International Journal of EXERCISE SCIENCE

Original Research

Congruent Accuracy of Wrist-worn Activity Trackers during Controlled and Free-living Conditions

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ABSTRACT

International Journal of Exercise Science 11(7): 575-584, 2018. To examine activity tracker accuracy for measuring steps, energy expenditure, and heart rate in controlled and free-living conditions. Forty participants performed four, five-minute stages (walking: 53.7 m·min-1, 80.5 m·min-1; running: 134.1 m·min-1, 160.9 m·min-1) while wearing the Fitbit Charge HR (FB) and the Mio FUSE (MF) activity trackers. Measurements included steps, energy expenditure (kcals), and heart rate (beats·min-1). In addition to the FB and MF, participants wore the NL-1000 (NL) activity tracker during waking hours of the subsequent day. One way ANOVAs with Tukey's post hoc analyses were performed to compare mean values for steps, kcals, and mean heart rate between the FB, MF, and criterion measures. Levels of agreement for heart rate with 95% confidence intervals were examined with Bland-Altman plots. Compared to criterion measures, the FB and MF underestimated steps and overestimated kcals at 53.7 m·min-1 (FB: 12.7% for steps, 89.2% for kcals; MF: 15.8% for steps, 44.9% for kcals, *p*<.001) and 80.5 m·min-1 (FB: 9.7% for steps, 69.9% for kcals; MF: 13.4% for steps, 32.0% for kcals, *p*<.001). During free-living conditions, the MF significantly underestimated steps by 30.0% (*p*<.05). Increasing exercise intensity is indicative of heightened accuracy for step detection and kcal estimation for the FB and MF, while decreasing heart rate accuracy for the FB. However, the MF performed poorly for estimating total daily activity.

KEY WORDS: Physical activity, steps, heart rate, energy expenditure, assessment

INTRODUCTION

Insufficient levels of physical activity have long been shown to contribute to many chronic disease states (16), rendering the exploration of strategies to reverse this pattern to be of paramount importance in managing population health. Activity monitors have demonstrated success at facilitating positive physical activity behavior changes in diverse populations by providing self-monitoring, and supporting motivation and timely feedback (8). Recently, companies have inundated consumers with activity trackers equipped with accelerometer technology, thus boasting the capacity to monitor numerous physical activity metrics (i.e. steps, time spent in sedentary/high intensity activities, distance traveled, stairs climbed, and heart rate) to link data to the device's visual interface, smartphone applications, and internet websites. Therein lies massive potential for these intervention tools to reach broad segments of the population.

There is immense popularity and interest in activity trackers, with the number of devices used expected to triple by 2018 (from an estimated 19 million in 2014; 22). However, such devices' accuracy is the crucial component in regulating their potential impact on health and fitness. Companies such as Fitbit and Mio have released numerous styles of wrist-worn activity trackers that are widely available, with an associated expanding body of literature exploring their respective accuracy (8, 10, 18, 24, 28). The Fitbit activity trackers have generally demonstrated acceptable precision for step counts as ambulatory velocity increases (2, 13), however their ability to accurately report heart rate (24, 28) and energy expenditure (18, 25) are variable. Similar to the Fitbit devices, the Mio devices are capable of measuring ambulation, in addition to energy expenditure (4, 20). Yet, newer models in circulation have (to date) not been investigated studied for accuracy, and most existing studies focused on controlled, laboratory conditions.

The majority of daily activities are intermittent, varying in intensity and duration. Thus, research on activity trackers in laboratory settings (i.e. controlled treadmill speeds) may not be generalizable to overall daily activity in free-living conditions. There is limited research examining Fitbit devices in both free living and laboratory conditions (13, 18, 25). Furthermore, there is a dearth of research on the Mio devices for any physical activity metric, other than heart rate (4, 20, 24, 28). Therefore, the purpose of this study is to examine the wrist-worn Fitbit Charge HR (FB) and Mio FUSE (MF) for their accuracy in measuring steps, energy expenditure, and heart rate in both controlled and free-living settings.

METHODS

Participants

A convenience sample of forty individuals participated in this study (23 female and 17 male), with participant recruitment accomplished via word of mouth and flyers. Inclusion criteria was limited to participants between 18 and 30 years of age, having no physical limitations to walking/running, and completion of the Physical Activity Readiness Questionnaire (PAR-Q) without any contraindications. The full contents and procedures of this study were submitted and approved by the University's Institutional Review Board, and all participants read and signed the informed consent prior to engaging in the study protocol.

