Contemporary Clinical Trials 64 (2018) 13–21

Contents lists available at ScienceDirect

Contemporary Clinical Trials

journal homepage: www.elsevier.com/locate/conclintrial

Review

Wearable activity monitors in oncology trials: Current use of an emerging technology

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ARTICLE INFO

Keywords:
Cancer
Oncology trials
Physical activity
Wearable activity monitors
Wearable technology
Outcome assessment
Cancer survivorship

ABSTRACT

Background: Physical activity is an important outcome in oncology trials. Physical activity is commonly assessed using self-reported questionnaires, which are limited by recall and response biases. Recent advancements in wearable technology have provided oncologists with new opportunities to obtain real-time, objective physical activity data. The purpose of this review was to describe current uses of wearable activity monitors in oncology trials.

Methods: We searched Pubmed, Embase, and the Cochrane Central Register of Controlled Trials for oncology trials involving wearable activity monitors published between 2005 and 2016. We extracted details on study design, types of activity monitors used, and purpose for their use. We summarized activity monitor metrics including step counts, sleep and sedentary time, and time spent in moderate-to-vigorous activity.

Results: We identified 41 trials of which 26 (63%) involved cancer survivors (post-treatment) and 15 trials (37%) involved patients with active cancer. Most trials (65%) involved breast cancer patients. Wearable activity monitors were commonly used in exercise (54%) or behavioral (29%) trials. Cancer survivors take between 4660 and 11,000 steps/day and those undergoing treatment take 2885 to 8300 steps/day.

Conclusion: Wearable activity monitors are increasingly being used to obtain objective measures of physical activity in oncology trials. There is potential for their use to expand to evaluate and predict clinical outcomes such as survival, quality of life, and treatment tolerance in future studies. Currently, there remains a lack of standardization in the types of monitors being used and how their data are being collected, analyzed, and interpreted.

Precis: Recent advancements in wearable activity monitor technology have provided oncologists with new opportunities to monitor their patients' daily activity in real-world settings. The integration of wearable activity monitors into cancer care will help increase our understanding of the associations between physical activity and the prevention and management of the disease, in addition to other important cancer outcomes.

1. Introduction

Physical activity is associated with improved outcomes and quality of life in cancer survivors [1,2]. Given the importance of physical activity to health and recovery, the majority of oncology trials involve tools to capture activity-related measures including exercise, sleep, energy expenditure, and functional performance. While a number of validated questionnaires have been used extensively to estimate physical activity and sleep, they are based on self-report and limited by recall and response biases [2,3]. Thus, physical activity tends to be overestimated with regards to activity frequency, duration, and intensity [4].

Recent technological advances in wearable activity monitors, have created new opportunities to collect continuous, objective patient data in a non-obtrusive manner. Wearable activity monitors measure movement to estimate the number of steps taken each day, distance travelled, energy expenditure, sleep parameters, and heart rate, among other activity metrics. There are different types of wearable devices that

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https://doi.org/10.1016/j.cct.2017.11.002
Received 5 August 2017; Received in revised form 16 October 2017; Accepted 1 November 2017
Available online 09 November 2017

can be used to monitor components of daily activity. This review focuses on wearable activity monitors used for monitoring and tracking fitness-related metrics. Devices commonly used are: (1) Pedometers: "estimate the number of steps taken through mechanical or digital measurements in only the vertical plane"; (2) Accelerometers: "Detect acceleration in one, two or three directions to determine the frequency, quantity and intensity of movements"; (3) Integrated multisensor systems: "Combine accelerometry with other sensors that capture body responses to exercise (e.g. heart rate) in an attempt to optimize physical activity assessments." [5–7].

Although pedometers have been used to record step counts for decades, the emergence of contemporary activity monitors into oncology trials is relatively new. With the rapid technological advancements of wearable activity monitors and complex systems in place to measure different components of activity, the use and applications of activity monitors in healthcare has broadened. Currently, there is a lack of knowledge on how wearable activity monitors are being integrated into the design and conduct of clinical trials. Furthermore, there is a need to better understand physical activity levels as measured using wearable activity monitors in cancer survivors or patients undergoing cancer treatment, as most studies have focused on summarizing physical activity levels in healthier populations. Thus, we conducted a review of the literature: (1) Describe current uses of wearable activity monitors in oncology trials; (2) Summarize physical activity patterns in cancer patients; (3) Identify opportunities for future applications. Findings from this review will provide information on the use of this emerging technology and on current physical activity levels of cancer survivors.

