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Should we use activity tracker data from smartphones and wearables to understand population physical activity patterns?

Jacqueline L Mair PhD[1*], Lawrence D Hayes PhD[2], Amy K Campbell MSc[3], Nicholas Sculthorpe PhD[2]

[1]Future Health Technologies, Singapore-ETH Centre, Campus for Research Excellence and Technological Enterprise (CREATE), Singapore

[2] School of Health and Life Sciences, University of the West of Scotland, Lanarkshire, United Kingdom

[3] School of Science, Technology and Health, York St. John University, York, United Kingdom

*Corresponding Author:

Jacqueline Mair, Future Health Technologies, Singapore-ETH Centre, Campus for Research Excellence and Technological Enterprise (CREATE), Singapore.

jacqueline.mair@sec.ethz.ch

+65 6601 6076

ABSTRACT

Researchers, practitioners, and public health organisations from around the world are becoming increasingly interested in using data from consumer-grade devices such as smartphones and wearable activity trackers to measure physical activity. Indeed, large-scale, easily accessible, and autonomous data collection concerning physical activity as well as other health behaviours is becoming ever more attractive. There are several benefits of using consumer-grade devices to collect physical activity data including the ability to obtain big data, retrospectively as well as prospectively, and to understand individual-level physical activity patterns over time and in response to natural events. However, there are challenges related to representativeness, data access, and proprietary algorithms that, at present, limit the utility of this data in understanding population-level physical activity. In this brief report we aim to highlight the benefits, as well as the limitations, of using existing data from smartphones and wearable activity trackers to understand large-scale physical activity patterns and stimulate discussion amongst the scientific community on what the future holds with respect to physical activity measurement and surveillance.

KEY WORDS

m-Health; big data; surveillance; wearable technology, fitness trackers, smartphone

INTRODUCTION

Physical activity (PA) and exercise have pronounced positive effects on physical, mental, and social health and wellbeing and, according to recent estimates, prevent 3.9 million premature deaths worldwide annually (Strain et al., 2020). Accordingly, global PA guidelines recommend all adults to undertake 150–300 min of moderate-intensity, or 75–150 min of vigorous-intensity PA, or some equivalent combination per week (Bull et al., 2020). Such guidelines rely on population level surveillance methods to regularly monitor PA indicators and inform public health policy, and the most common approach in this regard is to assess PA using self-report methods. Self-report remains an accepted method of large-scale data collection due to its cost effectiveness, unobtrusiveness, and adaptability to different country contexts (Troiano et al., 2020). This is despite the accepted limitations of self-reporting with respect to accuracy, recall bias and social-desirability (Brenner & DeLamater, 2014; Prince et al., 2008). Advances in technology over the last two decades have created new possibilities for PA measurement, not only for population-level surveillance but at an individual-level in terms of cohort studies, intervention research, and the evaluation of public health promotion programs. Research-grade devices such as wrist, hip, and thigh worn accelerometers have been used widely in such studies as they remove the biases associated with self-reporting and are able to provide a more granular quantification of PA. Nevertheless, research-grade accelerometers are costly to use at scale and cannot assess the domain or context in which PA takes place. Furthermore, accelerometers, as with self-report methods, only offer a ‘snapshot in time’ to infer usual PA behaviour (typically a 7-day period) meaning assessment of longer-term dynamic patterns of PA, particularly in response to natural events, is either not possible or not feasible. Over the last 15 years, the emergence of consumer-grade devices, such as smartphones and wearable activity trackers, has opened new doors in the field of PA measurement. These devices gather rich activity data continuously in a free-living setting thus providing large-scale and low-cost datasets that could advance our understanding of PA patterns in a way that was never possible before. While this seems an exciting prospect, as with any other PA measurement tool, the use of data from consumer-grade devices should be carefully considered before being used in PA research.

Comparing and contrasting all the available PA measurement methods available to researchers, practitioners, and public health professionals is beyond the scope of this brief report. Instead, we focus on the emerging opportunities offered by consumer-grade devices, including smartphones and wearable activity trackers, and how these may be utilised in PA surveillance, and in other study designs, e.g., cohort studies, intervention research, and evaluation of public health promotion programs.

