Validity of FitBit, Jawbone UP, Nike+ and other wearable devices for level and stair walking

Yangjian Huang, Junkai Xu, Bo Yu, Peter B. Shull *

State Key Laboratory of Mechanical System and Vibration, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

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ABSTRACT

Background: Increased physical activity can provide numerous health benefits. The relationship between physical activity and health assumes reliable activity measurements including step count and distance traveled. This study assessed step count and distance accuracy for Nike+ FuelBand, Jawbone UP 24, Fitbit One, Fitbit Flex, Fitbit Zip, Garmin VivoFit, Yamax CW-701, and Omron HJ-321 during level, upstairs, and downstairs walking in healthy adults.

Methods: Forty subjects walked on flat ground (400 m), upstairs (176 steps), and downstairs (176 steps), and a subset of 10 subjects performed treadmill walking trials to assess the influence of walking speed on accuracy. Activity monitor measured step count and distance values were compared with actual step count (determined from video recordings) and distance to determine accuracy.

Results: For level walking, step count errors in Yamax CW-701, Fitbit Zip, Fitbit One, Omron HJ-321, and Jawbone UP 24 were within 1% and distance errors in Fitbit Zip and Yamax CW-701 were within 5%. Garmin VivoFit and Omron HJ-321 were the most accurate in estimating step count for stairs with errors less than 4%. An important finding is that all activity monitors overestimated distance for stair walking by at least 45%.

Conclusion: In general, there were not accuracy differences among activity monitors for stair walking. Accuracy did not change between moderate and fast walking speeds, though slow walking increased errors for some activity monitors. Nike+ FuelBand was the least accurate step count estimator during all walking tasks. Caution should be taken when interpreting step count and distance estimates for activities involving stairs.

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1. Introduction

The recent flood of wearable activity monitors into commercial markets has enabled unprecedented access to tracking human movement [1]. Increased physical activity can provide numerous cardiorespiratory and musculoskeletal health benefits and can lower the risk of life-threatening diseases [2,3]. Walking 10,000 steps/day is often recommended for healthy adults [4] and walking briskly about 2000 steps/day or more can reduce the risk of chronic diseases and adverse health outcomes [2]. Distance walked is frequently used as an index in tests of physical function such as the 6 min walk test as a health metric [5], and can be used to assess medical outcomes such as for chronic airflow limitation [6], cholesterol reduction to the peripheral arterial [7], and gastric bypass surgery [8]. Accurate step count and distance estimates are vital output metrics to assess human health.

While activity monitors provide an objective measure of physical activity [9], there are varying degrees of accuracy [10,11]. One study performed laboratory testing on a treadmill with Omron HJ-720IT-E2, Omron HJ-113E, and Yamax Digi-Walker SW-200 which resulted in step count errors of 2% or less, while distances were overestimated by up to 20% and underestimated by as much as 15% [12]. Similarly, treadmill testing with Fitbit One reported step count errors of less than 1.3% and distance errors as high as 39.6% [10]. Sportline 345 worn on the belt introduced step count errors of 19.9% during stair ascent, 10.8% during stair descent, and 2.3% during a 400-m walk over flat ground [13]. Another study reported that on average Yamax Digi-Walker DW-800, Lifecorder, and Omron HJ-700IT underestimated step count during stair walking by 8.6%, 16.1%, and 48.8% respectively for stepping rates below 80 steps/min [14].

In contrast with traditional activity monitors, the accuracy of modern wearable activity monitors such as Jawbone UP, Fitbit Zip, Fitbit Flex, and Garmin VivoFit have been studied relatively little.
While it is clear that these monitors can discriminate between some activity and no activity [9], policy makers, doctors, physicians, and physical therapists may lack confidence in prescribing the use of these activity monitors due to the uncertainty of accuracy and reliability. Similarly, users may not trust unverified activity monitors. In addition, though stair climbing provides health benefits such as increasing lower limb muscle power and improving bone density [15,16] and reducing the risk of heart attack [17], validation studies rarely include stair walking.

The purpose of this study was to assess step count and distance accuracy in eight modern wearable activity monitors for walking on flat ground, upstairs, downstairs, and on a treadmill at various speeds. These eight activity monitors were selected because they are widely available, and thus their accuracies for measuring physical activities could significantly impact the general public. To our knowledge, this is the first study to analyze step count and distance accuracy during level walking, stairs walking, and walking at different speeds for Jawbone UP, Fitbit Zip, Fitbit Flex, and Garmin Vivofit.

