Wearable Physical Activity Measurement Devices Used in Arthritis: Actical, Actigraph GT1M, GT3X, GT3X+, ActivPAL, RT3, Fitbit, Intelligent Device for Energy Expenditure and Activity, and SenseWear Pro3

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The benefits of physical activity (PA) for individuals with arthritis are well-established and studies on PA interventions targeting this population are increasing (1–3). Objective PA measures may provide robust and detailed assessments of these PA interventions, as well as have the potential to assist in clinical-decision making processes (4). The use of objective measures may address limitations of self-report PA measures (e.g., poor recall and failing to capture light intensity activities; (5)). Doubly labelled water, indirect calorimetry, and direct observation can be considered criterion measures of objective energy expenditure or PA measurement; however, these devices place large burden on the participant and may be inappropriate for the free-living environment.

Wearable PA measurement devices are increasingly becoming available, improving our ability to measure PA in the free-living environment. Research grade accelerometers allow the user to flexibly collect and analyze data by measuring acceleration in various planes to capture PA. Consumer-grade accelerometers are readily available for purchase by the public, typically with limited flexibility in data collection and analysis. Pedometers are more simplistic in their purpose, capturing only steps. Multi-sensor devices combine accelerometery with other measures such as heart rate, temperature, and galvanic skin responses to estimate PA. Across these wearable device categories, there are advantages and disadvantages to their use. Within these devices categories there are several device manufacturers and models, making selection of an objective wearable PA measurement device seemingly overwhelming.

The purpose of this review was to i) summarize general and specific characteristics of wearable PA measurement devices used in arthritis research conducted in the free-living environment, ii) define the psychometric properties of these devices when used among people with arthritis, and iii) provide a critical appraisal of each device's value to the rheumatology

community. The list of included devices is not exhaustive. Devices were included in the review if both psychometric information and use of the device to assess PA in a randomized controlled trial were available specific to arthritis populations. Given the limited evidence available in the arthritis population, evidence in older adults is provided where evidence is lacking in arthritis. The gait of people with arthritis has been found to be similar to that of elderly people and those with cautious gait (6–9). Specifically, reduced stride length and gait velocity are commonly observed among both older adults and populations with lower limb arthritis (6,7).

General considerations (e.g., measurement capabilities, cost, researcher and participant burden, measurement advantages and disadvantages) for selecting whether research or consumer grade accelerometers, pedometers, or multi-sensor systems are a suitable device are provided in Table 1. Specific measure descriptions, practical applications, psychometric information, examples of use in randomized controlled trials (RCT) and a critical appraisal of overall value of the device to the rheumatology community are described for individual measures below and are summarized in Supplementary Tables 1-3. Nine devices were included (the Actical, Actigraph GT1M, GT3X, and GT3X+, activPAL, RT3, Fitbit, Intelligent Device for Exergy Expenditure, and the Sensewear Pro3). No pedometer devices met the inclusion criteria. For a description of the search methods used to identify relevant psychometric papers see Supplementary File 1.

Research grade accelerometers

Actical

Description

Device description. The Actical is an omni-directional accelerometer that measures energy expenditure and step count through Motion BioSensors.

Measurement capabilities/features. The device is capable of capturing acceleration, step counts, and energy expenditure. Sampling rate is set at 32Hz and there is 32MB of on-board memory.

Where to obtain. The device can be purchased by contacting the manufacturer (https://www.actigraphcorp.com/support/activity-monitors/).

Practical application

Wear instructions. The Actical can be worn at the wrist, waist, or ankle throughout the day. It is waterproof in 1 meter of water for up to 30 minutes. The battery life can run up to 12 days in raw mode or 194 days when set at 1s epoch (time sampling interval) mode. Once the battery life is depleted, the CR2025 lithium coin cell battery must be replaced.

Data processing. The ActiReader is needed as a communication interface to process the data. Actical software is used to interpret the data and allows for programmable cut-points. The user can manipulate the epoch (1, 2, 5, 15, 30, 60s) and/or sampling mode (raw + steps, epoch, epoch + steps).

Psychometric information

Reliability. Not reported in arthritis populations.

Validity. To our knowledge, no studies assessed the validity of the Actical with another objective measure among people with arthritis. In young people with juvenile idiopathic arthritis (n=88), poor to moderate convergent validity was found between ActiCal and a self-reported activity diary when measuring “rest” (intra-class correlation coefficient [ICC] 0.41, 95% CI 0.19 to 0.60), light PA (ICC 0.17, 95% CI 0.08 to 0.40), and moderate-vigorous PA (MVPA) (ICC

0.24, 95% CI -0.01 to 0.46). Bland Altman plots demonstrated the Actical overestimated rest (mean bias=10 minutes, limits of agreement [LOA] 130.3 to 150.1) and light PA (mean bias=16 minutes, LOA 141.3 to 173.9), but underestimated moderate to vigorous PA (mean bias=-26 minutes, LOA –50 to 102.1) compared to the activity diary (10). In older adults (n=34), the Actical was compared with the CHAMPS Questionnaire. The Actical demonstrated correlations with the CHAMPS when measuring weekly frequency for moderate activity (r=0.36, confidence intervals not reported), caloric expenditure (r=0.37) and weekly frequency for all activity (r=0.40) (11).

