's disease [24]).

Our system is envisaged for outdoor use; however, a large portion of seniors spend most of their time at home. Future work should focus on

Table 3
Results of the between-condition analysis of gait parameters on 19 older adults. For each gait indicator, we report: median and interquartile range (IQR) for each walking condition; p-value of the Friedman (p-value < 0.05 indicates significance and is highlighted in bold); significant p-values of the pairwise comparisons adjusted with Bonferroni (p-value < 0.05 indicates significance). None of the indicators reported significant differences between 3MWT-ST1 and 3MWT-ST2, or between 3MWT-DTEco and 3MWT-DTCog and for this reason, comparison is not reported in the table.

Gait Indicator	Median (IQR) on 19 subjects				p-values			
	Trials				Friedman Test	Pairwise Comparison		
	3MWT-ST1	3MWT-ST2	3MWT-DTEco	3MWT-DTCog		3MWT-ST1	3MWT-ST2	
Cadence [steps/minute]	112.36 (10.41)	114.50 (12.62)	109.16 (14.13)	108.14 (15.76)	0.003		0.007	3MWT-DTEco
							<0.001	3MWT-DTCog
Gait Cycle M [seconds]	1.063 (0.091)	1.044 (0.115)	1.107 (0.135)	1.118 (0.162)	0.001		0.003	3MWT-DTEco
							<0.001	3MWT-DTCog
Gait Cycle CV	0.055 (0.030)	0.057 (0.030)	0.064 (0.022)	0.074 (0.044)	<0.001			3MWT-DTEco
						0.042	0.005	3MWT-DTCog
Step Time M [seconds]	0.531 (0.045)	0.522 (0.057)	0.554 (0.068)	0.559 (0.081)	0.001		0.005	3MWT-DTEco
							<0.001	3MWT-DTCog
Step Time CV	0.096 (0.030)	0.106 (0.047)	0.109 (0.108)	0.121 (0.110)	0.822			3MWT-DTEco
								3MWT-DTCog
Single-Support Time M [seconds]	0.395 (0.039)	0.389 (0.037)	0.403 (0.032)	0.405 (0.046)	0.281			3MWT-DTEco
								3MWT-DTCog
Single-Support Time CV	0.082 (0.021)	0.072 (0.023)	0.080 (0.026)	0.085 (0.043)	0.588			3MWT-DTEco
								3MWT-DTCog
Double-Support Time M [seconds]	0.272 (0.049)	0.273 (0.074)	0.301 (0.050)	0.311 (0.072)	<0.001	<0.001	0.003	3MWT-DTEco
						0.001	<0.001	3MWT-DTCog
Double-Support Time CV	0.181 (0.047)	0.180 (0.035)	0.187 (0.078)	0.200 (0.110)	0.055			3MWT-DTEco
								3MWT-DTCog
Stance Time M [seconds]	0.653 (0.061)	0.655 (0.090)	0.705 (0.096)	0.706 (0.109)	<0.001	0.024	0.004	3MWT-DTEco
						0.020	<0.001	3MWT-DTCog
Stance Time CV	0.070 (0.028)	0.074 (0.036)	0.091 (0.037)	0.093 (0.056)	0.003			3MWT-DTEco
						0.043	0.010	3MWT-DTCog
Stance Percentage M [seconds]	0.630 (0.015)	0.634 (0.021)	0.637 (0.017)	0.641 (0.024)	<0.001	<0.001	0.004	3MWT-DTEco
						<0.001	<0.001	3MWT-DTCog
Stance Percentage CV	0.037 (0.012)	0.038 (0.011)	0.036 (0.010)	0.040 (0.012)	0.195			3MWT-DTEco
								3MWT-DTCog
Swing Time M [seconds]	0.395 (00.039)	0.389 (0.037)	0.403 (0.032)	0.405 (0.046)	0.281			3MWT-DTEco
								3MWT-DTCog
Swing Time CV	0.082 (0.021)	0.072 (0.023)	0.081 (0.026)	0.085 (0.043)	0.588			3MWT-DTEco
								3MWT-DTCog
Swing Percentage M	0.370 (0.015)	0.366 (0.021)	0.363 (0.017)	0.359 (0.024)	<0.001	<0.001	0.004	3MWT-DTEco
						<0.001	<0.001	3MWT-DTCog
Swing Percentage CV	0.061 (0.019)	0.063 (0.021)	0.064 (0.015)	0.072 (0.025)	0.022			3MWT-DTEco
								3MWT-DTCog

