Assessing physical activity and function in patients with chronic kidney disease: a narrative review

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ABSTRACT

Physical activity potentially improves health outcomes in patients with chronic kidney disease (CKD) and recipients of kidney transplants. Although studies have demonstrated the beneficial effects of physical activity and exercise for primary and secondary prevention of non-communicable diseases, evidence for kidney patients is limited. To enlarge this evidence, valid assessment of physical activity and exercise is essential. Furthermore, CKD is associated with a decline in physical function, which may result in severe disabilities and dependencies. Assessment of physical function may help clinicians to monitor disease progression and frailty in patients receiving dialysis. The attention on physical function and physical activity has grown and new devices have been developed and (commercially) launched on the market. Therefore the aims of this review were to summarize different measures of physical function and physical activity, provide an update on measurement instruments and discuss options for easy-to-use measurement instruments for day-to-day use by CKD patients. This review demonstrates that large variation exists in the different strategies to assess physical function and activity in clinical practice and research settings. To choose the best available method, accuracy, content, preferable outcome, necessary expertise, resources and time are important issues to consider.

Keywords: assessment, disabilities, exercise, kidney disease, measurement, physical function, physical activity, sedentary behaviour, validity

INTRODUCTION

The beneficial effects of physical activity in the general population are well documented and include risk reductions for major non-communicable diseases such as cardiovascular disease, type 2 diabetes, cancer, dementia, all-cause mortality [1, 2] and kidney function loss in the elderly [3]. The World Health Organization stated that physical inactivity is the fourth most important risk factor for all-cause death, resulting in 6% of all
Physical activity, on the other hand, is described as any bodily movement produced by the contraction of skeletal muscle that requires energy expenditure [4]. Finally, exercise is defined as a planned, structured and repetitive form of physical activity. It includes aerobic exercise—activities that use large muscle groups continuously and rhythmically, such as brisk walking—and resistance or muscle-strengthening exercise, which is based on repeated use of isolated muscle groups to stimulate muscle strength and growth.

**Physical function**

A decline in physical function may result in severe disabilities and dependencies. The assessment and characterization of physical function can be established by measuring physiological impairment, functional limitations and functional disability/self-reported physical functioning [26, 28]. The characteristics of these three measures of physical function are provided in Table 1.

**Measurement tools and their implementation in clinical and research settings**

Physiological impairment. Physiological impairment reflects physical function at the organ or system level and is determined by exercise tolerance and capacity tests [26, 28]. The gold standard to measure CRF is cardiopulmonary exercise testing to assess oxygen (O₂) consumption. The peak oxygen uptake (VO₂max) can be defined as the absolute volume of maximum O₂ consumption per minute (L/min) or as the relative volume per kilogram of bodyweight per minute (ml/kg/min). An incremental exercise test should be performed on a treadmill or cycle ergometer using a predefined protocol [28–31] to determine VO₂max. Standardized criteria are used to define whether the maximum effort is reached [32]. When gas exchange measurements are not available, VO₂max can be estimated based on the peak workload and heart rate [29–31, 33]. However, such prediction formulas have not been validated for CKD patients [28]. In addition, CRF tests in CKD patients with severe deconditioning and muscle weakness might not always be possible and are subject to floor effects.

Another way of determining physiological impairment is assessing muscular fitness. Muscular fitness is reflected by maximum strength and muscle endurance. Muscle strength leads to movement (isokinetic force) or to force without movement (isometric force). Isokinetic force can be measured with an isokinetic dynamometer, but such equipment is expensive and requires well-trained personnel. Alternatively, a cheaper and easy-to-use measure to evaluate isometric handgrip strength is a hand dynamometer [34, 35]. Dynamic muscle strength can be assessed in all muscle groups using 1, 3 or 5 repetition maximum (RM) protocols for both the upper and lower body [26]. It is important to familiarize untrained adults with two to three sessions of the RM protocol to achieve the true maximum strength [36, 37]. Muscular endurance can be determined by the maximum number of repetitions at a predefined RM level, such as 60% of 1 RM or 80% of 5 RM [26].

Within laboratory and clinical research settings, CRF and muscular fitness are used to correlate physiological impairment to major events and mortality and to evaluate exercise intervention studies. In clinical care settings, cardiopulmonary exercise testing is used to diagnose underlying cardiovascular disease and to detect respiratory limitations, but outcomes can also be used to prescribe exercise regimes with certain intensities. CRF is also a strong predictor of mortality and may be used...
to stratify patients into risk groups [38]. However, assessing CRF is labour intensive and requires specialized personnel. Therefore these tests might not always be feasible in daily clinical practice but could provide important information in specific cases. For example, determining VO₂max is potentially useful in pretransplant cardiovascular screening [39]. Muscular fitness-related measures may help clinicians to monitor disease progression and frailty in patients receiving dialysis and to detect early signs of adverse clinical outcomes like severe muscle loss and malnutrition [40]. The use of isokinetic dynamometers in clinical practice is usually cumbersome and not feasible, but measuring handgrip strength is an easy-to-use alternative that could also assist in the diagnosis of sarcopenia [41].

Functional limitations. Functional limitations reflect the physical function of the whole body [26, 28]. Functional limitations refers to the ability to perform basic physical tasks in daily life, such as walking and standing up from a chair. Roughly, functional limitations tests can be divided into walk tests and physical performance tests. One of the most commonly used walk tests is the 6-min walk test (6MWT), in which participants are asked to walk comfortably for 6 min. The researcher or clinician measures the distance travelled [26, 28, 42–44]. Other options include the 2MWT and 12MWT or walk tests with a predetermined distance, such as the 400-m walk test. Although the 6MWT cannot replace the CRF test, the correlation between the two is moderate to high [43, 45, 46]. Another walk test is the intermittent shuttle walk, in which patients walk back and forth on a 10-m course [46, 47]. An audio signal by a metronome directs the walking speed and increases the walking speed until the patient is unable to follow. This measure has good reliability and is moderately to strongly correlated with the CRF test [48]. The last variant of walk tests is the gait speed test. Gait speed is usually assessed as the walking pace over a short distance (6 m).

Examples of physical performance tests are the chair stand test or sit-to-stand test [49], stair climb test [50, 51], timed up and go test [52] and the short physical performance battery (SPPB) [53]. The chair stand test is based on the number of sit–stand–sit cycles within 30 s. This test is highly feasible in clinical practice and only needs a chair without armrests and a stop-watch. The sit-to-stand test is the time needed to complete five sit-to-stand manoeuvres [26, 28, 54, 55]. The stair climb test measures the ability to climb stairs. The method of climbing the stairs (alternating steps and handrail dependence) and the speed of stair climbing are measured [26]. The timed up and go test assesses the time a patient needs to rise from an armchair, walk 3 m, turn around, return and sit down again [26, 54, 55]. The SPPB includes a balance test, walking speed test (usual pace over 4 m) and sit-to-stand test. For the balance test, the patient is asked to hold three challenging standing positions for 10 s. In general, the SPPB is reliable and valid [54–56]. All physical performance tests are relatively easy and quick to perform. However, the tests are less useful for highly fit and highly functional individuals because of ceiling effects.

