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Wearable activity trackers for promoting physical activity:

A systematic meta-analytic review

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Highlights

- We conduct a systematic meta-analytic review to synthesize the existing evidence on the effectiveness of wearable activity trackers (WATs) for promoting physical activity (PA)
- Interventions with WATs significantly increased daily steps and weekly moderate-to-vigorous physical activity (MVPA) but had no impact on light physical activity (LPA) or sedentary behavior
- Two PA outcomes (daily steps and weekly MVPA) were associated with participants' characteristics (i.e., gender, age, health status, and baseline PA level) and intervention features (i.e., technology features, types of expert support, and intervention length

Summary points

What already known on the topic?

- Wearable activity tracker (WAT) is a widely-accepted technology for nudging people toward a more active lifestyle.
- Inconsistent findings exist in the literature regarding the effectiveness of WATs for promoting physical activities.

What this review article adds?

- The interventions with WATs have small-to-medium effects on daily steps and weekly moderate-to-vigorous physical activities, whereas having no impact on light physical activities and sedentary behaviors.
- The effect size of daily steps and weekly MVPA, as outcomes of WATs-based interventions, is contingent on users' characteristics and interventions' features.

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Abstract

Purpose: Although wearable activity trackers hold a promise of nudging people toward a more active lifestyle, current research reveals inconsistent findings regarding their effectiveness. The objectives of this paper are two-fold: (1) to synthesize evidence on the effects of wearable activity trackers for improving physical activities, and (2) to identify potential moderators of effect size.

Methods: A systematic meta-analytic review was conducted. Forty-eight eligible papers based on forty-four distinct trials were identified through a systematic literature search process. Two authors independently extracted information from each study based on predefined data fields. Random-effects meta-analysis, subgroup analysis, and meta-regression analysis were employed.

Results: First, interventions with wearable activity trackers significantly increased daily steps and weekly moderate-to-vigorous physical activity but had no impact on light physical activity or sedentary behavior. Second, daily steps and weekly moderate-to-vigorous physical activity were associated with participants' characteristics (i.e., gender, age, medical condition, and baseline physical activity level) and intervention features (i.e., sensors, modes of expert support, and intervention duration). The identified factors explained 53% of the total variance for weekly moderate-to-vigorous physical activity.

Conclusions: The use of wearable activity trackers effectively improves conscious exercise behavior, including daily steps and weekly moderate-to-vigorous physical activity, but not effective for modifying habitual behavior, such as light physical activity and sedentary behavior. We also explicitly show that the extent to which the interventions with wearable activity trackers help users is contingent on the type of users and the design and delivery of interventions. Future studies are called to validate the findings and to offer theoretical explanations.

Keywords: Physical activity interventions; Wearable activity trackers; Effectiveness; Meta-analysis; Moderators

Paper type: Review article

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1. Introduction

1.1 Research background

In modern society, many people are habitually inactive during commuting, work, and leisure [1]. Insufficient physical activity (PA) is a leading risk factor for chronic diseases, mental health problems, and quality of life [2]. For substantial health benefits, PA guidelines recommend that adults do at least 150 minutes of moderate-to-vigorous physical activity (MVPA) per week, accumulate 10,000 steps per day, and reduce sedentary behavior [3, 4]. Nevertheless, according to a global survey across 168 countries [2], over one-quarter of people do not meet the PA level recommendations.

Wearable activity trackers (WATs) have the potential to nudge people toward a more active lifestyle. By integrating sensors, algorithms, and human-computer interaction designs, WATs could benefit users in two ways. First, WATs support self-monitoring of PA, such as steps taken, timing and intensity of PA, distance walked, and calories burned. Second, WATs help build self-regulatory skills, including goal-setting, action plans, behavior control, and goal achievement [5, 6].

1.2 Problem statement and research objectives

Despite the increasing popularity of WATs (e.g., Fitbit, Mi Band, Apple Watch, Garmin) in the consumer market, formal adoption in public health practice is scarce [7]. One exception was a national public health project carried out by Fitbit and Singapore's Health Promotion Board in 2019. Some empirical studies have been conducted to assess the effectiveness of WATs, albeit with mixed findings (e.g., [8, 9]). The extent to which WATs are able to promote PA remains unclear in the literature. Hence, a meta-analysis method has been employed by several review studies. This approach can overcome the equivocation in the existing literature by calculating the weighted average value [10]. Although several relevant meta-analytic papers have come out in recent years [11-24], there are still two research gaps.

First, previous review articles did not examine all types of PA. Existing meta-analytic reviews found that WATs are effective for improving PA by assessing step counts [11, 12, 14, 16, 17, 19, 22-24], MVPA [12, 14, 17, 19, 22-24], or overall PA [13, 15, 16, 18, 20, 21]. However, there is a lack of in-depth analysis of light PA (LPA) and sedentary behavior, leading to an incomplete understanding of the WATs' effectiveness. To fill this gap, we propose the first research objective.

RO1: To synthesize evidence on the effects of WATs for promoting PA in terms of steps, LPA, MVPA, and sedentary behavior

Second, although large heterogeneity of WATs' effect size was observed, potential moderators were not systematically investigated. Specifically, by comparing between reviews with a focus on at-risk populations (e.g., chronic disease patients, older adults) [13, 15-19] and those without a specific population focus [21-24], we noticed that the former often reported larger PA effect sizes (reflected by *standard mean difference*, *SMD*) (Table 1).

Table 1. Comparison between reviews focused on at-risk populations and reviews without a specific population focus

PA	Reviews focused on at-risk populations	Reviews without a specific population focus
Step counts	[19] *SMD* = 1.23, 95% *CI* 0.75-1.70 [16] *SMD* = 0.55, 95% *CI* 0.40-0.70 [17] *SMD* = 0.54, 95% *CI* 0.34-0.73	[23] *SMD* = 0.25, 95% *CI* 0.17-0.32 [22] *SMD* = 0.24, 95% *CI* 0.16-0.33
MVPA	[17] *SMD* = 0.34, 95% *CI* 0.15-0.52 [19] *SMD* = 0.22, 95% *CI* -0.62-1.06	[22] *SMD* = 0.27, 95% *CI* 0.15-0.39 [23] *SMD* = 0.01, 95% *CI* -0.15-0.13
Overall PA	[18] *SMD* = 0.43, 95% *CI* 0.19-0.68 [13] *SMD* = 0.30, 95% *CI* 0.16-0.44 [15] *SMD* = 0.34, 95% *CI* 0.23-0.44	[21] *SMD* = 0.26, 95% *CI* 0.04-0.49

Note: SMD = standard mean difference*; CI* = confidence interval

In addition to health status, past research suggested that participants' gender, age, and baseline PA level were associated with PA outcomes of using WATs [11, 25, 26]. Such findings indicated that different target populations could respond diversely to WATs. Notably, previous articles mainly focused on a particular population, lacking a comparison between multiple groups.

