E F O R T *open reviews*

Use of accelerometer-based activity monitoring in orthopaedics: benefits, impact and practical considerations

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- Studies of the effectiveness of orthopaedic interventions do not generally measure physical activity (PA). Applying accelerometer-based activity monitoring in orthopaedic studies will add relevant information to the generally examined physical function and pain assessment.

- Accelerometer-based activity monitoring is practically feasible in orthopaedic patient populations, since current day activity sensors have battery time and memory to measure continuously for several weeks without requiring technical expertise.

- The ongoing development in sensor technology has made it possible to combine functional tests with activity monitoring.

- For clinicians, the application of accelerometer-based activity monitoring can provide a measure of PA and can be used for clinical comparisons before and after interventions.

- In orthopaedic rehabilitation, accelerometer-based activity monitoring may be used to help patients reach their targets for PA and to coach patients towards a more active lifestyle through direct feedback.

Background

The overall aim of surgical or non-surgical interventions in orthopaedics, besides pain relief, is to restore function and enable patients to live physically active lives. Paradoxically, physical activity (PA) as an outcome measure has not received much attention in orthopaedics, although injuries to the musculoskeletal system directly affect which movements and physical activities can be performed. It is increasingly recognized that PA is a major or even dominant factor in preventing or delaying orthopaedic diseases[1,2] as well as non-orthopaedic conditions.[3] Thus, the assessment of PA, in addition to pain and physical function, is suggested to be relevant and can offer reference values or provide patient feedback. The aim of this review was to describe the benefits and impact of accelerometer-based PA monitoring in orthopaedics, and, additionally, to discuss the practical considerations when applying this assessment method in research and clinical practice.

Current state of physical activity assessment in orthopaedics

Physical activity is a complex dimension which has been shown to have a considerable impact on human health, both physically and mentally, and in terms of quality of life.[4,5] It is defined as any 'bodily movement produced by skeletal muscles that results in energy expenditure',[6] and can thus vary from household activities to strenuous exercise. Whether PA beneficially affects the health of an individual seems to depend on the type, intensity and frequency of an activity.[7] To give an example, regular bicycling might protect against the functional decline of knee and hip in patients with osteoarthritis,[8] whereas PA involving heavy loading might be a risk factor for further deterioration of the articular cartilage.[9] Nonetheless, moderate exercise and PA generally have a protective effect against the development of chronic diseases such as cardiovascular disease or osteoarthritis.[10,11] More recently, studies have shown that physical inactivity and sedentary lifestyle detrimentally affect both the physical and mental wellbeing of individuals.[11–13] Physical inactivity and sedentary lifestyle

Fig. 1 An accelerometry-based activity sensor worn laterally on the thigh.

large number of participants.[10] Self-reports rely on participant to recall previous activities, which may lead to errors caused by recall bias.[10,11] Furthermore, difficulties might arise when determining the frequency, duration and intensity of PA using these tools.[10] To avoid these limitations, objective methods for the assessment of PA have been gaining popularity. These methods focus on either energy expenditure (EE) or activity classification.[5] Energy expenditure, which can be measured by indirect calorimetry, doubly-labelled water and accelerometry, is directly related to mortality risk from so-called lifestyle diseases (e.g. cardiovascular disease) and therefore relevant to assess.[17] More recently, accelerometry-based activity sensors have been used to classify activities of daily life. These activity sensors can either be single sensors (of which an example is shown in Fig. 1) or multi-site systems. The parameters extracted from this method seem more discriminative in describing the physical behaviour of patient populations, compared to overall energy expenditure.[18] Especially in orthopaedics, where the ability to perform movements and be physically active is generally limited, knowledge regarding which activities are commonly performed during daily life could be used to e.g. assess the efficacy of treatments. Since accelerometers can detect the types of movements and activities during daily life, they have been argued to be the most suitable method to monitor PA in orthopaedic patients.[19]

Accelerometry used to measure physical activity: what can be measured?

