

Article

Validity of a Smart-Glasses-Based Step-Count Measure during Simulated Free-Living Conditions

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Abstract: Step counting represents a valuable approach to monitor the amount of daily physical activity. The feet, wrist and trunk have been demonstrated as the ideal locations to automatically detect the number of steps through body-worn devices (i.e., step counters). Key features of such devices are high usability, practicality and unobtrusiveness. Therefore, the opportunity to integrate step-counting functions in daily worn accessories represents one of the recent and most important challenges. In this context, the present study aimed to investigate the validity of a smart-glasses-based step-counter measure by comparing their performances against the most popular commercial step counters. To this purpose, smart glasses data from 26 healthy subjects performing simulated free-living walking conditions along a predefined path were collected. Reference measures from inertial sensors mounted on the subjects' ankles and data from commercial (waist- and wrists-worn) step counters were acquired during the tests. The results showed an overall percentage error of 1%. In conclusion, the proposed smart glasses could be considered an accurate step counter, showing performances comparable to the most common commercial step counters.

Keywords: smart glasses; inertial sensors; step counter

1. Introduction

Monitoring daily physical activity (PA) is a key aspect in the evaluation of people's quality of life. The absence of PA has been identified as the fourth leading risk factor for global mortality, and its levels are rising in many countries, with major implications for the prevalence of non-communicable diseases, i.e., cardiovascular and chronic respiratory disorders, diabetes and cancers [1]. The amount of PA in daily life represents an important risk predictor for hospital readmission and mortality in patients with obstructive pulmonary diseases [2]. Moreover, regular PA contributes to the primary and secondary prevention of several chronic diseases, according to the relation between the volume of PA and the health status [3]. Therefore, there is a strong interest in monitoring daily PA in people of all ages, in order to improve individuals' lifestyles.

Thanks to the recent developments in miniaturized sensing technology, wearable sensors represent a practical and low-cost solution to track human behaviors in free-living conditions [4]. Furthermore, due to their ever-decreasing cost and ease of deployment, wearable sensors are getting a wider acceptance [5]. In recent years, numerous interactive and mobile technology solutions to track daily PA (i.e., devices able to monitor it through a range of sensors) have been proposed, and their adoption is already widespread. The ability of such instruments to continuously store vast amounts of information on small and inexpensive computer chips that can be easily incorporated into daily worn objects has fundamentally changed the field of PA assessment [4,5]. The use of such technology in clinical and epidemiological studies has confirmed the significant relationship between habitual patterns of PA and risks of chronic diseases. The careful use of such devices in tracking daily PA could therefore facilitate

large-scale surveys, allowing epidemiologists to switch from correlating output with indirect indicators of disease to the use of clinical incidents [6], and the potential growth of this technology could even transform the physiology research [7]. Moreover, wearable sensors enabling PA esteem play a central role in remote healthcare-monitoring systems that have attracted the attention of many researchers and entrepreneurs in recent years. Such systems, inclusive of a variety of specific wearable sensors, help to monitor people at their home rather than in healthcare facilities, representing a reassuring and comfortable solution and, simultaneously, an efficient and cost-effective alternative to on-site clinical monitoring for the clinicians and the healthcare institutions [8].

The most suitable instruments to monitor daily PA are represented by activity trackers, and one of the favorite metrics for quantifying daily PA is the number of steps. A step is defined as “a movement made by lifting the foot and putting it down in a different place”, and it represents a fundamental unit of locomotion [9]. Starting in the mid-1900s, researchers became interested in using steps to quantify PA, since they are intuitive, easy to measure and objective [10]. Strong associations between steps per day and health variables have been demonstrated in several studies [11–14]. Moreover, in combating sedentary lifestyles, wearable step counters, also called pedometers, could be very useful, and their feedbacks could encourage lazy people or those with limited mobility to perform daily PA. At the same time, feedback from such devices can get the more active people to monitor their training progress, allowing them to reach better results. However, the adoption of such devices is often characterized by a low level of user engagement and early abandonment. The main aspects affecting the cast aside of such technology are its aesthetics, its ease of use, its functionality, its practicality and the accuracy perceived by the user [15].