Protocol

Devices: *Fitbit Charge HR.* The wrist-worn Fitbit Charge HR (FB; Fitbit, San Francisco, CA, USA; 22.7 g; 20.8 cm x 2.0 cm x 1.0 cm) is equipped with a tri-axial accelerometer to sense motion, translating this output to steps taken, flights of stairs climbed, distance traveled, and time spent in higher intensity movements. Heart rate was detected in real-time via photopletysmography. Based on the individual's age, sex, height, and weight proprietary algorithms estimated basal metabolic rate and energy expenditure.

Mio FUSE. The wrist-worn Mio FUSE activity tracker (MF; Mio, Vancouver, British Columbia; 39.7 g; 3.0 cm x 25.9 cm x 1.5 cm) utilizes a tri-axial accelerometer to measure steps, distance, heart rate via photopletysmography, and energy expenditure. This device has a "workout" function that enables the devices to collect data only during activated timeframes.

NL-1000. The NL-1000 (NL) is a tri-axial piezoelectric accelerometer that measures steps, time spent in moderate-vigorous intensity activity, and distance travelled. This device has demonstrated acceptable validity in controlled (12) and free-living conditions (17), with the NL reporting <4.8% fewer minutes in moderate-vigorous physical activity, compared to Actigraph accelerometry (17). As such, the cost-effective NL was used as the criterion measurement for step counting during the free-living observation period.

Participation consisted of two lab visits and one 24 hour period for physical activity observation. The first lab visit consisted of reviewing the informed consent, measuring height (nearest 0.1 inch, converted to meters), weight (nearest 0.1 pound, converted to kg), and stride length. Stride length was determined over a set distance of fifty feet through a count of the steps taken to traverse the distance. Height, weight, sex, and age were entered into the mobile applications for the FB and the MF, enabling the generation of individualized data (steps, energy expenditure [kcals], and heart rate). Stride length was programmed into the NL for each individual.

The FB and MF were both worn on the non-dominant wrist, with the MF worn superior to the FB. The NL was worn on the dominant hip waistband at the midline of the thigh. An accurate tool to assess exercise heart rate (11), a Polar heart rate monitor (T31, Polar Electro Oy, Kempele, Finland) was worn around the chest of the participant with direct contact to the skin, transmitting data to the FT1 monitor to record heart rate data as a criterion measure during the treadmill protocol. Following the treadmill protocol, participants were instructed to wear the FB, MF, and NL during waking hours of the ensuing day to obtain free-living data. The third lab visit occurred on the day after the free-living observation when the participants returned all devices.

Treadmill Protocol: The treadmill protocol consisted of four five-minute stages (walking speeds at 53.7 m·min-1 and 80.5 m·min-1, jogging speeds at 134.1 m·min-1 and 160.9 m·min-1), measuring steps, heart rate, and energy expenditure (kcals). If the participant's heart rate eclipsed 85% of their age predicted heart rate for two consecutive minutes, the protocol was terminated. A five minute rest period preceded the treadmill protocol, as well as in between each stage, to allow heart rate to return to resting levels. Heart rate was recorded from the FB, MF, and Polar at every minute of each stage. Participants were instructed to straddle the treadmill belt with hands on the guard rails at the beginning and end of each stage for data collection purposes.

The MF workout mode was initiated/terminated at the onset/completion of each stage, enabling steps and energy expenditure to be collected for time spent on the treadmill. For each stage, final steps and energy expenditure from the FB were subtracted from the values recorded at the onset of the stage.

Steps were manually counted via a hand tally (criterion measure) during each stage by a trained research assistant. Energy expenditure output from the FB and MF were compared with kcals derived from kcals calculated via MET values of treadmill intensities (1).

Free-Living Monitoring Period: Participants wore the FB, MF, and NL to measure steps during waking hours in the day following the treadmill protocol. The device was advised to be worn for all activities (i.e. work, school, leisure and exercise-type activities), with the exception of bathing, showering, and swimming. Steps were retrieved from the devices upon their return.