In laboratory and clinical research settings, measures of functional limitations could be used to predict survival and to evaluate interventions. For example, in cardiopulmonary patients, an increase of ~30 m after a 6MWT has been shown to be clinically relevant [44, 46]. In patients with ESKD, an increase

| Characteristics | Physiological impairment | Functional limitations | Functional disability/self-reported physical functioning |
|-----------------|--------------------------|------------------------|--------------------------------------------------------|
| Objective/subjective | Objective | Objective | Subjective |
| Examples | Exercise tolerance/capacity tests, cardiopulmonary exercise testing and muscular fitness; maximum strength and muscle endurance | Physical performance tests such as walk tests and functional muscular fitness tests | Self- and/or proxy reports, questionnaires such as SF-36, RAND-36, PROMIS-29 and KDQoL |
| Basis | Lab-/hospital-based | Mainly lab-/hospital-based | Day-to-day life |
| Advantages | Gold standard | Objectively measured | Patient-focused information |
| | Easy to quantify | Easy to quantify | Reflects one’s perception of their abilities in their environment |
| | Less suspect of floor/ceiling effects | More useful in comparisons between cultures and geographical environments | Applicable to large number of individuals |
| | More useful in comparisons between cultures and geographical environments | Relatively simple, quick and cost-effective | Easy, cost effective, time efficient and risk free |
| Disadvantages | May have limited practical utility | No gold standard | Subject to external influences |
| | Requires trained personnel | Potentially suspect of ceiling effects | Self-reported and therefore lower validity and reliability |
| Requirements | Trained personnel, expensive equipment and specific analytic skills/knowledge | Familiarization and adherence to protocols | Literacy and ability to understand the language |
| Practical considerations | Reliant on technical experts | Less easy to interpret and translate to real-world situation (e.g. walking distance improvement, 1 SPPB point increase) | Choosing the outcome of the self-reported tool necessary to answer the clinical or research question |

Table 1. Measurement tools to assess physical function [26, 28, 55]
of 20 m after a 6MWT was associated with a lower risk of the combined endpoint of death, incident cardiovascular disease and hospitalization [57]. Gait speed was associated with function decline among 752 haemodialysis patients. Patients who walked <0.6 m/s had a 2.17 (95% CI 1.19–3.98) higher risk of mortality compared with participants walking ≥0.6 m/s and this risk was even higher in patients unable to walk (hazard ratio [HR] 6.93 [95% confidence interval (CI) 4.01–11.96]). This study also revealed that each 0.1 m/s decrement in gait speed was associated with a 17% greater risk of death [HR 1.17 (95% CI 1.05–1.31)] [58].

In clinical care settings, assessing functional limitations is easier and more feasible than measuring physiological impairment, as all tests are relatively simple, quick, cheap and less labour-intensive. In addition, they provide useful information on the patient’s ability to perform basic tasks. Repeatedly assessing functional limitations on the occasion of a visit to the dialysis centre could help to identify and monitor patients with serious functional limitations. For example, the tests are especially useful in the risk prediction or stratification of older adults [59, 60], whereas gait speed <0.8 m/s is associated with adverse health outcomes in older adults [41, 60]. However, the clinical utility and evaluation criteria still need to be established in patients with CKD.

Functional disability/self-reported physical functioning. Functional disability and self-reported physical functioning represent the physical function of the person as a whole [26, 28] and are associated with sociocultural environment. Both are usually captured by questionnaires, resulting in important patient-focused information. Self-reported physical function is significantly associated with survival in patients with CKD [61]. Commonly used questionnaires capturing physical function include the 36-Item Short Form Health Survey (SF-36) [62], RAND-36 [63] or Patient-Reported Outcomes Measurement Information System (PROMIS) Global Health and PROMIS-29 [64, 65]. Examples of other self-report tools [26, 28, 64] used in patients with kidney disease are activity of daily living [66], health-related quality of life [67], kidney disease quality of life [68], Katz Index of Independence in Activities of Daily Living [70] and some dimensions of the sickness impact profile [71].

Due to its relatively simple, cost-effective, time-efficient and risk-free nature, the routine assessment of functional disability is easy to implement in research settings and clinical practice. However, more evidence is needed to examine its clinical utility and to establish the evaluation criteria of these self-reported tools. A cohort study in 951 ESKD patients showed that physical function assessed by the SF-36 was the strongest predictor of risk-free nature, the routine assessment of functional disability and self-reported physical functioning represent the physical function of the person as a whole [26, 28] and are associated with sociocultural environment. Both are usually captured by questionnaires, resulting in important patient-focused information. Self-reported physical function is significantly associated with survival in patients with CKD [61]. Commonly used questionnaires capturing physical function include the 36-Item Short Form Health Survey (SF-36) [62], RAND-36 [63] or Patient-Reported Outcomes Measurement Information System (PROMIS) Global Health and PROMIS-29 [64, 65]. Examples of other self-report tools [26, 28, 64] used in patients with kidney disease are activity of daily living [66], health-related quality of life [67], kidney disease quality of life [68], Duke Activity Status Inventory [69], Katz Index of Independence in Activities of Daily Living [70] and some dimensions of the sickness impact profile [71].

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Physical activity and sedentary behaviour

Physical activity consists of structured and incidental activities. Structured physical activities or ‘exercise’ are planned and purposeful activities to promote health and fitness benefits. Incidental physical activities are unplanned activities in daily life. Physical activities can be described in four dimensions and domains. The four dimensions include mode or type of activity, frequency, duration and intensity of the performing activity. The four most common domains are occupational, domestic/household, transportation and leisure time [73]. Physical activity is quantified as energy expenditure in kilocalories (kcal) or by using the metabolic equivalent of tasks (METs) of the activity. One MET is equal to the resting energy expenditure and can be converted to kilocalories (1 MET = 1 kcal/kg/h). Summing up all physical activities into one outcome results in the total physical activity per day or week; for example, physical activity–related energy expenditure per day or MET minutes per day. Total MET minutes per day can be calculated by multiplying the intensity (e.g. 3 METs), duration (e.g. 30 min) and frequency (e.g. 2 times/day), resulting in 3 × 0.5 × 2 = 3 MET minutes.