2. Methods

2.1. Eligibility criteria

Eligible studies were limited to randomized controlled cancer trials that used activity monitors to gain understanding of their specific use in controlled settings. Study participants could be either newly diagnosed, undergoing active treatment, or survivors of any cancer type. All activity monitors were considered eligible if they could be worn (e.g., on the wrist, arm, waist, hip, or ankle) and were used to track any form of physical activity. Activity metrics of interest included step count, activity count, energy expenditure, sleep, heart rate, duration of activity or any other form of physical activity that can be tracked and monitored by a wearable device. Published clinical trial protocols were reviewed and summarized for trials that are ongoing or not yet complete. Validation studies and other non-randomized or quasi-randomized studies were not included in the review. The search was limited to RCTs published between 2005 and 2016, to capture the more contemporary applications of devices. No language restrictions were applied.

2.2. Search strategy

While this was not intended to be a formal systematic review of the literature, we followed similar methods when screening and reviewing articles. Search terms for the population and devices were combined to identify studies for inclusion in Medline, EMBASE, the Cochrane Central Register of Controlled Trials (CENTRAL), and conference abstracts. Study screening, selection and data extraction were completed in Covidence- a Cochrane tool specifically used for systematic reviews. Two independent reviewers (GG & LG) screened titles and abstracts. Discrepancies were discussed and a third reviewer (AS) was consulted if needed. Full-text review was conducted in a similar manner.

2.3. Data extraction

Details on study design, interventions and outcomes of interest were extracted. Study details including study title, authors, year, country and registration number; study design (e.g., parallel, crossover, adaptive…); number of arms; number of participants; study duration and follow-up time were recorded. Primary and secondary outcomes were recorded and further categorized as "Physical activity"; "Behavioral/Cognitive"; "Quality of Life/Functional status"; and "Treatment/Survival" outcomes. Information on the study population including the cancer type (s), age groups, gender, and other baseline characteristics were extracted. Details of the devices used were recorded including the name and manufacturer of device, type of device (pedometer/accelerometer/multi-sensor system), placement, total wear-time, definition of valid wear-time and device output were recorded. If available, adherence rates and information on valid wear-days were extracted. Study results were extracted if they provided a step count or total time spent active and sedentary/asleep. Data from the baseline visit of the study population or control group (if overall data not reported) were used for the quantitative analysis.

2.4. Statistical analysis

Summary statistics were generated for trial characteristics. Where applicable, the average daily step count, sleep duration, sedentary time, and active minutes were summarized and plotted. Studies that did not report these activity data were excluded from the quantitative analysis. STATA version 13.0 was used for all analyses.

3. Results

The initial search identified 508 individual studies. Further screening of titles and abstracts yielded 71 trials to be included for full-text review. Excluded were multiple reports of the same trial, non-cancer trials, and trials that were not fully randomized. After full-text review, a total of 41 randomized clinical trials involving wearable activity monitors in cancer populations were included (Fig. 1). Trials were published between January 1st, 2005 and December 31st, 2016. Most trials were conducted in North America (USA/Canada) (68%). Additional study locations included Europe (15%), Asia (7%) and other countries (10%). Characteristics of the included trials are displayed in Supplementary Table 1.

3.1. Population

Over half of the trials were done in individuals who had completed treatment or were considered by their oncologist to have no evidence of disease (survivors) (n = 26, 63%). The majority of these were breast cancer patients (n = 17, 65%), followed by multiple cancer types

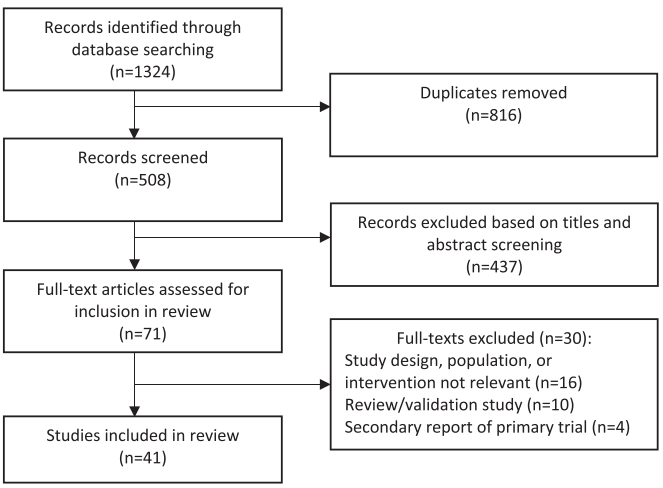

Fig. 1. Study selection flowchart.