2. Methods

Forty healthy participants (30M/10F; age: 23.9 ± 2.8 yr; height: 1.72 ± 0.07 m; weight: 63.4 ± 9.7 kg; BMI: 21.4 ± 2.5 kg m⁻²; stride length: 0.69 ± 0.07 m) participated in this study after giving informed consent in accordance with the Declaration of Helsinki. A subset of ten subjects (7M/3F; age: 23.6 ± 2.1 yr; height: 1.69 ± 0.07 m; weight: 60.3 ± 10.8 kg; BMI: 20.9 ± 2.3 kg m⁻²; stride length: 0.65 ± 0.10 m), performed treadmill walking trials for three different walking speeds. To be eligible, individuals had to be older than 18 years, able to walk on flat ground for at least 10 min and up or down stairs for at least 6 min continuously, and have a body mass index (BMI) less than 32 kg m⁻², since BMIs higher than 32 may be a confounding factor influencing activity monitor accuracy [18]. Participants with previous history of injury or disease inhibiting normal gait were excluded.

Eight wearable activity monitors were assessed in this study: Nike+ FuelBand SE, Jawbone UP 24, Fitbit One, Fitbit Flex, Fitbit Zip, Garmin Vivofit, Yamax CW-701, and Omron HJ-321. Participants wore wristband activity monitors Nike+ FuelBand SE, Garmin Vivofit, Fitbit Flex, and Jawbone UP 24 on either wrist (except for Jawbone UP 24 which was required to be worn on the wrist of the non-dominant arm according to manufacture instruction) distal of the triqueter bone. Yamax CW-701, Omron HJ-321, Fitbit One, and Fitbit Zip were placed at the waist per manufacture instructions.

To initialize the wearable activity monitors, participants first self-reported age, gender, height, weight, and dominant hand on a questionnaire. Participants walked 10 steps in a straight line over flat ground and the total distance walked was divided by 10 to give the average stride length for Yamax CW-701, Omron HJ-321, Fitbit One, and Fitbit Zip. For initialization, Yamax CW-701 only required weight, while all other activity monitors required both height and weight. All activity monitors output step counts and output distances to a precision of 0.01 km, except Yamax CW-701 (0.016 km), Omron HJ-321 (0.1 km), and Nike+ FuelBand (no distance output).

For flat ground testing, participants walked at a consistent self-selected speed for 400 m [19] (measured with a measuring tape) in a straight line along a flat, paved road (approx. 5 min). They performed two trials (four activity monitors used on the forward trial and a new set of four different activity monitors used on the return trial) with a 3 min rest between each trial. During each trial, participants wore four activity monitors: one on each wrist and two at the posterior of the waist. Step count and distance values were recorded at the beginning and end of each trial. A study facilitator followed participants and video recorded their steps during each trial.

For stair testing, participants ascended and descended 16 short flights of stairs located inside a building stairwell. They walked at a consistent self-selected pace. Total stair walking time for each trial was less than 2.5 min, which is comparable to other stair climbing validation studies [14], and there were no noticeable changes in stair climbing speed. Each flight contained 11 stairs (height = 15.8 cm, depth = 32.0 cm) for a total of 176 stairs. The stair height and depth were selected to be similar to other stair walking validation studies [14]. Participants first ascended, then rested (3 min), then descended, and this sequence was repeated twice testing four activity monitors on the first sequence and the other four activity monitors on the second sequence. Total stairs walking distance was 0.093 km, and was computed as:

\[
\text{Stairs distance} = \sqrt{\text{strairs depth}^2 + \text{stairs height}^2} \times 176 \text{ stairs} + \pi \times r \times 15 \text{ semicircles}
\]

where \( r \) is defined as the turning radius for each flight of stairs (63.5 cm).

Step count, distance, and video data were collected in the same way as flat ground testing.

For treadmill testing, 10 participants walked on a treadmill (LepowA1680, Shandong, China) at slow, moderate, and fast walking speeds (0.9, 1.33, and 1.78 m/s, respectively) [20]. Subjects performed six total trials wearing four activity monitors for each trial as described above. Each walking trial lasted 3 min [21] with a 3 min rest between each trial. Step count, distance, and video data were collected in the same way as described above.

