Gabrys L[1], Vogt L[2]

Accelerometry and Wearable Devices in Sports Medicine and Health Promotion

Akzelerometrie und Wearables in der Sportmedizin und Gesundheitsförderung

CLINICAL REVIEW

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1. UNIVERSITY OF APPLIED SCIENCES FOR SPORT AND MANAGEMENT POTSDAM (FHSMP), *Department of Sport and Prevention, Potsdam, Germany*
2. GOETHE-UNIVERSITY FRANKFURT/MAIN, *Department of Sports Medicine and Exercise Physiology, Frankfurt/Main, Germany*

Summary

- **Since more than two decades,** accelerometers are used in sports medicine and health promotion to assess physical activity. The basis for this is the measurement of accelerations caused by physical movement. Accelerometers were originally developed for research purposes, but are also installed into smartphones, thus enabling a broad use in research and practice.
- **Accelerometers** can assess various dimensions of physical activity (e.g., duration, frequency, intensity) and monitor physical activity goals. In research practice, parameters like wearing time, body position, and cut-off values must be considered to get meaningful data. In addition to pre-processed physical activity data, many devices give access to raw acceleration data, which improves comparability between different types of devices.
- **Consumer-graded wearable devices** and smartphone apps for physical activity assessment and monitoring offer a great opportunity for large scale interventions and long-term behavior change.

KEY WORDS:
Recommendations, Intervention, App, Physical Activity, Monitoring

Introduction

Accelerometry can be used for the assessment of physical activity behavior in a wide variety of applications including sports medicine, health promotion etc. This relatively new technology measures and stores the change of velocity of the body while performing bodily movement or physical activity. Data is normally recorded in milli g and stored as raw acceleration data or as preprocessed descriptors such as counts, steps, sedentary bouts, or activity levels (44).

In the last decades exercise physiologists and engineers developed more and more accurate devices and algorithms to assess physical activity under real life conditions, to predict energy expenditure and to characterize physical activity behavior. Accelerometer can also be used to monitor individual progress and to prescribe physical activity or exercise for prevention and rehabilitation (9). In addition to primarily research-grade devices commercially available tools like fitness trackers are available for a wide range of people who are interested in fitness and health. And at least, since the introduction of the first smartphone in 2007, nearly everybody has the opportunity to assess and monitor his or her own activity behavior. Meanwhile all smartphones have an internal inertial sensor (internal measurement unit, IMU) as a standard chipset on board and almost all manufacturers provide more or less sophisticated applications for physical activity monitoring, fitness testing or exercise training.

In this narrative review we want to give a short summary of what kind of devices are available for research purposes and how they can be used in the clinical setting or in the field of physical activity and health promotion. We further differentiate between research-grade devices, fitness trackers or wearables and smartphone applications. We want to give answers to questions like how valid the generated data are, do we have scientific evidence for the effectiveness of those tools, what are the general recommendations for the use in different target groups and how to interpret this kind of data?

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CORRESPONDING ADDRESS:
Prof. Dr. Lars Gabrys
University of Applied Sciences for Sport and Management Potsdam (FHSMP), Department of Sport and Prevention
Olympischer Weg 7, 14471 Potsdam, Germany
: gabrys@fhsmp.de

Table 1

Commonly used outcome parameters of research-grade accelerometer devices.

PA BEHAVIOR	SLEEP	BODY POSITION	ENERGY EXPENDITURE
Steps	Duration	Laying	kcal
Sedentary Time	Quality	Sitting	MET
PA Itensity		Standing	
- Low PA			
- Moderate PA			
- Vigorous PA			

Research-Grade Devices

Accelerometers are widely used to assess sedentary time, duration and intensity of physical activity, physical activity energy expenditure (PAEE), sleep-related behaviors and body positioning (11). Accelerometers are accepted to be the gold-standard in physical activity assessment under free-living conditions with acceptable to good validity and good to high reliability in various target groups like adults, children or persons with specific diseases and settings (3, 9, 20, 22, 25, 28, 31, 35). Some devices can additionally measure heart rate or heart rate variability (HRV) by using ECG signals or photo-plethysmography (PPV). Among various accelerometer types and brands, the most often used and best evaluated accelerometers are the devices from Actigraph with the GT3X as the currently most used accelerometer in physical activity studies (28, 31). Other accelerometers which are applied in research studies are the Step Watch Activity Monitor, SenseWear, activPAL, GENEactive, Actical, Actiheart or the accelerometers from movisens (27, 30, 31).