Even if focusing on a particular target population, previous meta-analytic reviews reported large heterogeneity of effect size across trials [11, 12, 14, 16, 19, 20]. However, the sources of the heterogeneity were not well explained. The heterogeneity of effect size could stem from intervention features, such as functionalities of WATs, intervention duration, and intervention delivery [23, 27]. Unfortunately, there is a lack of comprehensive evidence on how intervention features could moderate the effects of WATs.

Therefore, we propose the second research objective.

RO2: To explore potential moderators of WATs' effects through examining participants' characteristics and intervention features

This article is important in three ways. First, by considering the PA outcome at various intensity levels (i.e., steps, MVPA, LPA, and sedentary behavior), we analyze the influence of WATs use on PA thoroughly. This helps to understand the role of WATs from a fine-grained perspective. Second, by reporting eligible studies on a wide range of populations (see TableA.1 for details), we provide a holistic view of the effectiveness of WATs. This allows for comparing the role of WATs in promoting PA across different target user groups. Third, by analyzing the moderating role of participants' characteristics and intervention features, we fill a common gap in previous review articles: lacking a systematic investigation into the cross-studies heterogeneity.

2. Methods

We conducted and reported this review according to *the Cochrane Handbook for Systematic Reviews of Interventions* [28] and *the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines* [29]. The details of the applied methods were described as following.

2.1 Eligibility criteria

We assessed the eligibility of studies based on article type, participants, interventions, comparators, outcomes, and study design (Table 2).

Article type. Eligible studies were restricted to English-language publications. To ensure the credibility of the sources, only peer-reviewed journal papers were considered. Other publications, including book sections, conference abstracts, generics, and theses, were excluded.

Participants. One research objective of this review is to compare the effects of WATs across different populations, so we did not apply any population restrictions at first. However, we excluded participants with impaired movement ability from analysis as their activity patterns were non-comparable to other populations.

Interventions. WATs in this review refer to pedometer- or accelerometer-based devices, which are attached to the body to collect PA information [13]. Studies were included if they applied WATs alone or in combination with other intervention components to promote PA. Thus, technology design studies, validation tests, and studies that only used WATs as measurement tools were excluded because of irrelevance.

Comparators. The meta-analytic review must choose studies that involving a non-WATs (or blinded-WATs) comparator group. Studies provided any unblinded activity monitors to comparator group participants were excluded from analyses.

Outcomes. Studies were included if they reported objectively measured PA outcomes including step counts, MVPA, LPA, and sedentary behavior. Studies were excluded if they did not report any PA outcomes or only provided self-reported measures.

Study design. Only randomized controlled trials were included, while other study designs such as qualitative studies, cross-sectional surveys, pre-post or literature reviews were excluded.

Table 2. Inclusion and exclusion criteria

Domain	Inclusion/exclusion criteria
Article type	• Inclusion- English-language, peer-reviewed journal papers; ○ Exclusion- Non-English records; Article types other than peer-reviewed journal articles (e.g., book sections, conference abstracts, generics, theses);
Participants	• Inclusion- A broad range of populations were eligible to be included; ○ Exclusion- Participants with impaired motor ability, or for whom it was unsafe to be physically active without health professional supervision (e.g., patients diagnosed with a stroke, people immediately after surgery);
Interventions	• Inclusion- Studies conducted a PA intervention by using WATs; ○ Exclusion- Studies did not investigate WATs as an intervention tool for promoting PA (e.g., technology design studies, validation tests, WATs were solely used as a measurement tool in the studies);
Comparators	• Inclusion- Studies involved a comparator group that did not provide unblinded WATs to participants; ○ Exclusion- Studies lacked a non-WATs/blinded-WATs comparator group;
Outcomes	• Inclusion- Studies reported objective measures of PA such as step counts, LPA, MVPA, and sedentary periods; ○ Exclusion- Studies did not report PA outcomes or only provided self-reported PA;
Study design	• Inclusion- Studies designed a randomized controlled trial (RCT) or cluster RCT with at least one intervention group and one control group; ○ Exclusion- Studies did not apply RCTs (e.g., editorials, qualitative studies, literature reviews, conceptual papers, cross-sectional studies, pre-post study design).

2.2. Information sources and search

Six major electronic databases were searched on March 25, 2020, including PubMed, PsycINFO, EMBASE, CINAHL, Science Direct, and Web of Science. Also, we updated our search results on March 24, 2021, to include the most recent research.

We used a combination of free-text terms and medical subject headings (MeSH) to develop the search query (Table 3). Two sets of keywords were used to identify papers involving WATs and PA outcomes of interest. We applied the search query in the field of title, abstract and keywords. The search query was adapted for each database as necessary. Furthermore, reference searching was performed to identify additional studies that the database search might have missed.

Table 3. The development of search query

Purposes	Search query
Identifying studies involving WATs	#1: wearable tracker* OR wearable monitor* OR wearable device* OR wearable technolog* OR "activity tracker*" (*MeSH*) OR activity monitor* OR activity device* OR activity technolog* OR fitness tracker* (*MeSH*) OR fitness monitor* OR fitness device* OR fitness technolog*
Identifying studies involving PA	#2: physical activit* *(MeSH)* OR behavio*r change OR exercis* (*MeSH*) OR sedentary behavio*r (MeSH) OR sitting OR step*
For this review	#1 AND #2

2.3. Study selection

Retrieved records were screened in a three-step process. First, all records were imported into Endnote 20 (Clarivate, Pennsylvania), and duplicates were removed automatically. Second, the article type, title and abstract of each record were examined. Any records that did not meet the inclusion criteria were excluded. Third, all papers identified as requiring full-text review were examined. The primary author initially performed the three-step data selection process. To avoid bias, another author then performed the third step to verify the included/excluded studies. Any differences were resolved by consensus. The study selection process was similar to methods applied by Ringeval, Wagner [24].

2.4. Data collection and coding process

Data collection was informed by the Oxford Implementation Index, a common tool for incorporating implementation data into systematic reviews and meta-analysis [30]. We developed a data extraction sheet containing the following data items: citation; country/region; participants' characteristics of recruitment settings, gender distribution, mean age, average baseline PA level, and medical condition; intervention descriptors of the model of WATs, sensor, functionalities, intervention duration, and combined intervention components; retention rate, sample size; and statistic findings (mean and SD of PA outcomes for the intervention and comparison groups).