Sedentary behaviour is at the opposite end of the energy expenditure continuum and is defined as any waking behaviour characterized by an energy expenditure ≤1.5 MET while in a seated, reclined or lying posture [74, 75]. Contrary to physical activity, a high level of sitting time is associated with increased risks of mortality [76, 77].

The time that an individual is physically active at a certain intensity is one of the most common measures of interest. For example, one may assess whether a CKD patient adheres to the recommended physical activity guidelines [16]. On the other hand, activities could be performed at a light, moderate or vigorous intensity and may be classified in absolute and relative terms [73]. For example, two individuals walk 3 mph, which is equivalent of 3.5 MET [78] from an absolute standpoint. However, when the heart rate is recorded, individual A is found to walk with a heart rate 35% of his maximum heart rate, whereas individual B walks at 60% of his maximum heart rate. In relative terms, individual A walks at a light intensity, whereas B walks at a vigorous intensity.

Objective measurement tools and their implementation in clinical and research settings

Objective methods to assess physical activity include wearable monitors that directly measure biosignals, such as motion, heart rate and energy expenditure. Generally, objective measures of physical activity can be divided into measures of energy expenditure, physiological measures, motion sensors and methods that combine different sensors [79]. Characteristics of measures of physical activity are provided in Table 2.

Energy expenditure. There are three measurement tools available to measure energy expenditure: indirect calorimetry, doubly labelled water and direct observation. Indirect calorimetry measures the ventilatory volume and amounts of oxygen consumed and carbon dioxide produced. This latter method is the gold standard under controlled conditions (laboratory based) [80–82]. Doubly labelled water measures total energy expenditure during daily life activities based on the difference in elimination rate between two stable isotopes, oxygen-18 (18O) and deuterium (2H) [83–85]. Direct observation needs an observer watching or videotaping an individual [86, 87]. All three measures are highly valid but are very labour intensive and require specialized personnel. In addition, the patient burden is potentially high; the measure is expensive and cannot be performed in large populations. Therefore indirect calorimetry, doubly labelled water and direct observation are of limited use in clinical practice and are only useful in very specific research designs.

Physiological measures. Heart rate monitoring is a practical and feasible way to assess physical activity. Heart rate monitoring is accurate for measuring moderate- to vigorous-intensity activities, since heart rate increases linearly and proportionally in healthy individuals [88]. However, low-intensity activities (e.g. sedentary behaviour and standing) are more difficult to capture because heart rate is influenced by sympathetic reactivity.
Furthermore, heart rate has some delayed response to activities and may therefore miss sporadic activities or overestimate the duration of certain activities. Current heart rate monitors are small wrist-worn devices that receive signals from a chest strap. New technologies have made it possible to measure and store heart rate for days. The newest devices measure heart rate on the wrist and do not need a chest strap. However, the validity of these new devices needs further investigation [89].

In clinical practice, heart rate monitors are easy-to-use instruments to collect information on the time that patients spend in moderate–vigorous physical activities and physical

| Objective/subjective | Objective | Objective | Objective | Subjective |
|----------------------|-----------|-----------|-----------|------------|
| Examples             | Indirect calorimetry, doubly labelled water and direct observation | Heart rate monitoring | Accelerometers and pedometers | Questionnaires, logs and diaries |
| Basis                | Lab-/hospital-based | Lab-/hospital-based and day-to-day life | Day-to-day life | Lab-/hospital-based and day-to-day life |
| Advantages           | Gold standard | Relatively inexpensive | Relatively inexpensive | Low cost |
|                      | High validity and reliability | Low burden for patients/ participants | Low burden for patients/participants | Questionnaires have low burden |
|                      |                        | High validity for moderate-to-vigorous activities | Easy to wear 24 h 7 days per week | Applicable to large number of individuals |
|                      |                        | Assists in physical activity and exercise interventions | Provides detailed information about intensity, frequency and duration | Assessment of different domains and dimensions |
|                      |                        |                                | Applicable to large number of individuals | Questionnaires are valid to assess structured physical activity |
|                      |                        |                                | Pedometers are intuitive, understandable and could motivate individuals | Logs/diaries provide a good overview of physical activity and energy expenditure |
|                      |                        |                                | Might increase daily physical activity | Easy to implement in clinical practice |
|                      |                        |                                | Not able to distinguish between types of activities | Questionnaires are subject to recall bias and socially desirable answers |
|                      |                        |                                | Depending on the placement, it neglects upper-body activities and differs in validity | Questionnaires have low validity in incidental physical activity |
|                      |                        |                                | For accelerometers, data reduction, transformation and processing takes time | Logs/diaries have a very high burden on participants, patients and personnel |
|                      |                        |                                | Pedometers are less valid for energy expenditure | Need to be population and culture-specific |
|                      |                        |                                | Might increase daily physical activity | Requirements Trained personnel, expensive equipment and specific analytic skills/knowledge |
|                      |                        |                                | No specific requirements | Practical considerations Reliant on technical experts |
|                      |                        |                                | Choosing the outcome of the self-reported tool necessary to answer the clinical or research question | Require calibration |
|                      |                        |                                | | Lower feasibility |

*Table 2. Measurement tools to assess physical activity [73, 110]*

(e.g. emotional status, temperature and caffeine consumption). Furthermore, heart rate has some delayed response to activities and may therefore miss sporadic activities or overestimate the duration of certain activities. Current heart rate monitors are small wrist-worn devices that receive signals from a chest strap. New technologies have made it possible to measure and store heart rate for days. The newest devices measure heart rate on the wrist and do not need a chest strap. However, the validity of these new devices needs further investigation [89].

In clinical practice, heart rate monitors are easy-to-use instruments to collect information on the time that patients spend in moderate–vigorous physical activities and physical
activity-related energy expenditure. However, for a complete overview of the patient’s physical activity patterns, the patient needs to wear the monitor for several days and the data need to be processed, which makes the assessment more labour intensive. The accuracy of the estimated outcomes improves by calibrating an individuals’ heart rate and energy expenditure response on different levels of activities using oxygen consumption measurements [90, 91]. To overcome individual calibration, group calibration [92, 93] is useful to predict the energy expenditure using multivariate predictive equations derived for group data of CKD patients. Heart rate monitoring could also be helpful when a patient wants to exercise at a certain intensity to gain health and fitness benefits. However, the use of heart rate monitoring might be limited in patients using medication affecting heart rate responses (e.g. ß-blockers) or in patients suffering from cardiac autonomic neuropathy. When the patient’s heart rate is affected by medication or other health conditions, it may be impossible to achieve a high or maximal heart rate. In this case, the intensity of physical activities can be determined in combination with the Borg Scale, a rating of perceived exertion. The Borg Scale ranges from 6 to 20 (i.e. very, very light to very, very hard) [94].