Step counting is mostly entrusted to accelerometers embedded within wristbands, bracelets and belts [16–23] which wirelessly send data to a mobile computing device that can use the signals to recognize the number of steps performed. The most common wearable step counters can be divided into five categories, based on their placement: (a) waist, (b) pocket, (c) thigh, (d) ankles/foot and (e) wrist. Each location shows weak points: Waist-worn step counters, for instance, underestimate the number of steps in case of slow walking speed and obesity. The same behavior characterizes the devices carried in the pocket. Step counters placed on thigh and/or ankles may overestimate the number of steps in free-living conditions when bicycling, leg swinging and heel tapping. Finally, the most common wrist-worn devices show some limitations: In a free-living environment, they can record extra steps because of extraneous arm movements. Indeed, they usually register invalid steps when folding laundry or gesturing while talking [10]. Therefore, it is possible to conclude that the accuracy of step counters is strictly dependent on the device location, and, as demonstrated in [10], higher accuracies are achieved with waist-worn and ankles/foot-worn mounted devices.

An interesting alternative to wrist- or foot-worn devices allowing the integration of step-counting functions in daily worn accessories (such as glasses or a headset) is represented by head-worn devices [24–26]. With the advent of wearable technologies and the internet, the eyeglasses sector is going to undertake another turning point that will further reshape the concept of eyeglasses, providing to the customer a new viewing and living eyewear experience, combining traditional features with a plethora of new digital services and interaction touchpoints with customers, opticians, the environment and other devices. Small wearable sensors can be easily mounted on the frame of eyeglasses, to ensure a continuous monitoring of real-life parameters (e.g., eyeglasses wearers' activity), thus enabling multiple applications that will ultimately improve the eyewear users' healthcare and well-being. Smart glasses (i.e., eyewear equipped with sensors) with a step-counting functionality can offer significant advantages over other body placements, e.g., they would become a totally unobtrusive and practical everyday step counter when prescription lenses are required. Moreover, the way in which eyeglasses are worn is less reliant on the normal use of accessories, if compared with sensors embedded within bracelets or watches, and the users' ease to strictly replicate the predefined placement of the device is very helpful in ensuring a proper working of the device.

In such a context, the current study aims to propose and validate the step-counting measure provided by a smart glasses prototype, i.e., Essilor Connected (EC) glasses (a sensor-equipped frame of glasses produced by Essilor International S.A.), by comparing their performances against reference values obtained by commercially available and research-based devices.

In fact, due to the potentiality of step counters to measure activity and provide valuable information related to the user's quality of life, their accuracy needs to be known and evaluated. To this purpose, in previous studies [24,27–30], participants were asked to walk along an over-the-ground straight path for a fixed duration (e.g., 2 or 6 min), while the number of steps performed was recorded by a trained researcher, using a visual observation (directly or by means of video-registration) and a hand-tally counting device [24,28,29]. In other studies, a reference device (a wrist-worn step counter in Reference [27] and foot-switches in Reference [30]) was used to obtain the actual number of steps performed. Other studies [30–33], in order to deeply explore the potentiality of the step counter under test, have examined bouts of activities of daily living or leisure time in a predefined path (including stairs, turning, jogging, walking among obstacles and walking at slow, comfortable speed and fast speed). The reference value of the number of steps performed by each participant was obtained in such studies through manual counting [32,33] or gold-standard systems (inertial sensors in Reference [31] and foot-switches in Reference [30]). Lastly, studies [34–37] investigated the validity of step counters in free-living condition, with observation periods of 8 to 24 h, for a week, using an ActiGraph as reference, while only two studies [38,39] analyzed bouts of continuous treadmill walking at different speeds.

The objective of the present study is therefore twofold: (1) to validate the EC glasses in terms of number of steps counted against gold-standard measures in real-life contexts; (2) to compare EC glasses' performances in terms of number of steps counted with the most reliable step counters available on the market, worn on the waist and on the wrist, in real-life contexts. The validation of the EC glasses against gold-standard measures and the comparison of their performance with other commercially available step counters were carried out in out-lab controlled conditions, with healthy subjects, under the supervision of qualified researchers.