Statistical Analysis

All statistical analyses were performed utilizing SPSS 20.0 (Chicago, IL, USA). Descriptive statistics were presented as mean ± standard deviation. Mean absolute percent errors (MAPE) were calculated for each treadmill stage by subtracting the experimental outcome derived from the FB and MF from the criterion measurement (manually tallied steps, metabolic equations, Polar heart rate monitor), then dividing by the criterion value. One way ANOVAs with Tukey's post-hoc analyses were performed to compare steps, kcals, and mean heart differences from the FB and MF to criterion measures, with an alpha level of 0.05 used to determine statistical significance. Levels of agreement for heart rate with 95% confidence intervals were additionally examined with Bland-Altman plots.

RESULTS

This sample of 40 participants represents a young (21.6±2.0 years), healthy population, with the mean body mass index falling within the "normal" range (24.6±4.2 kg·m^{2}-1). More than half the sample was female (57.5%), and the average stride length was 67.6±6.1 cm·step-1.

Table 1. Physical Activity During Treadmill Ambulation

Speed	Manually Tallied Steps	Fitbit Charge HR Steps	Fitbit Charge HR MAPE	Mio FUSE Steps	Mio FUSE MAPE
53.7 m·min-1	487±37	425±83*	-12.7%	410±89*	-15.8%
80.5 m·min-1	576±32	520±52*	-9.7%	499±40*	-13.4%
134.1 m·min-1	759±111	743±116	-2.1%	725±109	-4.5%
160.9 m·min-1	735±141	717±140	-2.5%	700±141	-4.8%

Note. * p < 0.001 compared to manually tallied steps; MAPE: mean absolute percent difference. Negative values represent underestimations.

Steps: The steps taken during both walking (53.7 m·min-1, 80.5 m·min-1) and running treadmill stages (134.1 m·min-1, 160.9 m·min-1) are presented in Table 1. The ANOVA analyses revealed a significant difference in steps measured between groups at 53.7 m·min-1 ($F(2,117) = 12.313$, p=.000) and at 80.5 m·min-1 ($F(2,117) = 36.048$, p<.001). Tukey post hoc analyses revealed the FB to underestimate steps by an average of 12.7% at 53.7 m·min-1 (p<.001) and 9.7% at 80.5 m·min-1 (p<.001), and the MF to similarly underestimate steps by 15.8% at 53.7 m·min-1 (p<.001) and 13.4% at 80.5 m·min-1 (p<.001). There were no significant differences in steps measured by either of the activity trackers during the running speeds.

Energy Expenditure: Energy expenditure (kcals) measured by the activity trackers during both walking and running stages are presented in Table 2. The ANOVA analyses revealed a significant difference in energy expenditure between groups at 53.7 m·min-1 ($F(2,117) = 37.722$, p=.000) and at 80.5 m·min-1 ($F(2,117) = 44.072$, p<.001). Tukey post hoc analyses revealed the FB to overestimate kcals by almost 90% and 70% at walking speeds of 53.7 m·min-1 and 80.5 m·min-1 (both p<.001), respectively. Additionally, the FB overestimated walking kcals by values approximately twice the MF at 53.7 m·min-1 (p<.001) and at 80.5 m·min-1 (p<.001). Despite this, the MF still overestimated kcals at 53.7 m·min-1 and 80.5 m·min-1 by 45% and 32%, respectively (both p<.001).

Table 2. Energy Expenditure During Treadmill Ambulation

Speed	Calculated kcals	Fitbit Charge HR kcals	Fitbit Charge HR MAPE	Mio FUSE kcals	Mio FUSE MAPE
53.7 m·min-1	17.6±3.9	33.3±8.1*†	89.2%	25.5±10.7*	44.9%
80.5 m·min-1	21.9±4.9	37.2±7.5*†	69.9%	28.9±8.9*	32.0%
134.1 m·min-1	49.4±13.0	51.8±12.8	4.8%	53.3±14.5	7.9%
160.9 m·min-1	54.7±14.4	50.1±11.6	-8.4%	54.6±9.6	0.0%

Note. * p < 0.001, compared to calculated kcals; † p < 0.001 compared to Mio FUSE; MAPE: mean absolute percent difference. Negative values represent underestimations.

Heart Rate: Bland-Altman plots are provided in Figures 1 and 2 for the FB and MF, respectively. The FB exhibited a trend to report lower mean heart rate values at running speeds of 134.1 m·min-1 and 160.9 m·min-1, compared to the Polar. This trend of underestimating heart rate appears to be amplified as the heart rate rises, as illustrated in Figure 1. The MF performed well during all treadmill stages, with mean heart rate values within 1.1 beats·min-1 of the Polar.