Consumer-grade devices: too good to ignore?

Technological advancements over the last decade, allied to the rapid proliferation of smartphone use in both developed and developing regions globally (Deloitte, 2017), have provided new possibilities in monitoring, understanding, and influencing human movement at scale. Compared to traditional approaches, objective, real-world PA data sets with very large sample sizes have become relatively low cost for researchers to collect or access. Consequently, we are now beginning to witness the emergence of big data on PA in the literature. For example, Althoff and colleagues (2017) recently used minute-by-minute step count data, collected from the smartphone's inbuilt inertial unit, from over 700,000 individuals across 111 countries, to identify variability in PA levels across the world. With this data they revealed city walkability as a factor associated with PA levels as well as associations between PA inequalities and obesity.

The questions that could be addressed, and the new insights afforded, by large-scale PA data from smartphones is an exciting prospect. However, concerns remain over the quality of the PA data that can be obtained from smartphones, including the validity and reliability of step detection, the restriction to only ambulatory activity, and their reliance on the individual carrying the smartphone (Brodie et al., 2018). Wearable activity trackers, although currently less prevalent than smartphones, are growing in popularity (Deloitte, 2017; Thompson, 2019) and can address some of these pitfalls. Activity trackers have progressed beyond simple pedometers and can now provide data on pulse rate, distance covered, moderate-to-vigorous PA minutes, stair flights climbed, energy expenditure, and sleep. Unlike research grade devices such as accelerometers, they also blend attractive design with invisible and effort-free data capture. This combination often results in high adherence (in terms of daily wear time) for extended periods of time. Additionally, while synchronisation of the activity tracker to a smartphone application displays summary information to users, these summary data are calculated from extensive intra-day data gathered at high frequency (e.g., 1 Hz), which are also stored. High adherence alongside high frequency data capture means individuals accumulate an extensive data resource that could be utilised to answer important PA questions.

Big data analyses from smartphones and wearable activity trackers have, thus far, been cross-sectional with no longitudinal follow-up, limiting our understanding of PA to a single point in time. However, given its perpetual collection and long-term storage, there is no reason why this data could not be used for prospective approaches such as longitudinal tracking of PA. Of note is the unique opportunity offered by smartphones and wearable activity trackers to analyse data retrospectively and in response to natural events without the need for foresight. This has had obvious implications during the coronavirus pandemic when objective accelerometery was neither possible, nor feasible, due to the speed and variability with which restrictions were imposed across the world. As a result, the need for remote and scalable means to both measure and support PA has become more prominent since the coronavirus pandemic. Although the use of smartphones and wearable activity trackers is not without inherent limitations (discussed further below), we feel they are unique in their ability to be utilised in retrospective cohort study designs (i.e., when the start of the study is only known after the event).

Interestingly, to date, there has been almost no large-scale reporting of existing data from wearable activity trackers, other than reports from the device manufacturers themselves. This might be due to the complexity of large-scale data access and processing from commercial wearables. A cross-sectional study of pulse rate data from over 8 million Fitbit users was recently published by the Fitbit Research team (Natarajan et al., 2020), reporting a positive relationship between heart rate variability and step count. Regardless of the study findings, it seems that collecting, processing, and interpreting this volume of data is possible, but requires an interdisciplinary team including data scientists, database analysts, and cardiovascular and behavioural scientists, which has so far been limited to large proprietary companies such as Fitbit. Furthermore, accessing this volume of data is, so far, only feasible for companies such as Fitbit because they require all users to give them permission to use the data collected by the device. For independent researchers it is possible to request access to the data from the user directly. But this would be on an individual basis, therefore, to amass a dataset of 8 million users would require 8 million individual access requests. The issue of data access is discussed on more detail below.

