The Objective Monitoring of Physical Activity

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ABSTRACT

Epidemiologists have long recognized the significant limitations of physical activity questionnaires. Advances in the development of objective monitoring devices such as accelerometers have spurred hopes of defining more accurately the relationships between habitual physical activity and chronic disease. As yet, realization of these objectives has been curbed by the failure of accelerometers to record important sources of energy expenditure and the limitation of sample size by labor-intensive checking of output data for artifacts. But in the near future, more complex devices that link the measurement of body accelerations to other phenomena such as posture and GPS location, together with computer-assisted checking of records and processing of data may earn objective monitoring a key place in large-scale epidemiological investigations.

Keywords: Accelerometer, MET levels, Pedometer, Sedentary periods, Step count

A major concern of epidemiologists has been to study possible relationships between habitual physical activity and the risk of developing various chronic diseases. Until fairly recently, most investigations of this type have relied upon physical activity questionnaires of varying complexity to characterize the behavior of individual subjects. Quite simple instruments such as the Godin and Shephard questionnaire[1] have shown moderate validity in terms of their correlations with other measures of daily energy expenditure and/or physical fitness, and such devices have proven fairly effective in classifying individuals as “active” or “inactive.” However, epidemiologists have also been eager to determine the threshold intensity of effort and the minimum daily dose of physical activity needed to protect against various clinical conditions, together with possible ceilings of benefit. Physical activity questionnaire data have been less helpful in this regard, with estimates of absolute activity levels sometimes differing from true values by a factor of 2–3.[2]

The advent of inexpensive and relatively accurate accelerometers has offered the prospect of obtaining objective data on an individual’s patterns of habitual physical activity, along with information on periods of sedentary behavior. The present brief review looks critically at the characteristics of available instruments, factors influencing their accuracy, the extent of new information garnered by adoption of this technology, and the potential for future advances in the objective measurement of human activity.

Basic characteristics of pedometers and accelerometers

Use of a simple mechanical pedometer to measure walking distance has been traced back to Vitruvius (27 BCE), and in the 19th century, the American President Thomas Jefferson monitored his long daily walks with such a device.[3] The characteristics and use of modern accelerometers have been summarized in a recent monograph, which offers a detailed bibliography covering many of the issues raised by this review.[4]

In the current generation of objective activity monitors, watch-like mechanical mechanisms have been replaced by piezoelectrical crystals that generate an electrical signal when a specific acceleration is applied to a weighted lever. The output is typically recorded as the number of steps taken per day, but this has the disadvantage that no measure is then made of the intensity of effort. Some modern accelerometers thus make inferences about the instantaneous metabolic rate of the wearer, based upon the rate at which impulses are being detected. For example, the Actical instrument includes a 3-part algorithm. The individual is credited with an energy expenditure of 1 MET if the rate of counting falls below an arbitrary “inactivity threshold.” The instrument switches to a calculation of metabolic rate based on a walk/run regression equation when the inactivity threshold is exceeded, and it resorts to an alternative lifestyle regression equation if the coefficient of variation of impulse generation over 4 consecutive 15-s epochs exceeds 13%. Unfortunately, the algorithms used to generate information on metabolic rates are often quite complex, and for the most part, their nature and derivation remain commercial secrets. The investigator is simply presented with a “black box” read-out, specifying the number of steps detected within a specified period, and the number of minutes when a subject is active at each of a range of MET levels. Some devices are also programmed to record peak activity indices (average step counts for the most
active part of an individual's day) and sedentary breaks (when the activity count drops below an arbitrary threshold such as 100 impulses/min).

In theory, triaxial accelerometers should capture a wider range of body movements than a single uniaxial device, thus providing a better picture of an individual’s habitual physical activity. One type of triaxial accelerometer (the DynaPort Move Monitor) includes an algorithm to evaluate gaits and postures. Another triaxial device, the MTI Actigraph, infers activity patterns from quite small population samples, and their generality remains to be established. Moreover, the interpretation of triaxial data under free-living conditions is as yet too complex and costly for their use by most epidemiologists.