Free-Living Conditions: The average wear time for all devices during free living conditions was 9.6 ± 2.3 hours, during which time the NL measured 7818 ± 4529 steps. ANOVA analyses revealed there significant differences in free-living steps measured between the devices. Tukey post hoc analyses revealed the MF (5470±3341 steps) significantly underestimated steps by approximately 30%, compared to both the NL (7818 ± 4529 steps) and FB (7991±4613 steps) (both p<.05).

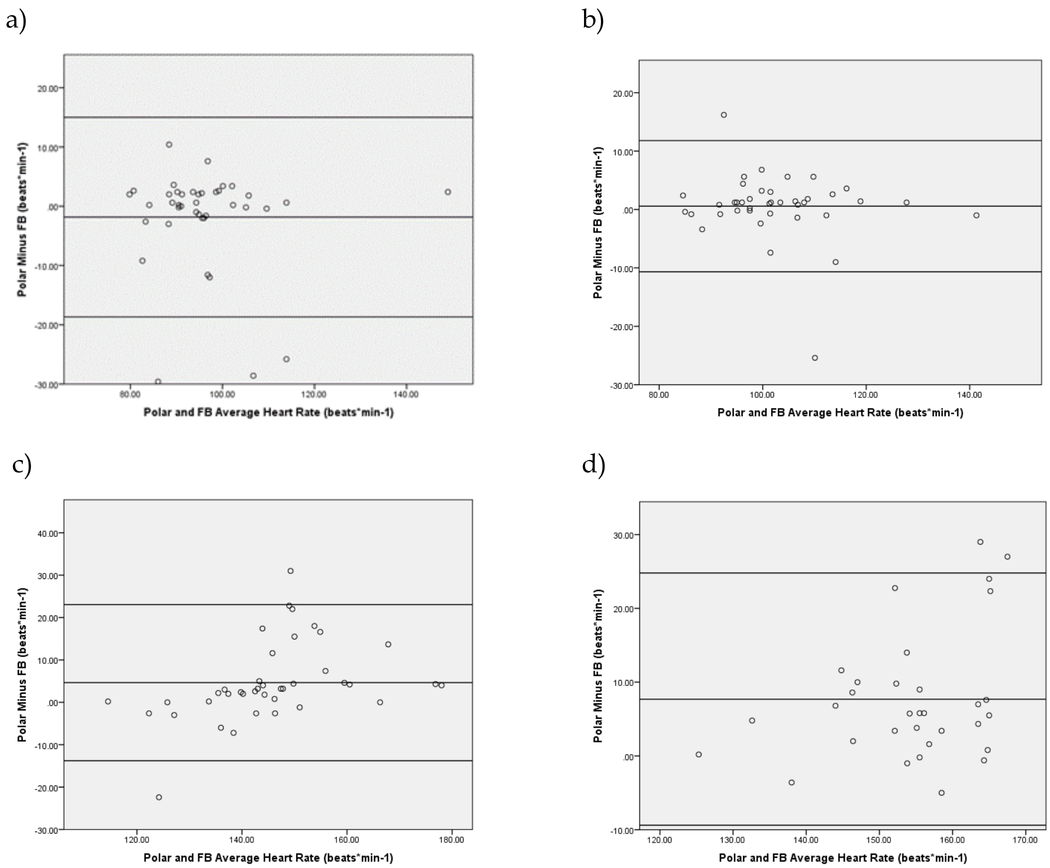

Figure 1. Fitbit Charge HR Heart Rate Precision. *Note*. a) 53.7 m·min-1; b) 80.5 m·min-1; c) 134.1 m·min-1; d) 160.9 m·min-1; FB: Fitbit Charge HR 2

DISCUSSION

The potential impact of activity monitors is inherently linked to their accuracy in assessing outcomes. Given the proliferation of activity trackers, this information has become increasingly beneficial in guiding consumers to informed decisions on which devices are most appropriate. The current study examined two wrist-worn activity trackers, the Fitbit Charge HR (FB) and Mio FUSE (MF) for their accuracy in quantifying steps, heart rate, and energy expenditure in laboratory conditions and ambulatory behavior in free-living conditions. The FB underestimated steps by 12.7% and 9.7%, and overestimated kcals by 89.2% and 69.9%, during treadmill walking speeds. Similarly, the MF, underestimated steps by 15.8% and 13.4% and overestimated kcals by 45% and 32% at the same speeds.