Balancing feasibility against validity, reliability, and sensitivity

When choosing a PA data collection tool or methodology, researchers must balance validity, reliability, and sensitivity of the approach with the costs and feasibility of its deployment in the target population. Despite their known limitations (Brenner & DeLamater, 2014; Prince et al., 2008), self-report methods remain an accepted means by which to collect large-scale and population-level PA data, particularly where cost and sample size make accelerometery an unfeasible approach. However, the volume and detail of information that can be obtained from self-report surveys can be limited, preventing more nuanced analysis of PA patterns. Device-based methods, such as accelerometery, provide a more valid and reliable estimate of PA than do self-report measures (Dowd et al., 2018), but also have several limitations. Not only are accelerometers costly, but their data also must be extracted from each device individually, making them unfeasible for large-scale use. Data from wearable activity trackers on the other hand should be considered feasible for large-scale use. Suitable activity trackers are generally cheaper than accelerometers and their attractive design should translate into greater wear time. Like accelerometers, they provide continuous data capture, and assuming a regular connection, they have the additional advantage of storing these data on a central server meaning data retrieval and analysis can occur remotely and at scale. Thus, in principle, it is possible to analyse the PA data of thousands of participants worldwide in a manner that is simply not possible with current research grade accelerometers. Research has shown wearable activity trackers to have high interdevice reliability for measuring steps, energy expenditure, and sleep (Evenson et al., 2015), and despite ongoing concerns, the accuracy of wearable activity trackers also continues to improve. In a recent systematic review of 67 studies, Fitbit devices were found to provide a relatively accurate measure of free-living steps (within ± 10%, 50% of the time) when compared to research-grade accelerometers (Feehan et al., 2018). Garmin activity trackers are also reported to have good-to-excellent correlation coefficients and acceptable (<10%) mean absolute percentage errors with respect to step count (Evenson & Spade, 2020). While the accuracy of wearable activity trackers in measuring step count in free-living settings is considered to be acceptable for normal walking pace (Evenson & Spade, 2020; Feehan et al., 2018; Fokkema et al., 2017), they do not yet provide a valid measure of moderate-to-vigorous PA (Redenius et al., 2019) or walking at very slow or very fast speeds (Fokkema et al., 2017). However, considering this evidence is based on devices manufactured up to 2015, refined algorithms over the past 5 years may have further improved accuracy.

For intervention research the responsiveness, or sensitivity, to change in PA over time may be a more important consideration than the validity of the tool. When examining the effectiveness of an intervention in changing PA it is paramount that the measurement tool employed is capable of detecting change. Research has shown the responsiveness indices for self-report and device-based methods to vary not just by tool, or device, but by PA variable measured. Reeves et al. (2010) compared the responsiveness of the Community Health Activities Model Program for Seniors (CHAMPS) questionnaire, the Active Australia Questionnaire (AAQ), and two items on exercise from the US National Health Interview Survey (USNHIS), and reported responsiveness indices ranging from 0.15 (AAQ) to 0.27 (USNHIS) for walking duration and 0.25 (AAQ) to 0.32 (CHAMPS) for moderate to vigorous intensity PA duration per week. Swartz et al. (2014) compared two research-grade accelerometers, the Actigraph GTX3 (ActiGraph LLC, Pensacola, Florida, USA) and the activPAL (PAL Technologies Ltd, Glasgow, Scotland, UK) and found both to have comparable responsiveness to change across a range of free living physical activity and sedentary behaviour variables (standardised response mean values between 0.159 – 0.436). Donnachie and colleagues (2020) compared a self-report PA measure (the International Physical Activity Questionnaire; IPAQ) and an accelerometer (activPAL), and found both to have comparable and moderate standardised response mean values of 0.54 (activPAL) and 0.59 (IPAQ) for total PA duration per day. There appears to be no evidence on the responsiveness to change of wearable activity trackers. This surprisingly under-researched topic warrants further attention by the PA research community.

We have an array of options to measure elements of PA (such as duration, intensity, type, domain, context, and quality), but no single tool can fully capture the complexity of PA behaviour. Consumer-grade devices offer new opportunities for combining PA data collection methods. For example, passive sensing of movement using a smartphone or wearable activity tracker, combined with synchronised 'smart' self-report techniques, such as ecological momentary assessment, could address many of the issues outlined previously. With further evidence to support the validity, reliability and sensitivity of such methods, this approach could provide powerful insights into PA patterns and help us better understand PA behaviour.

The issue of data harmonisation

Another issue researchers must consider when evaluating device-based PA measurement tools is the harmonisation or comparability between devices from different manufacturers.