optimizing the proposed solution for home-based use.

To conclude, we believe that the successful results presented in the current work represent a promising achievement that paves the way toward fruitful applications of the devised system to achieve accurate and ecological monitoring of daily-life walking activities, with the final aim of detecting early and/or subtle yet relevant alterations of gait.

Funding

This work was supported by the European MoveCare Project (H2020, GA no. 732158).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] World Health Organization. Ageing and life course. Ten facts on ageing and the life course, (n.d.). http://www.who.int/features/factfiles/ageing/ageing_facts/en/index.html (Accessed December 15, 2014).

[2] S. Polinder, W. Meerding, M.V. van Baar, H. Toet, S. Mulder, E.V. van Beeck, Cost estimation of injury-related hospital admissions in 10 European countries, J. Trauma 59 (6) (2005) 1281–1283.

[3] World Health Organization, Dementia: a public health priority, Dementia (2012) 112, https://doi.org/978 92 4 156445 8.

[4] N. Samaras, T. Chevalley, D. Samaras, G. Gold, Older patients in the emergency department: a review, Ann. Emerg. Med. 56 (2010) 261–269, https://doi.org/10.1016/j.annemergmed.2010.04.015.

[5] W. Pirker, R. Katzenschlager, Gait disorders in adults and the elderly: a clinical guide, Wien. Klin. Wochenschr. 129 (2017) 81–95, https://doi.org/10.1007/s00508-016-1096-4.

[6] L.P. Fried, C.M. Tangen, J. Walston, A.B. Newman, C. Hirsch, J. Gottdiener, T. Seeman, R. Tracy, W.J. Kop, G. Burke, M.A. McBurnie, Cardiovascular Health Study Collaborative Research Group, Frailty in older adults: evidence for a phenotype, J. Gerontol. A. Biol. Sci. Med. Sci. 56 (2001) M146–56 (Accessed March 24, 2017), http://www.ncbi.nlm.nih.gov/pubmed/11253156.

[7] J. Verghese, C. Wang, R.B. Lipton, R. Holtzer, X. Xue, Quantitative gait dysfunction and risk of cognitive decline and dementia, J. Neurol. Neurosurg. Psychiatry 78 (2007) 929–935, https://doi.org/10.1136/jnnp.2006.106914.

[8] S.A. Bridenbaugh, R.W. Kressig, Motor cognitive dual tasking Early detection of gait impairment, fall risk and cognitive decline, Z. Gerontol. Geriatr. 48 (2015) 15–21, https://doi.org/10.1007/s00391-014-0845-0.

[9] J.M. Hausdorff, A. Schweiger, T. Herman, G. Yogev-Seligmann, N. Giladi, Dual-task decrements in gait: contributing factors among healthy older adults, J. Gerontol. A. Biol. Sci. Med. Sci. 63 (2008) 1335–1343, https://doi.org/10.1093/gerona/63.12.1335.

[10] L. Lundin-olsson, L. Nyberg, Y. Gustafson, D. Himbert, P. Seknadji, D. Karila-cohen, "Stops walking when talking" as a predictor of falls in elderly people, Lancet 349 (1997) 617, https://doi.org/S0140-6736(97)24009-2 [pii]\r10.1016/S0140-6736(97)24009-2.

[11] K.Z.H. Li, R.T. Krampe, A. Bondar, An ecological approach to studying aging and dual-task performance, Cogn. Limitations Aging Psychopathol. (2005) 190–218, https://doi.org/10.1017/CBO9780511720413.009.