The results from the current study showed that both the FB and MF became more accurate in step detection proportional to exercise intensity. Numerous studies have explored wrist-worn Fitbit devices during various treadmill speeds (2, 5, 9, 10, 13, 15, 18, 25). Mean absolute percent errors (MAPE) not exceeding 10%, in relation to manually tallied steps, has been identified as a threshold for acceptable agreement (26). The wrist-worn Fitbit devices appear to underestimate steps during treadmill walking, with most studies reporting modest MAPE similar to the current study (2, 5, 10, 13, 18). Interestingly, two studies (9, 25) reported MAPE >20% for walking speeds. Older adults, however, were the target population in one study (9), who commonly demonstrate different gait patterns that influence activity tracker accuracy (21). In a study by Fokkema and colleagues (10), the Fitbit Charge HR was examined, showing acceptable performance, in that it only overestimated steps by 0.7% at 53.7 m·min-1, and underestimated steps by 2.0% and 5.2% at 80.5 m·min-1 and 107.3 m·min-1, respectively. The small error margins similarly shown in the current study are likely due to the ease of movement detection that results from the more intentional movements at higher speeds.

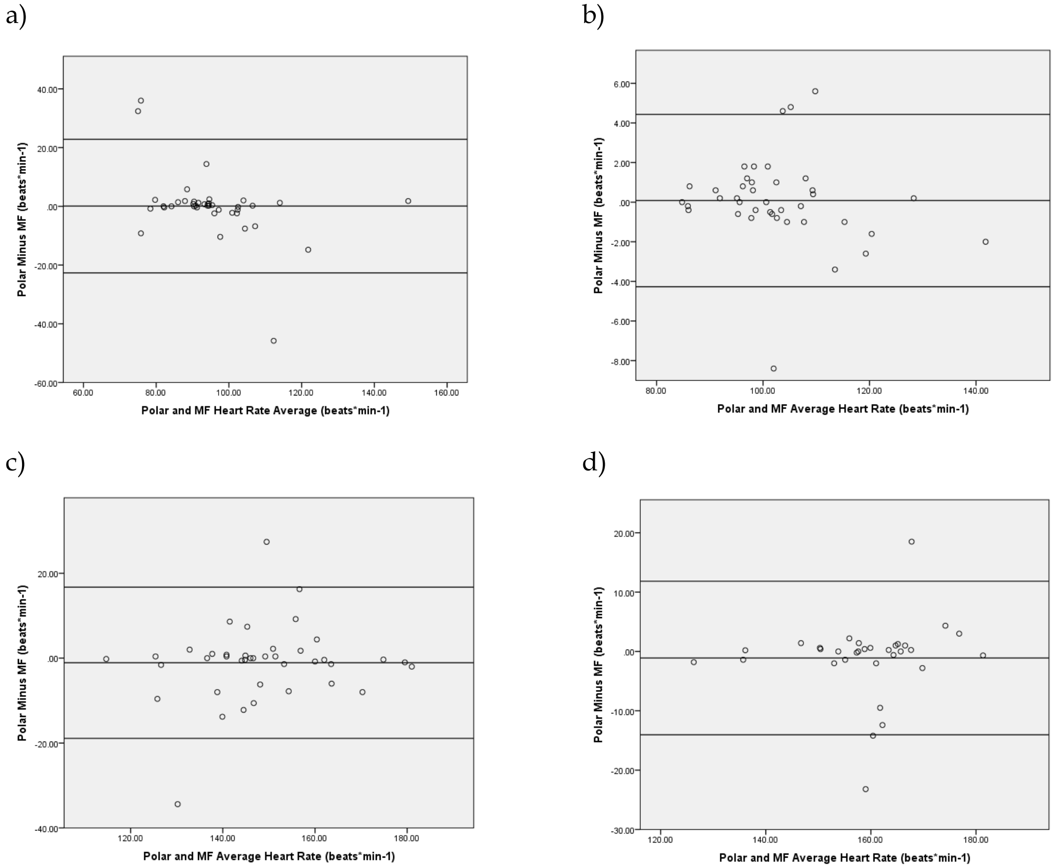

Figure 2. Mio FUSE Heart Rate Precision. *Note*. a) 53.7 m·min-1; b) 80.5 m·min-1; c) 134.1 m·min-1; d) 160.9 m·min-1; MF: Mio FUSE