Use in RCTs. The Actical has been used in a multi-centre randomized controlled trial to measure the effects of a cognitive behavioral program on time spent in rest, light, and moderate-vigorous PA in children with JIA (12).

Critical appraisal of overall value to the rheumatology community

Strengths. The Actical device can collect up to 32 MB of data and has the largest storage and recording time of the devices included in this review. Its light weight and small size may be beneficial to populations that are prone to skin sensitivities. The device is also waterproof.

Caveats and cautions. The Actical software is currently not compatible with Mac operating systems. Using the raw data collection mode yields a lesser run time of 12 days compared to using an epoch mode of 1 second + steps, which yields a maximum continuous run time of 194 days.

Clinical usability. Given the complexity of data processing, the Actical is better suited for research use.

Research usability. Sufficient research on the Actical among people with arthritis are lacking to support its validity. Specifically, no comparisons to criterion measures are made. With validation studies to date only comparing the device to self-report measures, it is challenging to make claims regarding the accuracy of the device. Nonetheless, it has been used in randomized controlled trials in people with arthritis and detected significant differences between groups. Furthermore, data collection and processing are flexible allowing researchers to manipulate cut-points and epoch length. Its long battery life (12-194 days depending on the chosen data collection mode) and large data storage supports long-term data collection. There is also no user interface (i.e., the user cannot see the amount of activity performed), helping to reduce bias as a result of monitoring.

Actigraph GT1M

Description

Device description. A uniaxial, micro-electro-mechanical systems-based accelerometer.

Measurement capabilities/features. The Actigraph GT1M is capable of capturing vertical acceleration and deceleration, steps, and energy expenditure (Kcal/minute). The device has 1MB of memory capacity, a sampling rate of 30Hz, and frequency range of .25-25Hz. Additionally, the device has a built-in filter to eliminate unit-to-unit variability, leaving only Actigraph's initial tolerance specification on sensitivity as the primary source of error (13)

Where to obtain. The device can be purchased by contacting the manufacturer (https://www.actigraphcorp.com/support/activity-monitors/gt1m/).

Practical application

Wear instructions. The Actigraph GT1M can be worn at the wrist, waist (hip), arm, or ankle but is recommended by the manufacturer to be worn at the centre of mass when measuring energy expenditure. The device has a 14-day battery life and takes under 3 hours to recharge.

Data processing. Actilife 6 software is needed to process the data. The user can flexibly manipulate epoch (1-240s options).

Psychometric information

Reliability. Not reported in arthritis populations.

Validity. In individuals with total knee arthroplasty (n=21), the GT1M underestimated energy expenditure (40-100% underestimation) compared to criterion methods during all walking and non-walking activities, with small to moderate agreement (ICC 0.00 to 0.38) compared to indirect calorimetry (MedGraphics VO2000). The SenseWear Pro3 demonstrated superior accuracy to that of the GT1M in this study. Authors also cautioned that the GT1M may not be appropriate for obese individuals as wearing the device in a vertical position on the waist may not be possible (14). The remaining studies compared the GT1M to self-report measures (International Physical Activity Questionnaire [IPAQ] and the Yale Physical Activity Survey [YPAS]) and demonstrated no to modest correlations among people with rheumatoid arthritis (RA) and osteoarthritis (OA) (15–17).

Use in RCTs. The Actigraph GT1M has been used to assess the effects of a motivational interviewing intervention on light, moderate, and vigorous amounts of PA among individuals with knee OA and RA (18).

It has been used to assess amounts of moderate and vigorous intensity PA in patients with early knee OA following a structured resistance training intervention (19).

Critical appraisal of overall value to the rheumatology community

Strengths. The device has a 14-day battery life and can be recharged within 3 hours.

Caveats and cautions. It has the shortest battery life of the Actigraph models assessed in this paper. It can only collect data in the uniaxial direction and the raw mode only yields a run time of 4.5 hours

Clinical usability. It is best used for research rather than clinical settings due to the complexity of the data analysis

Research usability. There are more recent devices from Actigraph that use tri-axial measurement and other devices that have better support for validity in this population.

Actigraph GT3X

Description

Device description. A tri-axial micro-electro mechanical system-based accelerometer (20).

Measurement capabilities/features. The device is capable of capturing acceleration, steps, active and sedentary bouts, intensity of PA, and energy expenditure. Based on the device's orientation, it is also able to detect the wearer's position. It has a sampling rate of 30Hz, a battery life up to 20 days (depending on mode and epoch selected), uses a rechargeable lithium ion battery (approximately 3-hour recharge time), 4MB of memory, and a frequency range of .25-25Hz. The user can manipulate the epoch (1-240s).