Motion sensors. The most commonly used motion sensors are accelerometers and pedometers. Accelerometers measure the acceleration in one, two or three planes and are attached to the hip, wrist, ankle, lower back or thigh [73]. Depending on the number of planes and place of attachment, accelerometers measure sedentary time, physical activity, physical activity-related energy expenditure and sleep-related behaviour. Acceleration signals are generally filtered and preprocessed by the monitor, resulting in activity counts. The amount and intensity of activity and sedentary time are derived from the classification of activity counts accumulated in a specific time interval and using different cut points [95]. Physical activity-related energy expenditure and sleep-related behaviour are estimated using (commercial) algorithms. In addition, to extract MET minutes and energy expenditure from activity counts, prediction equations [96, 97] or calibration [98] are needed. New methods to estimate these outcomes use raw acceleration signals (gravity units) instead of activity counts [99, 100] and may therefore be more valid and create the possibility to harmonize data of different accelerometers [101]. Researchers mostly use accelerometers of the brands ActiGraph, Actical, ActiPAL, Actiheart, Axivity and GENEActiv. Choosing the best accelerometer for a certain measurement needs some considerations. Accelerometers differ in size, battery, memory, number of axes, placement, software and cost [73]. In addition, decisions about data collection and data processing have a huge impact on the outcome [95]. For example, algorithms validated in adults might not be valid for older adults. Therefore it is crucial to carefully consider different accelerometers and criteria for data collection and data processing. Extensive information on the methodological issues are beyond the scope of this review, but helpful reviews are cited here [73, 95, 102-104]. To ensure that the data are representative of daily physical activity, the accelerometer should be worn 24 h/day for 7 consecutive days with a minimal wear time of 4 days [105]. The validity of accelerometers, expressed as correlation coefficients, ranges between 0.06 and 0.9 [103], but research validating accelerometers in CKD patients is very limited. Wrist- and hip-worn accelerometers are less valid for sedentary behaviour, but the validity greatly improves when attaching the accelerometer to the thigh (e.g. ActiPAL) to combine acceleration with posture [106, 107].

Pedometers are typically worn on a belt or waistband, in a pocket or at the ankle or foot and count the number of steps. An important advantage of pedometers is that steps are intuitive and understandable to laypersons. Simple pedometers quantify steps and estimate distance, whereas enhanced pedometers have a built-in time clock and memory and can estimate intensity and upload data to a computer [73]. StepWatch, Omron, New Lifestyles and Yamax are examples of commercially available pedometers. The number of steps per minute (cadence) can be used to estimate the intensity of physical activity [108]. In general, pedometers are accurate, but the main sources of error are slow walking speeds and obesity, which both result in an underestimation of steps [109]. Validation studies reveal a potential threshold of 100 steps/min for moderate-intensity activity [108, 109].

Motion sensors are generally used for research purposes. In clinical practice, they are important to objectively assess physical activity in daily life. However, the assessment of physical activity in the clinic is rare. Distributing devices, letting patients wear devices for 7 days, data processing, data transfer and data summarization are very time consuming. In addition, expertise in the characteristics, pitfalls and processing steps of a specific device is necessary to use the information for routine assessment. Therefore consumer-oriented devices or ‘wearables’ (e.g. Fitbit, Jawbone, Nike and Apple Watch) might be more feasible for patient use and integration into healthcare settings compared with pure research-grade accelerometers [110]. However, the activity outcomes (e.g. physical activity level, sleep, steps and calories) differ substantially across consumer-oriented devices. In addition, evidence for the validity of consumer-oriented devices is limited. Only a few reviews [110-112] have summarized the validity of consumer-oriented devices and found large variability in the accuracy, mainly depending on activity type. Consumer-oriented devices need to be improved to estimate energy expenditure since their accuracy depends on the type of activity and heterogeneity exists between devices. Improvements could be achieved with the addition of heart rate to accelerometry [111]. Taken together, consumer-oriented devices are widely available and have reasonable accuracy but may primarily be helpful to assist in patient’s awareness, behaviour counselling and goal setting. On the other hand, pedometers are easy to use and intuitive. Patients need to wear the pedometer for several days to provide insight into their habitual physical activity, but no data processing steps are required to translate information. In addition, pedometers are fairly cheap and easy to wear. Another upcoming way to assess step count is smartphone applications. A prospective study [113] found a relative difference in mean step count ranging from –0.3 to 1.0% for pedometers and accelerometers, –22.7 to –1.5% for wearable devices and –6.7 to 6.2% for smartphone applications. These findings suggest that smartphone applications are relatively accurate in measuring physical activity.

Limited evidence is available regarding if tracking physical activity behaviour using wearables and pedometers can effectively change this behaviour. A systematic review [114] including randomized controlled trials in older adults (~60 years) showed that activity tracker–based interventions resulted in an increase of 1558 steps per day (95% CI 1099–2018). A pilot study [115] in 60 dialysis patients revealed that the use of pedometers in combination with counselling resulted in an increase of 2256 (95% CI 978–3537) steps/day. However, this increase disappeared after cessation of the intervention. Therefore change in behaviour might be dependent not only on wearable devices, but also on individual encouragement and effective feedback loops.
The role of wearables in inducing behavioural change is an important area of future research.

Multisensing methods. Some objective assessment tools are able to combine multiple parameters. Examples are the Actiheart (accelerometer and heart rate sensing) and Intelligent Device for Energy Expenditure and Activity (five accelerometers). Evidence for these devices is limited, but some studies have shown that multisensing devices could improve the validity for assessment of physical activity compared with single-sensing devices [73].

Subjective measurement tools and their implementation in clinical and research settings

Subjective measures use questionnaires and logs and rely on the individual to report his/her activities as they occur or to recall previously performed activity. Questionnaires are used to identify dimensions and domains of an individual’s physical activity behaviour. They can vary in detail and number of items and can be collected by interview or self-report. The validity is sufficient and is in general higher for vigorous-intensity activities compared with light–moderate activities [73, 117, 118]. The content of questionnaires about sedentary behaviour is similar

Table 3. Steps to select a measurement tool to assess physical function [26, 28, 55]

| Clinician/researcher needs to assess physical function characteristics | Available tools | Isometric dynamometer | Hand dynamometer | 1RM | Walk test | Transition test | SPPB | Self-report |
|---|---|---|---|---|---|---|---|---|
| Content | Clinical practice: behaviour counselling/risk stratification | Suitable |  |  |  |  |  |  |
| Research | Suitable |  |  |  |  |  |  |  |
| Consideration of outcome | Type of activity to be measured | Physiological impairment | Functional limitations | Functional disability | CRF | Muscular fitness | Mobility and performance | Perception of functional ability |  |  |  |  |  |  |
| Aspect of activity to be measured | CRF |  |  |  |  |  |  |  |  |
| Feasibility and practically | Cost of tool | Limited |  |  |  |  |  |  |
| Sample size/ participants to be measured | Low to medium |  |  |  |  |  |  |  |
| Patient/participant burden | Low |  |  |  |  |  |  |  |
| Resources | Staff burden | Low |  |  |  |  |  |  |
| Data processing/ transfer/ summarization | Easy/fast |  |  |  |  |  |  |  |
| Assessing | Time needed for assessment | <5 min |  |  |  |  |  |  |
| Immediate feedback for patient/participant | Yes |  |  |  |  |  |  |  |

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[116]. The role of wearables in inducing behavioural change is an important area of future research.