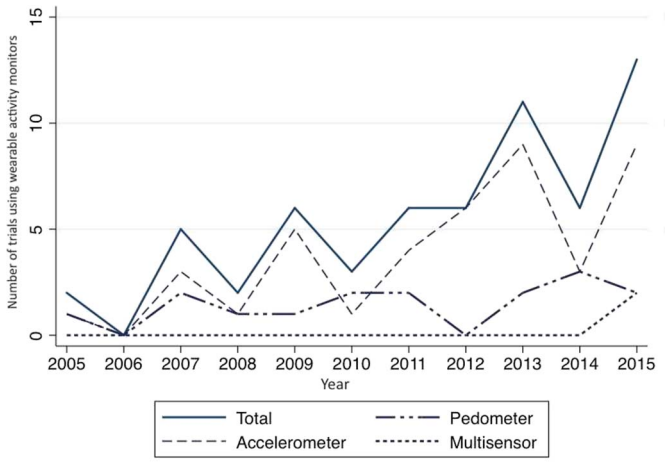

Fig. 2. Number of cancer trials involving wearable activity monitors, by year published.

(n = 7, 27%), lung cancer (n = 1, 4%) and colorectal cancer (n = 1, 4%). Most survivorship trials involved only females (72%), as a result of the large number of breast cancer studies. The mean age of survivors was 56 years, ranging from 44 to 67 years.

There were 15 trials (37%) that included patients with active cancer. Patients were on average 56 years old (range 46–62). Within this subset, 7 trials (47%) included non-metastatic or early-stage cancer patients, 5 trials (33.3%) included a mix of early and advanced stages (stages 1–4) and 3 trials (20%) involved only advanced or metastatic cancer patients. Cancer patients were either currently receiving treatment (radiation, chemotherapy, chemoradiation, or other multimodality treatment) in 9 trials (60%), had completed treatment in 3 trials (20%), were receiving only palliative care in 1 trial (6.7%), or had surgery only in 1 trial (6.7%). Therapy was received in the adjuvant setting in 3 of the 15 trials (27.3%) (Supplementary Table 1).

3.2. Wearable activity monitors

The number of cancer trials involving activity monitors has increased over the last decade (Fig. 2). There has also been a shift in the type of activity monitor used over time. While the use of pedometers has remained relatively constant over time, an increase in the use of accelerometers is observed most notably between 2009 and 2013. A transition from the use of single axis accelerometers to three-axis accelerometers (triaxial accelerometers) occurred between 2011 and 2016, mirroring the advancement of technology. A list of wearable activity monitor types, manufacturers, placement, and output is outlined in Table 1.

Activity monitor manufacturers were reported in 38 articles, representing 16 different manufacturers. The majority of activity monitors were manufactured by ActiGraph (Actigraph LLC., Pensacola, FL) (n = 15, 34%), followed by Philips Respironics (Philips, Koninklijke Philips LLC., N·V) (n = 4, 9%), Ambulatory Monitoring, Inc. (Ambulatory Monitoring, Inc., Ardsley, NY) (n = 3, 7%), Cambridge Neurotechnology (Cambridge Neurotechnology, LTD, Cambridge UK) (n = 2, 5%), and Mini-Mitter (Mini-Mitter Co. Inc. Bend, OR) (n = 2, 5%). The remaining devices were manufactured by different companies.

Activity monitor placement can affect how movement is recorded, thus affecting how activity data are collected [8]. Device placement included the wrist/arm (n = 25, 57%), waist or hip (n = 15, 34%), or leg/ankle (n = 4, 9%). Placement was dictated by type of activity monitor, since pedometers are most often worn at the hip, and accelerometers on the wrist. Multi-sensor monitors were placed on the leg, arm or wrist. One device was adhesive and taped to thigh (ActivPal, Pal technologies) [9]. Device output included step counts, activity counts, metabolic equivalents, time active, time spent in moderate-to-vigorous activity, sedentary time, sleep duration, sleep efficiency, total sleep time/sleep duration, sleep onset latency, and wrist movement per minute.

3.3. Clinical trial experimental and control groups

Trial interventions were categorized into physical activity/exercise (n = 22, 54%), behavioral (n = 12, 29%), and other (e.g., therapeutic, palliative care, or surgical interventions) (n = 7, 16%). Details of study interventions are provided in Supplementary Table 1. Physical activity interventions included home-based exercise programs, walking programs, strength-training, physical activity counselling, and other exercise programs. The majority of the physical activity/exercise trials involved cancer survivors (post-treatment) (68%) although there were seven oncology trials evaluated exercise programs in patients currently undergoing treatment [8,40,46,47,49,60]. These trials involved breast cancer patients (n = 3)[9,40,47], advanced lung cancer (n = 1)[46], and a mix of other malignancies (n = 3) [8,49,60]. Experimental interventions in active cancer patients included walking programs[8,60], aerobic exercise programs[9,40,47], strength-training[49], and neuromuscular stimulation of quadricepts[46].