The cost of individual monitoring units ranges widely, from around $20 to $670. Laura Rogers has published a helpful decision tree that may help investigators in their choice of instrumentation, taking account of available resources and the sophistication of the information that is being sought.[3]

Accelerometers can now either store information for a month or longer, or transmit it by radio-telemetry to the base laboratory. During prolonged periods of observation, it is simply necessary for subjects to attend a clinic once a month to report any clinical events—to reload batteries and/or to download data.

When examining data for an elderly population in Nakanojo, Japan, we have routinely recorded both the daily step count and the daily time for which energy expenditures exceeded an intensity of 3 METs. The latter may be considered as moderate physical activity for those aged 65–85 years. Interestingly, our conclusions regarding the impact of physical activity upon health have been relatively similar for both of these indices. Other investigators have adopted higher thresholds of moderate-to-vigorous activity when analyzing data in younger population samples.

Mechanical reliability and validity of accelerometers

A high level of mechanical reliability and validity has been claimed for modern accelerometers. Reliability has been assessed by mounting 2 instruments, 1 on each side of the body. In general, the readings obtained in this way have been closely correlated with each other, although some individuals have shown systematic differences between recordings from the left and the right sides of the body.

A simple measure of mechanical validity has been to shake the accelerometer on a test rig. One instrument activated by exposure to an acceleration of 2 m/s² showed a correlation of 0.996 between recordings and the actual number of oscillations of the rig, with a coefficient of variation of 1.5%. Instruments also respond relatively accurately to consistent movement patterns such as even-paced level walking. The 24-hour step count determined with 1 pedometer/accelerometer had an intra-modal reliability of 0.998 and the error in step count relative to 500 actual paces taken on a level 400 m track was only 0.2 ± 1.5 steps. A comparison of 5 commercial instruments found the most consistent results from the Yamax device at both moderate and slow walking speeds, with an average systematic error of 2% over a distance of 4.8 km. Another study of 10 commercially available instruments found that most estimated treadmill walking distances to within ±10% and gross energy expenditures to within ±30% of the actual value. However, as with older mechanical pedometers, the amount of physical activity tended to be underestimated at slow walking speeds; at 3.2 km/h, data from the Kenz Lifecorder and the Actigraph were, respectively, 92 ± 6% and 64 ± 15% of true values.

The output of any accelerometer of necessity depends upon the force of the stepping movement reaching the acceleration threshold needed to trigger the device (e.g., 2 m/s²), and this force inevitably varies with the individual’s age, sex, body mass, and speed of movement. Although many trials suggest that modern pedometer/accelerometers have a reasonable validity when a person is engaged in moderate walking (4–5 km/h), significant inaccuracies are introduced with slow walking speeds, a short stride length and abnormalities of gait, as well as by vigorous running. Moreover, errors are substantially increased on moving to free-living conditions, as subjects choose their own activity patterns rather than walking steadily over a fixed course at a pace that is optimal for the recording instrument. Both pedometers and accelerometers provide a poor indication of energy expenditures during cycling, skating, load-carrying, the performance of household chores, and other nonstandard types of activity; most are also not waterproof, and thus must be removed when a person is swimming. Further, they take no account of the additional energy expended when climbing hills or making isometric movements against external resistance, and on the other hand impulses suggesting physical activity may be generated when a person is traveling over bumpy ground in a car.

Field validity of objective monitors

Other problems arise when attempts are made to interpret accelerometer output in terms of an individual’s habitual behavior. There may be a reactive response to wearing of the instrument and often activity is sampled over too short a period.