Further, to address the second research objective (i.e., to explore potential moderators of effect size), four covariates related to participants' characteristics and three covariates related to intervention features were coded dichotomy or categorical variables. Table 4 shows the coding rules.

Table 4. Coding rules of covariates

Category	Covariates	Coding rules	Rationale
Participants' characteristics	Gender	"both male and female" = 0, "only male" = 1, "only female" = 2	Biological properties
	Age	"mean age $<$ 60 years" = 1, "mean age $\geq$ 60 years" = 2	The definition of elderly [31]
	Baseline PA level	"below guidelines" = 1, "above guidelines" = 2	PA guidelines [3, 4]
	Medical condition	"without medical conditions" = 1, "with a medical condition" = 2	With or without clinical confirmed diseases (e.g., [32])
Intervention features	PA sensor	"pedometer" = 1, "accelerometer" = 2	Types of activity sensors [13]
	Combined intervention components	"null" = 0, "expert support delivered through one-way communication" = 1, "expert support delivered through two-way communication" = 2	Communication types (i.e., with or without feedback) [33]
	Intervention duration	"$\leq$ 12 weeks" = 1, "$>$ 12 weeks" = 2	Short/long-term WATs-based interventions [16]

Data extraction and coding were performed independently by two authors. The inter-coder reliability was acceptable based on the agreement percentage (92%). The third author resolved all disagreements.

2.5. Risk of bias assessment

The *Cochrane Risk of Bias Tools* [34] was adapted to assess the risk of bias (ROB) for each study. The domain of *blinding participants* was excluded because the nature of the WATs-based intervention rendered blinding not feasible [13]. The domain of *blinding outcome assessment* was also excluded because of the use of objective PA measurements

[24]. Therefore, five ROB domains were assessed in this review, including *random sequence generation*, *allocation concealment*, *incomplete outcome data*, *selective reporting*, and *other sources of bias*. Each domain was scored as low, unclear, or high ROB following the criteria provided by Brickwood, Watson [22]. Two authors assessed the ROB of each selected study independently. The inter-coder reliability presented by the agreement percent was acceptable (94%). The third author resolved all disagreements.

2.6. Data synthesis, analysis, and interpretation

Empirical studies that investigated the effectiveness of WATs constitute the potential targets of our meta-analytic review. Meta-analysis can be conducted on two or more samples. However, to ensure robustness and practicability, the number of analyzable empirical studies must neither be too small nor too large. As a most recent review on this topic obtained a sample of 37 studies [24], we expect that the potential sample size of this review is suitable.

This review presented PA outcomes as steps/day, sedentary minutes/day, LPA minutes/day, and MVPA minutes/week to facilitate greater transferability for current PA guidelines [3, 4]. The mean and standard deviation (*SD*) of each PA outcome were derived for meta-analysis. Data presented as confidence interval level, standard error, p-values, and t-values were converted to *SD* based on statisticians' suggestions [28, 35]. We used R-3.6.2 to do random-effects meta-analyses.

For the first research objective, we calculated the mean difference (*MD*) and the standardized mean difference (*SMD*). The *SMD* was interpreted according to the Cohen rule of interpretation (small $0.2 \leq SMD < 0.5$, medium $0.5 \leq SMD < 0.8$, large $0.8 \leq SMD$) [36]. Heterogeneity across studies was assessed using I^2, with per Higgins values of 25%, 50%, 75% were used as boundary limits for low, moderate, or high heterogeneity [37]. Funnel plots and Egger's test were used to examine potential publication bias. The trim-and-fill method was used to adjust for potential missing studies. The fail-safe *N* was calculated to reflect the robustness of the results.

For the second research objective, subgroup meta-analysis and meta-regression analysis were conducted. First, interventions were sub-grouped according to each of the seven covariates (Table 4). Random-effects meta-analyses were conducted for each subgroup. T-tests were conducted to reflect the statistical significance of the intergroup difference. Second, the meta-regression analyses that including all covariates were calculated, and the model estimates were reported.

3. Results

3.1 Study selection

The initial search on the six databases resulted in 13,791 records. Of them, 6,298 were remained after removing duplicates. After a screening of article types, titles, and abstracts, 6,131 ineligible records were excluded. The remaining 167 articles were assessed based on the full-texts, resulting in 35 articles that met the eligibility criteria. Besides, 9 eligible articles were retrieved from reference searching. Also, 4 studies were identified through database updating (from March 25, 2020, to March 24, 2021). Finally, the formal dataset for coding and analysis comprised 48 articles (based on 43 distinct trials). Figure 1 outlines the process of dataset selection.