Behavioral interventions included cognitive behavior therapy, behavioral strategies, and lifestyle counselling targeted to improve nutrition/diet, sleep quality, insomnia, stress reduction, weight loss or cognitive behavior. In the above categories, activity monitors were used to measure adherence to the exercise or behavioral programs or as objective measures of physical activity. Experimental behavioral interventions tested in cancer survivors included cognitive behavioral therapy [39,42,51,57,59,61], nutritional supplements, lifestyle intervention and weight-loss plan[5,52], and mindful-ness stress reduction [68]. Half of these involved breast cancer survivors and the remaining involved a mix of cancer types. Behavioral interventions used in cancer patients undergoing active treatment included behavior therapy [45], nutritional supplements and programs[53], and a program to manage fatigue/sleep [48]. Trials categorized as using “other” interventions (n = 7) included cancer therapy trials [11,15,58] (n = 3), light therapy [50] (n = 1), or other therapeutic and surgical interventions [7,9,10].

The control groups consisted of usual care or “wait-list control” in 24 trials (58%), active controls (e.g., informational pamphlets, single-component educational programs, sham activity programs, etc.) in 14 trials (34%) and other controls in 6 trials (15%). Other controls included standard treatments (surgical; chemotherapy; psychiatric), dim light for sleep therapy, or subjective method for tracking moderate-to-vigorous activity.

3.4. Clinical trial outcomes

Physical activity measures were primary outcomes in the majority of trials (n = 16, 39%). Change in physical activity levels pre and post intervention were evaluated either through self-report physical activity questionnaires, in the lab using treadmill tests to assess maximum oxygen uptake (V02), maximum heart rate, and intensity, or with activity monitors (step count; minutes of intense activity). In two trials, the number of steps per day as measured using a wearable activity monitor was reported as the primary outcome. Three studies reported the mean daily steps, as measured using a wearable accelerometer, as a primary outcome [10,11]. A third trial reported the proportion of participants who completed 10,000 pedometer steps per day as a primary outcome [12]. Sleep was the second most commonly reported outcome, including sleep duration, sleep quality, or sleep behavior (n = 6). Related to sleep outcomes were fatigue, insomnia or sedentary outcomes (n = 8). Other reported outcomes included cognitive change or cognitive behavior towards physical activity and sleep (n = 2).

Quality of Life as a primary outcome was reported in two studies [13,14]. Quality of life was assessed using the EORTC QLQ-30 scale and

Table 1
Characteristics of devices reported in the literature.