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[73, 117, 118]. The content of questionnaires about sedentary behaviour is similar
to that on physical activity. Sedentary time (hours/day) can be measured in total, domain specific, during weekdays versus weekend days and during working versus non-working days [106, 107]. The validity of sedentary behaviour questionnaires is comparable with the validity of physical activity questionnaires. In the past few decades, many questionnaires have been developed to assess activity behaviour. In-depth information about these different questionnaires is beyond the scope of this review. Useful reviews for helping to decide on specific questionnaires are cited here [73, 106, 107, 110, 117–121]. Hour-by-hour or activity-by-activity information about physical activity and sedentary behaviour patterns could be obtained by logs or diaries. A well-known log is the Bouchard Physical Activity Record [122], which identifies nine types of movement behaviours every 15 min for 3 days. Currently the only measurement tool for resistance or muscle-strengthening exercise is questionnaires and logs/diaries, since there are no objective measures to assess this type of activity.

Questionnaires are an easy and cheap way to assess physical activity and sedentary behaviour. For research settings, their validity and reliability are sometimes too low. However, questionnaires are valid enough to get a rough idea of the physical activity and sedentary patterns of patient populations. In clinical practice, questionnaires can be easily administered at clinical visits and integrated into the clinical workflow.

Table 4. Steps to select a measurement tool to assess physical activity [73, 110]

| Clinician/researcher needs to assess physical activity characteristics | Available tools | Questionnaire | Logs and diaries | Heart rate monitor | Pedometer | Accelerometer | Multi-sensing |
|---|---|---|---|---|---|---|---|
| Content | Clinical practice: behaviour counselling/risk stratification | Suitable | | | | | |
| | | Less suitable | | | | | |
| Research | Suitable | | | | | | |
| | Less suitable | | | | | | |
| Consideration of outcome | Type of activity to be measured | Total physical activity | | | | | |
| | Total energy expenditure | | | | | | |
| | Walking behaviour | | | | | | |
| | Domain-specific | | | | | | |
| | Sedentary behaviour | | | | | | |
| | Aerobic exercise | | | | | | |
| | Resistance exercise | | | | | | |
| | Total time | | | | | | |
| | Intensity | | | | | | |
| | Duration | | | | | | |
| | Frequency | | | | | | |
| Feasibility and practically | Costs of tool | Limited | | | | | |
| | Medium | | | | | | |
| | High | | | | | | |
| | Number of patients/participants to be measured | Low to medium | | | | | |
| | High | | | | | | |
| | Patient/participant burden | Low | | | | | |
| | Medium | | | | | | |
| | High | | | | | | |
| Resources | Staff burden | Low | | | | | |
| | Medium | | | | | | |
| | High | | | | | | |
| | Data processing/transfer/summarization | Easy/fast | | | | | |
| | Moderately easy/fast | | | | | | |
| | More difficult/time-consuming | | | | | | |
| Assessing | Time needed for assessment | One time point | | | | | |
| | Few days of administer/wear time | | | | | | |
| Immediate feedback for patient/participant/health professional | Yes | | | | | | |
| | No | | | | | | |
Choosing the best tool

Routine assessments of physical function and physical activity are important. However, choosing the most appropriate measurement tool needs some thought, especially since in most cases the accuracy decreases when the ease of assessment increases. Classical criteria for deciding on the best available tool are based on the content validity, internal consistency, criterion validity, construct validity, reproducibility, responsiveness, floor and ceiling effects and interpretability [123]. Other factors are outcome of interest, cost, time, burden on the patient or medical personnel and the process of data extraction. Table 3 presents possible considerations when deciding on the most appropriate tool for physical function, whereas Table 4 presents possible arguments when deciding on the most appropriate tool for physical activity.

Conclusions

This review provides an overview of different tools to assess physical function and physical activity in lab- or hospital-based situations or in daily life. There exists a large variation in outcomes that can be measured, accuracy, necessary expertise and resources and time needed to obtain the desired information. We have distinguished between measurement instruments for use in clinical practice and in research settings. Routine assessment of physical function and physical activity needs to be integrated into the clinical workflow, for example, by adding easy measures to the electronic patient file. This creates the opportunity to discuss physical function and activity between healthcare professionals and patients and to follow declines and improvements over time.

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CONFLICT OF INTEREST STATEMENT

None declared.