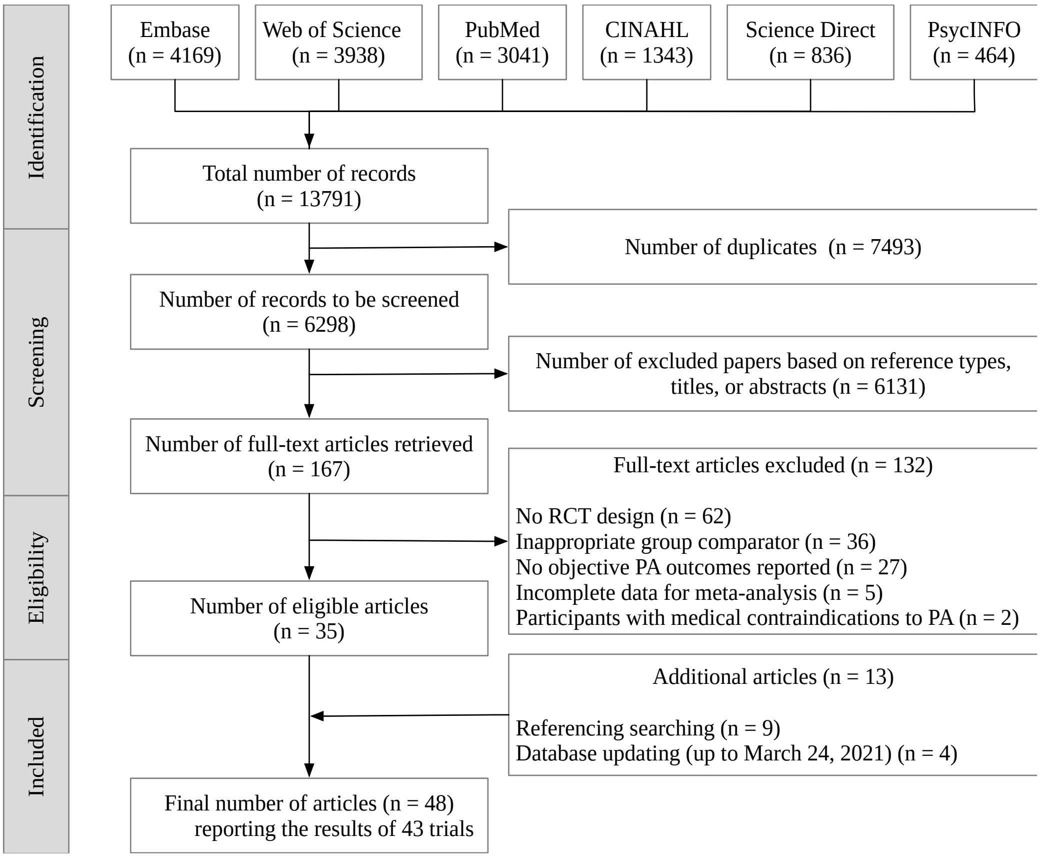

Figure 1. Flowchart of dataset selection

3.2. Characteristics of included studies

Most of the studies were published in the last 5 years (n = 37, 86%). A total of 5,808 participants were involved, with 3,218 in intervention groups and 2,679 in control groups. Descriptive statistics of participants, interventions, comparators, outcomes, and study design were stated below.

Participants. Table 5 presented a summary of participants' characteristics of gender, age, baseline PA level, medical condition, and recruitment settings. For detailed descriptions, one can refer to Table A.1 in the Appendix.

In summary, all trials were conducted in developed countries with an absence of literature in developing countries. Relatively small sample size was used in many trials (n = 30, 70%).

Many trials covered both male and female (*n* = 33, 77%), with a few focused solely on male (*n* = 4, 9%) or female (*n* = 6, 14%). About one-third of trials reached the elder (≥ 60 years old) (*n* = 14, 33%), leaving two-thirds involved younger populations (*n* = 29, 67%). More trials involved inactive participants (*n* = 25, 58%) than those involved with active participants (18, 42%).

About half trials recruited participants with a medical condition (*n* = 21, 49%), including diabetes [38, 39], cardiovascular disease [40, 41], peripheral artery disease [42], chronic obstructive pulmonary disease [43, 44], early knee osteoarthritis [45, 46], rheumatoid arthritis [47], systemic lupus erythematosus [47], and cancer [25, 32, 48-55]. The other half (*n* = 22, 51%) did not restrict participants according to medical conditions. Similarly, about half of the trials recruited participants mainly from clinics (*n* = 22, 51%). Other recruitment settings were communities (*n* = 9, 21%), workplaces (*n* = 7, 16%), social media (2, 5%), colleges courses (2, 5%), and newspapers (1, 2%).

Table 5. Summary of participants' characteristics

Characteristics	No. trials (%)	Characteristics	No. trials (%)
Countries		**Baseline PA levels**	
developed countries	43 (100%)	below PA guidelines	25 (58%)
developing countries	0 (0%)	above PA guidelines	18 (42%)
Sample size		**Medical condition**	
< 100	30 (70%)	with medical conditions	21 (49%)
≥ 100	13 (30%)	without medical conditions	22 (51%)
Gender		**Recruitment settings**	
both genders	33 (77%)	clinics	21 (51%)
only female	6 (14%)	communities	9 (21%)
only male	4 (9%)	workplaces	7 (16%)
Age		social Media	2 (5%)
< 60 years old	29 (67%)	college courses	2 (5%)
≥ 60 years old	14 (33%)	newspaper	1 (2%)

Note: numbers in parentheses are percentages

Interventions. A detailed description of each studies' intervention features was listed in Table A.2 in the Appendix. Table 6 summarized the intervention features of all trials, including the model of WATs, sensor, combined intervention components, and intervention duration.

The included trials utilized a wide range of WATs models. Fitbit devices were the most popular products (*n* = 20, 47%). The applied Fitbit models include Fitbit Alta [52], Fitbit Charge [40, 50, 51, 55], Fitbit Flex [45-47, 49, 53], Fitbit One [25, 32, 56-58], and Fitbit Zip [59-63]. Besides, Jawbone UP 24 [64-66] (*n* = 3, 7%), Polar (Polar M400 [54], Polar Active [67]) (*n* = 2, 5%), Garmin (Garmin Forerunner 210 [68], Garmin Vivofit [48]) (*n* = 2, 5%) and Fitbug [41, 44] (*n* = 2, 5%) were applied in more than one trials. Others (*n* = 13, 30%) adopted Activator [69], Active Link [70], Body Media FIT Core [71], LOMO Back[72], Misfit Flash [9], My Wellness Key [73], Sitfit [74], and study-specific WATs [38, 39, 43, 75, 76].

Two-fifths of trials applied pedometer-based WATs (*n* = 17, 40%), which could only monitor steps. The remaining three-fifths used accelerometer-based WATs (*n* = 26, 60%), capable of monitoring steps and timing and intensity of PA in detail.

About one-fifth of trials did not combine any intervention components other than WATs (*n* = 8, 19%). Others combined expert support (*n* = 34, 79%) and financial incentives (*n* = 1, 2%) into the PA interventions with WATs. Specifically, two delivery modes of expert support were identified: two-way communication (*n* = 26, 60%), including face-to-face interviews, phone calls, and group sessions; and one-way communication (*n* = 8, 19%) such as standard text messages, emails, and posts on social media.

Regarding intervention duration, the average intervention duration was 20-week. Short-term trials occupied two-thirds (*n* = 29, 67%), and one-third were long-term trials (*n* = 14, 33%).

Most trials had a high retention rate of over 80% (*n* = 33, 77%), indicating low attendance bias.

Table 6. Summary of intervention features

Intervention features	No. trials (%)	Intervention features	No. trials (%)
Model of WATs		**Combined intervention**	
Fitbit	20 (47%)	**components**	34 (79%)
Jawbone UP 24	3 (7%)	expert support	8 (19%)
Polar	3 (7%)	one-way	26 (60%)
Garmin	2 (5%)	communication	1 (2%)
Fitbug	2 (5%)	two- way	8 (19%)
Others	13 (30%)	communication	
		monetary rewards	29 (67%)
Sensor		NA	14 (33%)
pedometer	17 (40%)	**Intervention duration**	
accelerometer	26 (60%)	≤ 12 weeks	10 (23%)
		> 12 weeks	33 (77%)
		Retention rate	
		< 80%	
		≥ 80%	

Comparators, outcomes, and study design. Included trials designed blinded WATs (*n* = 4, 9%), wait-list control (*n* = 8, 19%), standard practice or usual care (*n* = 28, 65%), and blank control group (*n* = 3, 7%) as comparators. All comparators were treated the same in the analysis, according to Hodkinson, Kontopantelis [13].