Author (year)	Cancer type	Device type(s)	Device placement(s)	Device outcome(s)
Pinto [44]	Breast, post-treatment	(1) Caltrac accelerometer (2) Digiwalker Pedometer	Hip	(1) Minutes of moderate-intensity physical activity; Total weekly Energy Expediture (kcal) (2) Step count
Epstein [45]	Breast, post-treatment	Actigraph	Wrist	Sleep duration; Sleep efficiency
Matthews [18]	Breast, post-treatment	(1) Actigraph (2) Pedometer	Waist	(1) Activity Counts (ct/min/day); Activity Duration; Steps per day; METs (2) Steps per day
Nikander [46]	Breast, during treatment	(1) Newtest Oy triaxial accelerometer (2) Digiwalker Pedometer	Not reported	(1) Relative ground reaction force (2) Steps per day
Vallance [47]	Breast, post-treatment	Digiwalker SW-200 Pedometer	Not reported	(1) Steps per day
Espie [50]	Multiple cancer types, post-treatment	(1) Actigraph (Cambridge)	Non-dominant wrist	Sleep onset latency; total sleep time; wake time after sleep onsent; sleep efficiency
Irwin [17]	Breast, post-treatment	(1) Pedometer (2) Heart rate monitor	Not reported	(1) Steps per day (2) Heart rate reserve
Demark-Wahnefried [48] [49]	Breast + prostate, post-treatment	RT3 triaxial accelerometer	Not reported	Activity counts per minute; Minutes of moderate, high and very high exercise
Berger [51]	Breast, post-treatment	Motionlogger Actigraph	Wrist	Wrist movement per minute
Innominato [15]	Colorectal, during treatment	(1) Mini-Motionlogger (2) Actigraph	Non-dominant wrist	Rest-activity circadian rhythm parameters (I < 0, r24, meanAct)
Maddocks [52]	Lung, during treatment	ActivPAL	Thigh	Step count per day
Rogers [53]	Breast, during treatment	GT1M accelerometer (Actigraph)	Wrist	Activity counts
Haines [13]	Breast, during treatment	Pedometer	Unclear	Unclear
Barsevick [54]	Multiple cancer types, during treatment	Motionloggor Actigraph	Wrist	Sleep duration; Sleep efficiency
Djuric [83]	Breast, during treatment	Pedometer (Omron HJ112)	Hip	Sleep duration
Hacker [55]	Malignancy requiring hematopoietic stem cell, during treatment	Actiwatch-Scorel	Wrist	Physical activity
Reeves [56]	Breast, post-treatment	Actigraph GT3X +	Not reported	Change in accelerometer-derived moderate-to-vigorous activity
van der Meij [14]	Lung, during treatment	Physical activity monitor (PAM) accelerometer (model AM101, PAM BV)	Hip	Physical activity score; minutes of low/moderate-intense activity
Ancoli-Israel [57]	Breast, during treatment	Actiwatch-Light (MiniMitter/Phillips/ Respironics)	Wrist	Sleep, circadian rhythm
Gielissen [58]	Multiple cancer types, post-treatment	Actometer	Ankle	Physical activity (unspecified)
Coleman [82]	Multiple Myeloma, during treatment	ActiGraph	Not reported	Minutes of daytime/nighttime sleep
Bruera [59]	Multiple cancer types, palliative	Actiwatch	Wrist	Sleep onset; sleep efficacy; wake after sleep onset; total sleep time
Takiguchi [11]	Gastric, during treatment	Activtracer AC-301A	Waist	Recovery of physical activity
Guinan [16]	Breast, post-treatment	(1) RT3 accelerometer (Stayhealthy Inc) (2) Heart rate monitor (Polar FT4F)	(1) Hip (2) Chest	(1) Physical activity (METs, time sedentary, intensity) (2) Aerobic intensity zone
Pinto [60]	Colorectal, post-treatment	CSA monitor	Waist	Active minutes
Prinsen [61]	Multiple cancer types, post-treatment	Actigraph	Ankle	Activity counts
Jones [62]	Breast, post-treatment	Pedometer	Not reported	Step count per day
Clark [9]	Breast, post-treatment	(1) ActivPAL inclinometer (2) Actigraph GT3X + accelerometer	(1) Waist (2) Adhesive	Sedentary time
Mustian [63]	Multiple cancer types, post-treatment	Actiwatch 64 (Mini Mitter)	Wrist	Sleep efficiency, sleep latency, and wake after sleep onset
Garland [64]	Multiple cancer types, post-treatment	GT1M Actigraph	Wrist	Sleep duration/efficiency
Mayo [65]	Multiple cancer types, during treatment	Pedometer	Wrist	Step count per day
Backman [12]	Breast + colon, during treatment	Pedometer	Wrist	Step count per day
Savard [66]	Breast, post-treatment	Actiwatch-64	Wrist	Sleep onset latency, wakening after sleep onset, number awakenings, number/ duration naps, total sleep time, sleep efficiency)
Rogers [67]	Breast, post-treatment	ActiGraph	Wrist	Sleep efficiency
Lengacher [68]	Breast, post-treatment	Actiwatch Score	Non-dominant wrist	Sleep duration/ efficiency
Short [69]	Breast, post-treatment	Pedometer	Not reported	Steps
Pinto [70]	Breast, post-treatment	ActiGraph	Not reported	Active minutes

(*continued on next page*)

Table 1 (*continued*)

Author (year)	Cancer type	Device type(s)	Device placement(s)	Device outcome(s)
Rogers Courneya [71]	Breast, post-treatment	ActiGraph	Wrist	Activity counts
James [72]	Multiple cancer types, post-treatment	Pedometer	Hip	Steps
Roveda [73]	Breast, post-treatment	Actigraph Actiwatch	Non-dominant wrist	Actual sleep time; actual wake time; sleep efficiency; sleep latency; immobility time; mean activity score; movement and gramentation index
Ungar [84]	Multiple cancer types, post-treatment	ActiGraph	Wrist	Active minutes

Fig. 3. Reported baseline step counts* from clinical trials using wearable activity monitors.
*Steps per day are the average number of steps taken each day. Horizontal line indicates the recommended 10,000 steps per day average. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

functional status was evaluated based on the Karnofsky Performance Scale [14]. In this trial, an accelerometer was used to obtain objective measurements of physical activity. A second trial, which included a pedometer to measure steps, used EQ-5D & VAS, EORTC C30, and BR23 as quality of life instruments [13]. Another example includes a randomized therapeutic trial that evaluated activity data from the accelerometer as a predictor of survival outcomes and functional outcomes [15]. The primary outcomes of the trial were overall survival and progression free survival and secondary outcomes included quality of life and performance status, measured using the EORTC Quality of Life Questionannaire-C30 and the WHO PS scale, respectively. Quality of life as a secondary outcome was evaluated or mentioned in a total of 19 articles (46%).