The actual number of steps taken was determined by observing video recordings offline. An observer counted the number of steps taken from the video on two occasions separated by at least 1 week [22]. Step count values were re-analyzed until consensus was reached for cases of dissimilar count totals. The actual distance for flat ground and stairs walking was measured prior to testing as described above, and the actual distance for treadmill walking was read from treadmill’s display after each trial [10]. Step count and distance errors were calculated as:

\[
\text{Step count error} = \frac{\text{Steps}_{\text{measured}} - \text{Steps}_{\text{actual}}}{\text{Steps}_{\text{actual}}} \times 100\%
\]

and

\[
\text{Distance error} = \frac{\text{Distance}_{\text{measured}} - \text{Distance}_{\text{actual}}}{\text{Distance}_{\text{actual}}} \times 100\%
\]

where \( \text{Steps}_{\text{measured}} \) and \( \text{Distance}_{\text{measured}} \) are the value of steps and distance recorded by activity monitors, \( \text{Steps}_{\text{actual}} \) was the number of steps manually counted from video, and \( \text{Distance}_{\text{actual}} \) was the distance measured prior to testing for flat ground and stairs walking or reading the treadmill’s distance output display. One-way ANOVA was used to determine whether a difference existed between accuracy of activity monitors [11] and whether there was any difference between each activity monitor’s accuracy for different treadmill walking speeds. In cases when ANOVA showed a significant difference, post hoc analysis was performed via Bonferroni tests or, when variances could not be assumed equal, via Games-Howell tests. Bland-Altman plots [23] were constructed to visually display the distribution of step count errors with respect to total distance traveled [11]. We performed a paired \( t \)-test to compare the accuracies of activity monitors during up and down stairs walking. Statistical analyses were conducted via SPSS, and the significance level was \( p = 0.05 \).
3. Results

Yamax CW-701 overestimated step count by 0.2 ± 1.3% (mean ± standard deviation) while Fitbit Zip, Fitbit One, Omron HJ-321, Jawbone UP 24, Garmin Vivofit, Fitbit Flex, and Nike+ FuelBand underestimated step count by 0.1 ± 0.6, 0.1 ± 0.9, 0.2 ± 0.2, 0.8 ± 5.9, 3.9 ± 7.7, 11.7 ± 12.7 and 16.7 ± 16.5%, respectively, during flat ground walking (Fig. 1). Step count accuracies for Nike+ FuelBand and Fitbit Flex were significantly lower than all other activity monitors (p < 0.05). Fitbit Zip, Fitbit One, Omron HJ-321, and Yamax CW-701 did not show any apparent systematic bias based on step count number (supplemental file 1). Conversely, there were trends of systematic bias in Jawbone UP 24 (slope = 0.3, R = 0.20), Garmin Vivofit (slope = 0.4, R = 0.19), Fitbit Flex (slope = 0.8, R = 0.49), and Nike+ FuelBand (slope = 1.1, R = 0.54) showing underestimation for lower step count walked and overestimation for higher step count walked via a positive proportional gain (slope).

Garmin Vivofit and Jawbone UP 24 overestimated distance by 5.1 ± 11.4 and 5.2 ± 9.8%, respectively and Fitbit Zip, Yamax CW-701, Fitbit One, Omron HJ-321, and Fitbit Flex underestimated distance by 4.1 ± 8.1, 4.1 ± 8.1, 5.4 ± 8.6, 6.3 ± 13.6, and 12.8 ± 15.4%, respectively during flat ground walking (Fig. 2). Distance estimates for Garmin Vivofit and Jawbone UP 24 were different from all other activity monitors (p < 0.01) and Fitbit Flex was less accurate than Yamax CW-701 (p = 0.04) and Fitbit Zip (p = 0.04).

All activity monitors underestimated step count while walking upstairs with Fitbit Zip, Garmin Vivofit, Fitbit One, Omron HJ-321, Yamax CW-701, Jawbone UP 24, Fitbit Flex, and Nike+ FuelBand underestimating by 1.1 ± 2.7, 1.4 ± 5.8, 2.3 ± 4.7, 3.9 ± 5.5, 5.7 ± 9.4, 7.7 ± 22.2, 7.9 ± 7.4, and 34.3 ± 26.8%, respectively (Fig. 1). Nike+ FuelBand was less accurate than all other activity monitors (p < 0.01), and Fitbit Flex was less accurate than Fitbit Zip (p < 0.01), Garmin Vivofit (p < 0.01), and Fitbit One (p < 0.01). With the exception of Garmin Vivofit, which overestimated by 1.5 ± 12.3%, all other activity monitors underestimated step count while walking downstairs with Omron HJ-321, Yamax CW-701, Fitbit Zip, Fitbit One, Fitbit Flex, Jawbone UP 24, and Nike+ FuelBand underestimating by 2.5 ± 6.5, 4.3 ± 9.6, 5.3 ± 10.0, 6.0 ± 10.0, 7.1 ± 10.2, 14.3 ± 19.8, and 26.8 ± 18.7%, respectively (Fig. 1). Nike+ FuelBand was less accurate than all other activity monitors (p < 0.01) except Jawbone UP 24 (p > 0.05), whose accuracy was significantly different from Garmin Vivofit (p < 0.01) and Omron HJ-321 (p = 0.02). For walking upstairs and downstairs, all activity monitors showed apparent systematic bias for step count number (supplemental files 2 and 3).