2. Materials and Methods

2.1. Essilor Connected Glasses Prototype

The EC glasses consist of a sensorized frame of glasses (Essilor International S.A., Prais, France) embedding a magneto-inertial measurement unit (Bosch Sensortec GmbH, Reutlingen, Germany), a UV sensor (Vishay Intertechnology, Inc., Malvern, PA, USA), a rechargeable battery and a Bluetooth module inside the left temple (weight: 26 gr, size: 13.5 × 3.5 × 14 cm). The Bluetooth antenna allows the transmission of the acquired data to a dedicated mobile app (i.e., Zero mApp, Essilor International S.A., Prais, France) compatible with both Android and iOS environment. The Zero mApp analyzes the sensors' data, to provide, in real time, the number of steps. The EC glasses, the Zero mApp and the EC glasses worn by a subject are represented in Figure 1a–c, respectively.

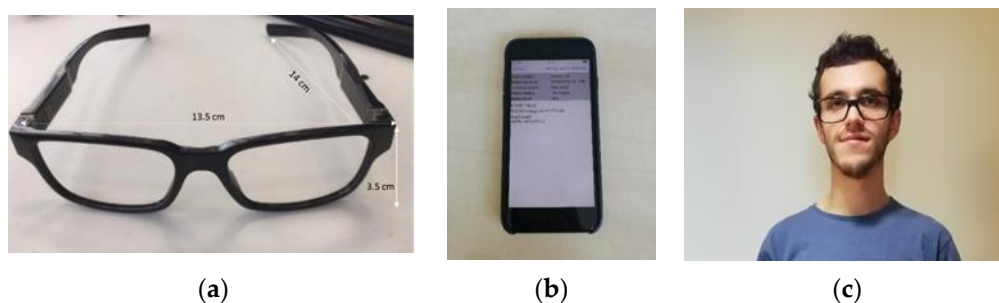


Figure 1. (a) Essilor Connected (EC) glasses, (b) Zero mApp on iPhone 8 and (c) subject wearing EC glasses.

2.2. Equipment

The number of steps counted by EC glasses was acquired through the Zero mApp installed on an iPhone 8. The following devices were used as gold-standard and comparison tools:

1. Two inertial measurement units (Shimmer3 IMUs, Shimmer Sensing, Dublin, $f_s = 128$ Hz): commercially available motion sensors ($f_s = 128$ Hz) worn at the ankles and used as gold standard (Figure 2a);
2. Waist-worn step counter (Fitbit zip, Fitbit, San Francisco, CA, USA): a commercially available step counter used as comparison tool (Figure 2b);
3. Wrist-worn step counter (Fitbit Alta, Fitbit, San Francisco, CA, USA): commercially available step counter used as comparison tool (Figure 2c);
4. Wrist-worn step counter (Garmin vivo smart HR, Garmin, Olathe, KS, USA): commercially available step counter used as comparison tool (Figure 2d).



Figure 2. Technological devices used as gold-standard and comparison tools: (a) Shimmer3 IMUs, (b) Fitbit zip, (c) Fitbit Alta and (d) Garmin vivo smart HR.

2.3. Sample Population

Subjects were recruited at San Raffaele Hospital, including all the workers, students and any other person who could be in contact with them. The following exclusion criteria were considered: (a) age < 18 years old.; (b) refusal to sign the informed consent; and (c) presence of any pathology, health disorder (neuro-motor disorders, etc.) or condition. Being the main objective of the study, the validation of the EC glasses output “number of steps” against gold-standard measure (e.g., accuracy, errors, etc.) in supervised test conditions, the sample size computation for the study was primarily based on scientific literature that proposes validation studies of measures of wearable devices against gold-standard ones. As reported in the scientific literature, the population sample for such type of studies goes from 15 to 50 subjects. However, in the present study, $N = 20$ subjects was considered as the minimum sample size according to Reference [40]: Indeed, it corresponds to twenty degrees of freedom for error in statistical tests and any statistical test that can be said to be robust to violations of normality of the variables. The maximum sample size, instead, was defined as $N = 30$, assuming, according to the literature [24], a standard deviation equal to 2 and a desired total width of confidence interval of 95% between the number of steps obtained by EC glasses and that one collected by gold-standard measures of 1.5. For those reasons, a sample population of between 20 and 30 subjects was considered. Subjects responding to the proper inclusion criteria were contacted and briefly informed about the current study details and scopes, and then they were invited to participate to the study.