Trials reported at least one PA outcome of interest, such as step counts, MVPA, LPA, and sedentary behaviors. MVPA was the most frequently reported outcomes (*n* = 31, 72%), followed by step counts (*n* = 28, 65%), sedentary behavior (*n* = 19, 44%), and the least reported was LPA (*n* = 9, 21%).

All included trials conducted RCTs. Individual-based (*n* = 38, 88%), paired (*n* = 1, 2%), and cluster-based (*n* = 4, 9%) randomization were applied. All randomization methods were treated the same in the analysis.

3.3. Risk of bias

According to the ROB assessment results (refers to Table A.3 in the Appendix), most trials had moderate-to-high-quality methodological design (*n* = 39, 91%). In comparison, a few of them might at high risk of bias as they met only one or two criteria (*n* = 4, 9%).

In detail, one trial was assessed as a high risk of selection bias because the group assignment was not based on randomization [59]. The management of incomplete data was assessed as high risk in nine trials as those omitted missing data regardless of the impact, for instance, Kenfield *et al.*, [32]. Two trials [71, 77] declared potential conflicts of interest. Thus high risks of other sources of bias were detected from them.

3.4. Overall effects of WATs

Table 7 summarized the results of meta-analyses on daily steps, weekly MVPA, LPA, and sedentary behavior. Overall, there were a significant moderate increase in daily steps and a small increase in weekly MVPA. However, the effect on LPA and sedentary behavior was small and nonsignificant. Detailed information was described in the following.

Table 7. Summary of overall effects meta-analyses

Outcomes	***k***	**Inverse-Variance Random Effects**		
		MD (95% *CI*)	I^2	*SMD* (95% *CI*)
Steps/day	32	**1078.53** *** (772.18, 1384.87)	78%***	**0.50***** (0.36, 0.63)
MVPA min/week	34	**42.99***** (28.07, 57.92)	84%***	**0.33***** (0.16, 0.51)
LPA min/day	10	-0.11 (-12.27, 12.06)	88%***	0.09 (-0.28, 0.45)
Sedentary min/day	21	-0.24 (-15.83, 15.35)	98%***	0.01 (-0.46, 0.48)

Note: significant estimates are bolded; CI = confidence interval; significant codes include 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1

Steps. A total of 32 records coded from 28 trials were analyzed to estimate the effects on daily steps (see Figure A.1). WATs-based interventions were associated with a significant increase in daily steps compared with the control groups (*MD* = 1078.53, 95% *CI* 772.18-

1384.87). The average effect size reached medium level (*SMD* = 0.50, 95% *CI* 0.36-0.63). High heterogeneity (I^2 = 78%) of the effect sizes across trials was observed.

Publication bias was detected by visual inspection of the funnel plot (Figure A.2) and Eggers' test (p = 0.05). As recommended [78], we applied the trim-and-fill method to examine the sensitivity of the results to potential publication bias. It turned out that the adjusted effect was still significant at p < 0.001, suggesting the result was less likely to be impacted by publication bias. Besides, the fail-safe *N* was 2063, further suggesting the robustness of the result.

MVPA. The meta-analysis for MVPA was based on 34 records coded from 31 trials (eFigure 3). There was a significant increase in weekly MVPA when comparing intervention groups versus controls (*MD* = 42.99, 95% *CI* 28.07-57.92). The *SMD* indicated that the effect size was small (*SMD* = 0.33, 95% *CI* 0.16-0.51). The heterogeneity was significantly large in terms of the magnitude of effect sizes across trials (I^2 = 84%). Publication bias was not observed by visual inspection of the funnel plots (Figure A.4) and the Egger test (p = 0.19). The fail-safe *N* for the meta-analysis of MVPA was 712, indicating the robustness of the results.

LPA and sedentary behavior. Meta-analysis results indicated small and nonsignificant effect on LPA (*MD* = -0.11 min/day, 95% *CI* -12.27-12.06; *SMD* = 0.09, 95% *CI* -0.28-0.45) and sedentary behavior (*MD* = -0.24 min/day, 95% *CI* -15.83-15.35; *SMD* = 0.01; 95% *CI* -0.46-0.48). Thus, WATs-based intervention seemed to have no impact on the two PA outcomes, therefore they were not included in further analysis.

3.5. Analysis of Moderators

Subgroup analyses. Table 8 shown the subgroup analyses results according to participants' characteristics (i.e., gender, age, medical condition, baseline PA level) and intervention features (sensor, modes of expert support, and intervention duration). All the subgroups revealed statistically significant effects on daily steps and weekly MVPA, indicating the effectiveness of WATs across different populations and diverse intervention designs.

Participants' characteristics as moderators. Gender, age, and medical condition were significantly associated with PA outcomes of daily steps and weekly MVPA. Baseline PA level was associated with daily steps but not associated with weekly MVPA.

Specifically, the subgroup analysis for gender suggested that the male population achieved significantly more increments than females in daily steps (MD_{male} = 1324.52, 95% *CI* 942.15-1706.90; MD_{female} = 669.84, 95% *CI* 80.79-1318.90; *t* = 3.22) and weekly MVPA (MD_{male}= 108.46, 95% *CI* 44.60-172.33; MD_{female} = 69.44, 95% *CI* 39.97-98.90; *t* = 1.97).

Subgroups for age indicated the pooled effects on daily steps (MD_{older} = 1245.21, 95% *CI* 602.77-1887.66; $MD_{younger}$ = 985.08, 95% *CI* 657.74-1312.42; *t* = 2.47) and weekly MVPA (MD_{older} = 57.63, 95% *CI* 43.62-71.64; $MD_{younger}$ = 40.01, 95% *CI* 18.96-61.05; *t* = 6.41) were significantly larger in older populations than in younger populations.

Subgroup analysis by medical condition suggested a significant difference between participants with versus without a medical condition in favor of the former for increment in daily steps ($MD_{with\ a\ medical\ condition}$ = 1342.30, 95% *CI* 829.60-1854.99; $MD_{without\ a\ medical\ condition}$ = 818.32, 95% *CI* 514.97-1121.67; *t* = 6.90) and weekly MVPA ($MD_{with\ a\ medical\ condition}$ = 56.48, 95% *CI* 40.00-73.97; $MD_{without\ a\ medical\ condition}$ = 30.59, 95% *CI* 8.76-52.41; *t* = 7.42)

Sub-grouping by baseline PA level suggested that inactive participants significantly increased more daily steps ($MD_{below\ guidelines}$ = 1158.22, 95% *CI* 708.86-1607.58;

$MD_{above\ guidelines}$ = 968.24, 95% *CI* 627.38-1309.09; *t* = 2.58) than those already active at baseline. However, there is no difference regarding weekly MVPA.