The term reactivity here implies a change in personal behavior induced by wearing of the monitor. It is difficult to hide the fact that monitoring is occurring, and in consequence an individual may be stimulated to take a greater than normal volume of physical activity for the first few days when observations are recorded. Cora Craig claimed there was no evidence of reactivity when she studied the physical activity of a large sample of Canadian youth, but she based this conclusion simply on a comparison between the first and subsequent days of a 1-week evaluation, and a reactive response may continue for a week or longer. Cleges et al.[4] found a substantial difference of behavior between a week when subjects could see their pedometer count (11,385 steps/d) and a second week (when the dial was hidden, and participants thought they were simply wearing a posture monitor) (9541 steps/d). Plainly, the problem can be overcome by habituation, but unfortunately for practical reasons most observers have limited their period of data collection to 4–7 days.
Problems also arise from day-to-day variations in personal behavior. Patterns of physical activity usually vary over a weekly cycle, and they are also influenced by seasonal factors, including extremes of heat and cold, rain and snow. Togo et al.[7] used sophisticated mathematical modeling to determine how many days of consecutive observation were needed to estimate the habitual activity of seniors relative to average records for an entire year. To achieve 90% reliability, 105 and 37 days of monitoring were required in men and women, respectively. However, if data were collected randomly throughout the year, 90% reliability could be obtained with 11 and 9 days of observation, respectively, and if sampling was deliberately distributed to take account of days of the week and season of the year, the respective observation periods for men and women could be reduced to 16 and 12 days. This research needs to be extended to younger age groups, as it is likely that in younger people even longer periods of observation will be required to obtain representative information. Plainly, the 4–7 days of recording that many investigators have adopted is inadequate.

Finally, it is important to ensure that subjects have worn the recording device over the intended recording period, preferably throughout 24 hours per day, rather than simply the supposed waking hours. There is some evidence that 24-hour compliance is greater when devices are fitted to the wrist rather than other parts of the body.

**Data handling**

The recording of activity patterns on each member of a substantial population for several weeks or more presents substantial challenges in terms of setting rules for quality control and data cleaning, with a careful manual or automated review of records to exclude artifacts, an appropriate shaping of the acquired information, and adequate arrangements to organize and store data.

Accelerometers may average behavior over epochs that range from 4 to 60 seconds, and there is some evidence that the choice of too long an epoch misses or underestimates some movements (particularly in children, where individual bursts of activity are of short duration).

With prolonged periods of measurement, there are inevitably periods when data are missing, and in calculating daily averages a decision must then be made whether to tolerate short periods when recordings are lost, or to devise rules for imputing replacement data. Mechanisms must also be established to inspect records for outlying data. Advances in computer technology are progressively allowing the mechanization of what has been a tedious manual process for the analysis and correction of records.

**Relationships between physical activity and health**

How far has accelerometry added to our understanding of relationships between physical activity and health relative to the information that was previously obtained from physical activity questionnaire data? We will consider the relationship between accelerometer data and currently accepted public health recommendations, dose–response relationships as seen in accelerometer studies, the issue of cause and effect, and the potential to obtain objective information on economic benefits from a modest increase in active behavior by a small segment of the population.

**Public health recommendations on the minimum daily dose of physical activity**

Public health recommendations on the minimum daily amount of physical activity needed to maintain good health have been based primarily upon subjective, activity questionnaire-based epidemiological data. Although it seems logical that the optimum intensity and volume of physical activity will vary from 1 condition to another, most expert bodies have in fact recommended a single optimal dose for good health. The advice has differed a little from 1 advisory group to another, but in terms of aerobic activity the typical recommendation has been to engage in a minimum of 150 minutes of moderate intensity physical activity per week.

Optimal accelerometer step counts have commonly been interpreted in their own right. Typical values have ranged from 9000 to 10,000 steps/d in young and middle-aged adults, 10,000–16,000 steps/d in children, and 6000–8500 steps/d in people aged > 50 years. We found that at least in the elderly, the relationship between accelerometer step counts and health outcomes was nonlinear. Those who were dependent and took little physical activity still registered counts of up to 2,000 steps/d, and those who were housebound reached totals of up to 4,000 steps/d. The remainder of the population fell into 4 quartiles with counts of 4,000–5,000, 5,000–7,000, 7,000–8,000, and 8,000–10,000 steps/d, respectively (Fig. 1).