Where to obtain. The device can be purchased by contacting the manufacturer https://www.actigraphcorp.com/support/activity-monitors/gt3x/.

Practical application

Wear instructions. The Actigraph GT3X can be worn at the wrist, waist (hip), arm, or ankle but is recommended by the manufacturer to be worn at the centre of mass for energy expenditure. Using the lowest sampling rate, the rechargeable battery can last up to 20 days.

Data processing. Actilife 6 software is needed to process the data. The user can flexibly manipulate epoch (1-240s options).

Psychometric information

Reliability. Not reported in arthritis populations.

Validity. An assessment of convergent validity demonstrated significant correlations between the GT3x and VO_{2max} at all intensities (light rho=.35, p<0.01; moderate rho=.34, p=0.01; MVPA rho=.33, p=0.01) among people with RA (21). The GT3x has demonstrated weak relationships with the self-report measure, IPAQ, in people with systemic lupus erythematosus (SLE; n=120; (22)), juvenile dermatomyositis (n=19) and juvenile SLE (n=20; (23)). When compared to the Actigraph GT3X, Bland-Altman analysis revealed that the IPAQ underestimated sedentary time, light PA, and MVPA in juvenile dermatomyositis (mean bias 105.7, LOA 199.8 to 6.0 minutes respectively) and juvenile SLE (mean bias 36.4, LOA 227.8min to 15.2 minutes respectively) (23), but overestimated among people with RA (21).

Use in RCTs. The Actigraph GT3X was used to assess the effectiveness of a behaviour change intervention on sedentary time, PA time spent in light, moderate-vigorous, and bouts of moderate-vigorous PA in people with ankylosing spondylitis (24). It has been used to measure total PA in a subsample of individuals with hip or knee OA undergoing a web-based PA

intervention (25), and to assess the time spent in sedentary, light, and moderate PA during a low-load resistance training program in patients with RA (26).

Critical appraisal of overall value to the rheumatology community

Strengths. The device has single, dual, and three axis raw data collection modes and a long battery life.

Caveats and cautions. If the battery dies, the device needs to be reinitialized to continue use. Additionally, the device can only hold up to 4MB of data.

Clinical usability. Given the complexity of data processing, the Actigraph GT3X is better suited for research use.

Research usability. Newer versions of Actigraph devices are available; however, support for the device's validity across light to moderate-vigorous intensity activities has been supported in a criterion validation study among people with RA (21).

Actigraph GT3X+

Description

Device description. The Actigraph GT3X+ is a tri-axial accelerometer that uses an electro-mechanical system and an ambient light sensor with wireless or USB options.

Measurement capabilities/features. The device is capable of capturing acceleration, ambient light, steps, sleep, wear time. Sampling rate is user selectable and ranges from 30 to100Hz.

Where to obtain. The device can be purchased by contacting the manufacturer (https://www.actigraphcorp.com/support/activity-monitors/).

Practical application

Wear instructions. The Actigraph GT3X+ can be worn at the wrist, waist (hip), arm, or ankle but is recommended by the manufacturer to be worn at the centre of mass for energy expenditure. It is water resistant and can be submerged in 1 meter of water for up to 30 minutes. Using the lowest sampling rate, the battery life can last 31 days with a memory limit of 42.5 days. The device can be recharged in under 4 hours.

Data processing. Actilife 6 software is needed to process the data. The user can flexibly manipulate epoch (e.g., 1 second, 60 second) or filter techniques to analyze raw data.

Psychometric information

Reliability. Not reported in arthritis populations.

Validity. Among people with polymyalgia rheumatica (n=27), the GT3X+ performed well when compared to direct video observation and when using the low frequency extension filter (walking mean bias: 20 steps; 95% CI 8 to 33; LOA -40 to 81; stair climbing mean bias: 0 steps; 95% CI -1 to 1; LOA -5 to 5; (27)). It has been recommended to wear the device at the ankle and use the low frequency extension for those with slower gait speeds (27,28).

Use in RCTs. It has been used to evaluate the feasibility and preliminary effect of a supervised outdoor walking group and interactive workshop on walking activity among older adults (29).

Critical appraisal of overall value to the rheumatology community

Strengths. The device has a long battery life and large memory storage. Ambient lights sensors allow for light information to be analyzed alongside activity information, providing insights into the relationship between the environment, activity, and sleep behaviours. Actilife software is compatible with both Mac and PC. A unique feature to that listed by other devices is wear time allows the researcher to objectively assess user fidelity to wear.

Caveats and cautions. If the battery dies, the device needs to be reinitialized to continue use; however, this is unlikely to be necessary given the long battery life. It is suggested to use the lower frequency extension and wear at the ankle for individuals with slower gait speeds (27,28)

Clinical usability. Given the complexity of data processing, the Actigraph GT3X+ is better suited for research use.

Research usability. The limited psychometric information available in arthritis supports its use for assessing walking. More research is needed to assess usability at moderate intensities and higher in arthritis. There is a low frequency extension option that increases sensitivity to slow movement or very light steps which may be observed in populations with arthritis. Raw data can be flexibly manipulated using different filter techniques or accumulation sizes giving the researcher more control in the data analysis.