Data harmonisation is an essential step if researchers wish to conduct analyses on data derived from different sources (Pearce et al., 2020). While all activity tracking devices gather raw uni- or tri-axial accelerations, each manufacturer applies different algorithms to process the data into its summary form thereby influencing the comparability of the data gathered. Therefore, researchers who wish to use data from multiple devices/manufacturers to increase sample representativeness and reach will need to consider data harmonisation using statistical models derived from validation studies (Pearce et al., 2020). This could be problematic when algorithms change, and validation data are no longer available. Manufacturers of research-grade devices publish open source algorithms allowing researchers to evaluate the impact of changes on measurement properties (Evenson et al., 2015), however consumer-grade device manufacturers keep this information proprietary. The use of different proprietary algorithms by each consumer-grade device manufacturer is undoubtedly an issue for harmonisation too. In the longer term, this could be solved by manufacturers making raw data counts available or at least allowing researchers to apply to access this information. However, due to the proprietary nature of data processing, it is unclear if raw data or only processed data are available. In the short-term however, comparative validation between devices should enable statistical techniques that allow for between device data pooling without compromising data quality. Finally, it is also worth noting that there is a small but growing sector of ‘hackable’ wearables. These devices are usually based on small form factor processing boards (e.g., small Raspberry Pi or Arduino boards) which include tri-axial accelerometers, heart rate measurement, WIFI and Bluetooth. These devices also support the remote storage of raw data signals, which would overcome the limitations of unknown and proprietary algorithms. Although useful for research studies, it seems unlikely that such devices will achieve the market penetration of larger manufacturers.

The issue of representativeness

Given the widespread use of smartphones and the growing use of activity trackers, we should not ignore the possibility that in the near future wearable activity tracker data could also be used as a population PA surveillance tool. However, at present the primary challenge relating to such data is that it likely over-represents individuals who are more physically active and more proactive in setting and meeting activity goals relative to the general population who may not be tracking their activity level (Omura et al., 2017; Strain et al., 2019). Therefore, any cohort or surveillance research exclusively involving participants who own, and wear, activity trackers will introduce selection bias. The issue of representativeness is, however, not necessarily limited to wearable activity trackers. Selection bias might also occur in data derived from public calls to self-report PA or participate in cohort studies involving self-report or device-based measures of PA. Indeed, it has previously been suggested that selection bias is a significant issue in many cohort studies including those with objective assessments (Barreto et al., 2013; Folley et al., 2018; Stamatakis et al., 2021). Nevertheless, in such cohort and surveillance studies it is possible to use weighting to adjust for non-responders. This is not currently possible for data from wearable activity tracker and future research should focus on statistical approaches to estimate the population effect, and the effect in those with trackers, to help overcome this limitation.

While activity tracker sales and usage are increasing, the demographic reach appears, so far, to be constrained to young adults from more affluent backgrounds (Omura et al., 2017; Strain et al., 2019). Nevertheless, the cost of activity trackers has decreased significantly in recent years making them more affordable and accessible. This, combined with the increasing interest in activity trackers as behaviour change tools, may reduce this constrained demographic reach over time. For example, recent initiatives to provide activity trackers as part of health care (NHS England, 2019), health improvement (Yao et al., 2020) or health insurance (Buckle et al., 2020) may serve to increase the breadth of the population using the devices. The more initiatives and interventions utilising activity trackers, the more they could be adopted by individuals from underserved populations, such as older adults and those with lower incomes.