All activity monitors overestimated distance by at least 45% during stair testing. For walking upstairs, average distance error for all activity monitors was 60.0 ± 31.8% with Omron HJ-321 overestimating the least, 48.3 ± 52.9%, and Garmin Vivofit overestimating the most, 83.1 ± 14.8% (Fig. 2). For walking downstairs, the average distance error for all activity monitors was 64.9 ± 35.7% with Omron HJ-321 overestimating the least, 48.3 ± 52.9%, and Garmin Vivofit overestimating the most, 97.6 ± 26.1% (Fig. 2). Garmin Vivofit’s distance accuracy was worse than all other activity monitors for walking upstairs (p < 0.03) and downstairs (p < 0.01). Two activity monitors showed statistically significant differences in step count (Fitbit One (p = 0.01) and Fitbit Zip’s (p < 0.01)) and three activity monitors showed statistically significant differences in distance (Yamax CW-701 (p = 0.02), Garmin Vivofit (p < 0.01), Fitbit Flex’s (p < 0.01)) between accuracies of activity monitors during up and down stairs walking.

Step count and distance accuracy did not change between moderate and fast walking speeds for any activity monitors. Slow walking significantly decreased step count accuracy for Fitbit One and Nike+ FuelBand and significantly decreased distance accuracy for Yamax CW-701, Fitbit Zip, Fitbit One, and Fitbit Flex (Table 1).

Fig. 1. Step count estimation errors averaged across all participants for (top) level walking, (middle) walking up stairs and (bottom) walking down stairs for all eight activity monitors. Errors were computed from the difference between activity monitor step count reading and the manually counted steps from video recordings. Error values were expressed as a percentage of the total steps taken as determined from the video recordings. A circle depicts the mean step count error for each activity monitor and whiskers show the 95% confidence interval of the mean.
monitors for level walking, stairs walking, and treadmill walking at different speeds.

During level walking, Yamax CW-701, Fitbit Zip, Fitbit One, Omron HJ-321, and Jawbone UP 24 were all highly accurate with step count errors of less than 1%. Step count errors for Yamax CW-701 in the present study were comparable to the level walking step count errors of about 3% for Yamax SW-200 [24]. Omron HJ-321’s step count error of 0.2 ± 0.2% in the present study concurs with Omron HJ-720 and HJ-113’s step errors of less than 1.5% [12]. Fitbit One’s step count error was 2.3 ± 4.7% in this study which is similar to another study which reported step count error of less than 1.3% [10] and step count mean absolute percentage error of less than 2.6% reported by Storm et al. [25]. Large underestimations for Nike+ FuelBand in the present study aligns with previous studies, which reported underestimated step counts of 33.9% [22] and 36.4% [25].

In general, walking on stairs caused wearable activity monitors to both underestimate step count and overestimate distance measurements (Figs. 1 and 2). Garmin Vivofit and Omron HJ-321 were the most accurate with step count errors of less than 4% for walking upstairs and downstairs. Findings for step count errors of Yamax CW-701 and Omron HJ-321 in the present study were slightly higher but in general agreement with previous findings [14], which reported step count errors during stair climbing of 1.1 ± 4.3% for Yamax DW-800 and −1.3 ± 3.8% for Omron HJ-700IT. Relative inaccuracy of step count during stair walking compared to level walking may partially be attributed to differences in arm and hip movement mechanics and changing foot strike impact acceleration magnitudes [26].