REFERENCES

1. Lee IM, Shiroma EJ, Lobelo F et al. Effect of physical inactivity on major non-communicable diseases worldwide: an analysis of burden of disease and life expectancy. Lancet 2012; 380: 219–229
2. Sallis JF, Bull F, Guthold R et al. Progress in physical activity over the Olympic quadrennium. Lancet 2016; 388: 1325–1336
3. Robinson-Cohen C, Katz R, Mozaffarian D et al. Physical activity and rapid decline in kidney function among older adults. Arch Intern Med 2009; 169: 2116–2123
4. Organization WH. Global recommendations on physical activity for health. Switzerland, 2010. https://www.who.int/dietphysicalactivity/factsheet_recommendations/en/ (30 December 2019, date last accessed)
5. Matsuzawa R, Matsunaga A, Wang G et al. Habitual physical activity measured by accelerometer and survival in maintenance hemodialysis patients. Clin J Am Soc Nephrol 2012; 7: 2010–2016
6. Beddhoo S, Wei G, Marcus RL et al. Light-intensity physical activities and mortality in the United States general population and CKD subpopulation. Clin J Am Soc Nephrol 2015; 10: 1145–1153
7. Zelle DM, Klaassen G, van Adrichem E et al. Physical inactivity: a risk factor and target for intervention in renal care. Nat Rev Nephrol 2017; 13: 318–318
8. Zelle DM, Corpeleijn E, Stolk RP et al. Low physical activity and risk of cardiovascular and all-cause mortality in renal transplant recipients. Clin J Am Soc Nephrol 2011; 6: 898–905
9. Beddhoo S, Laird BC, Zitterkopf J et al. Physical activity and mortality in chronic kidney disease (NHANES III). Clin J Am Soc Nephrol 2009; 4: 1901–1906
10. Lopes AA, Lantz B, Morgenstern H et al. Associations of self-reported physical activity types and levels with quality of life, depression symptoms, and mortality in hemodialysis patients: the DOPPS. Clin J Am Soc Nephrol 2014; 9: 1702–1712
11. Manfredini F, Mallamaci F, D’Arrigo G et al. Exercise in patients on dialysis: a multicenter, randomized clinical trial. J Am Soc Nephrol 2017; 28: 1259–1268
12. Howden EJ, Coombes JS, Strand H et al. Exercise training in CKD: efficacy, adherence, and safety. Am J Kidney Dis 2015; 65: 583–591
13. Greenwood SA, Koufaki P, Mercer TH et al. Aerobic or resistance training and pulse wave velocity in kidney transplant recipients: a 12-week pilot randomized controlled trial (the Exercise in Renal Transplant [ExeRT] trial). Am J Kidney Dis 2015; 66: 689–698
14. Heiwe S, Jacobson SH. Exercise training in adults with CKD: a systematic review and meta-analysis. Am J Kidney Dis 2014; 64: 383–393
15. Barcellos FC, Santos IS, Umpierre D et al. Effects of exercise in the whole spectrum of chronic kidney disease: a systematic review. Clin Kidney J 2015; 8: 753–765
16. Chapter 3: Management of progression and complications of CKD. Kidney Int Suppl (2011) 2013; 3: 73–90
17. Williams AD, Fassett RG, Coombes JS. Exercise in CKD: why is it important and how should it be delivered? Am J Kidney Dis 2014; 64: 329–331
18. Han M, Williams S, Mendoza M et al. Quantifying physical activity levels and sleep in hemodialysis patients using a commercially available activity tracker. Blood Purif 2016; 41: 194–204
19. Avesani CM, Trolonge S, Deleval P et al. Physical activity and energy expenditure in haemodialysis patients: an international survey. Nephrol Dial Transplant 2012; 27: 2430–2434
20. Zelle DM, Kok T, Dontje ML et al. The role of diet and physical activity in post-transplant weight gain after renal transplantation. Clin Transplant 2013; 27: E484–90
21. Gordon JH, Prohaska TR, Gallant MP et al. Exercise training and pulse wave velocity in kidney transplant recipients: a 12-week pilot randomized controlled trial (the Exercise in Renal Transplant [ExeRT] trial). Am J Kidney Dis 2015; 66: 689–698
22. Donet ML, de Greef MH, Krijnen WP et al. Longitudinal analysis of physical activity, fluid intake, and graft function among kidney transplant recipients. Transpl Int 2009; 22: 990–998
23. Donet ML, de Greef MH, Krijnen WP et al. Longitudinal measurement of physical activity following kidney transplantation. Clin Transplant 2014; 28: 394–402
24. Morooman D, Suri R, Hiremath S et al. Benefits and barriers to and desired outcomes with exercise in patients with ESKD. Clin J Am Soc Nephrol 2019; 14: 268–276.
25. Bravata DM, Smith-Spangler C, Sundaram V et al. Using pedometers to increase physical activity and improve health: a systematic review. *JAMA* 2007; 298: 2296–2304

26. Painter P, Marcus RL. Assessing physical function and physical activity in patients with CKD. Clin J Am Soc Nephrol 2013; 8: 861–872

27. Painter P, Stewart AL, Carey S. Physical functioning: definitions, measurement, and expectations. *Adv Ren Replace Ther* 1999; 6: 110–123

28. Koufaki P, Kouidi E. Current best evidence recommendations on measurement and interpretation of physical function in patients with chronic kidney disease. *Sports Med* 2010; 40: 1055–1074

29. Myers J, Arena R, Franklin B et al. Recommendations for clinical exercise laboratories: a scientific statement from the American Heart Association. *Circulation* 2009; 119: 3144–3161

30. Myers J, Forman DE, Balady GJ et al. Supervision of exercise testing by nonphysicians: a scientific statement from the American Heart Association. *Circulation* 2014; 130: 1014–1027

31. Fletcher GF, Ades PA, Kligfield P et al. Familiarization and reliability of one repetition maximum strength testing in older women. *J Strength Cond Res* 2013; 27: 1636–1642

32. American Thoracic Society, American College of Chest Physicians. ATS/ACCP statement on cardiopulmonary exercise testing. *Am J Respir Crit Care Med* 2003; 167: 211–277

33. Young DR, Hivert M-F, Alhassan S et al. Sedentary behavior and cardiovascular morbidity and mortality: a science advisory from the American Heart Association. *Circulation* 2016; 134: e262–79

34. Stark T, Walker B, Phillips JK et al. The reliability and validity of a 6-minute walk test as a measure of physical endurance in older adults. *J Aging Phys Act* 1998; 6: 363–375

35. ATS Committee on Proficiency Standards for Clinical Pulmonary Function Laboratories. ATS statement: guidelines for the six-minute walk test. *Am J Respir Crit Care Med* 2002; 166: 111–117

36. Bellet RN, Adams L, Morris NR. The 6-minute walk test in outpatient cardiac rehabilitation: validity, reliability and responsiveness—a systematic review. *Physiotherapy* 2012; 98: 277–286

37. Phillips WT, Batterham AM, Valenzuela JE et al. Added value of a 6-minute walk test in outpatient cardiac rehabilitation: validity, reliability and responsiveness—a systematic review. *Physiotherapy* 2012; 98: 277–286

38. Holland AE, Spruit MA, Troosters T et al. An official European Respiratory Society/American Thoracic Society technical standard: field walking tests in chronic respiratory disease. *Eur Respir J* 2014; 44: 1428–1446

39. Singh SJ, Morgan MD, Scott S et al. Development of a shuttle walking test of disability in patients with chronic airways obstruction. Thorax 1992; 47: 1019–1024

40. Singh SJ, Puhan MA, Andrianopoulos V et al. An official systematic review of the European Respiratory Society/American Thoracic Society: measurement properties of field walking tests in chronic respiratory disease. *Eur Respir J* 2014; 44: 1447–1478

41. Csuka M, McCarty DJ. Simple method for measurement of lower extremity muscle strength. *Am J Med* 1985; 78: 77–81

42. Beaudart C, Rolland Y, Cruz-Jentoft AJ et al. A short physical performance battery assessing lower extremity function: association with self-reported disability and prediction of mortality and nursing home admission. *J Gerontol A* 1994; 49: M85–M94

43. Mijnarends DM, Meijers JM, Halfens RJ et al. Validity and reliability of tools to measure muscle mass, strength, and physical performance in community-dwelling older people: a systematic review. *J Am Geriatr Soc* 2002; 50: 663–670

