Time Trends in Physical Activity Using Wearable Devices: A Systematic Review and Meta-analysis of Studies from 1995 to 2017

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ABSTRACT

CONGER, S. A., L. P. TOTH, C. CRETSINGER, A. RAUSTORP, J. MITÁŠ, S. INOUE, and D. R. BASSETT. Time Trends in Physical Activity Using Wearable Devices: A Systematic Review and Meta-analysis of Studies from 1995 to 2017. *Med. Sci. Sports Exerc.*, Vol. 54, No. 2, pp. 288–298, 2022. **Introduction:** Conflicting evidence exists on whether physical activity (PA) levels of humans have changed over the last quarter-century. The main objective of this study was to determine if there is evidence of time trends in PA, from cross-sectional studies that assessed PA at different time points using wearable devices (e.g., pedometers and accelerometers). A secondary objective was to quantify the rate of change in PA. **Methods:** A systematic literature review was conducted of English-language studies indexed in PubMed, SPORTDiscus, and Web of Science (1960–2020) using search terms (time OR temporal OR secular) AND trends AND (steps per day OR pedometer OR accelerometer OR MVPA). Subsequently, a meta-analytic approach was used to aggregate data from multiple studies and to examine specific factors (i.e., sex, age-group, sex and age-group, and PA metric). **Results:** Based on 16 peer-reviewed scientific studies conducted between 1995 and 2017, levels of ambulatory PA are trending downward in developed countries. Significant declines were seen in both males and females ($P < 0.001$) as well as in children ($P = 0.020$), adolescents ($P < 0.001$), and adults ($P = 0.004$). The average study duration was 9.4 yr (accelerometer studies, 5.3 yr; pedometer studies, 10.8 yr). For studies that assessed steps, the average change in PA was −1118 steps per day over the course of the study ($P < 0.001$), and adolescents had the greatest change in PA at −2278 steps per day ($P < 0.001$). Adolescents also had the steepest rate of change over time, expressed in steps per day per decade. **Conclusions:** Evidence from studies conducted in eight developed nations over a 22-yr period indicates that PA levels have declined overall, especially in adolescents. This study emphasizes the need for continued research tracking time trends in PA using wearable devices. **Key Words:** STEPS PER DAY, PEDOMETER, ACCELEROMETER, SECULAR TREND, TEMPORAL TREND, TECHNOLOGY

There is evidence to suggest that levels of physical activity (PA) have been trending downward over the past couple of decades. One way to address this question is to examine societal indicators of PA domains. For adults, PA domains typically include household, occupational, active transport, and leisure-time activities (including sport). For children, PA domains include household, school-based, active transport, and after-school activities (including sport). Reviews in both U.S. adults (1–3) and U.S. children (4,5) indicate that substantial declines have occurred within several domains, except sports/leisure activities. For instance, U.S. Department of Labor statistics indicate that the percentage of high-active occupations has diminished, whereas the percentage of low-active occupations has increased (6). Time use surveys suggest that the amount of time women spend on housework has declined (2). Travel survey data from the United States indicate that the percentage of trips taken by walking and cycling has declined in both children (7–9) and adults (10). On the other hand, data obtained with PA questionnaires and time-use surveys suggest that leisure-time PA (LTPA) in adults has increased over the past couple of decades (11–13). LTPA includes purposeful exercise (i.e., PA done to improve health, fitness, or performance) and sport. The percentage of U.S. high school youth who participate in daily physical education has declined (14), but participation in high school sport has increased dramatically in females but not males (15). Studies conducted in Brazil (16), Australia (17), Finland (18), Canada (19), and Russia (20) indicate that

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similar changes in PA within specific domains have occurred in other parts of the world (21).

Self-report methods are often used as indicators of PA in large populations because they are simple, inexpensive, and capable of quickly capturing data (22). However, there are several potential problems with using data sources such as these to examine trends in overall PA. For example, the self-report data are often categorical (e.g., high-active occupation vs low-active occupation); they are often specific to one PA domain (or they show disparate changes in various domains), and they are prone to several sources of bias and measurement error, including the cognitive challenge of recalling intermittent activities over a day, the challenge of how to decide on the classification of activities while multitasking, and the potential for social desirability bias. This has made it challenging to determine if overall levels of PA are rising or falling and to quantify the magnitude of the changes in PA.

In 2012, Ng and Popkin (23) examined time trends in PA in five countries (United States, United Kingdom, Brazil, China, and India). They used time allocation and occupational data from multiple data sets, combined with estimated energy expenditures obtained via the Compendium of PA, to compute domain-specific and overall PA energy expenditure in adults. The slight upward trends in LTPA in the United States, United Kingdom, and Brazil were small in relation to the large declines observed in other domains, in every country. Overall levels of PA energy expenditure (expressed as MET-hours per week) declined in all countries, over study periods ranging from 1965–2009 to 2000–2005 (23).

Over the past quarter-century, other methods of assessing PA have been developed that provide a more direct assessment of overall PA. Wearable devices respond to a user's movements and can objectively quantify PA. Traditionally, PA is measured as minutes of moderate to vigorous PA (MVPA) per day. However, with the advent of wearable devices, many studies began to express PA as total steps per day or activity counts per minute (CPM). Although wearable devices have their own unique limitations, two advantages of relying on data obtained from wearable devices are as follows: 1) it eliminates "recall bias" that may be present when using PA questionnaires, and 2) it provides a measure of the total ambulatory activity performed throughout the day, as opposed to PA performed within a specific domain.

Thus, the main purpose of this study was to determine if there is evidence of time trends in PA, from cross-sectional studies that assessed PA at different time points using wearable devices. A secondary objective was to quantify the rate of change in PA. To answer these questions, a systematic literature review was conducted to identify studies that conducted repeated, cross-sectional assessments of PA within a specific population at two or more time points, using wearable devices (i.e., pedometers or accelerometers). Subsequently, a meta-analytic approach was used to aggregate data obtained from multiple studies and to examine experimental factors (i.e., sample population characteristics and PA metrics) associated with the studies that could account for the variability among the included studies.