3.5. Wearable activity monitor metrics

Mean daily step counts were reported in 12 trials, of which 10 involved cancer survivors (Fig. 3). In survivors, mean step counts ranged from 4,660 to 11,000 steps per day. Daily step counts were slightly lower in patients undergoing active treatment for their cancer, reported in 2 articles (2,885 to 8,300 steps/day). Active minutes per week were reported in 7 trials and ranged from 109 to 336 active minutes per week Supplementary Figure 1). Sleep duration was reported in seven trials articles and ranged from 402 to 498 min of sleep per night. Sedentary time was reported in six trials and ranged from 413 to 556 min sedentary per day. Heart rate was assessed in two trials and one protocol. Two trials used the heart rate monitors to evaluate mean heart rate and max heart rate during exercise sessions,[16,74] and one trial measured average heart rate and maximal heart rate to estimate performance intensity during 30 min of moderate-to-vigorous aerobic exercise using a heart-rate monitor during treadmill sessions [17]. Overall, the wearable activity monitor output depended on the cancer population, types of interventions and outcomes specified in each trial (Table 1, Supplementary Table 1).

3.6. Adherence to wearable activity monitor

The percentage of participants adhering to wearing the device for the specified period of time was reported in nine trials. Adherence ranged from 73% to 97%, with a median value of 82%. The number of days of activity data required to be considered adherent or evaluable was reported in 17 trials, ranging from 3 to 7 consecutive days of

Table 2
Comparison of wearable activity monitors used in oncology triales.

	Pedometer	Accelerometers (Uni or triaxial)	Consumer-based multi-sensor systems
Examples of activity monitors	• Digiwalker • Fitbit Zip	• ActiGraph GT3X + • RT3 Research Tracker	• Fitbit Charge HR • Apple Watch
Average cost	~$10.00 to $60.00	~$200 to $1000.00 + software	~$150.00 to $400.00
Most common placement	• Hip/Waist • Wrist	• Hip/Waist • Wrist	• Wrist
Battery life	Up to 6 months	Up to 30 days	Up to 5 days
Syncing	• Not available for simple models (e.g., Digiwalker) • Wireless sync for more contemporary models	• Additional software required (e.g., ActiSync)	• Wireless sync with smartphones or tablets through Wifi or Bluetooth
Compatibility	• Not available for simple models	• Windows	• iOS • Android • Windows
Primary activity output	• Steps	• Activity counts • Heart Rate • Acceleration	• Steps • Heart Rate
Activity export (derived metrics from primary activity output)	• Distance	• Steps • Distance • Activity intensity • Calories • Sleep • Metabolic Equivalents	• Stairs • Distance • Active minutes • Calories • Sleep • Metabolic Equivalents
Additional Features	• Clock display • Water resistant	• Clock display • Water resistant • GPS tracking	• Clock display • Notifications • GPS tracking • Exercise type • Water resistant (some models water proof) • Food and weight logs
Pros (+)	+ Inexpensive + Longer battery life + Easy to use	+ Validated for clinical and sleep research (some models FDA-approved) + Export of raw acceleration available + More sensitive to movement and sleep activity	+ Real-time accessible data on personal devices + Inexpensive + User friendly + Comfortable + Aesthetically pleasing
Cons (−)	− Limited activity output − Lack of real-time data − Less accurate than triaxial accelerometers or multi-sensor systems	− Expensive − Additional syncing software required − Less user friendly and comfortable − May not sync with personal devices (e.g., phones, tablets)	− Validity still being explored in cancer populations − Shorter Battery life − Proprietary algorithms − Cannot be blinded
Recommendations	Recommend for low-budget clinical trials if primary purpose is to log steps and accuracy of step data less important. More sophisticated models with syncing capabilities recommended.	Recommended for studies of shorter durations where accurate estimates of activity and sleep are desired. Given cost of devices and software, a larger study budget is needed.	Recommended for studies of longer duration if it is of interest to obtain real-time activity data. Useful for studies integrating devices with other web-based applications and interventions.

activity data. The most commonly reported number was 3 consecutive days, reported in 5 trials. Valid wear time was defined based on the minimum number of hours of wear per day, ranging from 5 h per day to 10 h per day, in 6 trials. A detailed description of how missing actigraphy data were handled was provided in only one trial [18]. In most trials, methods for handling nonwear time and missing data were unclear.

3.7. Current protocols

Published protocols of clinical trials [74–81] involving wearable activity monitors in cancer populations are listed in Supplementary Table 2. The most commonly reported device among protocols is the triaxial GT3X + accelerometer (n = 3) [76,79,81]. Other trial designs include the use multisensor systems paired with smart phone applications (n = 2) [79,80], pedometers/step counters (n = 2) [74,77], and other accelerometers (n = 2) [75,78], and two trials plan to use more than one device [77,79].