The issue of data access

Finally, it is worth noting some of the challenges inherent in accessing data from consumer-grade activity trackers. To access data, researchers can establish an industry agreement with a relevant company (e.g. Fitbit or Garmin) whose terms of service for collecting research data are different from those governing commercial access (Hicks et al., 2019). While the specific manufacturers control access to the data repositories, the data remains the property of the individual user, therefore to access any data collected by the device, each individual user must consent and agree to share the data. Managing thousands, and possibly tens of thousands, of data sharing requests to individual users, and subsequently also having to manage their authorisation and access details, brings its own logistic challenges. The most effective approach is for participants to be directed to a project website which manages participant information, consent, and authorisation requests via the specific manufacturers API. Following successful authorisation, access codes for each user can be securely sent to the research team for subsequent processing. It is worth noting that, even with successful authorisation, there remain additional challenges. Remote access to users' data is often controlled using common web frameworks (e.g., OAuth2). While these frameworks help maintain the security of access to user data, they are time limited and often require users to re-approve access to their data frequently (Jones & Hardt, 2012). This could make longer-term follow-up assessments a logistical challenge in studies of very large cohorts where direct contact with participants is limited. In addition, it is users, not researchers, who define the scope of the data that can be accessed; therefore, users may allow access to all or only some of their data (e.g., only pulse rate, or step count, or some combination thereof), resulting in incomplete data sets. Additionally, most devices allow users to manually add activity to account for any activity not passively detected by the device (e.g., swimming or cycling). At present, it is unclear if such self-reported estimates affect validity. Most databases separate device collected (passive) data from user added (self-reported) data, meaning the research team have to make a decision regarding which should be regarded as the 'canonical' source of users' PA.

Clearly, these challenges are not trivial, and future research teams will require multi-disciplinary skills, including specialists in behavioural science, PA, data science, and software and web development to successfully manage such projects. Nevertheless, if accessed and interpreted appropriately, these data may allow understanding of PA behaviour at a scale previously unimaginable. We are in the process of using this method at a national level to understand the impact of coronavirus, but future research using this technique could examine worldwide PA patterns, both prospectively and retrospectively, using multi-site and multi-lingual research teams.

CONCLUSIONS

As with other device-based and self-report methods, we propose that consumer-grade activity tracker data be considered with their limitations in mind rather than dismissed as a flawed approach, particularly in scenarios in which the feasibility of large-scale accelerometery is prohibitive. Given the rising popularity of wearable activity trackers, the volume of data collected, and the possibilities in analysing data retrospectively, we believe data from wearable activity trackers should be considered a viable PA measurement tool. To be clear, we are not advocating that other tools, particularly self-report methods, should be consigned to history or replaced by wearable activity tracker 'big data'. Quite the contrary, despite their limitations self-report methods have provided critical insights into PA behaviour and are likely to remain important in the future. Rather, our view is that if PA researchers, practitioners, and public health professionals can use and interpret self-report data in light of their limitations, the same should be possible for data from consumer-grade devices.

LIST OF ABBREVIATIONS

AAQ	Active Australia Questionnaire
API	Application Programming Interface
CHAMPS	Community Health Activities Model Program for Seniors
IPAQ	International Physical Activity Questionnaire
PA	Physical Activity
USNHIS	US National Health Interview Survey

DECLARATIONS

Ethical Approval

Not Applicable

Consent for Publication

Not Applicable

Competing Interests

None to declare.

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Authors’ Contributions

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REFERENCES

Althoff, T., Sosič, R., Hicks, J. L., King, A. C., Delp, S. L., & Leskovec, J. (2017). Large-scale physical activity data reveal worldwide activity inequality. *Nature*, *547*(7663), 336–339. https://doi.org/10.1038/nature23018

Barreto, P. de S., Ferrandez, A.-M., & Saliba-Serre, B. (2013). Are Older Adults Who Volunteer to Participate in an Exercise Study Fitter and Healthier Than Nonvolunteers? The Participation Bias of the Study Population. *Journal of Physical Activity and Health*, *10*(3), 359–367. https://doi.org/10.1123/jpah.10.3.359

Brenner, P. S., & DeLamater, J. D. (2014). Social Desirability Bias in Self-reports of Physical Activity: Is an Exercise Identity the Culprit? *Social Indicators Research*, *117*(2), 489–504. https://doi.org/10.1007/s11205-013-0359-y

Brodie, M. A., Pliner, E. M., Ho, A., Li, K., Chen, Z., Gandevia, S. C., & Lord, S. R. (2018). Big data vs accurate data in health research: Large-scale physical activity monitoring, smartphones, wearable devices and risk of unconscious bias. *Medical Hypotheses*, *119*, 32–36. https://doi.org/10.1016/j.mehy.2018.07.015

Buckle, J., Hayward, T., Singhal, N., & Desai, K. (2020). *The role of wearables in private medical insurance* (p. 24). Milliman.