METHODS

Systematic literature review. For this study, the preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines were followed (24). Systematic searches of PubMed, SPORTDiscus, and Web of Science electronic databases were completed using the following search terms: (time OR temporal OR secular) AND trends AND (steps per day OR pedometer OR accelerometer OR MVPA). The time period from January 1, 1960, to May 31, 2020, was examined. However, because population-based research almost never used wearable devices (e.g., pedometers and accelerometers) before 1995 (25,26), no relevant studies that included data collected before 1995 were located. To complete a thorough literature search, reference lists of accepted articles in peer-reviewed journals were screened, and experts in the PA field were consulted to identify additional, potentially relevant articles.

The dependent variable was PA, expressed either as steps per day or average CPM. The most commonly reported metric was steps per day, which has seen increasing acceptance in scientific studies in recent years. Steps per day has several advantages. It is a measure that is easily understood by researchers and laypersons, and it is objective, valid, and reliable (25). When applied to intervention studies, a daily step goal is motivational (27). Steps per day also lends itself to being translated into public health recommendations (28). For ActiGraph accelerometer studies, we chose to report PA as CPM. CPM is similar to total activity counts per day (TAC per day) (29,30). The difference is that CPM has a built-in adjustment for monitor wear time, whereas TAC per day does not. Both CPM and TAC per day are directly computed from acceleration and are unaffected by the choice of cut points or algorithms used to estimate minutes of MVPA per day (29). This improves data harmonization and comparison of results across multiple studies.

Articles were included for analysis if they met the following criteria: 1) included an objective measure of PA (i.e., steps per day or average CPM) using a wearable activity monitor; 2) assessments were secular in nature, examining sample populations of the same age and sex on at least two separate time points separated by at least 1 yr; 3) the same model of pedometer or accelerometer was used to assess PA at each time point within each study; 4) the wearable activity monitor was worn on the same location on the body for each assessment within each study; 5) assessments were at least 1 d in duration (all waking hours, except when performing water activities); 6) studies did not include an intervention as a component of the experimental protocol (e.g., intervention for increasing total PA or weight loss); 7) articles were published or available in English; and 8) participants within each study were generally healthy (i.e., studies specifically targeting obese, overweight, or those who lived in institutionalized settings were excluded). Twenty-six articles were identified for potential analysis. After full text review, 10 articles were excluded for reasons including: PA was determined by self-report methods, samples overlapped with other articles, multiple devices used at different time points, no inclusion of secular-type sampling, and review article. A total of 16 studies were included in the analysis (12,31–45). The review and the selection process for the identification of included articles are summarized in Figure 1.

Statistical analysis. PA data were extracted from each study in the form of means, SD, and sample sizes. Data from each study were converted into the same format by calculating the effect size (ES) as the standardized difference in means:

$$\frac{\left(M_{\text{Time point}_1} - M_{\text{Time point}_2}\right)}{\text{SD}_{\text{within}}} \quad [1]$$

where M is the mean and $\text{SD}_{\text{within}}$ is the within-groups SD, pooled across groups and calculated as follows (46):

$$\sqrt{\frac{(n_1-1)\text{SD}_1^2 + (n_2-1)\text{SD}_2^2}{n_1+n_2-2}} \quad [2]$$

where n_1 and n_2 are the sample sizes of the two groups, and SD_1 and SD_2 are the SD in the two groups.

In studies that reported more than two time points, the data from the first and last time points were used to calculate the ES. Every study reported data from at least two different groups (i.e., men and women; children, adolescents, and adults; etc.). The average ES values for each group and their associated variances were used to calculate the meta-analyses' overall ES for each study. The overall ES values were calculated using a random-effects model that accounts for true variation in effects occurring from study to study as well as random error within a given study. The random-effects model was chosen over a fixed-effects model because experimental factors such as the PA metric (i.e., total steps per day vs. average CPM), population demographics, and study duration varied across studies. An ES of zero would indicate that there were no differences between the PA levels reported at time point_1 and time point_2; a negative ES would indicate that the PA had decreased across the time points, and a positive ES would indicate that PA had increased across the time points. A leave-one-out analysis was completed to ensure that the results of a single study did not unduly influence the overall results.

To assess whether various experimental factors could explain the variation in ES observed among the studies, subgroup meta-analyses were also conducted. Subgroup meta-analyses were used to examine the effects of categorical data: PA metric, sex, age-group, and sex by age-group. Age categories of participants were as follows: children (4–11 yr), adolescents (11–19 yr), and adults (>19 yr) (47).

ES calculated as the standardized mean difference allows for the inclusion of all objective PA assessment methods into one analysis. However, the resulting ES lacks units, thus limiting its interpretability. By analyzing the studies that reported PA using similar units separately, it is possible to quantify the magnitude of the decline in PA as either steps per day or average CPM. Therefore, to aid in the clinical interpretation of the data, meta-analyses were also conducted separately on the studies that used steps per day data and those that used CPM, by calculating the mean difference ([time point_1 − time point_2]). The overall mean differences were calculated using a random-effects model. In addition, because the study durations varied,