[12] M. Di Rosa, J.M. Hausdorff, V. Stara, L. Rossi, L. Glynn, M. Casey, S. Burkard, A. Cherubini, Concurrent validation of an index to estimate fall risk in community dwelling seniors through a wireless sensor insole system: a pilot study, Gait Posture 55 (2017) 6–11, https://doi.org/10.1016/j.gaitpost.2017.03.037.

[13] V. Stara, R. Harte, M. Di Rosa, L. Glynn, M. Casey, P. Hayes, L. Rossi, A. Mirelman, P.M.A. Baker, L.R. Quinlan, G. ÓLaighin, Does culture affect usability? A trans-European usability and user experience assessment of a falls-risk connected health system following a user-centred design methodology carried out in a single

European country, Maturitas 114 (2018) 22–26, https://doi.org/10.1016/j.maturitas.2018.05.002.

[14] F. Lunardini, M. Luperto, M. Romeo, J. Renoux, N. Basilico, A. Krpic, N. Borghese, S. Ferrante, The MOVECARE Project: home-based monitoring of frailty, IEEE EMBS Int. Conf. Biomed. Heal. Informatics (2019).

[15] B. Klimova, P. Poulova, Older people and technology acceptance, in: J. Zhou, G. Salvendy (Eds.), Hum. Asp. IT Aged Popul. Accept. Commun. Particip., Springer International Publishing, Cham, 2018, pp. 85–94.

[16] L. Farid, D. Jacobs, J. Do Santos, O. Simon, J.-M. Gracies, E. Hutin, FeetMe® Monitor-connected insoles are a valid and reliable alternative for the evaluation of gait speed after stroke, Top. Stroke Rehabil. 0 (2020) 1–8, https://doi.org/10.1080/10749357.2020.1792717.

[17] M.F. Folstein, S.E. Folstein, P.R. McHugh, Mini-mental state": a practical method for grading the cognitive state of patients for the clinician, J. Psychiatry Res. 12 (1975) 189–198, https://doi.org/10.1016/0022-3956(75)90026-6.

[18] G. Atkinson, A.M. Nevill, Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine, Sports Med. 26 (1998) 217–238 (Accessed May 30, 2018), http://www.ncbi.nlm.nih.gov/pubmed/9820922.

[19] T.K. Koo, M.Y. Li, A guideline of selecting and reporting intraclass correlation coefficients for reliability research, J. Chiropr. Med. 15 (2016) 155–163, https://doi.org/10.1016/j.jcm.2016.02.012.

[20] M.A. Bujang, N. Baharum, A simplified guide to determination of sample size requirements for estimating the value of intraclass correlation coefficient: a review, Arch. Orofac. Sci. 12 (2017) 1–11.

[21] S. Jeon, C. Kim, S. Song, G. Lee, Changes in gait pattern during multitask using smartphones, Work 53 (2016) 241–247, https://doi.org/10.3233/WOR-152115.

[22] C. Caramia, I. Bernabucci, C. D'Anna, C. De Marchis, M. Schmid, Gait parameters are differently affected by concurrent smartphone-based activities with scaled levels of cognitive effort, PLoS One 12 (2017) 1–13, https://doi.org/10.1371/journal.pone.0185825.

[23] A. Peppe, C. Chiavalon, P. Pasqualetti, D. Crovato, C. Caltagirone, Does gait analysis quantify motor rehabilitation efficacy in Parkinson's disease patients? Gait Posture 26 (2007) 452–462, https://doi.org/10.1016/j.gaitpost.2006.11.207.

[24] N.C. Reynolds, J.B. Myklebust, T.E. Prieto, B.M. Myklebust, Analysis of gait abnormalities in huntington disease, Arch. Phys. Med. Rehabil. 80 (1999) 59–65, https://doi.org/10.1016/S0003-9993(99)90308-8.