4. Discussion

This review focused on characterizing and understanding applications of wearable activity monitors in oncology trials. We identified 41 randomized controlled trials published between 2005 and 2016 that used wearable activity monitors in cancer survivors. We found that wearable activity monitors are increasingly being used for the objective measurement of daily physical activity in clinical trials involving cancer survivors. More studies are using triaxial accelerometers and multi-sensor systems as they have become more abundant at decreased costs in the last five years. The rapid increase in the use of activity monitors is apparent when comparing our findings to those in a recent literature review conducted in 2010, where only 10 oncology trials that used activity monitors were identified [19]. Overall, there remains substantial heterogeneity in the types of devices used, the outcomes measured, duration of time they were worn and how the data were analyzed and reported in this review. A summary of the features of each of the three primary types of wearable activity monitors identified in this review and recommendations for their use in future clinical trials is provided in Table 2. The primary purposes for activity monitors are also described in the paragraphs that follow.

4.1. Wearable activity monitors allow for objective measurement of physical activity

We found that the most common purpose for wearable activity monitors was for the objective measurement of physical activity, either

as step counts, duration of activity, or activity intensity. Most trials involved exercise and behavioral interventions to increase daily activity. The emphasis on physical activity after cancer diagnosis emerges from evidence that physical activity is associated with improved outcomes in cancer survivors [20,21]. While there is more evidence available regarding the benefits of exercise in cancer survivors, some trials have also shown benefits for physical activity during cancer treatment [1,22]. Current physical activity guidelines for cancer patients recommend 150 min of exercise per week [23]. However, few cancer survivors meet the recommended guidelines [23,24]. Consequently, exercise and behavioral programs are being developed and tested in randomized controlled settings to determine their effectiveness at increasing physical activity among cancer populations and encouraging lifestyle changes. The use of wearable activity monitors will allow for the objective monitoring of physical activity in cancer while reducing the biases and patient burden associated with self-report physical activity questionnaires and diaries [25].

4.2. Wearable activity monitors are used to motivate physical activity goals

The most simple and oldest activity monitor is the pedometer, with the specific function of counting steps. Investigators that used pedometers in the reviewed trials defined a per day step goal and measured a participant's adherence to achieving that goal. Some studies evaluated the proportion of participants achieving a step goal after a specified period of day. A cut-point of 10,000 steps per day has been traditionally used, although there is increasing evidence that this cut-off is not accurate in people living with chronic conditions [26]. Such people take fewer steps, and have been shown to be more active in household chores that may not be accurately captured by the pedometer [15]. While pedometers are simple and inexpensive, they are limited in tracking activity other than step counts.

The accelerometer records additional activity outcomes such as activity counts and intensity, obtained from the raw acceleration data of the device. The studies identified in this review used accelerometers to measure the amount of time spent in different levels of activity such as sedentary, light or moderate-to-vigorous activity. Sedentary time is an important outcome as increased sedentary behavior is associated with poor health outcomes [27]. Interventions focused at decreasing sedentary behavior were evaluated in six trials where accelerometers were used as objective measures of sedentary time. Other interventions were developed to increase time spent in moderate-to-vigorous activity. Moderate-to-vigorous physical activity has also been shown to be associated with improved outcomes. In the cancer survivor guidelines, approximately 150 min per week of moderate intensity or 75 min per week of vigorous activity [23,28]. Additional limitations and precautions, however, are listed for survivors who are currently on radiation treatment, or experiencing side effects from the cancer or treatment [23].

4.3. Wearable activity monitor data are correlated with sleep

Sleep and fatigue are considered important patient-reported outcomes in oncology trials. There were fourteen oncology trials identified in this review that used accelerometry to obtain objective measures of sleep. The ActiGraph was the most commonly used device in these studies. Cancer patients report high levels of sleep-related problems including insomnia, excessive fatigue, leg restlessness, and sleepiness. The association between sleep and cancer has been explained by disruption of circadian rhythms in the brain and periphery, thus making sleep tracking an important feature of wrist-worn activity monitors [29]. Fatigue is an important symptom in cancer patients, characterized by feelings of exhaustion, weariness, malaise, lack of energy, motivation and inability to concentrate [30]. Given the biochemical evidence, many clinical trials have focused on measuring and reporting sleep variables and fatigue. Sleep has been found to be a correlate of autonomic dysfunction, which is prevalent in cancer patients [31,32]. More recent evidence has also suggested an association between telomere length, sleep and cancer [33]. Self-reported sleep duration and quality are often collected through quality of life questionnaires or sleep scales, but are also of limited value due to recall biases, as observed in self-reported physical activity. Objective monitoring of sleep, using actigraphy, has allowed for investigators to objectively measure sleep duration, sleep latency, number of awakenings, and sleep efficiency within their own home environment.