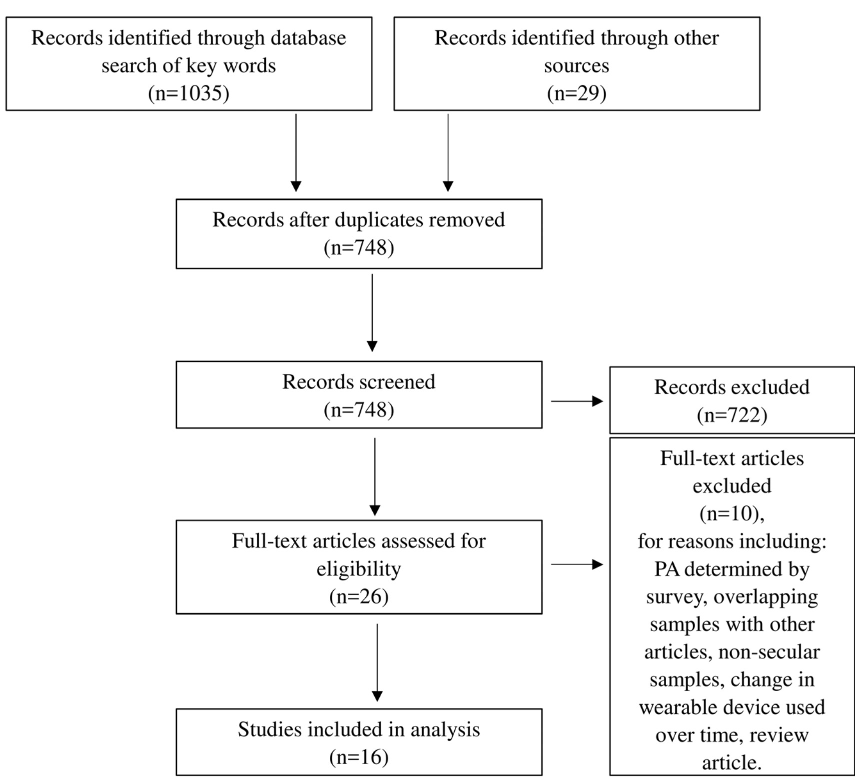

FIGURE 1—Selection of articles for meta-analysis of secular changes in PA, as measured by pedometers or accelerometers.

the mean differences were divided by the study duration (in years) to determine average change in PA per year. Then, the rate of change per decade was estimated by multiplying by 10. These values were subsequently weighted based on the study sample size to determine the weighted average change in PA per decade.

All calculations were completed using Comprehensive Meta-Analysis, version 2.2.064 (Biostat, Eaglewood, NJ). ES values of |0.2|, |0.5|, and |0.8| were considered small, medium, and large, respectively, with ES of less than |0.2| considered to be trivial (48). Unless noted, all data are presented as mean ± 95% confidence interval (CI). An α level of 0.05 was used for all analyses to indicate statistical significance.

RESULTS

Sixteen studies conducted in developed countries and published between 2009 and 2020 were included in this meta-analysis. Some of the studies came from large nationally representative samples, whereas others were from sampling frames as small as a single school. There were a total of 256,876 participants (120,320 males and 136,556 females) between the ages of 4 and ≥90 yr that included data collected between 1995 and 2017. Because some studies collected data for more than two data points, only the sample sizes from the first and last data collection periods were used in the analysis. Thus, data from 56,650 participants (26,928 males and 29,722 females) were included in this analysis. The studies reported 24 groups of data from male participants and 24 groups from female participants. Thirteen of the studies focused on youths 19 yr of age or younger, whereas three studies included data for adults over the age of 19 yr (Table 1). Participant populations from eight different countries across Europe (Norway, Czech Republic, Denmark, Greece, and Sweden), Asia (Japan), and North America (Canada and United States) were included in the analysis. All of these are developed countries, although that was not an inclusion criterion. Graphs showing the average steps per day, and how it changed over time, are shown in Figures 2 and 3.

The sample sizes of the studies varied considerably (mean = 3540, median = 879, range = 233 to 29,629). Of the 16 studies, 14 reported PA data for males and females separately. In the studies that did not report data for males and females separately, we contacted the study authors, and they reanalyzed their data to make it suitable for inclusion in our analysis (30,43,44). The duration of the studies also varied considerably (mean = 9.4 yr, median = 8.5 yr, range = 3 to 21 yr). Twelve studies (12,31,33–37,39–42,45) reported PA data from one combined age-group, whereas four studies (31,32,38,43) reported PA data for multiple age-groups. We used the general age-group classifications of children (<11 yr), adolescents (11–19 yr), and adults (>19 yr) (47). In some cases, the reported age-groups in a study may have differed slightly from these categories. For example, Matthiessen et al. (12) used

TABLE 1. Study characteristics for studies included in the meta-analysis.

Author	Years of Data Collection	No. of Assessments	*N*	Age Range (yr)	% Male	Device and Model	Outcome Measure	Country	Sampling Technique
Cameron et al. (31)[a]	2006–2014	7	38325[b]	5 to 19	50.5	Yamax SW-200	Steps per day[c]	Canada	Cross-sectional, nationally representative sample
Gortmaker et al. (32)	2003–2006	2	3381	6 to 19	50.6	ActiGraph 7164	CPM	United States	Cross-sectional, nationally representative sample
Itoi et al. (33)	1999–2009	2	233	11 to 12	50.6	Kenz Lifecorder EX	Steps per day[d]	Japan	Convenience
Kolle et al. (45)	1999–2005	2	718	9[e]	53.2	ActiGraph 7164	CPM	Norway	Cross-sectional cluster sampling
Matthiessen et al. (12)	2007–2012	2	1624	18 to 75	48.2	Yamax SW-200	Steps per day[c]	Norway	Cross-sectional, nationally representative sample
Mitáš et al. (34)	2010–2017	3	1908	15 to 19	40.8	Yamax Digiwalker SW-700	Steps per day[c]	Czech Republic	Cross-sectional cluster sampling[f]
Møller et al. (35)	1997–2004	2	1562	8 to 10	44.7	ActiGraph 7164	CPM	Denmark	Cross-sectional cluster sampling
Pelclová et al. (36)	2008–2013	6	4647	25 to 65	44.3	Yamax Digiwalker SW-700	Steps per day[c]	Czech Republic	Cross-sectional, nationally representative sample
Raustorp and Ekroth (37)	2000–2008	2	421	13 to 14	45.1	Yamax SW-200	Steps per day[d]	Sweden	Convenience
Raustorp et al. (39)	2000–2013	3	373	8 to 12	52.3	Yamax SW-200	Steps per day[d]	Sweden	Convenience
Raustorp and Fröberg (38)	2000–2017	2	894	8, 11, and 14[e]	50.3	Yamax SW-200	Steps per day[d]	Sweden	Cross-sectional cluster sampling[g]
Sasayama and Adachi (40)	2003–2017	2	834[h]	9 to 10	48.3	Kenz Lifecorder EX	Steps per day[d]	Japan	Convenience
Sigmund et al. (41)	2005–2015	2	368	4 to 7	53.5	Yamax SW-200	Steps per day[i]	Czech Republic	Cross-sectional cluster sampling[g]
Takamiya and Inoue (42)	1995–2016	22	196,642	20 to 90	46.1	Yamax SW-200	Steps per day[c]	Japan	Cross-sectional, nationally representative sample
Thompson et al. (43)	2001–2006	5	3973	8.2, 12.2, and 16.4[e]	46.7	ActiGraph GT1M	CPM	Canada	Cross-sectional cluster sampling
Venetsanou et al. (44)	2005–2017	5	973	5 to 6	49.7	Omron Walking Style Pro HJ-720IT-E2	Steps per day[d]	Greece	Cross-sectional cluster sampling[g]