Bull, F. C., Al-Ansari, S. S., Biddle, S., Borodulin, K., Buman, M. P., Cardon, G., Carty, C., Chaput, J.-P., Chastin, S., Chou, R., Dempsey, P. C., DiPietro, L., Ekelund, U., Firth, J., Friedenreich, C. M., Garcia, L., Gichu, M., Jago, R., Katzmarzyk, P. T., … Willumsen, J. F. (2020). World Health Organization 2020 guidelines on physical activity and sedentary behaviour. *British Journal of Sports Medicine*, *54*(24), 1451–1462. https://doi.org/10.1136/bjsports-2020-102955

Deloitte. (2017). *Global mobile consumer trends, 2nd edition*. https://www2.deloitte.com/content/dam/Deloitte/us/Documents/technology-media-telecommunications/us-global-mobile-consumer-survey-second-edition.pdf

Donnachie, C., Hunt, K., Mutrie, N., Gill, J. M. R., & Kelly, P. (2020). Responsiveness of Device-Based and Self-Report Measures of Physical Activity to Detect Behavior

Change in Men Taking Part in the Football Fans in Training (FFIT) Program. *Journal for the Measurement of Physical Behaviour*, *3*(1), 67–77. https://doi.org/10.1123/jmpb.2019-0018

Dowd, K. P., Szeklicki, R., Minetto, M. A., Murphy, M. H., Polito, A., Ghigo, E., van der Ploeg, H., Ekelund, U., Maciaszek, J., Stemplewski, R., Tomczak, M., & Donnelly, A. E. (2018). A systematic literature review of reviews on techniques for physical activity measurement in adults: A DEDIPAC study. *International Journal of Behavioral Nutrition and Physical Activity*, *15*(1), 15. https://doi.org/10.1186/s12966-017-0636-2

Evenson, K. R., Goto, M. M., & Furberg, R. D. (2015). Systematic review of the validity and reliability of consumer-wearable activity trackers. *International Journal of Behavioral Nutrition and Physical Activity*, *12*(1), 159. https://doi.org/10.1186/s12966-015-0314-1

Evenson, K. R., & Spade, C. L. (2020). Review of Validity and Reliability of Garmin Activity Trackers. *Journal for the Measurement of Physical Behaviour*, *3*(2), 170–185. https://doi.org/10.1123/jmpb.2019-0035

Feehan, L., Geldman, J., Sayre, E., Park, C., Ezzat, A., Yoo, J., Hamilton, C., & Li, L. (2018). Accuracy of Fitbit Devices: Systematic Review and Narrative Syntheses of Quantitative Data. *JMIR Mhealth Uhealth*, *6*(8), e10527. https://doi.org/10.2196/10527

Fokkema, T., Kooiman, T. J. M., Krijnen, W. P., Van Der Schans, C. P., & De Groot, M. (2017). Reliability and Validity of Ten Consumer Activity Trackers Depend on Walking Speed. *Medicine & Science in Sports & Exercise*, *49*(4), 793–800. https://doi.org/10.1249/MSS.0000000000001146

Folley, S., Zhou, A., & Hyppönen, E. (2018). Information bias in measures of self-reported physical activity. *International Journal of Obesity*, *42*(12), 2062–2063. https://doi.org/10.1038/s41366-018-0223-x

Hicks, J. L., Althoff, T., Sosič, R., Kuhar, P., Bostjancic, B., King, A. C., Leskovec, J., & Delp, S. L. (2019). Best practices for analyzing large-scale health data from wearables and smartphone apps. *Npj Digital Medicine*, *2*. https://doi.org/10.1038/s41746-019-0121-1

Jones, M., & Hardt, D. (2012). *RFC6750: The OAuth 2.0 Authorization Framework: Bearer Token Usage*. Internet Engineering Task Force (IETF). https://getrfc.com/rfc6750

Natarajan, A., Pantelopoulos, A., Emir-Farinas, H., & Natarajan, P. (2020). Heart rate variability with photoplethysmography in 8 million individuals: A cross-sectional study. *The Lancet Digital Health*, *2*(12), e650–e657. https://doi.org/10.1016/S2589-7500(20)30246-6