4.4. Potential for wearable activity monitor data to estimate quality of life

Quality of life (QOL) is an outcome that has been increasingly measured as a primary outcome in oncology trials. In oncology, QOL is considered a patient-centered outcome measure often collected using self-reported questionnaires such as the EORTC QLQ-30 [34]. The assessment of QOL in cancer patients is increasing as a result of a growing recognition for the importance of QOL in healthcare and cancer settings [35,36]. A recent Cochrane review reported on the association between physical activity on quality of life in cancer patients, and demonstrated beneficial effects of physical activity on QOL domains including physical functioning, role function, social functioning, and fatigue [37]. Thus, there is a growing interest in correlating objective activity metrics, as measured using wearable activity monitors, with subjective scales and overall quality of life. As it is a relatively new concept, only three trial reports focused on correlating objective activity with quality of life in this review [13,14,29]. However, there are several ongoing trials that are evaluating the relationships between objectively measured physical activity and quality of life. Further, it is anticipated that more oncology trials will use wearable activity monitors to measure and predict quality of life in the next few years [38]. Further correlations with Patient-Reported Outcome measures such as the NIH PROMIS® scales are also expected to increase in the next few years [39–41].

4.5. Summary of physical activity in cancer patients

Based on the available baseline data, we found that survivors (post-treatment) walk between 4660 and 11,000 steps per day while cancer patients undergoing treatment walk between 2885 and 8300 steps per day. These findings are similar to other reports including a review that looked at step counts in elderly and special populations (Range: 6500–8500 steps/day) [22]. The broad range reported may be explained by the substantial heterogeneity in oncology trials with regards to the cancer severity, treatment type, and duration. Thus, it is difficult to apply findings from our own review to a general cancer population. Given the substantial differences between activity patterns in cancer survivors who have completed treatment and those who are currently undergoing therapy for their cancer, it is recommended that activity levels are reported separately for these two groups. There is also a need for more trials involving cancer patients currently undergoing treatment in order to better understand how different therapies may impact their physical activity levels. Despite the observed differences across populations and broad range in physical activity, however, the average daily step count was consistently below the average recommended 10,000 steps per day for healthy adults in the trials included in this review.

4.6. Limitations associated with the use of wearable activity monitors in clinical settings

These activity estimates were based on data from monitors worn either on the wrist, hip or other parts of the body, manufactured by 16 different companies and worn for different durations of time. These findings highlight the challenge investigators face with the integration of activity monitors into clinical research and practice. There is a lack of

standardization across the types, placement and purpose for device use in oncology trials, affecting the accuracy of the data. Furthermore, there is uncertainty with regards to how the activity data are managed and analyzed, which is echoed in several reports [26,32–42]. Other methodological issues discussed include the challenge with the identification of wear-time of the accelerometer, defining the minimal number of hours of wear for a valid day, identifying artefactual movement, computing summary variables and aggregating days of data, and extracting patterns of activity [3]. In this review, the majority of reports did not include methods for handling missing data and did not elaborate on the different issues surrounding the use of wearable activity monitors. Thus, it is unclear what data are being used to derive such estimates, and accurate summaries of physical activity may be difficult to achieve. The lack of discussion of missing data in clinical trial reports seriously limits the ability to determine the overall validity of the study.

A final limitation associated with the use of activity monitors in clinical settings is that not all monitors being used are validated for clinical purposes or for the population under study. While many devices that have been validated in healthy populations, only few have been validated in chronically ill or cancer populations [6,43]. A previously published systematic review identified 134 validation studies of activity monitors where 118 were conducted in healthy adults and the remaining 16 were conducted in chronically ill populations [6]. Validation of these devices will continue to be a challenge as the technological platform grows and new and improved devices emerge with greater frequency.

Despite the new challenges faced with the onset and growth of an emerging technology, the use of wearable activity monitors presents new and promising opportunities in cancer care. As wearable activity monitors continue to be integrated into future clinical trials, applications for their use will broaden. For instance, trials may involve more sophisticated technology including multi-sensor systems or biosensors to capture multiple physical components. Furthermore, wearable activity monitors can be used in therapeutic clinical trials to measure a patient's improvement or decline over the course of treatment and assess their function and performance status. Third, the use of wearable activity monitor data for long-term, real-time monitoring of a patient's well-being and activity during and after treatment will be important as the cancer survivor population continues to grow. In conclusion, the use of wearable activity monitors in oncology trials as well as other clinical settings demonstrates strong potential towards the improvement in healthcare that we are only beginning to understand.

Conflicts of interest

All authors of the manuscript report no conflicts of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cct.2017.11.002.

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