We initially assumed that distance estimation errors for stair walking would be comparable to errors during walking over level ground but instead found rather extreme differences, with all activity monitors overestimating distance by at least 45%. This may be due to distance algorithms ignoring stride length differences between stair walking (0.32 m) and level ground walking (0.69 m). While algorithms for computing distance are proprietary, it is likely that distance is computed simply by multiplying step count by a stride length value assumed for over ground walking resulting in distance overestimation for stair walking. Since stair climbing is a common daily activity (adult males typically walk an average of 50–150 steps per day [30]) and provides unique health benefits [15,16], accurate step and distance estimation during stair walking may be a critical future design requirement of wearable activity monitors [26].

Nike+ FuelBand was the least accurate activity monitor for measuring steps during all walking tasks and was the only activity monitor evaluated that does not provide distance estimation. Distance estimation algorithms are often directly linked to step count, commonly by a simple scaling factor, and thus it seems likely that the Nike+ FuelBand distance estimation would similarly be quite inaccurate. NikeFuel and comprehensive movement activity estimates from other manufacturers may be useful for motivating activity as compared to no activity, but these measures should be used with caution for estimating precise activity amount or intensity, especially if based on inaccurate step or distance estimates.

Walking speed did not influence activity monitor accuracy except for Yamax CW-701, Fitbit Zip, Fitbit One, Fitbit Flex’s distance output and Fitbit One, Nike+ FuelBand’s step counts. Activity monitors tend to underestimate step counts at slower walking speeds [12,27] which we also observed for Yamax CW-701, Omron HJ-321, Nike+ FuelBand, and Jawbone UP 24 (Table 1). A possible explanation is that lower speeds cause smaller magnitude impact accelerations insufficient to register these movements as steps [28]. In addition, some of activity monitors such as Fitbit Zip, Fitbit One, Fitbit Flex, Omron HJ-321, and Yamax CW-701 overestimated distance at slower speeds and

4. Discussion

The purpose of this study was to compare step count and distance accuracy in eight modern wearable physical activity

Fig. 2. Distance estimation errors averaged across all participants for (top) level walking, (middle) walking up stairs and (bottom) walking down stairs for seven activity monitors. Nike+ FuelBand does not provide distance estimation. Errors were computed from the difference between activity monitor distance reading and the pre-measured trial distance. Error values were expressed as a percentage of the pre-measured trial distance. A circle depicts the mean distance error for each activity monitor and whiskers show the 95% confidence interval of the mean.
underestimated distance at faster speeds which concurs with previous findings for Omron HJ-720 and HJ-113 [12].

Activity monitor cost and performance seem to be unrelated. The two most inexpensive wearable activity monitors, Yamax CW-701 and Omron HJ-321, were two of the top performing activity monitors while more expensive activity monitors showed varying degrees of accuracy. It may be that the addition of smart-phone connectivity, gamification, wearability, and esthetics contribute to higher priced activity monitors despite lower step and distance estimation accuracies.

Previous research has shown that when self-reporting (as done in this study) subjects tend to slightly under-report weight and over-report height, though this tendency is more pronounced in overweight individuals [29,30]. This study is a convenience sample of healthy male college students and thus we did not account for different potential confounding factors such as BMI, wearable monitor placement, and age, which could potentially influence accuracy [19]. Because the proportion of stair walking to flat ground walking is relatively low for the average walker, the importance of stair walking accuracy may be limited for much of the population and most useful for individuals who walk up and down stairs more frequently such as for those who frequently perform stair related exercises. We have not explored the influence of walking in different outdoor terrains, and thus a comprehensive study of activity monitor accuracy under various conditions reflecting typical daily life activities could provide greater confidence in accuracy values.

In conclusion, most activity monitors accurately estimated step count during level ground walking, while walking up and down stairs tended to cause wearable activity monitors to both underestimate step count and overestimate distance measurements. Walking speed did not influence activity monitor accuracy except for Yamax CW-701, Fitbit Zip, Fitbit One, Fitbit Flex’s distance output and Fitbit One, Nike+ FuelBand’s step counts. Nike+ FuelBand was the least accurate activity monitor for measuring steps during all walking conditions. Caution should be taken when interpreting step count and distance estimates for activities involving stairs.

### Conflicts of interest

None of the authors had any professional or financial affiliations that may be perceived to have biased the presentation. The use of trade names in this document is for identification purposes only and does not imply endorsement by the authors.

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### Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gaitpost.2016.04.025.

### References


### Table 1

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<td>Step error (%)</td>
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<td>Fitbit Zip</td>
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<table>
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<th>Distance error (%)</th>
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<td>33.8 ± 33.9</td>
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