NHS England. (2019). *Digital diabetes prevention rolled out as part of NHS Long Term Plan*. https://www.england.nhs.uk/2019/08/digital-diabetes-prevention-rolled-out-as-part-of-nhs-long-term-plan/

Omura, J. D., Carlson, S. A., Paul, P., Watson, K. B., & Fulton, J. E. (2017). National physical activity surveillance: Users of wearable activity monitors as a potential data source. *Preventive Medicine Reports*, *5*, 124–126. https://doi.org/10.1016/j.pmedr.2016.10.014

Pearce, M., Bishop, T. R. P., Sharp, S., Westgate, K., Venables, M., Wareham, N. J., & Brage, S. (2020). Network Harmonization of Physical Activity Variables Through Indirect Validation. *Journal for the Measurement of Physical Behaviour*, *3*(1), 8–18. https://doi.org/10.1123/jmpb.2019-0001

Prince, S. A., Adamo, K. B., Hamel, M. E., Hardt, J., Gorber, S. C., & Tremblay, M. (2008). A comparison of direct versus self-report measures for assessing physical activity in adults: A systematic review. *International Journal of Behavioral Nutrition and Physical Activity*, *5*(1), 56. https://doi.org/10.1186/1479-5868-5-56

Redenius, N., Youngwon, K., & Wonwoo, B. (2019). Concurrent validity of the Fitbit for assessing sedentary behavior and moderate-to-vigorous physical activity. *BMC Medical Research Methodology*, *19*, 29. https://doi.org/10.1186/s12874-019-0668-1

Reeves, M. M., Marshall, A. L., Owen, N., Winkler, E. A. H., & Eakin, E. G. (2010). Measuring Physical Activity Change in Broad-Reach Intervention Trials. *Journal of Physical Activity and Health*, *7*(2), 194–202. https://doi.org/10.1123/jpah.7.2.194

Stamatakis, E., Owen, K. B., Shepherd, L., Drayton, B., Hamer, M., & Bauman, A. E. (2021). Is Cohort Representativeness Passé? Poststratified Associations of Lifestyle Risk Factors with Mortality in the UK Biobank. *Epidemiology (Cambridge, Mass.)*, *32*(2), 179–188. https://doi.org/10.1097/EDE.0000000000001316

Strain, T., Brage, S., Sharp, S. J., Richards, J., Tainio, M., Ding, D., Benichou, J., & Kelly, P. (2020). Use of the prevented fraction for the population to determine deaths averted by existing prevalence of physical activity: A descriptive study. *The Lancet Global Health*, *8*(7), e920–e930. https://doi.org/10.1016/S2214-109X(20)30211-4

Strain, T., Wijndaele, K., & Brage, S. (2019). Physical Activity Surveillance Through Smartphone Apps and Wearable Trackers: Examining the UK Potential for Nationally Representative Sampling. *JMIR MHealth and UHealth*, *7*(1), e11898. https://doi.org/10.2196/11898

Swartz, A. M., Rote, A. E., Cho, Y. I., Welch, W. A., & Strath, S. J. (2014). Responsiveness of motion sensors to detect change in sedentary and physical activity behaviour. *British*

Journal of Sports Medicine, *48*(13), 1043–1047. https://doi.org/10.1136/bjsports-2014-093520

Thompson, W. R. (2019). WORLDWIDE SURVEY OF FITNESS TRENDS FOR 2020. *ACSM's Health & Fitness Journal*, *23*(6), 10–18. https://doi.org/10.1249/FIT.0000000000000526

Troiano, R. P., Stamatakis, E., & Bull, F. C. (2020). How can global physical activity surveillance adapt to evolving physical activity guidelines? Needs, challenges and future directions. *British Journal of Sports Medicine*, *54*(24), 1468–1473.

Yao, J., Tan, C. S., Chen, C., Tan, J., Lim, N., & Müller-Riemenschneider, F. (2020). Bright spots, physical activity investments that work: National Steps Challenge, Singapore: a nationwide mHealth physical activity programme. *British Journal of Sports Medicine*, *54*(17), 1047–1048. https://doi.org/10.1136/bjsports-2019-101662