[a]Cameron et al. (31) additionally included an assessment from 2005 to 2006; however, step count was assessed with a different monitor (New Lifestyles NL-2000) compared with all subsequent time points (Yamax SW-200). This assessment period has been removed from analysis to promote measurement consistency.
[b]*N* adjusted after excluding participants in the first time point (2005–2006), when data were collected with a different activity monitor compared with all subsequent time points.
[c]Each participant recorded step counts by hand in a daily diary or log.
[d]Pedometers remained sealed until step counts were recorded by researchers.
[e]Mean age; age range not included in article.
[f]Sampling was completed in a cluster of schools.
[g]Sampling was completed in schools within the same area of the country.
[h]Sample size from raw data provided in article.
[i]Study used proxy reporters (parents or teachers) to record daily step counts from pedometers.

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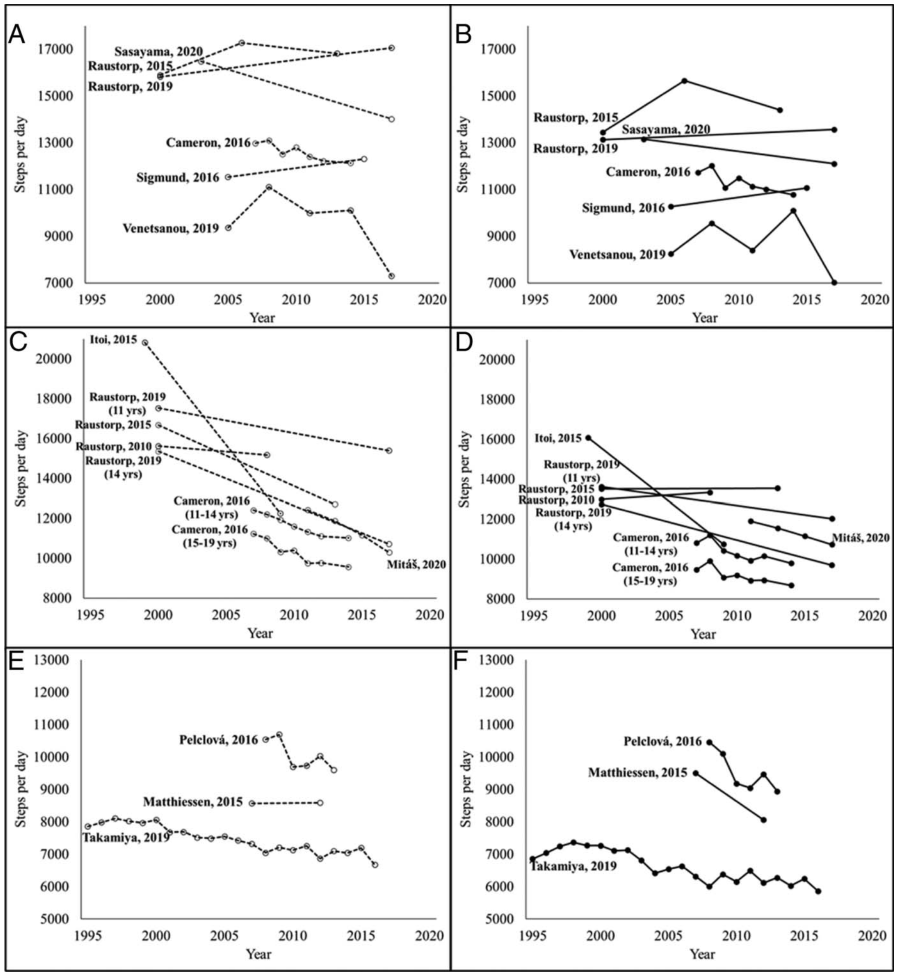

FIGURE 2—Change in steps per day across measurement periods. Panels A and B are studies of children, C and D are adolescents, and E and F are adults. ***Dashed lines*** **and** ***open markers*** **indicate boys/men.** ***Solid lines*** **and** ***closed markers*** **indicate girls/women.**

an adult age range of 18 to 75 yr, which slightly overlapped the adolescent group by the American Academy of Pediatrics definition (47). In these instances, the intended population of the study was considered when determining the appropriate age-group for data analysis. In the study by Raustorp et al. (39), longitudinal PA data were reported for a group as they transitioned from childhood to adolescence. These data were not included in the analysis by age-group.

There were a large range of ES calculated for the studies ranging from −1.703 (favoring a decrease in PA across the time points) to 0.212 (favoring an increase in PA across the time points). A majority of the studies (11 of 16) showed a decline in the calculated ES for PA across the time points (12,31,33–36,38,40,42–44). Overall, the ES was −0.284 (95% CI = −0.383 to −0.185, $P < 0.001$), which reflects a small ES favoring a decline in PA over time. Figure 4 shows the forest plot of the individual ES for each study along with the overall ES across all studies. There was significant heterogeneity across studies ($Q(15) = 316.5$, $P < 0.001$). The amount of total variance attributed to the total amount of within-study heterogeneity was high ($I^2 = 95.3\%$), whereas between-study heterogeneity was low ($\tau^2 = 0.03$). The overall results were not significantly influenced by the results from one study. A leave-one-out analysis revealed that the overall ES remained significantly different after removing any single study with ES ranging from −0.219 ($P < 0.001$) to −0.314 ($P < 0.001$).