Intervention features as moderators. The type of sensors and intervention duration significantly impacted the effect size of WATs-based interventions on daily steps and weekly MVPA. The delivery modes of expert support were associated with daily steps but not weekly MVPA.

Subgroup analysis by sensors suggested that accelerometer-based WATs had a significantly larger effect than pedometer-based WATs for daily steps ($MD_{accelerometer}$ = 1153.83, 95% *CI* 723.94-1583.72; $MD_{pedometer}$ = 1009.85, 95% *CI* 554.06-1465.64; *t* = 1.78) and weekly MVPA ($MD_{accelerometer}$ = 51.94, 95% *CI* 31.39-72.50; $MD_{pedometer}$ = 24.00, 95% *CI* 14.77-33.23; *t* = 10.72)

According to tests of expert support types, one-way communication had more effects for daily steps ($MD_{one-way\ communication}$ =1556.94, 95% *CI* 746.91-2366.98; $MD_{two-way\ communication}$ =1075.87, 95% *CI* 645.51-1506.23; *t* = 3.23) than two-way communication. The between-group difference for weekly MVPA was small and nonsignificant.

As for subgroup analysis by intervention duration, short-term interventions reported more effects than long-term interventions for improving daily steps ($MD_{\leq 12-\mathrm{week}}$ = 1402.21, 95% *CI* 950.00-1766.17; $MD_{>12-\mathrm{week}}$ = 528.12, 95% *CI* 258.15-785.24; *t* = 13.4) and weekly MVPA ($MD_{\leq 12-\mathrm{week}}$ = 56.46, 95% *CI* 34.83-68.31; $MD_{>12-\mathrm{week}}$ = 30.89, 95% *CI* 4.99-56.79; *t* = 4.89).

Table 8. Subgroup analyses of potential moderators: participants' characteristics and intervention features.

Sub-group	Daily steps				MVPA minutes/week			
	k	*MD* (95% *CI*)	*p*[a]	t-test (*p*[b])	*k*	*MD* (95% *CI*)	*p*[a]	t-test (*p*[b])
Gender				**3.22 (0.02)**				**1.97 (0.08)**
male	3	1324.52 (942.15-1706.90)	<0.001		3	108.46 (44.60-172.33)	0.001	
female	4	699.84 (80.79-1318.90)	0.03		6	69.44 (39.97-98.90)	<0.001	
Age				**2.47 (0.02)**				**6.41 (<0.001)**
<60-year	21	985.08 (657.74-1312.42)	<0.001		23	40.01 (18.96-61.05)	<0.001	
≥60-year	11	1245.21 (602.77-1887.66)	<0.001		11	57.63 (43.62-71.64)	<0.001	
Medical condition				**6.90 (<0.001)**				**7.42 (<0.001)**
without	16	818.32 (514.97-1121.67)	<0.001		16	30.59 (8.76-52.41)	0.006	
with	16	1342.30 (829.60-1854.99)	<0.001		18	56.48 (40.00-73.97)	<0.001	
Baseline PA level				**2.58 (0.01)**				-0.65 (0.52)
below guidelines	22	1158.22 (708.86-1607.58)	<0.001		12	40.98 (19.77-62.19)	<0.001	
above guidelines	10	968.24 (627.38-1309.09)	<0.001		22	43.47 (23.24-63.70)	<0.001	
Sensors				**1.78 (0.08)**				**10.72 (<0.001)**
pedometers	14	1009.85 (554.06-1465.64)	<0.001		10	24.00 (14.77-33.23)	<0.001	
accelerometers	18	1153.83 (723.94-1583.72)	<0.001		24	51.94 (31.39-72.50)	<0.001	
Expert support				**3.23 (0.004)**				-0.39(0.69)
one-way communication	9	1556.94 (746.91-2366.98)	<0.001		7	43.96 (14.55-73.37)	0.003	
two-way communication	15	1075.87 (645.51-1506.23)	<0.001		19	41.58 (21.99-61.16)	<0.001	
Duration				**13.4 (<0.001)**				**4.89 (<0.001)**
≤12-week	23	1358.08 (950.00-1766.17)	<0.001		22	51.58 (34.83-68.31)	<0.001	
>12-week	9	521.70 (258.15-785.24)	<0.001		12	30.89 (4.99-56.79)	0.02	

Note: statistically significant between-group difference are bolded; CI = confidence interval;

Meta-regression analyses. Mixed-effect meta-regression was applied to examine the explanatory power of the identified participants' characteristics and intervention features for WATs' effects on daily steps and weekly MVPA.

Meta-regression analysis for daily steps. Results of the meta-regression model for daily steps were presented in Table 9. The current model slightly reduced the amount of unexplained heterogeneity from I^2 = 78% to 71% (Table 6), but the residual heterogeneity was still significant (QE = 65.14, p < 0.01). The amount of variation accounted for was R^2 = 6%, whereas, the model was not statistically significant (F = 1.34, p = 0.27).

Among the tested factors, expert support modes and intervention duration were statistically significant at p <0.1. Specifically, interventions with expert support delivered through one-way communication exerted more improvements in daily steps (β = 1209.74, p = 0.05) than those delivered through two-way communication (β = 293.79, p = 0.53). The coefficient estimates of duration indicated that long-term interventions reported fewer increments of daily steps (β = -907.97, p = 0.08) than short-term interventions. These findings were consistent with the results of subgroup analyses (Table 8). Although significant differences were observed in subgroup analyses, gender, age, medical condition, PA level, and sensors turned nonsignificant in the model with all the seven factors.

Table 9. Results of the meta-regression model for daily steps

Model	Estimates: β	
F = 1.34, p = 0.27;	intercept	**1250.14 ***
R^2 = 6%;	Gender: male	-219.91
I^2 = 71%;	Gender: female	-160.77
QE = 65.14, p < 0 .01	Age: ≥60 years	216.84
	Medical condition: with	-72.76
	PA level: above	-463.03
	Sensor: accelerometer	-368.59
	Expert support: one-way communication	**1209.74 ***
	Expert support: two-way communication	293.79
	Duration: >12-week	**-907.97^**

Note: significant estimates of covariates are bolded*;* significant codes include 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1

Meta-regression analysis for MVPA. Table 10 presented the results of the meta-regression model for weekly MVPA. The multivariable model was significant (F = 2.77, p = 0.02) and explained a large part of the total variance (R^2 = 53%). The identified covariates reduced unexplained heterogeneity across studies from I^2 = 84% (Table 6) to 57%. However, the residual heterogeneity was still significant (QE = 31.12, p < 0.01).