Demonstrating consistency between conditions, the results from Fokkema and colleagues (10) in laboratory settings mimic the FB performance during free-living conditions in the current study (i.e. 2.2% overestimation). Among studies examining wrist-worn Fitbit devices during free-living conditions, there appears to be a wide range of MAPE from 3.7% to 47% (3, 6, 14, 22, 25, 27), influenced by the intensity and volume of activities engaged in. One study utilizing the Charge HR (27) showed a 28% overestimation of steps, however the sample population was children with congenital heart disease, which likely influenced activity with smaller gait patterns, and thus, accuracy. Therefore, these results appear as an outlier to the FB's capable performance in monitoring activity in free-living conditions, as evidenced in the current study with a healthy, young adult participant sample.

Similar to step detection, estimation of energy expenditure was least accurate during walking speeds for both devices. It is interesting to note the trend for waist-worn Fitbit devices in underestimating kcals (19, 23), with reference to wrist-worn Fitbit devices. Diaz and colleagues (5) demonstrated the Fitbit Flex to overestimate kcals during moderate and brisk walking by 52% and 33%, respectively, with similar results (53% and 35% overestimation) by Nelson el al. (18) during walking and jogging. Additionally, Dooley, Golaszewski, and Bartholomew (7) reported the Charge HR to overestimate kcals during light intensity by 82%, 42% during moderate intensity, and 3% during vigorous intensity. In free-living conditions the Flex was found to overestimate kcals by 32% (25). The present study utilized predictive equations to estimate energy expenditure, as opposed to indirect calorimetery, yet the overestimation in kcals from wrist-worn Fitbit devices mirrors trends in the aforementioned studies where the largest overestimation errors occur during light ambulation and decreases as intensity increases.

To our knowledge, there exists no literature on the MF's accuracy in step detection in either laboratory or free-living conditions. Although the MF closely mirrored the FB's performance during treadmill activities, it substantially underestimated steps in free-living observation, which may be due to its difficulty in detecting sporadic movements. Although there are no studies examining the FB and MF concurrently on these outcomes, they both performed within ±10% MAPE for step detection and energy expenditure estimation during treadmill running, suggesting that the devices are more precise during higher intensity activities.

Unlike step detection and estimation of energy expenditure, there is ample data to infer the accuracy of the FB and Mio devices during heart rate detection. The Fitbit Charge HR has been shown to underestimate heart rate as exercise intensity/heart rate increases (7, 14), in accordance with the current study. Conversely, the Mio activity trackers have demonstrated excellent precision (roughly 95% accuracy) during walking, running, and cycling (4, 20). Two other studies examined the FB and another Mio product, the Mio Alpha (24, 28), arriving at conclusions consistent with the current study. In a 30 minute continuous treadmill protocol the FB and Mio Alpha MAPEs were 4.6% and 6.2%, respectively (24), whereas an hour long, multi-mode protocol showed MAPE for the FB (8.8%) and Mio Alpha (4.2%) (28). No studies exist comparing the FB to the MF (to the authors' knowledge), yet the MF performed on par with previous research on Mio devices (4, 20), and better than the Mio Alpha in the studies concurrently compared to the FB (24, 28). Thus, the MF garners support for accurate heart rate measurement, although caution is warranted with the FB due to the device's tendency for underestimation, especially during high intensity activities and for those with cardiac conditions.

This study is unique in examining two wrist-worn activity trackers, which appear to have both advantages and disadvantages. The FB and MF detected steps and predicted energy expenditure with heightened precision as exercise intensity increased. However, in free-living conditions, the MF significantly underestimated steps taken. The MF performed well in measuring heart rate at all exercise intensities, whereas the FB began to underestimate heart rate as exercise intensity increased. There are several limitations to the current study. The population examined was derived from a convenience sample, and is not representative of all ages and health profiles, who may have characteristics that influence activity tracker accuracy. Also, activity energy expenditure was estimated from MET classifications. Despite this, the FB performed on par with other research employing similar methodologies (14). Future studies are warranted to explore activity trackers' efficacy with a diverse sample of participants engaging in a spectrum of physical activities (i.e. household, occupation) to observe the generalizability of these devices to the broad population.

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