2.4. Experimental Procedure

To assess the validity of EC glasses against both gold-standard measures and commercially available step counters, an adequate testing protocol was designed in accordance with the European Union’s Clinical Practice Rules and the current revision of the Helsinki Declaration [41]. In particular,

possible differences in step counting according to walking speed, walking surface, walking type and potential dissimilarity between walking and climbing stairs were addressed.

Subjects were asked to follow a predefined path, including walking activities in different contexts, at the San Raffaele Hospital, in both inside and outside environments (Figure 3a), while wearing the EC glasses, two Shimmer 3 IMUs at the ankles, Fitbit Zip at the waist, Fitbit Alta at the left wrist and Garmin vivo smart HR at the right wrist (Figure 3b).

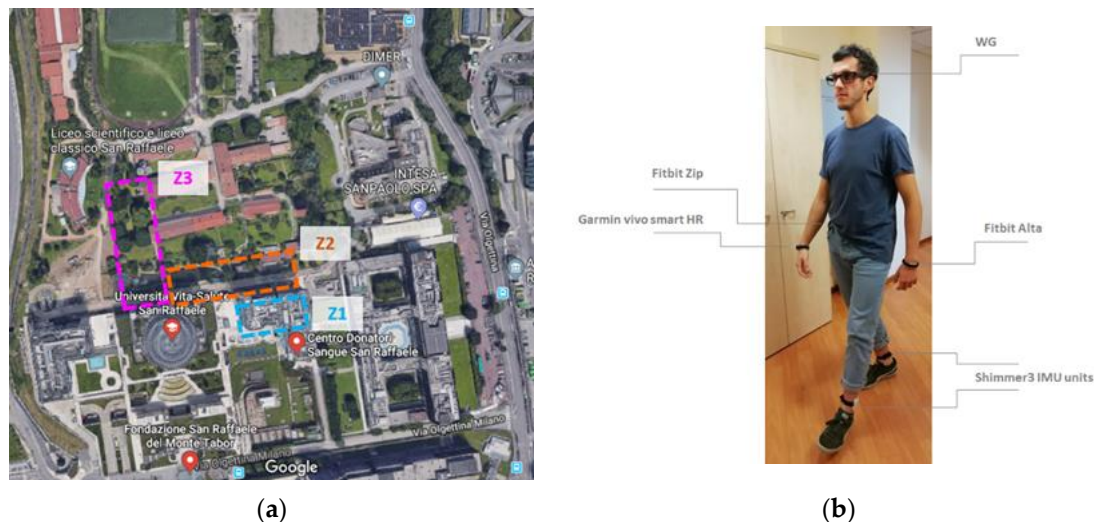


Figure 3. (a) Predefined path at San Raffaele Hospital and (b) the experimental setup.

The predesigned flow of activities is clustered according to the addressed parameters:

- *Walking speed*—The participant was invited to walk on a straight surface, in Z2 (Figure 3a), at a comfortable speed, and the activity was then repeated twice: at a self-selected fast speed and at a self-selected slow speed.
- *Walking surface*—The participant was invited to walk at comfortable speed, in Z3 (Figure 3a), on a sloped surface first and then on a grassy surface.
- *Walking type*—The participant was invited to perform several walking activities: walking while pushing the cart and walking among the people in Z1 (Figure 3a); walking with a bag (twice, both for left and right side) and walking with a phone (twice, both for left and right side), in Z2 (Figure 3a); and walking along a curved path in Z3 (Figure 3a).
- *Climbing stairs*—The participant was invited to go up and down stairs, at a comfortable speed, in Z2 (Figure 3a).

Lastly, participants were invited to freely walk for about 10 min.