ActivPAL

Description

Device description. The activPAL is a miniature electronic logger designed to quantify free-living daily activities using a tri-axial accelerometer.

Measurement capabilities/features. The device is capable of capturing activity intensity and total time spent doing a classified activity, number of transitions (i.e. interruptions of sedentary time), and discriminates upright from seated or lying activities.

Where to obtain. The device can be purchased by contacting the manufacturer (http://www.palt.com/)

Practical application

Wear instructions. The activPAL is usually taped on to the thigh. It records up to 14 days of activity.

Data processing. PAL Software Suite is required to analyze the data. Measurements of position are made every 20th of a second in its standard configuration. The devices has a sampling frequency of 10Hz (30).

Psychometric information

Reliability. Not reported in arthritis populations.

Validity. Among people with RA (n=24), the activPAL significantly underestimated step counts by 26% and transition counts by 36% compared to direct observation; however, no significant differences were observed between the activPAL activity monitor and the criterion measure for time spent in sedentary, standing or light activity, and walking behaviors.

Use in RCTs. activPAL has been used to objectively monitor change in daily sitting time as a result of motivational counselling sessions and SMS reminders in patients with RA (31). This device has been used to assess the effect of a rehabilitation program on walking time among inpatient older adults (>60 years old). The activPAL was also used as a motivational tool in this

study; a report was generated from the walking data and made available to the participants every week (32).

Critical appraisal of overall value to the rheumatology community

Strengths. The device allows quantification of time spent in various positions/activities (sitting, lying, standing, walking) and is of moderate cost (33).

Caveats and cautions. Mild skin irritation can occur because the device is often taped onto the subject's skin (34). Moderate participant burden has also been reported (33).

Clinical usability. Given the complexity of data processing, it is better suited for research use.

Research usability. The activPAL is not well-supported for accurately assessing step and transition counts in people with RA; however, may be appropriate when measuring sedentary, standing or light activity, and walking behaviors among people with RA. It is unclear whether it is appropriate for higher intensity activity behaviours.

RT3

Description

Device description. A tri-axial accelerometer that measures motion along the vertical, medio-lateral, and antero-posterior planes using a piezoelectric accelerometer and microprocessor.

Measurement capabilities/features. The device is capable of capturing activity counts and energy expenditure. Data collected using 1-s epochs can be stored for 9 hours or 60-s epochs can be stored for 21 days (35).

Where to obtain. Despite the device no longer being available, the RT3 was reviewed given its widespread use.

Practical application

Wear instructions. The RT3 is worn on the waist/hip and has a battery life of 60 days (38)

Data processing. Stayhealthy RT3 Assist version 1.0.7 software is needed to process the data (36). Data can be downloaded onto the computer via a docking station, counts are then converted to energy expenditure (37). It includes both low-pass (0.1Hz) and high-pass (16Hz) filters (38).

Psychometric information

Reliability. RT3 units were tested moving in two directions (entero-posterior and medio-lateral) at speeds of 150 and 275 RPM on a shaker for three 24-hour periods. Good within-unit reliability was observed for total activity counts of the RT3 (coefficient of variation: 0.29% to 1.81%) and repeatability coefficients ranging from 19.98 to 105.36 counts/minute, representing 5% of each 3-day trial's mean. Poor between-unit reliability (coefficient of variation: 9.5% to 34.7%) was observed among the 22 units (35).

Vibration frequency appears to impact accuracy with more accurate values generated at higher frequencies (35). Twenty-three RT3 monitors were tested using a motorized vibration table at 2.1, 5.1 and 10.2 Hz to assess intra- and inter- instrument variability (39). The intra-instrument coefficient of variation (CV) decreased as frequency increased (2.1 to 56.2%, 0.3 to 2.5%, and 0.2 to 2.9% at 2.1, 5.1, and 10.2 Hz, respectively). Inter-instrument CV decreased as frequency

increased (2.1Hz: 21.9 to 26.7%, 5.1Hz: 6.3 to 9.0%, and 10.2Hz: 4.2 to 7.2%; (39)). The ICC between RT3s was 0.99 regardless of the axis (39). It has also been suggested that the device should be worn on the same-side hip throughout a trial (38).

Validity. Following regression analyses, the RT3 demonstrated a statistically significant correlation with the IPAQ self-report measure ($r=0.35$, $p=0.02$) among people with RA (n=50). The RT3 and IPAQ demonstrated moderate agreement, weighted kappa index=0.27 (95% CI 0.06 to 0.48, $p=0.02$; (40)). Among older adults, the RT3 demonstrated a strong correlation with the self-reported Leisure-Time Exercise Questionnaire for reported minutes of MVPA ($r=0.48$, $p<0.001$; (41)).