Outcome Parameters

Next to pre-processed data for the end-user, most research-grade devices offer the opportunity to analyze raw data for particular research purposes. Pre-processed physical activity data output is based on internal algorithms for physical activity analysis. Algorithms are device specific and mainly not accessible for the research community. Typical outcome parameters are shown in table 1.

Raw data analyses have the advantage that outcome measures do not result from "black-box processing" and computation methods can be compared between different devices (44). Another advantage of raw data is that open-source algorithms can be easily applied to these data and researchers can develop new or improve existing analytic methods and share their results with the community. The most often used method of choice for acceleration raw data analyses is machine learning-based modelling (12). All analytic methods for raw data or pre-processed data are based on specific cut-off values (cut-points) or acceleration patterns to define physical activity behavior, sleep and body position or to estimate physical activity energy expenditure.

Cut-Points

Regarding a systematic review, the most often applied and well accepted cut-points for the definition of physical activity intensity for adults are based on studies from Freedson 1998, Sasaki 2011 and Troiano 2008 (19, 38, 42). All studies for adults which are listed in table 2 focused on the devices of Actigraph and defined the following cut-off values based on the concept of counts per minutes (cpm). Activity counts are calculated internally with the corresponding software.

For children the cut-point definition seems much more difficult and is next to device specificity dependent on childrens' age. The following table number 3 provides examples of often used cut-off definitions for physical activity intensity assesment in children using devices from Actigraph or Actical (6, 14, 18, 32, 34, 36, 37, 41).

Next to pre-processed accelerometer cut-points by cpm, physical activity intensity and/or steps can be calculated from raw data, when devices give access to this data sets. For example, in a study by Migueles et al. (2019) (29) on young adults wearing the ActiGraph GT3X, cut points were empirically found for dominant and nondominant wrist placement, based on the Euclidean norm minus one g (ENMO) (43). These values were found to be: sedentary time (less than 50 milli-g), light physical activity (50-110 milli-g), moderate physical activity (110–440 milli-g), and vigorous physical activity (more than 440 milli-g) (44).

Body Position

Some, but not all, accelerometers can be worn at different body positions. The Actigraph GT3X for example can be strapped to the hip or can be worn at the wrist. The position of the device is dependent on the research question and may have impact on study compliance and adherence of study participants. A systematic review of Migueles et al. (2018) compared study results regarding the wearing position of the GT3X (hip vs. wrist-worn) (28). In summary, both wearing positions produced reliable data, but the placement on the hip produced more accurate data and lower variability in terms of locomotion (e.g., steps) and physical activity energy expenditure. The wrist-worn position was associated with better compliance and superior in predicting activities with significant arm movement. Furthermore, the wrist-worn position seems superior to differentiate sleeping from activity behavior (28).

Wear-Time

In order to obtain reliable data on individual physical activity behavior, the wear-time plays another important role in physical activity assessment. This reflects the fact that one day of activity recording seems not sufficient to draw conclusions about the general activity behavior. Overall, there is scientific agreement that a 24h movement recording is required for seven consecutive days with a minimum of 4 valid days. A valid day is defined as ≥10 hours wear time to draw reliable conclusions on individuals' physical activity behavior (9, 28). Non-wear time is often but not always defined as 60 minutes of zero acceleration and must be subtracted from total wear time (21, 31).

Reporting Template

Next to the parameters mentioned above studies give practical considerations and suggest standardized reporting of the following information in accelerometer studies (28, 31) (table 4):

Wearable Devices and Smartphone Apps

Advancements in technology have led to the development of novel accelerometer-based consumer graded devices and applications. Wearable sensors, smartphone apps, and integrated systems offer new opportunities for collecting and analyzing accelerometer data. Therefore, wearable activity trackers are gaining attraction in medical research, providing both real-time and remote monitoring of physical activity and physi-

Table 2

Cut-off values for the definition of PA intensity based on counts per minute (cpm) in adults.