According to the coefficients, weekly MVPA was larger when interventions focused on males (β = 70.41, p = 0.01). The finding of gender was in line with subgroup analyses (Table 7). However, the impact of other covariates turned nonsignificant in the meta-regression analysis.

Table 10. Results of the meta-regression analysis for weekly MVPA

Model	**Estimates: β (p)**	
F = 2.77, p = 0.02; R^2 = 53%; I^2 = 57%; QE = 31.12, p < 0 .01	Intercept	**36.87^**
	Gender: male	**70.41 ****
	Gender: female	**36.06^**
	Age: ≥60 years	1.77
	Medical condition: with	23.74
	PA level: above	3.61
	Sensor: accelerometer	12.49
	Expert support: one-way communication	-31.88
	Expert support: two-way communication	-30.06
	Duration	-15.28

Note: significant estimates of covariates are bolded; significant codes include 0 '***' 0.001 '**' 0.01 '*' 0.05 '^' 0.1

4. Discussion

4.1. Key findings

RO1: Overall, we found that interventions with WATs had a medium effect on daily steps and a small effect on MVPA. The positive findings were consistent with some previous reviews [13, 17, 20, 22]. By involving studies on a broad range of populations, this review provides evidence with greater generality in supporting the use of WATs for improving steps and MVPA.

However, this paper could not support the use of WATs for improving LPA or reducing sedentary behavior. Comparison of findings of LPA was not possible due to a lack of quantitative assessment in previous review papers. As for findings on sedentary behavior, similar results were reported by Ringeval, Wagner [24], who found that Fitbit-based interventions did not improve sedentary behaviors. We assume that the null effect for LPA and sedentary behavior might because: existing WATs-based intervention mainly targeted at motivating individuals' conscious effort to exercise (i.e., to reach weekly MVPA goals or daily steps goals) rather than altering habitual behaviors (i.e., to change LPA or sedentary behavior). It is known that regulatory processes of conscious behaviors differed from habitual activities [79]. Regulatory strategies for improving conscious exercises, such as monitoring, goal settings, feedbacks, and rewards, are often applied in existing WATs designs (e.g., [60, 64]). However, habit reversal or formation strategies, such as automatic association and priming effects, are not common in existing WATs-based PA intervention designs.

RO2: Daily steps and weekly MVPA were associated with participants' characteristics and intervention features in similar patterns (see Table 7 and Figure 2), which was reasonable as the two measurements reflecting the same construct of PA levels. The identified moderators explained a large part of the variance of weekly MVPA (Table 10) but failed to explain the variance of daily steps across studies (Table 9).

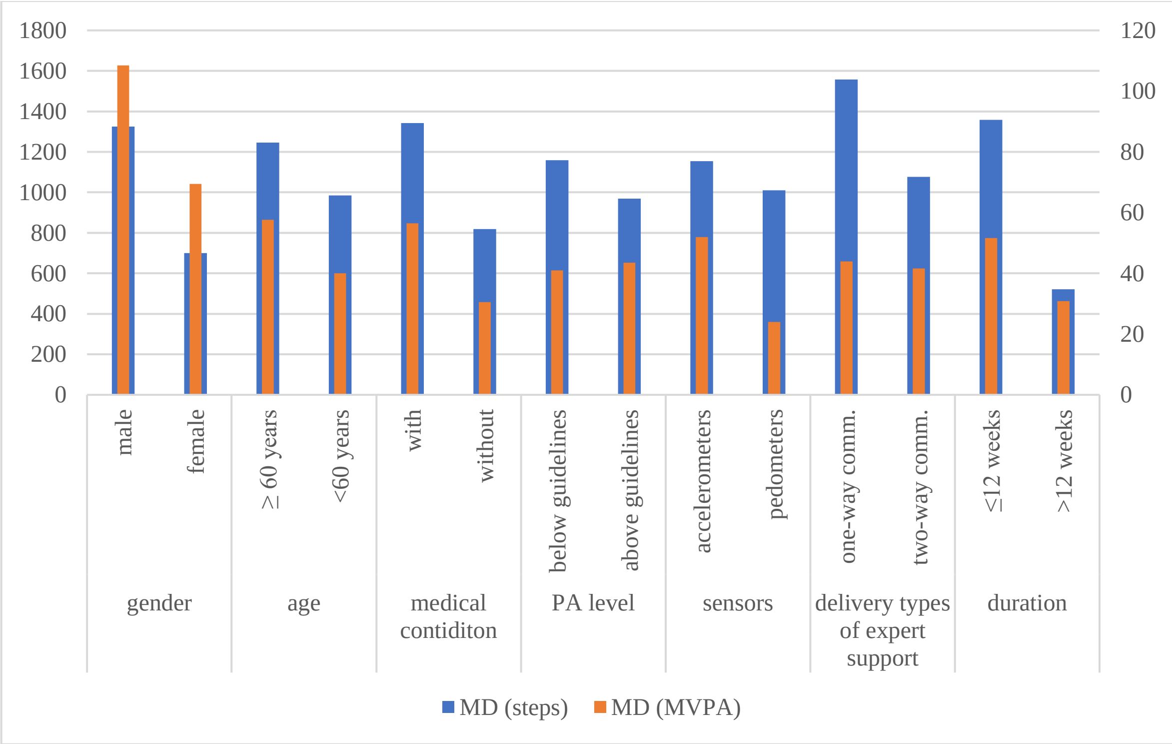

Figure 2. Pooled MD for daily steps and weekly MVPA from subgroup meta-analysis

Participants' characteristics. We found that the effect size of WATs-based interventions for PA promotion varied across different populations (see Table 7 and Figure 2). Specifically, subgroup analyses indicated that the effects of WATs-based interventions tended to be larger when involved males, older, or participants with medical conditions, for both steps and MVPA. Also, inactive participants achieved more daily steps than active participants, but there was no difference for weekly MVPA.

Franssen et al. [11] investigated the impact of participants' gender and age on the effects of consumer WATs for improving PA in a meta-analytic review. Their findings of gender were consistent with our findings (i.e., male participants benefit more than females from WATs-based PA interventions). However, their study reported that younger users had a higher increase in PA, which conflicted with ours. The impacts of participants' characteristics of with/without medical condition and baseline PA level were not examined in previous review papers. Because of lacking enough evidence in the literature, findings of WATs' effect among different populations from this review were not conclusive and need further verification in the future.