Use in RCTs. The RT3 was used to measure moderate-vigorous and total PA following counseling and primary care visits on walking and strength exercise compared to discussion of the participant's choice of health education topics among older primary care patients (42). Change in daily total activity levels over a 7 day period was measured by the RT3 to determine the effectiveness of a behavior change intervention with or without a pedometer to increase PA in sedentary older women (43). The RT3 was used to measure activity counts over 7 days following delivery of twice-weekly physiotherapist-led exercise classes in-hospital (44).

Critical appraisal of overall value to the rheumatology community

Strengths. The RT3 has a long battery life (37) and up to 21 days of memory (45)

Caveats and cautions. It only has 9 hours of memory when used at the 1-s epoch (45). The device is much larger than most research grade accelerometers available today. Researchers have no knowledge of how energy expenditure is estimated and must accept the output variables at face value (37).

Clinical usability. Given the complexity of data processing, the RT3 is better suited for research use.

Research usability. Other research grade accelerometers are likely to be more beneficial with increased flexibility to manipulate and filter the data. No comparisons with criterion measures have been made in this population; support for its validity is unclear.

Multi-sensor devices

Intelligent Device for Energy Expenditure and Activity (IDEEA)

Description

Device description. The IDEEA is a portable gait and posture analysis system and PA monitor with 5 bi-axial sensors connected to one microprocessor (46,47).

Measurement capabilities/features. The device is capable of detecting postures, activity, mechanical power output, energy expenditure, and includes a gait function analysis that allows the researcher to playback an animation for a selected time period (e.g., at what time did a subject fall, what was the last supporting leg). Using the company's analysis software, more than 40 types of movements (e.g., jumping, stair climbing/descending, picking up an object, standing, leaning, lying, etc.) can be identified. The device includes a 32-bit microprocessor unit with up to 200MB of storage capacity (48), and a sampling rate of 32Hz (47).

Where to obtain. The device can be purchased by contacting the manufacturer (http://www.minisun.com/).

Practical application

Wear instructions. Three sensors are attached to both thighs and sternum and are connected by wires to the main recorder (micro-processor) worn at the waist. Two foot sensors are worn on the inferior side of each foot and connected to two sub-recorders by wires that are attached above the ankle on the lateral side (49). The device has a battery life of <60 hours.

Data processing. Uses GaitView software and connects to a PC using a USB (47).

Psychometric information

Reliability. ICC's across two days for nonmovement and movement behavior was moderate-high except for going up and down steps (ICC=0.34, 95% CI 0.17 to 0.48) among 126 older adults. It has been recommended that to achieve reliable data, as few as 2 days of wear for nonmovement behavior and standing, 6 days for slow walking behaviour, and as many as 16 days to detect stair climbing/ascending are needed to achieve ICC's of 0.80 (49).

Validity. Among patients with hip OA (n=26), IDEEA-measured gait was compared to the criterion GAITRite software. ICC's were acceptable for all parameters except for step length (ICC 0.78): gait cycle 0.99, swing 0.93, double support 0.82, cadence 0.99, and speed 0.93. Among patients with RA (n=24), the IDEEA was compared to the criterion GAITRite walkway and total number of steps output recorded by video. Bland-Altman plots demonstrated agreement with automated step counts for the control group at 200 steps (21.47; LOA -9.29 to 52.23) but differed significantly for the RA group (-25.16; LOA 137.66 to 87.34). The IDEEA further underestimated the number of steps taken in patients with slower walking speeds. Wider LOA indicated poorer agreement for all IDEEA derived temporal and spatial gait parameters except gait velocity, compared to other devices (Step-N-Tune, A4L) that were compared with the gold

standard. IDEEA underestimated both gait velocity and double support time as compared to the gold standard (48).

Use in RCTs. IDEEA was used to measure patients' gait patterns such as step length, width, and speed to compare the difference between bicompartmental knee arthroplasty and total knee arthroplasty in restoring knee function in individuals with OA (50).

Critical appraisal of overall value to the rheumatology community

Strengths. The IDEEA uniquely captures activity type and can be used for gait analysis. The company identified 40 activities the device can distinguish between in the free-living environment.

Caveats and cautions. IDEEA's software is not compatible with Mac operating systems. The device is not waterproof and may be cumbersome for the user to wear the main recorder, two sub-recorders, and 5 sensors. The device has a very short battery life.

Clinical usability. Given the complexity of data processing and wear, it is better suited for research use.

Research usability. The IDEEA is one of few devices that can detect postures, activity, mechanical power output, energy cost, and gait analysis in the free-living environment with a small criterion validity study supporting its use in patients with hip OA for certain gait parameters. However, the accuracy of the device to assess step counts, and temporal and spatial gait parameters was not supported among a small sample of people with RA. If the primary goal is not to assess gait or activity type, rather volume of PA, other devices are likely more accurate and less obtrusive for the user.

SenseWear Pro 3

Note. A newer version, the Sensewear Mini, has been used as a measurement tool in arthritis populations (e.g., (51,52)). This device was not assessed for psychometrics in individuals with arthritis and was therefore not included in this review; however, the Sensewear Mini device has been reviewed extensively in the general population (e.g., (53,54)).