The technological advances and decrease in costs during the last decades have enabled the widespread use of accelerometers. Sensor miniaturization and increased battery life have made it possible to measure for days or weeks without the need for large and bulky batteries or base stations. Data analysis consequentially has become more complex. Accelerometer-based activity monitoring has evolved from simple step counters and intensity classification to activity identification and even qualitative movement analysis based on either a single sensor or multi-site systems. The data analysis techniques used to identify physical activities have been described in an extensive review by Preece et al[20] and later in 2015 by Attal et al.[21]

Several identification algorithms have been validated and published. The activities that can be identified with these algorithms range from postures (sitting, standing, lying down) to running and Nordic walking (Table 1).

In some cases, algorithms classify the complete dataset per unit of time (event-based classification), an example of which is shown in Table 2. To be of any clinical value, specific activity parameters have to be extracted from this list

are two distinct behaviours, as sedentary behaviour encompasses any waking behaviour characterized by an energy expenditure below 1.5 metabolic equivalent of task (METs) while sitting or reclining,[14] whereas physical inactivity is considered to be the absence of sufficient moderate-to-vigorous physical activity (MVPA).[15] Both types of behaviour are associated with chronic diseases, such as cardiovascular disease and type 2 diabetes mellitus, but also orthopaedically related conditions such as osteoporosis, and may ultimately lead to premature death.[5,16] As a consequence, the stimulation of PA and prevention of an inactive and sedentary lifestyle have been the main targets in health guidelines and intervention programmes.[5,11] The monitoring of PA, including physical inactivity and sedentary behaviour, has therefore gained major interest during the last decade.

Many tools are currently available to examine PA during daily life. In general, they can be divided into subjective and objective tools.[5,10,16] The subjective tools consist primarily of diaries and self-reports, which are also known as PA questionnaires.[5] The self-reports are the most commonly used assessment tool, as they are an easy-to-use and a cost-effective way to collect PA information about a

Table 1. Validation studies on the physical activities identifiable by various algorithms

Study	Year	Single sensor or multi-site system	Postures and activities
De Vries et al[22]	2011	Single sensor	Sitting, standing, stairs, cycling, walking
Ermes et al[23]	2008	Multi-site system	Lying, sitting, standing, (Nordic) walking, football, cycling, running
Khan et al[24]	2010	Single sensor	Resting, stairs, walking, running, vacuuming
Nyan et al[25]	2006	Multi-site system	Walking, climbing and descending stairs
Lipperts et al[26]	2017	Single sensor	Sitting, standing, sit-stand transitions, cycling, climbing and descending stairs, step count
Fortune et al[27]	2014	Multi-site system	Lying, sitting, standing, walking, jogging
O'Donoghue et al[28]	2014	Single sensor	Sitting, standing, sit-stand transitions, walking, step count
Laudanski et al[29]	2015	Multi-sensor system	Walking, climbing and descending stairs

Table 2. Example of identification algorithm output

Start time (s)	Stop time (s)	Activity
0.00	120.55	Sitting
120.55	128.05	Walking
128.05	150.00	Standing
150.00	165.00	Walking
165.00	173.00	Stair climbing (up)

of classified activities. Some examples are: total number of steps, total number of sit-to-stand transitions, the ratio of physically active time/rest time, average walking cadence or total time spent cycling per day. Another option is that algorithms classify outputs per minute (or a pre-specified epoch). In this case, the monitor will attempt to classify the entire epoch as one executed activity.

Despite the number of validation studies, most clinical studies in orthopaedics still only use MVPA minutes or step count as activity or outcome parameters. Time spent in MVPA has been used in the assessment of knee osteoarthritis and anterior cruciate ligament reconstruction surgery.[15,30,31] Time spent in different postures and activities has further been used in a study on neck and shoulder pain as well as in an assessment of outcome after total knee arthroplasty (TKA).[32–34]

The following will describe some of the activity parameters that can furthermore be extracted from activity identification algorithms. In addition to step count and time spent walking, it is possible to measure the number of walking bouts,[32] and the duration of each bout. In particular, the number of short bouts (e.g. < 10 steps) is of interest as people with lower-limb problems (e.g. knee or hip osteoarthritis) will limit the occurrence of possibly painful movements, such as e.g. getting up from a chair or couch, by only performing 'necessary' activities (e.g. going to the toilet). Furthermore, it is clinically relevant to measure prolonged, continuous bouts, to assess patients' ability to walk long distances and determine whether they adhere to recommendations on PA. Cadence is a qualitative parameter that can also be extracted when combining step count with walking bout duration. Cadence has been shown to differ between healthy subjects and different groups of patients.[32,35] Examining slow or shuffling gait