ADULTS	PHYSICAL ACTIVITY (PA) INTENSITY IN CPM				
STUDY	SEDENTARY	LIGHT	MODERATE	VIGOROUS	VERY VIGOROUS
Freedson et al. (1998)	<100	≤1951	1952-5724	5725-9498	≥9499
Troiano et al. (2008)	<100	≤2019	2020-5998	≥5999	
Sasaki et al. (2011)		≤2689	2690–6166	6167–9642	≥9643

Table 3

Cut-off values for the definition of PA intensity based on counts per minute (cpm) in children.

CHILDREN			PHYSICAL ACTIVITY (PA) INTENSITY IN CPM			
STUDY	MONITOR	AGE	SEDENTARY	LIGHT	MODERATE	VIGOROUS
Treuth et al. (2004)	Actigraph	13-14	0-50	51-1499	1500-2600	>2600
Puyau et al. (2002)	Actigraph	6-16	0-799	800-3199	3200-8199	≥8200
Pate et al. (2006)	Actigraph	3-5		≤419	420-841	≥842
Evenson et al. (2008)	Actigraph	5-8	0-25	26-573	574-1002	≥1003
Puyau et al. (2004)	Actical	7-18	0-99	100-1499	1500-6499	≥6500
Pfeiffer et al. (2006)	Actical	3-5		≤714	715-1410	≥1411
Evenson et al. (2008)	Actical	5-8	0-11	12-507	508-718	≥719

Table 4

Recommendations for reporting standards in accelerometer studies.

ITEMS TO REPORT	EXAMPLES FOR REPORTING
Target group	Adults, children, Age-group
Accelerometer brand and model	Actigraph, GT3X
Placement (body position)	Hip, wrist (dominant, non-dominant hand)
Sampling frequency	in Hz
Epoch length	Data collection: 1s, Data analysis: 60s
Valid day (definition)	≥10 hours
Minimum wear time	4 valid days
PA intensity (cut-off)	Sedentary, low, moderate, vigorous (incl. reference and equation)

cal fitness (10). Next to devices from Garmin, Jawbone or Polar, the gadgets from Fitbit seem to be by far the most often used and validated wearable devices in medical research and health promotion (10, 15, 39). Usually, these devices assess parameters like steps, energy expenditure, activity intensity, activity time and sleep. Validation studies show sufficient validity for steps with ICC mainly > 0.8 but tend to underestimate EE (15, 39). Overall, time and duration of physical activity seem to be recorded correctly with less accurate detection of sleep time and quality (39).

One of the most challenging and maybe unfavorable facts is that nearly all consumer-based devices do present PA data as pre-processed data which is based on internal algorithms where researchers and clinicians do not have access to. This makes data comparisons and interpretation difficult because processing algorithms come as black-boxes (44). Otherwise, for individual monitoring and PA progression wearable devices seem quite promising because they are easy to handle and often come with numerous functions for PA assessment, health monitoring and tracking. Table 5 gives an overview of parameters which can be assessed by wearable technologies or smartphone apps (13).

Especially the continuous monitoring of vital signs and additional parameters like blood glucose can have an immediate added value for clinical practice. For example, the Apple watch 1-lead ECG is cleared by the US Food and Drug Administration for detecting atrial fibrillation and measures heart rate with clinically acceptable accuracy during exercise (16, 40).

Effectiveness of Wearable Devices for PA and Health Promotion

Based on a systematic review of 39 systematic reviews and meta-analyses of 163,992 persons, the authors summarized that the use of activity trackers improved physical activity, body composition and fitness, equating to approximately 1800 extra steps per day, 40 min per day more walking, and reductions of approximately 1 kg in bodyweight. Effects for other physiological (blood pressure, cholesterol, and glycosylated hemoglobin) and psychosocial outcomes were small and often non-significant. Activity trackers appear to be effective at increasing physical activity in a variety of age groups and clinical as well as non-clinical populations. The benefit seems clinically important and sustained over time (17).

Table 5

Selection of parameters that can be captured by wearable devices or smartphone apps.