Intervention features. Interventions that applied accelerometer-based WATs reported a larger effect size than pedometer-based trackers. The finding indicated that monitoring PA information in detail instead of reporting simple step counts made WATs more useful for users. In contrast, Hodkinson, Kontopantelis [13] reported that pedometers demonstrated more increase in PA than accelerometers ($SMD_{\text{pedometers}}$ = 0.52, 95% *CI* 0.32-0.72; $SMD_{\text{accelerometers}}$ = 0.30, 95% *CI* 0.16-0.44). However, we noticed that Hodkinson, Kontopantelis [13] did not assess steps and MVPA separately but compared pedometers' impact on daily steps with accelerometers' impact on MVPA/total PA [13]. As we pooled a larger effect on daily steps than MVPA (Table 7) from both accelerometer- and pedometer-based WATs, we assume that the effect size of pedometers might be exaggerated compared to accelerometers in Hodkinson's study [13].

When comparing the two delivery modes of expert support, we found human-dependent two-way communication (e.g., face-to-face communication) was no better than computer-facilitated one-way communication (e.g., automated message push). A similar conclusion was drawn from an experimental study, which found that combined interviewing into a Fitbit Charge group failed to achieve more benefits [80]. Such findings promise to transform traditional human-depended PA interventions into more accessible and cost-effective computer-delivered interventions during health practices.

The investigation of intervention duration suggested that shorter interventions reported more increment for both PA outcomes than interventions with longer periods. Along with existing studies [1, 12], this indicated that the effects of WATs lessened over time.

The explanation power of the identified covariates. The seven factors' meta-regression analysis was significant and explained a large part of the effect-size variation (R^2 = 53%) for weekly MVPA. However, it was not effective for explaining the cross-study variance of daily steps. Predictors of daily steps resulting from WATs-based intervention remain to be explored, and the explanation power of them for weekly MVPA needs to be verified in future studies.

4.2. Implications for literature

Based on the key findings discussed above, four theoretical contributions are summarized and implications for relevant literature are proposed.

First, we provided a more comprehensive and fine-grained understanding of the effectiveness of WATs by including steps, MVPA, LPA, and sedentary behavior as PA outcomes. The effectiveness of WATs depends on the applied PA measurements (i.e., medium effect in steps, small effect in MVPA, null effect in LPA, and sedentary behavior). As related empirical studies are still accumulating, future work is suggested to look into different PA outcome measurements to present a broader picture.

Second, we found that WATs had no impact on LPA and sedentary behaviors. We speculate that existing WATs-based PA intervention strategies did not help in modifying habitual activities [79]. Future trials and conceptual studies are warranted to improve WATs technologies and interventions to support the regulation of habitual activities.

Third, we found that the degree of effectiveness was affected by participants' characteristics and intervention features. There is a trend that the increment of PA tends to be larger when interventions involved males, older, or participants with a medical condition. Simultaneously, accelerometer-based, short-term interventions reported larger PA outcomes. However, these findings were not conclusive and more evidence is needed in future research.

Besides, it is unclear why the increment in PA was different across populations and how WATs-based intervention features influenced PA outcomes. For a deeper understanding of the role of WATs in nudging users' behavior change, we suggest more theory-driven studies to investigate the psycho-social mediators linking the technological interventions to behavioral outcomes.

Fourth, the findings of this review might be biased to developed countries because none of the included studies were conducted in developing countries. The research and application of WATs in developing countries may be hindered by the relatively high cost and technical barriers. Future studies in developing countries are expected as societies move up the economic ladder as well as the advancement of technologies.

4.3. Implications for health practices

The findings have several implications for health practitioners, including WATs developers and health management practitioners.

First, we noticed that steps and MVPA, which are mainly featured by conscious activities, could be improved by WATs-based interventions. Also, the effectiveness of WATs for promoting steps and MVPA is reliable because the effect size reached statistical significance regardless of participants' characteristics and intervention features. Thus, we recommend that health management practitioners consider WATs a reliable intervention tool for improving steps and MVPA.

Second, no evidence was found to support the use of WATs for improving LPA or sedentary behaviors, which were mainly accumulated by an individual's routine/habitual PA. The effectiveness of WATs for increasing steps and MVPA lessened over time, indicating the importance of developing an internal exercise habit rather than depending on external interventions. More efforts, such as the adaptation of environmental factors, are needed to alter habitual PA, in addition to WATs. For instance, the introduction of a flexible sit-stand workstation combined with WATs may have substantial benefits for reducing the sitting time of office-based employees [81].

Third, related practitioners should be aware that different types of populations might respond differently to WATs-based interventions. As the female, younger, and healthy populations benefit less than other populations, there needs more effort to focus on these populations. For instance, designers could help those populations by developing their self-determined motivations, as suggested by James et al. [5].

Fourth, accelerometer-based WATs, which provide in detail PA information [4], including step counts, and timing and intensity level of PA, are more effective for promoting PA than pedometers [82]. Therefore, we suggest future PA interventions apply accelerometer-based PA trackers rather than pedometers.

Fifth, the results showed that human-dependent two-way communication was no better than computer-facilitated one-way communication for delivering WATs-based PA interventions. As human resources are generally high cost and with limited access [70], designers must consider computer-facilitated communication as an alternative way of delivering WATs-based PA interventions.

5. Conclusion

This systematic meta-analytic review analyzed 48 papers (based on 43 distinct trials) involving 5,808 participants. We found promising evidence on the effects of WATs for promoting daily steps and weekly MVPA. The extent to which the WATs help was contextual—that is, the effect of WATs for promoting PA was contingent on the type of users and the design and delivery of interventions. As the emerging of more empirical studies, future work is needed to examine the validity of the findings from the current study. Theory-driven studies are warranted to deeply understand the psycho-social mechanisms underlying the relationship between the use of WAT and users' PA. Also, we found that interventions with WATs had no impact on LPA and sedentary behavior. Thus, the development of strategies specifically for modifying habitual PA, such as sedentary behavior and LPA, is one of the directions for advancing design for advancing future WAT technology design.

Appendix

Appendix was provided as a supplement document.

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CRediT authorship contribution statement

Caining Li: Conceptualization, Methodology, Data Curation, Formal Analysis, Writing-original draft, Writing-review & editing.

Xiaoyu Chen: Conceptualization, Data Curation, Writing-original draft, Writing-review & editing.

Xinhua Bi: Supervision, Writing-review & editing.

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