(e.g. post-joint arthroplasty) is, however, known to be a challenge. Slow gait stepping namely results in relatively low acceleration magnitudes, which are thus more difficult to identify.[36]

By identifying stair events (either ascending or descending), patients' ability and willingness to climb stairs can be assessed. Similar to walking, the number of stair events, the number of steps and cadence are potentially interesting parameters. The ability to ascend and descend stairs can impact considerably on patients' independence and thus quality of life. It is even feasible to determine whether patients climb or descend stairs step-by-step or step-over-step.[26] It should, however, be noted that, as far as the authors are aware, current algorithms are not able to differentiate stair climbing from e.g. climbing curbs and ramps. However, the functional effort to manage these may be comparable.

In addition to the total time spent sitting, the number of long (> 30 minutes) periods of uninterrupted sitting is characteristic of a sedentary lifestyle,[37] making it a worthwhile parameter to detect. The identification of cycling and running can provide information regarding the ability to participate in sports. Furthermore, cycling is an activity that, especially in Europe, is considered a part of daily life and is often used in rehabilitation programmes.[38]

Ongoing sensor development has opened doors to combine functional tests, measured during hospital visits, and activity monitoring in patients' home environments. For example, a timed up-and-go movement can be assessed during daily life.[18] With accelerometer-based activity sensors, the 'true' functional status of a patient can be monitored, as they are measured and monitored in daily life in their natural environment, without the supervision of a doctor or researcher.

It is currently possible to measure many activity parameters due to the development of applications and software to handle accelerometry data. The selection of the most relevant parameters will depend on the clinical question or goal of the intervention. When comparing e.g. different knee implants, the ability to ascend and especially descend stairs and ramps will be interesting. In an orthopaedic population, the possibility of performing sports again might be a relevant goal to achieve. Therefore, it is important that

clinicians and researchers co-operate to determine the most relevant outcome parameters.

Where is the added clinical value of activity sensors in orthopaedics?

Since the introduction of patient-reported outcome measures, clinicians and researchers have been eager to measure patient-reported function (e.g. Oxford Hip (OHS) or Knee (OKS) Score, the Hip (HOOS) or Knee (KOOS) disability and Osteoarthritis Outcome Score) or PA (e.g. University of California, Los Angeles (UCLA) activity scale, the Tegner score, or the Activity Rating Scale) after surgical interventions. The orthopaedic community had realized that it was not optimal that only the surgeon or the physiotherapist rated the patient's function or PA after an intervention. It is an improvement in the evaluation of treatment effectiveness that patient-reported questionnaires have gained widespread acceptance and application, as the patient is the ideal person to rate his/her own functional capacity or level of PA. The questionnaires do not, however, provide the full picture of physical function or PA. For example, patients may rate their PA as high if they are satisfied with their functional capacity, even though PA is fairly low.[39,40] Not all patients climb stairs or go for a run as a part of daily living and thus they may state in the questionnaire that these activities are not causing problems. There is a general lack of agreement between self-reports and objectively measured PA and thus objective measures are recommended.[41] Activity sensors are able to measure the frequency, intensity, time and type of PA of the patient and the output from the activity sensors is not influenced by patient satisfaction, recall bias, floor or ceiling effects.[18]

Physical activity and function: different pictures?

Traditionally, clinicians in orthopaedics have not distinguished between function and PA. Physical function has been described as the ability to perform the basic actions that are essential for maintaining independence.[42] It has been an implicit understanding that when pain decreases and function increases after surgery or rehabilitation, PA would also increase. In other words, the patients would translate the improved function into a higher level of PA. In reality, this is not necessarily always the case. A recent meta-analysis by Hammett et al showed that six months post-operatively, the objectively determined PA levels of TKA and THA (total hip arthroplasty) patients were not significantly different from the pre-operative levels.[43] After 12 months, however, a small to moderate, yet significant, increase in PA levels was found.[43] It should be noted that physical function was greatly improved at both timepoints. The same pattern was found in patients with hip dysplasia where there were no improvements in PA one

year after joint-preserving surgery compared with pre-operatively, although physical function improved considerably.[44] Physical activity and function are two separate outcome measures, and PA is probably to a large degree affected by barriers such as motivation and embarrassment.[45] It is important to consider that a substantial reduction in joint pain and a major improvement in function do not necessarily change a person's level of PA, especially in the short term.