Additional analyses were conducted to assess the effects of moderator variables (PA metric, sex, age, and sex by age) as potential factors that could explain the varying ES that were observed among the different studies. There were two different PA metrics that were used in the included studies: accelerometer CPM and steps per day. Four studies reported PA as CPM, and the remaining 12 studies reported data as steps per day. In one study (31), the NL-2000 pedometer was used during the first time point and the Yamax SW-200 was used during the remaining seven time points. To enable this study to qualify for inclusion in our analysis, data from the first time point were excluded and only the data from the second and last time points (that used the Yamax SW-200) were included in our analysis. ES values were less than zero (reflecting a decrease in PA over time) using both metrics; however, the ES using CPM (−0.078, 95% CI = −0.275 to 0.119) was not statistically different from zero ($P = 0.440$). The ES using steps per day was −0.364 (95% CI = −0.485 to −0.243, $P < 0.001$),

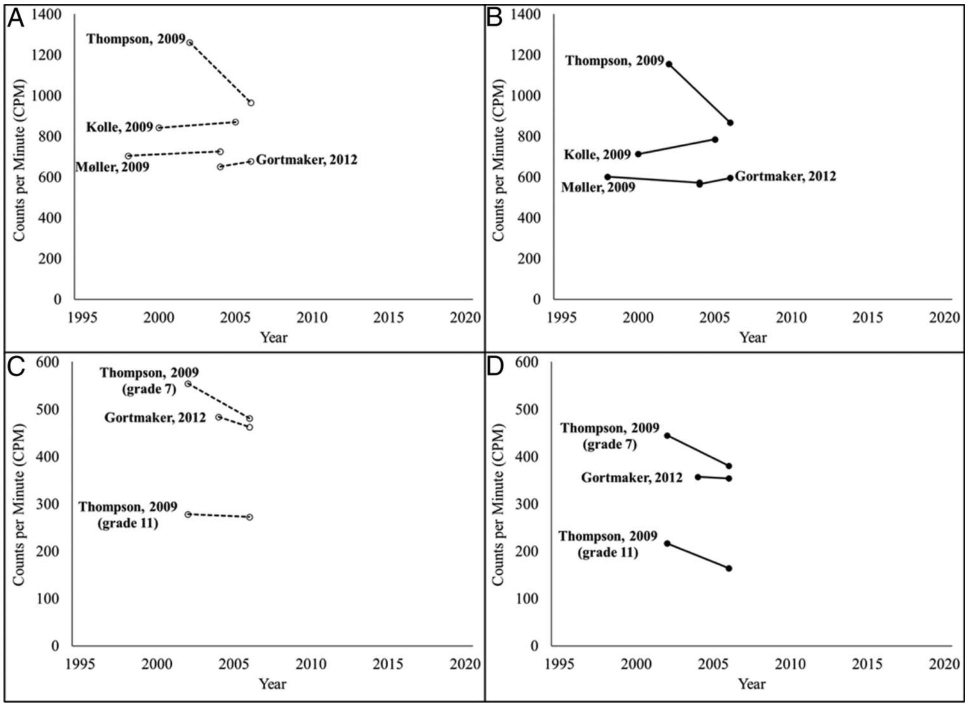

FIGURE 3—Change in CPM across measurement periods. Panels A and B are studies of children and C and D are adolescents. *Dashed lines* and *open markers* indicate boys/men. *Solid lines* and *closed markers* indicate girls/women.

indicating that the ES was significantly less than zero when steps per day were reported. There were no statistical differences between PA metrics.

In analyzing the impact of sex, the ES for both male and female subjects was less than zero (reflecting a decrease in PA over time). For male subjects, the ES was −0.310 (95% CI = −0.410 to −0.209, $P < 0.001$), whereas the ES for female subjects was −0.254 (95% CI = −0.354 to −0.153, $P < 0.001$). There were no statistical differences between sexes.

Analysis of the impact of age was completed, using three age-groups: <11 yr old (n = 6708), 11 to 19 yr old (n = 8190), and >19 yr old (n = 32,118). The ES for children <11 yr old was −0.127 (95% CI = −0.234 to −0.020, $P = 0.020$), the ES for adolescents was −0.437 (95% CI = −0.545 to −0.330, $P < 0.001$), and the ES for adults was −0.282 (95% CI = −0.472 to 0.092, $P = 0.004$). The ES in adolescents was also significantly less than that seen in children ($P < 0.001$).

Further investigation into the relationship between age-groups and sex was completed with a subgroup meta-analysis. PA in both adolescent girls (ES = −0.373, 95% CI = −0.560 to −0.186, $P < 0.001$) and adolescent boys (ES = −0.550, 95% CI = −0.739 to −0.361, $P < 0.001$) were significantly different from zero. Additionally, PA in adult women (ES = −0.378, 95% CI = −0.716 to −0.040, $P = 0.028$) were significantly

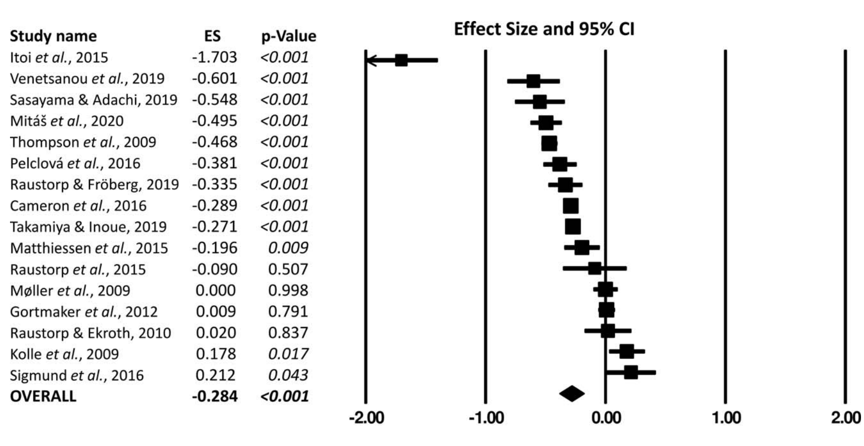

FIGURE 4—Forest plot with ES for individual studies (*squares*) and overall ES (*diamond*) on the change in objectively measured PA for all 16 studies included in the meta-analysis. Error bars indicate the 95% CI, and the size of the squares indicates the relative weight assigned to the individual study based on the sample size in the study. Studies are listed in ascending order of ES.