The overall test lasted 50 min per subject, and it was completed in one day for each subject.

2.5. Data Analysis

In order to address the specific aims of the study, the following measures were considered:

- Errors between number of steps by EC glasses and number of steps by Shimmer3 IMUs;
- Errors between number of steps by the employed commercial step counters (Fitbit zip, Fitbit Alta and Garmin vivo smart HR) and number of steps by Shimmer3 IMUs.

The differences, in terms of percentage error (E), between the number of steps estimated by each device (s_e) and the relevant reference value (s_r) obtained from ankle mounted IMUs (Shimmer3) by applying a peak detection algorithm to the medio-lateral angular velocity (low-pass filtered at 2 Hz), were calculated as follows:

$$E = \frac{|s_r - s_e|}{s_r} \times 100 \quad (1)$$

3. Results

3.1. Sample Population

Twenty-six healthy subjects among students and workers from San Raffaele Hospital were recruited in the study (Table 1). All participants provided informed written consent edited in accordance to the Declaration of Helsinki [41].

Table 1. Sample population.

Gender	Subjects' Number (#)	Age (Years Old) <i>m(sd)</i>	Weight (kg) <i>m(sd)</i>	Height (m) <i>m(sd)</i>
Male	9	25 ± 4	73 ± 7	1.8 ± 0.1
Female	17	27 ± 8	60 ± 9	1.7 ± 0.1

3.2. Experimental Procedure

According to IMUs data, a total number of 32,579 steps were performed, taking into account all activities provided by testing protocol and performed by every participant. Table 2 shows the overall *E* gained for each device (i.e., Garmin vivo smart HR, Fitbit Alta, Fitbit Zip and EC glasses).

Table 2. Error (*E*) of every investigated step counter.

Overall Steps (Ref.) (#)	<i>E</i> (%)			
	Garmin	Fitbit Alta	Fitbit Zip	EC Glasses
32,579	3	5	1	1

Table 3, instead, reports *E* of devices for each activity performed.

Table 3. *E* of devices for every performed activity.

Activities	Steps (Ref.) (#)	<i>E</i> (%)			
		Garmin	Fitbit Alta	Fitbit Zip	EC Glasses
Comfortable Speed	1812	3	1	1	2
Fast Speed	1636	5	4	2	3
Slow Speed	2003	3	4	2	0
Sloped Surface	5804	0	0	1	1
Grassy Surface	834	8	15	5	3
With bag (left)	1831	2	2	2	1
With bag (right)	2176	5	0	2	2
With phone (left)	1928	0	2	2	1
With phone (right)	1949	5	2	2	1
With cart	1488	100	99	7	11
Curved path	1409	0	0	1	0
Among people	2253	15	18	19	18
Stairs Up	409	4	1	3	6
Stairs Down	367	20	15	8	8
Free Walk	6680	1	2	2	3

4. Discussion

The EC glasses show promising results. Overall, their step-count measure results are accurate, with a percentage error of 1%. Moreover, the experimental procedure was designed to assess EC glasses' step-counting performances in a wide variety of walking activities, by investigating the impact of the following parameters:

- Walking speed*—The step-counting functionality of the EC glasses is not affected by gait velocity, despite some slight fluctuations ($E = 2\%$ at comfortable speed, $E = 3\%$ at fast speed and $E = 0\%$ at slow speed). The lowest error is registered at a slow speed, contrary to the expectations, since step counters at central locations notoriously perform worse in the case of low speed, when compared with usual walking velocity. In that regard, the waist-worn Fitbit Zip presents an increase of 1% of error with respect to walking at a comfortable speed during walking both at slow and fast speeds. The same behavior is shown by the wrist-worn Fitbit Alta that reports an increase of error of 3% at both fast and slow speeds, when compared with the walking at comfortable speed. The wrist-worn Garmin vivo smart HR, instead, differs only at fast speed (+2% than at comfortable speed), by keeping the same error ($E = 3\%$) in walking at a comfortable and slow velocity. Lastly, it is worth emphasizing that participants involved in the study were physically homogeneous and no great disparity among their self-selected velocities was noticed.
- Walking surface*—The step-counting functionality of the EC glasses is not affected by the typology of surface: An increment of the only 1% is observed during walking at grassy surface, while an enhancement of accuracy is even resulted in “sloped surface” when compared with a “comfortable speed” task. Even if all devices preserve good performances when the incline of surface changes, different behaviors occur in the presence of grass. During walking on a grassy surface, Fitbit Zip registers an increase of 4%, Garmin vivo smart HR of 5% and Fitbit Alta an increment of 14%, with respect to the walking at comfortable speed. The grass probably makes the waist accelerations smoother, thus inevitably affecting the detection of steps, while the worsening of the wrist-worn devices is almost surprising, since the oscillating movements of the arms is preserved.
- Walking type*—The step-counting functionality of the EC glasses remained almost stable for most of the tested activities. EC glasses kept very reassuring results during walking with the bag, with the phone, and along a curved path, as well as in the free walk. However, higher errors in walking while pushing a cart and in walking among people are reported (+9% and +16% than the “comfortable speed” task, respectively). The worsening in step counting observed in EC glasses during walking while pushing a cart could be due to a poor compensation of gravity contribution, since the head position usually points downward in such activity. However, the “with cart” and “among people” tasks result critical for the other devices, too. Increments of 6% and 18% of E , when compared with “comfortable speed”, were respectively registered in the tasks performed using the Fitbit Zip. The wrist-worn devices, instead, experience errors comparable with the ones of EC glasses and Fitbit Zip in “among people”, but they totally fail in detecting steps in “with cart” (see Table 3). Such results are in line with what the literature suggests: Indeed, during a walk with the cart, the arms are fixed and they completely miss their oscillating movement typical of the gait. The poorer performances found by all devices in walking among people, instead, are probably due to the varied gait of such a task, which is characterized by successions of quick paths and interruptions while meeting other people, variations in gait cadences and tiny little movements in crowded contexts. Such an issue, however, is not to be considered critical, since the steps failed in those circumstances are not representative of the physical activity performed.

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- *Climbing stairs*—In climbing stairs, the body moves vertically, and it moves horizontally when walking. Fitbit Zip resulted in being the most reliable in step counting while climbing stairs, followed by the EC glasses, although all used step counters report a worsening in the detection of steps in that task when compared with the walking at comfortable speed along a straight path. In particular, going down the stairs represents a very challenging task for Garmin vivo smart HR and Fitbit Alta, where, excluding the “with cart” task, they reach their highest errors (20% and 15%, respectively).

5. Conclusions

To conclude, the EC glasses work properly as a step counter. Their performance is comparable with the one of Fitbit Zip, which benefits from a favorable central location (i.e., the waist) that makes it a notoriously accurate, although sometimes impractical, activity tracker. Moreover, the conditions that are supposed to be problematic for the EC glasses, such as slow gait speed and grassy surface, do not affect EC glasses’ functioning, thus revealing a good reliability and robustness of the prototype. In addition, EC glasses are able to provide a more accurate step counting when compared with the widespread wrist-worn devices in more than one circumstances: in a walk with the cart ($E_{ec} = 11\%$, $E_{ga} = 100\%$, $E_{alta} = 99\%$) or during an excursion in the park while walking on the grass ($E_{ec} = 3\%$, $E_{ga} = 8\%$, $E_{alta} = 15\%$) or, also, during climbing stairs ($E_{ec} = 8\%$, $E_{ga} = 20\%$, $E_{alta} = 15\%$). Thanks to the technology, EC glasses offer an adequate battery (i.e., 24 h of usage), a stable connection with the paired mobile phone and the possibility to integrate the step-counting functionality in an everyday accessory such as prescription eyewear. Such features make EC glasses appealing from a user perspective, as such glasses are a totally practical and unobtrusive step counter. For those reasons, EC glasses represent a valuable tool to monitor and encourage physical activity. It would be, however, interesting to explore their functionality in elderly subjects, since the users involved in the present study, characterized by similar and healthy motor patterns, were limited to young populations as the main target of the worldwide market of activity trackers.

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