Objectively measured PA as an outcome measure

Activity sensors used in research can be a guide to new treatment approaches in orthopaedic patients. In randomized controlled trials comparing surgical and non-surgical treatment, activity sensors can show whether patients regain their pre-treatment PA levels (and if so, how quickly) and whether there is a difference in the level of PA after the intervention between surgically and non-surgically treated patients. As described in this review, many PA-related parameters can be identified. Studies, however, have traditionally focussed on the total volume of PA (determined e.g. through steps/day or total time per day spent per activity). This suggestion is supported by the meta-analysis of Hammet et al, where the included studies mainly described PA as steps/min or time per day spent per activity.[46] However, the identification of certain types of activities and related qualitative parameters have been suggested to be more sensitive in detecting changes after treatment or between groups of patients.[18] For example, the peak cadence over a short walking bout (1 minute) and prolonged walking bout (30 minutes) improved significantly after TKA.[15] Furthermore, ascending/descending stairs and slopes was found to differ significantly between different subgroups of knee osteoarthritis patients.[47]

Other applications for activity sensors in orthopaedics

Another valuable aspect of activity sensors is the possibility to provide patient feedback on PA and thereby optimize rehabilitation programmes. This is of high importance as post-operative PA is known to positively affect recovery after surgery.[48] Optimally, the patient and physiotherapist collaborate on setting realistic goals for rehabilitation, and it is believed that when patients actively participate in goal setting they feel more responsible for meeting their targets.[46] As part of the orthopaedic rehabilitation, the physiotherapist can provide feedback to patients on how to adhere to planned PA targets (by either motivating them or preventing them from doing too much or taking insufficient rest).[49] Potentially, such an approach will further involve the patient in the rehabilitation process, which may result in faster recovery.[45,50] Patients may experience that their rehabilitation programme is personalized according to the mutually agreed goals, which is assumed to increase adherence to the programme.[50]

Activity sensors can be implemented additionally as a screening tool. For example, the authors of a recent meta-analysis suggested that objectively determined PA might predict functional recovery after surgery.[48]

Practical considerations when applying accelerometer-based activity sensors

The primary practical consideration when planning to use accelerometer-based activity sensors is to identify the desired parameters to be measured and to choose sensors that can measure these parameters with a high level of precision. In one clinical study, bicycling may be an important parameter to measure whereas in another study walking speed may be the most critical parameter to measure.

Technical precision

There is an abundance of different activity sensors available on the commercial market.[19] The actual accelerometer component placed inside these sensors is, however, often identical due to the limited number of manufacturers producing these units.[18] When choosing between the market supply of sensors, both the technical and clinical precision of the accelerometer unit, the need for data analysis skills and tools, the commercial customer support, and previous comparable studies performed using the sensor and the cost of the sensor should all be considered. The costs of single-sensor systems are low to moderate, but multi-sensor systems which combine accelerometry with other measures, such as heart rate or respiration, are quite costly.[19] The use of multi-sensor systems will increase precision and detail level on, especially, activity intensity.[51] However, such systems are complex to employ and not necessary if the primary aim is to provide an overview of the total volume of daily PA (e.g. steps per day). Thus, the final choice of sensor should be based on whether the outcome measures provided in the software are relevant and, preferably, that these measures have been validated and can be compared to previous studies.

Software options and customer support

Regarding software options, most commercial brands have developed plug-in software in combination with their sensor, which is generally easy and user-friendly.[19] When choosing a commercially available sensor, there will very often be one or a range of wear locations recommended and standardized protocols needed by the manufacturer, closely related to the features of the accompanying software.

When choosing a commercially available sensor, it may thus be vital that the manufacturer provides sufficient customer support and is able to specify how the parameters

Fig. 2 An overview of activity sensors' wear locations.

are defined and how thoroughly the reliability and validity of their sensor has been evaluated.