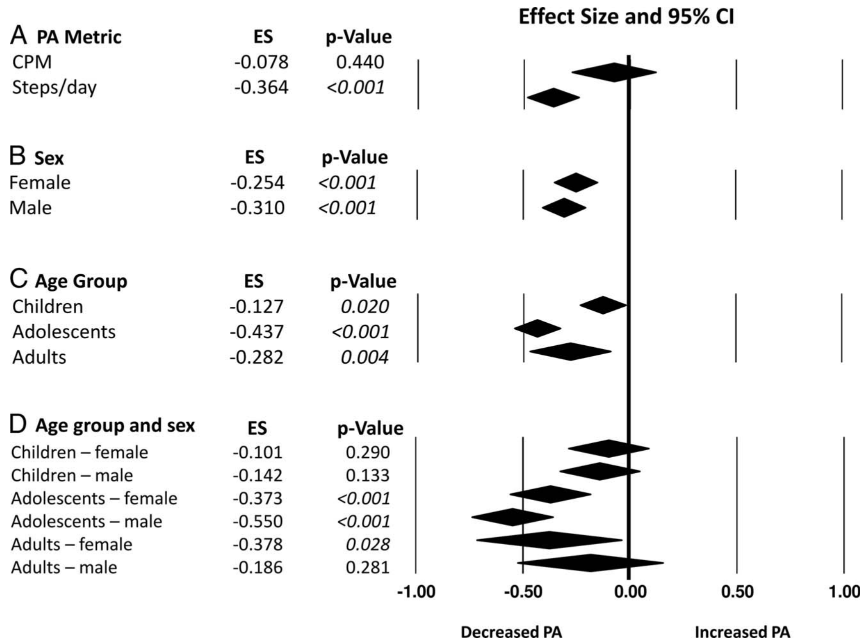

FIGURE 5—Summary ES of the subgroup meta-analyses examining the effects of PA metric (CPM vs steps per day), age-group, sex, and age-group and sex. The center of each diamond reflects the mean ES, whereas the width of the diamond represents the 95% CI.

different from zero. There were no other differences among the other age-groups and sexes. Figure 5 shows the overall ES for four of the subgroup meta-analyses that were conducted.

Figure 7 illustrates the change in PA over the duration of each study, and the overall change in PA for all studies combined. In studies that reported data as accelerometer CPM, there was an overall change of −5.36 CPM (95% CI = −109.71 to 98.99, $P = 0.920$). In studies that reported steps per day, there was an overall change of −1118 steps per day (95% CI = −1243 to −992, $P < 0.001$) (Fig. 6). Data from the children and adults indicated nonsignificant changes of −317 (95% CI = −1184 to 550, $P = 0.473$) and −1016 (95% CI = −2200 to 169, $P = 0.093$) steps per day over the course of the study, respectively. However, the steps per day of adolescents changed significantly by −2278 steps per day over the course of the study (95% CI = −3152 to −1404, $P < 0.001$) (Fig. 7).

The secondary objective of the study was to estimate the rate of change in PA. Because study duration and sample sizes varied considerably, we calculated the mean change in steps per day per decade and weighted it by the study sample size to provide a more appropriate comparison. In children, the mean rate of change was −823 steps per day per decade (95% CI = −837 to −809). In adolescents, the mean rate of change was −1497 steps per day per decade (95%

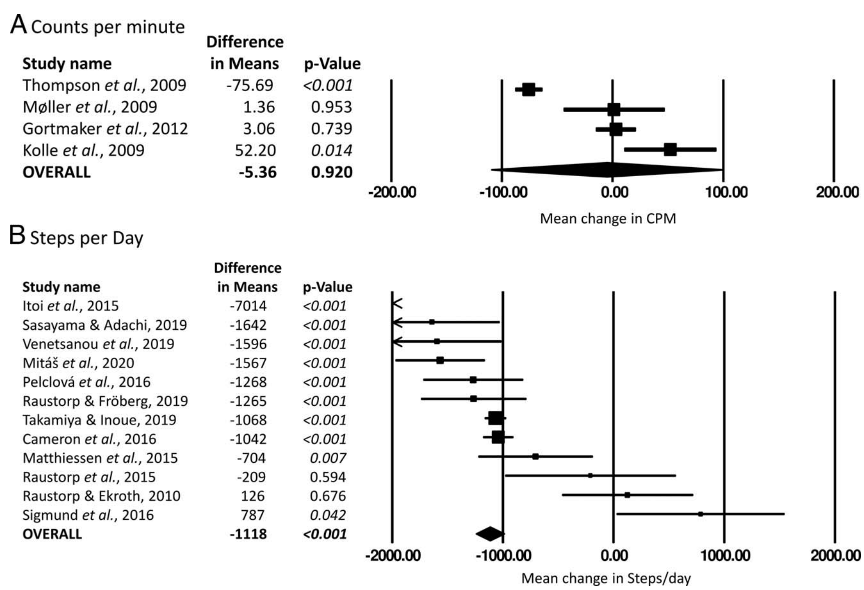

FIGURE 6—Forest plots with mean change in PA per decade for individual studies (*squares*) and overall mean change in PA per decade (*diamonds*) for studies that reported PA as mean CPM (A) and total steps per day (B). Error bars indicate the 95% CI, and the size of the squares indicates the relative weight assigned to the individual study based on the sample size in the study. Studies are listed in ascending order of mean differences.