Description

Device description. The SenseWear Pro 3 is a 2-axis accelerometer with four physiological sensors for skin temperature, galvanic skin response (sweat and dilation of sweat glands), heat flux (rate at which heat is dissipating from the body), and near body temperature.

Measurement capabilities/features. The device is capable of measuring energy expenditure, duration and levels of PA, number of steps, and sleep/wake states. The device uses a radio frequency of 2.4GHz (55).

Where to obtain. Despite the device no longer being available, the SenseWear Pro 3 was reviewed given its widespread use.

Practical application

Wear instructions. The device is to be worn at the back of the upper arm on the non-dominant arm.

Data processing. SenseWear Pro 3 uses InnerView software (InnerView ® Retrieve and InnerView ® Professional). It captures both basic statistics of data streams (i.e., averages) as well as more complex features (i.e., peaks, steps; (56)). Anthropometric data from the participant (e.g., gender, age, height, weight) is combined with physiological data to calculate energy expenditure (57).

Psychometric information

Reliability. The SenseWear Pro 3 demonstrated good to excellent test-retest reliability of energy expenditure measured in older adults during lie-down (ICC=0.78) and treadmill walking (ICC=0.94; (14)).

Validity. Among patients with RA, The SenseWear Pro 3 demonstrated substantial agreement and a strong relationship compared with indirect calorimetry when estimating total energy expenditure. The device also demonstrated correlations with low (0.77), medium (0.81), and high intensity activities 0.71); however, Bland-Altman plots revealed the device tends to overestimate energy expenditure at higher intensities and underestimate at lower intensities (58). Compared to the criterion video observation, the SenseWear Pro 3 showed a poor ability to estimate step counts (58).

In patients with total knee arthroplasty due to end-stage knee OA (n=21), when compared to the criterion measure, MedGraphics VO2000^{c} indirect calorimeter, the SenseWear Pro 3 demonstrated small differences and moderate to good agreement across activities of daily living, (ICCs ranged from 0.60 to 0.81). The Bland-Altman plots indicated no systematic bias. For walking activities, the differences between the two measures were small and not significant (ICCs ranged from 0.48 to 0.63). By contrast, among patients with hip OA (n=20), the SenseWear Pro 3 compared to indirect calorimetry (portable metabolic monitor- Cosmed K4b) demonstrated a significant average overestimation of 1.5Kcal/minute (95% CI 1.3 to 1.8) during activities of daily living (57). Specifically, during walking activities (self-paced and brisk walking) the SenseWear Pro 3 overestimated between 62% and 93% during walking activities and for outdoor activities such as gardening (170% overestimation) and indoor cleaning (use of

upper body; 119% overestimation). Significant underestimation was observed during ascending and descending stairs (-25%). The correlation coefficient across all activities (walking, non-walking) was 0.94. Despite the high correlation between the measures, the SenseWear Pro 3 significantly overestimates EE during common activities of daily living by on average of 72% (57).

Use in RCTs. The SenseWear Pro3 was used to assess volume of physical activity exceeding 1.5 metabolic equivalents following medical care, group exercise, and manual therapy/individual exercise in an outpatient research clinic among community dwelling older adults (> 60 years) diagnosed with or having had a history of lumbar spinal stenosis (59). The SenseWear Pro 3 was also used to assess light, moderate-vigorous PA and sedentary time in inactive older adults participating in a 12-week intervention tailored to decrease sedentary behavior or increase MVPA (60). In adults aged 60 and older with total knee replacement due to osteoarthritis or inflammatory arthritis, the device was used to compare change in energy expenditure during activity of at least light intensity following clinic-based physiotherapy, community based exercise, or usual care (61).

Critical appraisal of overall value to the rheumatology community

Strengths. The device can store 12 days of internal memory and can be fully recharged within 4 hours. It integrates 4 physiological sensors to estimate energy expenditure; this may have value in estimating strength training activity that is not typically detected in accelerometers (62,63); however, support for validity of the device to capture strength training activity has not been assessed in populations with arthritis.

Caveats and cautions. The device has been discontinued and can no longer be purchased.

Clinical usability. There is potential for the device to be used in a clinical setting as the InnerView ® Retrieve software allows patients to retrieve the data file and email to the clinician.

Research usability. Studies assessing criterion validity have been conducted comparing energy expenditure measured by indirect calorimetry with the SenseWear Pro 3. It should be noted that measuring energy expenditure is not interchangeable with measuring PA but may be used as a proxy measure (14). Although good agreement was found when assessed using ICCs, the use of ICCs for assessing validity have been criticized (for a review and justification see (64)). Taken together, use of the SenseWear Pro 3 for measuring energy expenditure during activities of daily living is cautioned amongst individuals with hip OA. Likewise, if using the SenseWear Pro 3 to estimate energy expenditure in the RA population during higher intensity activities, users should be cautioned that the device has a tendency to overestimate energy expenditure. Among individuals with total knee arthroplasty, the SenseWear Pro 3 appears to be appropriate for measuring activities of daily living. The InnerView ® Professional Software includes advanced algorithms that process SW data and generates graphs and reports that can be given to patients/participants to understand.