PARAMETERS
Physical activity
Distance
Time of trainings session
Intensity
Vital signs
Heart rate
Heart rate variability (HRV)
Blood pressure
Body temperature
Oxygen saturation (SpO_2)
Maximum oxygen uptake (VO_2max)
Sleep
Duration
Quality
Phase
Environment
Temperature
Altitude
Air pressure
Other (additional) parameters
Blood glucose (with additional sensor)

Conclusion

Based on the literature, accelerometers and digital tools like wearables or smartphone apps seem to be promising developments in sports medicine and physical activity research. Digital devices and technology have evolved in recent years and are now available to almost everyone at comparatively low costs. A valuable next step in improving health care should be the integration of these data in clinical settings and health services research. Based on the literature accelerometers, wearables or apps can be promising tools and can be recommended to be used in the following contexts:

Applications of Accelerometers, Wearables and Apps in Sports Medicine

1. Physical Activity Assessment: Accelerometers provide accurate and objective assessment of physical activity levels, enabling researchers and healthcare professionals to assess individuals‘ daily activity patterns. This information is crucial for evaluating the efficacy of interventions and designing personalized exercise programs (9, 31).
2. Training Load Monitoring: In sports medicine, monitoring training loads is essential for optimizing performance and preventing injuries. Accelerometers and accelerometer based wearable devices can quantify movement patterns and assess the intensity of training sessions. This data helps coaches and athletes to make informed decisions regarding training volume and intensity (5).
3. Gait Analysis: Accelerometers can support the assessment and analysis of movement patterns and facilitating the identification of mobility impairment in different clinical populations like persons with multiple sclerosis or stroke (33, 45). Some assessments like the 6-minute walking test or the sit to stand test are already available as smartphone applications with good validity and reliability (1, 24). Accelerometers can also be used for fall investigation. In this case the device has to be placed at the hip or lower back to produce valid and reliable data regarding fall detection (4).
4. Sleep assessment: Accelerometers offer possibilities for the objective assessment of sleep behavior related parameters and can thus complement instruments for subjective sleep quality assessment.

Applications of Accelerometers, Wearables and Apps in Health Promotion

1. Sedentary Behavior Monitoring: Accelerometers are valuable tools for assessing sedentary behavior, which has been linked to various health risks. They provide objective data on sitting time, breaks in sedentary behavior, and patterns of inactivity, aiding in the development of interventions to reduce sedentary time (8).
2. Physical Activity Promotion: Accelerometers and wearables can be used to deliver personalized feedback and interventions to individuals, motivating them to engage in physical activity and adopt healthier lifestyles. These devices offer real-time feedback, goal setting, and can be combined with behavior change strategies to enhance physical activity participation. Complex interventions that combine face to face intervention and accelerometer use seem to be more effective to promote PA than accelerometers alone (2, 23).
3. Chronic Disease Management: In chronic disease management, accelerometers can assess physical activity levels, monitor adherence to exercise regimens, and provide feedback to patients. This technology can improve self-management, increase patient engagement, and contribute to better health outcomes (7, 26).

Limitations and Challenges

Despite their numerous benefits, accelerometers and other wearable devices or apps have some limitations and challenges. These include issues with data interpretation, compliance, device placement, and the need for sophisticated data analysis methods, knowledge and resources. Practitioners must always have in mind that many device outputs are estimated instead of being directly measured (e.g. steps, PA intensity, sleep quality, EE). For some research-grade devices the underlying algorithms are available but for consumer-graded devices mostly not. This makes interpretation and comparison between devices complicated and sometimes impossible. For accelerometer-based PA assessment the best evaluated, and most valid body position is the placement on the hip. For special research questions or therapeutical assessments (e.g. monitoring of resistance training) the wrist worn position may have advantages compared to the hip worn position. In clinical practice, therefore, users must always weigh the potential benefits of such devices against potential harm. However, especially when physical activity is applied as a supportive measure in the treatment of chronic non-communicable diseases like diabetes, coronary heart disease, cancer or depressive symptoms, accelerometers, wearables, or smartphone apps can be a valuable support for both the patient (motivation) and the physician (monitoring). Particularly for the parameters of steps, duration, and PA intensity, a large proportion of these devices demonstrate sufficient validity to obtain a reliable estimation of a person's activity status. Some basic assessments for gait analysis and balance tests like the sit-to-stand test or the 6-minute walking test are already available as smartphone applications with good to excellent validity. For specific therapeutic interventions, the picture is not quite as clear yet, but there is a rapid development towards increased use in medical treatment and assessment. Future research should focus on addressing these limitations to enhance the accuracy and usability of accelerometer and wearable data for research, clinical practice and public health.

Conflict of Interest

The authors have no conflict of interest.

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