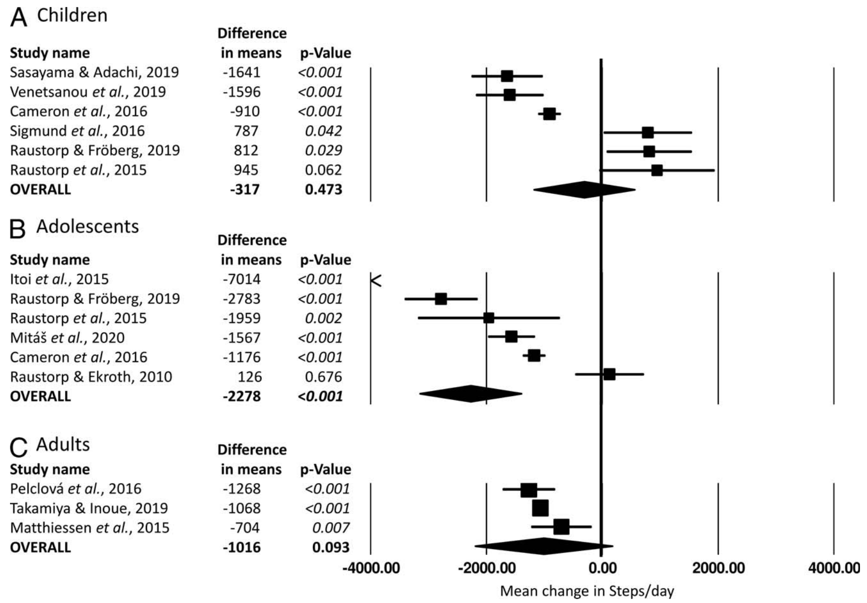

FIGURE 7—Forest plots examining the mean change in total steps per day for children (<11 yr) (A), adolescents (11–19 yr) (B), and adults (>19 yr) (C) for individual studies (*squares*) and overall mean change in steps per day (*diamonds*). Error bars indicate the 95% CI, and the size of the squares indicates the relative weight assigned to the individual study based on the sample size in the study. Studies are listed in ascending order of mean differences.

CI = −1519 to −1475). In adults, the mean rate of change was −608 steps per day per decade (95% CI = −613 to −604). The calculations for change in steps per day per decade, along with the complete data set of ES calculations, are presented in Supplemental Digital Content Tables 1 and 2 (http://links.lww.com/MSS/C434).

DISCUSSION

Based on 16 peer-reviewed scientific studies conducted in developed countries, it appears that levels of ambulatory PA are trending downward in all age-groups. Significant declines were observed in both males and females ($P < 0.001$). The decline in PA was seen most strongly in adolescents ($P < 0.001$), but significant declines in PA were also observed in children ($P = 0.020$) and adults ($P = 0.004$). The decline in PA showed a tendency to be slightly greater in women than in men. However, the decline in PA in adolescents was similar for boys and girls.

We considered whether the overall results were unduly influenced by the results of three studies that showed large decreases in PA in adolescents (Fig. 7B) (33,38,39). However, a reanalysis of the data after excluding these studies did not find this to be evident. After excluding these three studies (33,38,39), the overall ES was −0.217 (95% CI = −0.312 to −0.123, $P < 0.001$). A reanalysis by age-group after excluding these studies also indicated that the rate of decline in PA for adolescents remained significantly different from zero (ES = −0.255, 95% CI = −0.360 to −0.150, $P < 0.001$). Although these three studies reported larger decreases in PA than the other studies, they included only 2.5% of the total sample size. By mathematically weighting each study based on the sample size, the impact of a few, relatively small studies that found very large decreases in PA was reduced. In Figures 2C, 2D, 3C, and 3D, it can be observed that most studies found a decrease in PA over time in the adolescent age-group.

In youth studies that had a longer time span of at least 8 yr (31,33,34,38,40,44), a special pattern seems to occur. Studies from Europe, in both Sweden (38) and the Czech Republic (41), found no decrease in PA in younger children (i.e., 8-yr-olds and preschoolers, respectively). A study in Greek preschool children also found no decline from 2005 to 2014, but a drop in PA in 2017 (44). Some of these studies attributed the lack of decline in PA in young children to government intervention in schools and media campaigns. However, it should be noted that in slightly older children (i.e., 10–11 yr of age), declines in PA were reported in Sweden (38) and Asia (i.e., Japan) (33,40).

For teenagers in Europe, studies both in Sweden (38) and in the Czech Republic (34) found a decrease in PA in teenagers (14-yr-olds and 15- to 19-yr-olds, respectively). A study from North America, i.e., the Canadian CANPLAY study (31), supports this temporal decline in youth 11–14 yr of age and 15–19 yr of age. Previous authors have attributed the decline in PA among adolescents, at least in part, to dramatic increases in the use of mobile phones, Internet, and social media in developed nations, since around 2010 (38,39,49). Using Sweden as an example, in 2017, the percentages of girls and boys spending at least 3 $h \cdot d^{-1}$ on social media were as follows: 3% and 0% of 9-yr-olds, 10% and 2% of 11-yr-olds, and 39% and 19% of 14-yr-olds, respectively (50). Although other studies have reported that adolescent girls tend to have lower levels of PA than adolescent boys (51,52), our subgroup meta-analysis found that both adolescent boys and girls had a similar relative decline in PA. Although not mentioned in the studies we reviewed, it is possible that reductions in physical education (5,14) and walking or biking to school (7,8,53–55) also contributed to the decline in PA levels seen in adolescents.

Earlier studies in Sweden did not report a decline in pedometer-determined mean weekday steps per day among 7- to 9-yr-olds between 2000 and 2006 (56) or in 13- to 14-yr-olds between 2000 and 2008 (37). However, a more recent Swedish study revealed a substantial decline in mean steps per day among girls and boys, 11 to 14 yr of age (−12%, −12% and −24%, −30%), respectively, between 2000 and 2017 (38). In the 2017 data collection of Swedish pedometer data (38), a questionnaire was administered that asked, "How many hours/minutes did you spent on mobile phone/tablets last day?" Estimated smart phone use using self-report can be prone to bias and measurement error, including recall of intermittent activities over the course of a day, classification of activities while multitasking, and social desirability bias. Nevertheless, the results showed a moderate inverse correlation between steps per day and the use of smartphones and tablets (49). Similar declines in PA levels of adolescents have been confirmed by studies in other countries (39,49).