44. Podsiadlo D, Richardson S. The timed “Up & Go”: a test of basic functional mobility for frail elderly persons. *J Am Geriatr Soc* 1991; 39: 142–148

45. Guralnik JM, Simonsick EM, Ferrucci L et al. A short physical performance battery assessing lower extremity function: association with self-reported disability and prediction of mortality and nursing home admission. *J Gerontol A* 1994; 49: M85–M94

46. Freiberger E, de Vreede P, Schoene D et al. Performance-based physical function in older community-dwelling persons: a systematic review of instruments. *Age Ageing* 2012; 41: 712–721

47. Kernodle DS, McLaughlin T, Zajko A et al. Physical performance and clinical outcomes in dialysis patients: a secondary analysis of the EXCITE trial. *Kidney Blood Press Res* 2014; 39: 205–211

48. Kutner NG, Zhang R, Huang Y et al. Gait speed and mortality, hospitalization, and functional status change among hemodialysis patients: a US renal data system special study. *Am J Kidney Dis* 2015; 66: 297–304

49. Cesari M, Kritchevsky SB, Newman AB et al. Added value of physical performance measures in predicting adverse outcomes among older community-dwelling adults. *Age Ageing* 2015; 44: 278–286
health-related events: results from the health, aging and body composition study. J Am Geriatr Soc 2009; 57: 251–259.
60. Studenaksi S, Perera S, Patel K et al. Gait speed and survival in older adults. JAMA 2011; 305: 50–58
61. Clarke AL, Zaccardi F, Gould DW et al. Association of self-reported physical function with survival in patients with chronic kidney disease. Clin Kidney J 2019; 12: 122–128
62. OPTUM. SF-36v2 Health Survey. https://www.optum.com/solutions/life-sciences/answer-research/patient-insights/sf-health-surveys/sf-36v2-health-survey.html (30 December 2019, date last accessed)
63. RAND Health Care. 36-Item Short Form Survey. https://www.rand.org/health-care/surveys_tools/mos/36-item-short-form.html (30 December 2019, date last accessed)
64. Verberne WR, Das-Gupta Z, Allegretti AS et al. Development of an international standard set of value-based outcome measures for patients with chronic kidney disease: a report of the International Consortium for Health Outcomes Measurement (ICHOM) CKD Working Group. Am J Kidney Dis 2019; 73: 372–384
65. HealthMeasures. Obtain & Administer Measures. http://www.healthmeasures.net/explore-measurement-systems/promis/obtain-administer-measures (30 December 2019, date last accessed)
66. Lawton MP, Brody EM. Assessment of older people: self-maintaining and instrumental activities of daily living. Gerontologist 1969; 9: 179–186
67. Centers for Disease Control and Prevention. Health-Related Quality of Life (HRQOL). https://www.cdc.gov/hrqol/methods.htm (30 December 2019, date last accessed)
68. RAND Health Care. Kidney Disease Quality of Life Instrument (KDQOL). https://www.rand.org/health-care/surveys_tools/kdqol.html (30 December 2019, date last accessed)
69. Hlatky MA, Boineau RE, Higginbotham MB et al. A brief self-administered questionnaire to determine functional capacity (the Duke Activity Status Index). Am J Cardiol 1989; 64: 651–654
70. Katz S, Ford AB, Moskowitz RW et al. Studies of Illness in the aged. The index of ADL: a standardized measure of biological and psychosocial function. JAMA 1963; 185: 914–919
71. Bergner M, Bobbitt RA, Carter WB et al. The sickness impact profile: development and final revision of a health status measure. Med Care 1981; 19: 787–805
72. Torino C, Panuccio V, Tripepi R et al. The dominant prognostic value of physical functioning among quality of life domains in end-stage kidney disease. Nephrol Dial Transplant 2020; 35: 170–175
73. Strath SJ, Kaminsky LA, Ainsworth BE et al. Guide to the assessment of physical activity: clinical and research applications: a scientific statement from the American Heart Association. Circulation 2013; 128: 2259–2279
74. Sedentary Behaviour Research Network. Letter to the editor: standardization of use of the terms “sedentary” and “sedentary behaviours”. Appl Physiol Nutr Metab 2012; 37: 540–542
75. Tremblay MS, Aube S, Barnes JD et al. Sedentary Behavior Research Network (SBRN) – terminology consensus project process and outcome. Int J Behav Nutr Phys Act 2017; 14: 75
76. Ekelund U, Steene-Johannessen J, Brown WJ et al. Does physical activity attenuate, or even eliminate, the detrimental association of sitting time with mortality? A harmonised meta-analysis of data from more than 1 million men and women. Lancet 2016; 388: 1302–1310
77. Ekelund U, Tarp J, Steene-Johannessen J et al. Dose-response associations between accelerometer measured physical activity and sedentary time and all cause mortality: systematic review and harmonised meta-analysis. BMJ 2019; 366: 14570
78. Ainsworth BEH, Herrmann SD, Meckes N et al. The Compendium of Physical Activities Tracking Guide. Tempe: Healthy Lifestyles Research Center, College of Nursing & Health Innovation, Arizona State University
79. 2018 Physical Activity Guidelines Advisory Committee. 2018 Physical Activity Guidelines Advisory Committee Scientific Report. Washington, DC: US Department of Health and Human Services, 2018
80. Haugen HA, Chan LN, Li F. Indirect calorimetry: a practical guide for clinicians. Nutr Clin Pract 2007; 22: 377–388
81. da Rocha EE, Alves VG, da Fonseca RB. Indirect calorimetry: methodology, instruments and clinical application. Curr Opin Clin Nutr Metab Care 2006; 9: 247–256
82. Levine JA. Measurement of energy expenditure. Public Health Nutr 2005; 8: 1123–1132
83. Schoeller DA, Ravussin E, Schutz Y et al. Energy expenditure by doubly labeled water: validation in humans and proposed calculation. Am J Physiol 1986; 250: R823–30
84. Schoeller DA, Webb P. Five-day comparison of the doubly labeled water method with respiratory gas exchange. Am J Clin Nutr 1984; 40: 153–158
85. Schoeller DA, van Santen E. Measurement of energy expenditure in humans by doubly labeled water method. J Appl Physiol Respir Environ Exerc Physiol 1982; 53: 955–959
86. McKenzie TL. Use of direct observation to assess physical activity. In: Welk , GJ (ed). Physical Activity Assessments for Health-Related Research. Champaign, IL: Human Kinetics, 2002