Wear location

Since the accelerometer-based sensor only measures accelerations of the body part to which it is attached, wear location of the sensors is closely related to the parameters of interest. Originally, accelerometer-based sensors were used to estimate energy expenditure and were therefore placed at the lower back or at the waist, as these sites are as close as possible to the body's centre of mass.[52] Parallel to the technological advancements of accelerometry, the wear locations have been expanded to include various sites on the limbs and upper body. Common and user-friendly sites of placement are the wrist or the ankle where the sensor can easily be attached by a strap, or the waist where the sensor can be attached with a belt.[5] The validity of the output from wrist-worn sensors is, however, challenged because sensors with that wear location will measure upper-extremity movements that may confound the movements of interest from the lower extremities. Another site is the thigh, where the sensor can be attached using adhesive patches (Fig. 2).[26,32] In orthopaedic patients with lower-extremity problems, wearing the sensor on the

thigh may increase measurement precision since the sensor will measure the actual lower-limb accelerations. However, correct positioning on the thigh is a challenge in clinical studies where the patients are advised to remove the sensor during bathing or swimming and to position it again afterwards.

Battery time

Another important property of the sensor is battery time. This has been vastly improved over the last years and most modern-day activity sensors have battery time and memory for measuring continuously for several weeks.[5] Battery time is important, since PA should be monitored for at least 10 hours a day[53] during a week with a normal activity level[54] and include both working days and leisure time, especially if the person has not retired from work.[55] Shorter measurement periods have been used, but a measurement period of seven days enhances the robustness of the PA measurements[56] and is a manageable length of time for most patients to wear the sensor, resulting in sufficient compliance.[57] Some parameters like step counts are more affected by the duration of measurement period than others like step cadence, and thus rules for excluding days with fewer than 10 hours measurement time are advisable in clinical studies.

Remaining practical considerations

Several other aspects should be taken into account with regard to activity sensors and the analysis of accelerometer data. Firstly, it is worth noting that physical activity varies with the seasons, which is why the time of year that the monitoring is performed may have to be taken into account during the final analysis of data.[58] Furthermore, it should be taken into account that differences might exist between varying cultures with regard to commonly performed activities and the motivation to be physically active/perform sports.[59] Finally, several well-known wearable devices (e.g. Fitbit) are commercially available and gaining in popularity. Currently, however, these devices have been shown to be unable to accurately capture activity data.[60]

Discussion

The aim of this review was to describe the benefits, impacts and practical considerations of accelerometer-based PA monitoring in orthopaedics (both in research and in a clinical setting). The benefits are numerous; clinicians can obtain an objective measure of total volumes of PA and specific PA parameters that can be used for clinical comparisons before and after surgical or rehabilitation interventions. Furthermore, the added information on patients' PA levels will provide clinicians with a fuller picture of the

patient's status before or after an intervention. In other words, the clinician's toolbox can be expanded with a clinically important outcome measure and the clinician can combine results from functional tests with activity monitoring. From a patient perspective, accelerometer-based activity monitoring can be used during orthopaedic pre- or rehabilitation to help patients reach their PA targets. Moreover, accelerometer-based activity monitoring, either patient-administered or clinician-administered, can be used to coach patients towards a more active lifestyle.

There are several practical issues to consider before applying accelerometer-based PA assessment in research or in a clinical setting, such as the technical precision of the sensors, software options, manufacturer's costumer support, wear location, patient compliance and sensor battery time. All these factors should be considered as a part of the planning of a research project or collection of clinical data. Application of accelerometer-based activity monitoring is at this point practically feasible in orthopaedic patient populations.

In conclusion, during the last decade, the objective assessment of PA in daily life has greatly improved. A significant amount of PA parameters can be extracted, which will most likely further develop in the immediate future. The assessment of PA in orthopaedics is feasible due to recent advancements and can thus be employed by researchers and clinicians in orthopaedics. Most importantly, it is highly relevant to assess PA in orthopaedics, as injuries to the musculoskeletal system directly affect which movements and activities can be performed, and thus treatments are aimed at improving both function and PA.

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