The adult studies we reviewed mentioned the growth of television and computer use, as well as increased use of motorized transport, as factors that explain the downward trend in PA (12,36,42,57). In the Czech Republic, increased socioeconomic status was cited as a factor in the shift to automobiles (36). However, Czech Republic residents still walk more than people in most other countries. Some researchers have cited changes in urban design as a factor in the travel mode shifts in Japan, especially in rural areas (58).

In our systematic literature review, we examined studies that reported either steps per day or CPM as the dependent variable. Our analysis found that studies reporting CPM did not see a significant decrease in PA over time (ES = −0.078, P = 0.440), whereas studies that used the step-based activity monitors found a significant decrease over time (ES = −0.364, P < 0.001). One reason for this difference could be related to the duration of the studies. The average duration of the accelerometer-based studies was 4.25 yr (range = 2 to 6 yr), whereas the average duration of the step-based studies was 10.75 yr (range = 5 to 21 yr). Our primary analysis was completed based on absolute changes in PA rather than rates of change (i.e., change per year). Thus, longer duration studies were more likely to result in changes that were statistically different. Another reason for the differences may have been related to the populations sampled in the CPM studies. The four studies reporting CPM included children and adolescents (32,35,43,45), and two of them only included children (32,43). Overall, PA levels in children did not change to the same extent as in adolescents over time (Fig. 5C). The large influence of the data from the children's groups may explain why these four studies did not show a significant decrease.

The Old Order Amish provide insights into levels of PA in a population that has refrained from adopting modern technology. This religious group has a traditional, agrarian lifestyle similar to that of North Americans living 160 yr ago. They still plow their fields with horse-drawn plows, refrain from driving automobiles, heat their homes and cook on wood stoves, and do not own electrical appliances. Bassett et al. (59) found that Amish farmers took an average of 18,400 steps per day and Amish farm wives took an average of 14,200 steps per day in 2002, nearly three times that of men and women living in postindustrial, highly technological societies in North America (60,61). In 2005, Amish youth in this community (6–18 yr of age) were studied. Amish youth took 17,525 steps per day, averaged over 4 weekdays (62), about 40%–50% more than Canadian and American youth living in high-tech societies (63,64).

The small decline in adult PA during a 22-yr period (1995–2017) in the present study must be viewed in the context of long-term changes that have been ongoing for millennia. Throughout human history, small bands of hunter–gatherers and nomadic tribes had extremely high levels of PA (65,66). Beginning around 10,000 yr ago, agrarian societies developed as humans learned to grow crops from seeds and raise animals in captivity. These traditional farming societies also had extremely high levels of PA (59,67,68). The industrial revolution in Europe (1760–1840) sparked an economy based on manufacturing of goods, and machines began to replace human labor. By 1995, many developed countries were in a postindustrial phase where subsistence was based on service-oriented work, rather than agriculture or industry (69). Thus, large declines in adult PA likely occurred before the time period of studies included in this systematic review, but even within the last quarter-century further declines occurred. The decline in adolescent PA was more clearly evident because teenagers in modern society increased their screen time and decreased their active commuting to school during this time period (1995–2017) (5,21).

The current study has both strengths and limitations. Strengths are its reliance on peer-reviewed scientific studies that assessed PA using repeated, cross-sectional "snapshots" of specific populations. The analysis combined the results of multiple studies that asked the same question for a large number of participants in different populations from around the world. All of these studies assessed PA using valid, reliable, wearable devices at two or more time points, at least 1 yr apart. The analysis was limited to wearable devices, reducing potential for recall bias (compared with questionnaires). Most studies attempted to include a representative sample of their population of interest. All studies were conducted before 2018, eliminating the impact of the COVID-19 pandemic on steps per day.

There were also some inherent limitations in the analysis. Studies used different wearable devices and PA metrics. However, we limited the impact of these differences by using a more conservative random-effects meta-analysis model. Pedometer studies may have relied on participants to self-report steps per day. Self-reporting of steps could introduce an element of reporting errors, or social desirability bias. Only English-language studies were reviewed, and the literature review did not identify any studies conducted in developing nations. In the secondary analysis of the rate of change, only the data from studies that reported steps per day were included. In addition, the types of wearable devices used in these studies record only ambulatory activities and do not register activities such as bicycling, swimming, and resistance training. Swimming, cycling, and resistance training are common LTPA in some parts of the world (70) and are not registered by wearable devices. However, data from the most popular activities (i.e., walking, running, soccer, etc.) (70) and many activities of daily living are captured with wearable devices.

CONCLUSIONS

In conclusion, a systematic literature review was used to locate articles on time trends in PA that used wearable devices. Sixteen studies from eight developed countries on three continents were identified, and a meta-analysis showed evidence of a significant decline in PA measured by wearable devices. The change in PA was similar in both males and females. Children less than 11 yr of age showed less evidence of a change in PA than adolescents and adults. The average study duration was 9.4 yr (5.3 yr for studies that assessed CPM and 10.8 yr for those that assessed steps per day). For studies that reported steps per day, the average change was −1118 steps per day over the course of the study ($P < 0.001$); adolescents had the greatest change at −2278 steps per day ($P < 0.001$). These reductions in steps per day are equivalent to reductions of 11 and 22 min·d^{-1}, respectively, of moderate-intensity walking (71,72). Researchers attributed the change in adolescent PA between 1995 and 2017 to increased use of mobile phones, screen time, and Internet; declines in active transportation to school could have also contributed. The current study illustrates the need for governments to conduct PA surveillance, and track time trends in daily step counts with wearable devices. Additionally, it highlights a need for public health recommendations related to wearable devices and for more focus on PA in adolescents.

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EPIDEMIOLOGY

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