87. Welch WA, Swartz AM, Cho CC et al. Accuracy of direct observation to assess physical activity in older adults. J Aging Phys Act 2016; 24: 583–590
88. Strath SJ, Swartz AM, Bassett DR et al. Evaluation of heart rate as a method for assessing moderate intensity physical activity. Med Sci Sports Exerc 2000; 32: 5465–5470
89. Boudreaux BD, Herron B, Hollander DB et al. Validity of wearable activity monitors during cycling and resistance exercise. Med Sci Sports Exerc 2018; 50: 624–633
90. Livingstone MB, Prentice AM, Coward WA et al. Simultaneous measurement of free-living energy expenditure by the doubly labeled water method and heart-rate monitoring. Am J Clin Nutr 1990; 52: 59–65
91. Ceesay SM, Prentice AM, Day KC et al. The use of heart rate monitoring in the estimation of energy expenditure: a validation study using indirect whole-body calorimetry. Br J Nutr 1989; 61: 175–186
92. Dugas LR, van der Merwe L, Odendaal H et al. A novel energy expenditure prediction equation for intermittent physical activity. Med Sci Sports Exerc 2005; 37: 2154–2161
93. Keytel LR, Goedecke JH, Noakes TD et al. Prediction of energy expenditure from heart rate monitoring during sub-maximal exercise. J Sports Sci 2005; 23: 289–297
94. Borg GA. Psychophysical bases of perceived exertion. Med Sci Sports Exerc 1982; 14: 377–381
95. Migueles JH, Cadenas-Sanchez C, Ekelund U et al. Accelerometer data collection and processing criteria to assess physical activity and other outcomes: a systematic review and practical considerations. Sports Med 2017; 47: 1821–1845
96. Lyden K, Kozye SL, Staudenmeyer JW et al. A comprehensive evaluation of commonly used accelerometer energy expenditure and MET prediction equations. *Eur J Appl Physiol* 2011; 111: 187–201
97. Matthew CE. Calibration of accelerometer output for adults. *Med Sci Sports Exerc* 2005; 37: S512–S522
98. Welk GJ. Principles of design and analyses for the calibration of accelerometry-based activity monitors. *Med Sci Sports Exerc* 2005; 37: S501–S511
99. Hildebrand M, Vanh VT, Hansen BH et al. Age group comparability of raw accelerometer output from wrist- and hip-worn monitors. *Med Sci Sports Exerc* 2014; 46: 1816–1824
100. Hildebrand M, Hansen BH, van Hees VT et al. Evaluation of raw acceleration sedentary thresholds in children and adults. *Scand J Med Sci Sports* 2017; 27: 1814–1823
101. Wijndaele K, Westgate K, Stephens SK et al. Utilization and harmonization of adult accelerometry data: review and expert consensus. *Med Sci Sports Exerc* 2015; 47: 2129–2139
102. Troiano RP, McClain JJ, Brychta RJ et al. Evolution of accelerometer methods for physical activity research. *Br J Sports Med* 2014; 48: 1019–1023
103. Plasqui G, Bonomi AG, Westerterp KR. Daily physical activity assessment with accelerometers: new insights and validation studies. *Obes Rev* 2013; 14: 451–462
104. Van Remoortel H, Giavedoni S, Raste Y et al. Validity of activity monitors in health and chronic disease: a systematic review. *Int J Behav Nutr Phys Act* 2012; 9: 84
105. Trost SG, McIver KL, Pate RR. Conducting accelerometer-based activity assessments in field-based research. *Med Sci Sports Exerc* 2005; 37: S531–S543
106. Healy GN, Clark BK, Winkler EA et al. Measurement of adults’ sedentary time in population-based studies. *Am J Prev Med* 2011; 41: 216–227
107. Atkin AJ, Gorely T, Clemes SA et al. Methods of measurement in epidemiology: sedentary behaviour. *Int J Epidemiol* 2012; 41: 1460–1471
108. Tudor-Locke C, Rowe DA. Using cadence to study free-living ambulatory behaviour. *Sports Med* 2012; 42: 381–398
109. Bassett DR Jr, Toth LP, LaMunion SR et al. Step counting: a review of measurement considerations and health-related applications. *Sports Med* 2017; 47: 1303–1315
110. Lobelo F, Rohm Young D, Sallis R et al. Routine assessment and promotion of physical activity in healthcare settings: a scientific statement from the American Heart Association. *Circulation* 2018; 137: e495–e522
111. O’Driscol R, Turicchi J, Beaulieu K et al. How well do activity monitors estimate energy expenditure? A systematic review and meta-analysis of the validity of current technologies. *Br J Sports Med* 2020; 54: 332–340
112. Ewenson KR, Goto MM, Furberg RD. Systematic review of the validity and reliability of consumer-wearable activity trackers. *Int J Behav Nutr Phys Act* 2015; 12: 159
113. Case MA, Burwick HA, Volpp KG et al. Accuracy of smartphone applications and wearable devices for tracking physical activity data. *JAMA* 2015; 313: 625–626
114. Oliveira JS, Sherrington C, Zheng ERY et al. Effect of interventions using physical activity trackers on physical activity in people aged 60 years and over: a systematic review and meta-analysis. *Br J Sports Med* 2019; doi: 10.1136/bjsports-2018-100324
115. Sheshadri A, Kittiskulnam P, Lazar AA et al. A walking intervention to increase weekly steps in dialysis patients: a pilot randomized controlled trial. *Am J Kidney Dis* 2020; 75: 488–496
116. Patel MS, Asch DA, Volpp KG. Wearable devices as facilitators, not drivers, of health behavior change. *JAMA* 2015; 313: 459–460
117. van Poppel MN, Chinapaw MJ, Mokkink LB et al. Physical activity questionnaires for adults: a systematic review of measurement properties. *Sports Med* 2010; 40: 565–600
118. Forsen L, Loland NW, Vuillemin A et al. Self-administered physical activity questionnaires for the elderly: a systematic review of measurement properties. *Br J Sports Med* 2010; 44: 601–623
119. Helmerhorst HJ, Brage S, Warren J et al. A systematic review of reliability and objective criterion-related validity of physical activity questionnaires. *Int J Behav Nutr Phys Act* 2012; 9: 103
120. Silsburry Z, Goldamith R, Rushton A. Systematic review of the measurement properties of self-report physical activity questionnaires in healthy adult populations. *BMJ Open* 2015; 5: e008430
121. Milton K, Bull FC, Bauman A. Reliability and validity testing of a single-item physical activity measure. *Br J Sports Med* 2011; 45: 203–208
122. Bouchard C, Tremblay A, Leblanc C et al. A method to assess energy expenditure in children and adults. *Am J Clin Nutr* 1983; 37: 461–467
123. Terwee CB, Bot SD, de Boer MR et al. Quality criteria were proposed for measurement properties of health status questionnaires. *J Clin Epidemiol* 2007; 60: 34–42