Consumer-grade accelerometer

Fitbit

*The various models of Fitbit did not fit the inclusion criteria individually, however, given the device popularity, the Fitbit was included. Information is collapsed across the devices and highlights of specific devices are drawn when appropriate.

Description

Device description. Variable, please see Supplementary Table 1.

Measurement capabilities/features. The devices are capable of capturing active minutes, calories burned, distance, and steps. Some models are capable of capturing activity levels, floors climbed, sleep, altitude, heart rate, pace, stationary time. For specific details please see Table 2.

Where to obtain. The device can be purchased by contacting the manufacturer (https://www.fitbit.com/en-ca/home). Where devices have been discontinued, some can still be found from third party online sites.

Practical application

Wear instructions. The device placement varies from wrist, hip, to ankle. Battery life varies from 5 days to 6 months depending on the device and can be recharged in 1 to 2 hours (except for the Fitbit Zip; see Supplementary Table 1.)

Processing. Epoch and sampling frequency cannot be manipulated during collection. Data can be viewed from the Fitbit app and daily summary data can be exported to an Excel or CSV file. To access more types of data, the Fitbit web application programming interface can be used to obtain second-level, minute-level, or hour-level data. Access must be requested from Fitbit using a registered account and client ID. Alternatively, a third party, paid service such as Fitabase (https://www.fitabase.com) may be used. Fitabase collects all physical activity data captured by Fitbit devices including minute to daily totals of steps, activity intensity, metabolic equivalents, energy expenditure, floors climbed, sleep, and heart rate.

Psychometric information

Reliability. Not reported in arthritis populations.

Validity. Among the studies that compared Fitbit to a criterion measure (video observation), device placement impacted accuracy amongst participants with slower walking speeds (65,66). In older adults (n=42), at speeds of 0.4-0.9m/s, the Fitbit One worn at the ankle had a percentage error of less than 10% and did not record zero steps at any speed. The percentage error of the Fitbit One worn at the ankle was significantly lower than when worn at the waist at all speeds (66).

In older adults with reduced mobility (n=18), the Fitbit Ultra worn at the hip performed better than when worn at the wrist where the hip worn device underestimated step counts by 27.45% ± 79.9%, while the wrist-worn underestimated by 99.64% ± 0.8%. The Fitbit Ultra worn at the wrist also failed to detect any steps whatsoever in 80% of collections involving participants with reduced mobility and only detected 1.79% of steps taken in the trials where it did collect data (65).

When used amongst older adults with knee OA (n=15), relative to a hip-worn Actigraph GT3X+, the Fitbit Charge 2 overestimated steps by 39% (ICC 0.60) and sedentary time by 37% in knee OA patients. Additionally, it underestimated MVPA by 5 minutes. Compared to the wrist-worn Actigraph GT3X+, the Fitbit Charge 2 underestimated steps by 29% and MVPA by 158+/-93 minutes of MVPA (SD); however, the same cut-points were applied for the wrist-worn accelerometer as the hip-worn which may be inappropriate. For daily wear time, the Fitbit step-

based algorithm underestimated hours of wear compared to the HR-based algorithm (9.4 versus 11.1 hours; 14% bias; (67)).

Use in RCTs. The Fitbit ZIP was used in conjunction with the Jawbone Up pedometer in an intervention that compared step-monitoring diaries to diaries plus a step target to examine the effect of a pedometer-based intervention on increasing PA and decreasing fatigue. (68)

Critical appraisal of overall value to the rheumatology community

Strengths. The devices have a wide range of options for battery life ranging from days to months. The devices are user friendly and are accompanied by a free downloadable app that can be used on a mobile phone or tablet. The devices can be obtained online or in-store with varying price ranges. The devices can be worn throughout the day and night with the exception of the Fitbit Zip (which cannot be recharged). The Fitbit devices can be fully recharged within 1 to 2 hours.

Caveats and cautions. Some devices are not waterproof. If detailed data is needed, users must use the Fitbit web application program interface, request access to the intraday time series feature from Fitbit, or other third-party sites such as Fitabase. The device does not allow for epoch or sampling frequency to be manipulated. Fitbit Flex, One, Charge 2, and Ultra are no longer available for purchase through Fitibit.

Clinical usability. The devices can be used readily in a clinic setting without specialized training (69). The device app allows clinicians and the user to discuss progress if used as a motivational tool.

Research usability. Not recommended for use as a measurement tool in research. The accuracy of Fitbit in measuring PA is not supported and is especially limited in capturing slow walking speeds. For a comprehensive systematic review and narrative synthesis across all populations that also cautions the use of Fitbit as a measurement tool, please see (70). Additionally, researchers are restricted by the software of the Fitbit device (e.g., cannot flexibly manipulate epoch or access raw data).

Discussion

This review has described wearable PA measurement devices that have been assessed for use among arthritis populations. The findings regarding the reliability and validity of wearable PA measurement devices are overall mixed and is dependent upon the specific type of arthritis being studied; however, overarching considerations for device selection are discussed briefly. First, when selecting a device, it is important to consider the speed at which the participants in question ambulate. Certain research-grade accelerometers with specific filtering techniques are best used in people with slow gait speed and ankle placement is recommended (e.g., Actigraph GT3X+). It should be noted that this review only summarizes the evidence provided in arthritis populations (or older adults where evidence was lacking); however, in many cases, individuals with arthritis' movement does not differ from that of the general population. Not all types or severities of arthritis affect movement speed or gait. There are many examples of objective PA device reviews conducted in the general population that likely apply to individuals with arthritis whose movement is not affected, e.g.,(5,70–73).

Secondly, the choice of device should be informed by the intensity and type of PA performed by the users. The devices have varying strengths in detecting different activity

intensities (e.g., sedentary activity, light, and moderate to vigorous physical activity). Although generally, objective measures lack the ability to identify activity type (e.g., activities of daily living, swimming, biking, resistance training, etc.). It has been suggested that a combination of both subjective and objective measures may serve as a complementary approach to PA measurement where objective measures help address recall bias and subjective measures provide activity type information (3,5,74). This may be important clinically, where patients and clinicians can engage in goal setting and monitoring with the use of objective measures, and discuss the specifics of implementation strategies through self-report (51,52). Lastly, some of these devices can serve not only as measurement tools, but also to increase motivation. Self-monitoring is one of the most influential PA behaviour change techniques (75–77); if the purpose of the using these devices is strictly for measurement, devices should be set so that participants cannot view their data.

Future research should evaluate newer models of the devices that have not yet been evaluated for validity or reliability. Many existing devices were excluded for not having psychometric evidence specific to populations with arthritis (e.g., Garmin, pedometers). These devices should be evaluated against other criterion measures (e.g., direct observation, indirect calorimetry, doubly-labelled water) as no gold-standard objective or subjective PA measure currently exist in PA measurement. Studies evaluating the accuracy of devices to detect activity type are also needed. Lastly, future research on how both objective and subjective measures may be best employed and analyzed concurrently is encouraged.

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Table 1: General comparison of consumer- and research-grade accelerometers, pedometers, and multi-sensor devices

Measure	Purpose	Physical activity parameters measured	Participant considerations	Researcher burden (software, analysis)	Relative cost	Measurement Limitations	Measurement Advantages	Other useful information
Accelerometer (research grade)	Measures the quantity and intensity of activity by detecting acceleration in one (uniaxial), two (biaxial), or three (triaxial) planes (4)	Frequency Intensity Time	Limited participant burden to wear Do not necessarily have user interface capabilities (78)	Requires extensive training to conduct data collection and analysis (78)	Expensive	Does not capture activity type Particularly underestimates energy cost of walking/running on an incline and strength training (71)	Software packages can provide reasonable insight into activity patterns e.g., bouts, intensity based on manipulatable thresholds Can have longer battery (collection length) than consumer grade accelerometers May have ability to manipulate epochs and cut-points	Wear time recommended at a minimum of 10 hours of at least 3-5 days in adult populations (79,80) Cost may prohibit assessment of large sample size
Accelerometer (consumer grade)	Is readily available for consumer purchase and measures the quantity and intensity of activity by detecting acceleration in one (uniaxial), two	Frequency Intensity Time Type*	Limited participant burden to wear Typically includes user interface features (78)	Limited analysis flexibility	Typically, lower cost than research grade accelerome-ters depending	Participants may alter behaviour in response to readings (71) Typically less accurate than research-grade accelerometers	User can select activity type in some models/makes	Many consumers are already using a consumer grade accelerometer serving as an advantage for large scale data collection

	(biaxial), or three (triaxial) planes(4)		Can be used to track personal health data (78)		on the model/make			May be used as a behaviour change tool(78)
Pedometer	Measures the number of steps taken using mechanical or digital measurements in the vertical plane(4)	Number of steps Intensity may be inferred from step rate	Limited participant burden to wear	Easy data collection and analysis	Inexpensive	Does not capture activity type, patterns, intensity Participants may alter behaviour in response to readings (71)	If steps are the desired outcome in a large sample size, accuracy and cost of device makes this device favourable	Inexpensive cost serves as an advantage for large scale data collection
Multi-sensor	Combines accelerometry with other measures such as heart rate, temperature, galvanic skin response, inclinometer to estimate PA	Frequency Intensity Time Type* Other complementary parameters for interpreting PA	Dependent upon device, may be burdensome to wear	Requires extensive training to conduct data collection and analysis (71)	Expensive	Energy expenditure calculations may be inaccurate	Intensity assessed through other sensory measures may give greater insight to activity types that are not captured in other objective measures (e.g., walking/running on an incline, strength training)	Cost may prohibit assessment of large sample size

Note. *some devices may be capable of capturing activity type using auto-detect features or a user-selected method.