In younger adults, counts of 6,000–7,000 steps/d appear to reflect the minimum demands of daily life. Tudor-Locke et al.[8] have arbitrarily classified younger adults as sedentary (< 5000 steps/d), low active (5000–7000 steps/d), somewhat active (7500–10,000 steps/d), active (10,000–12,500 steps/d), and highly active (> 12,500 steps/d).

A few authors have also noted the average duration of moderate-to-vigorous physical activity; the U.S. NHANES survey found figures ranging from 8.7 min/d in those aged > 70 years to 9 min/d in those aged 6–11 years.[9] Unfortunately, there is as yet no consensus on the cut-point defining moderate physical activity for any given age group. In the context of the elderly, we have set this threshold at an intensity of 3 METs; based on this standard, we found times of less than 2.5 min/d for those who were bed-ridden or dependent and 2.5–5.0 min/d for those who were housebound.

The remainder of our population could be divided into quartiles who engaged in 5.0–7.5, 7.5–15.0, 15.0–20.0, and 20.0–30.0 minutes of moderate activity/d (Fig. 1).[10]

Average population values for either step counts or minutes of moderate physical activity are unlikely to be optimal for health. The first manufacturer of the modern type of pedometer (Yama-sa Tokei) recommended that adults achieve a reading of 10,000 steps/d. More recently, counts of 7,000–8,000 steps/d have been equated with the public health recommendation for adults. If we assume that incidental movements of little health value yield a baseline count of 4,000 steps/d, then an additional count of 3,500 steps/d, each with a pace length of 0.7 m would imply covering a total distance of 2.45 km, or if walked at a moderate pace (5 km/h), 29 minutes of walking, quite close to the public health recommendation.

**Dose–response relationships.** Accelerometer data have been used to study dose–response relationships between habitual physical activity and many chronic conditions.[10] With careful measurement of data for an entire year on samples of around 200 elderly people, it has been possible to demonstrate statistically significant differences in risk between population activity quartiles (Table 1). However, the minimum level of physical activity associated with benefit has differed for the various chronic medical conditions (Fig. 1).

The risk of mental illness, particularly depression, is lower in those taking > 4,000 steps/d, or spending < 5 min/d on physical activity with an energy cost of > 3 METs. This is a somewhat surprising finding because the mechanism of any exercise-induced
reduction of depression might be a greater cerebral arousal and/or an increased secretion of endorphins, responses normally associated with sustained and vigorous physical activity. Possibly, the explanation of the reduced level of depression seen even in those taking only small amounts of physical activity is a reversed association (see below).

**TABLE 1.**
Multivariate Cox proportional hazards model, showing the risk of the calcaneal osteosonic index falling below an arbitrary “fracture threshold.”

<table>
<thead>
<tr>
<th>Activity Quartile</th>
<th>Men (n = 212)</th>
<th>Women (n = 284)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Step Count (steps/d)</td>
<td>Relative Risk</td>
</tr>
<tr>
<td>Q1</td>
<td>4,072 ± 1,373</td>
<td>2.63 (1.35–4.14)</td>
</tr>
<tr>
<td>Q2</td>
<td>6,261 ± 1,041</td>
<td>1.75 (1.03–3.95)</td>
</tr>
<tr>
<td>Q3</td>
<td>7,658 ± 1,031</td>
<td>1.01 (0.55–3.37)</td>
</tr>
<tr>
<td>Q4</td>
<td>10,802 ± 1,897</td>
<td>1.00</td>
</tr>
<tr>
<td>P value for trend</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>Minutes &gt; 3 METs/d</td>
<td>Relative Risk</td>
<td></td>
</tr>
<tr>
<td>Q1</td>
<td>4.0 ± 3.6</td>
<td>2.77 (1.46–5.59)</td>
</tr>
<tr>
<td>Q2</td>
<td>9.9 ± 3.9</td>
<td>1.91 (1.02–3.99)</td>
</tr>
<tr>
<td>Q3</td>
<td>19.2 ± 4.6</td>
<td>1.00 (0.48–2.27)</td>
</tr>
<tr>
<td>Q4</td>
<td>33.8 ± 10.5</td>
<td>1.00</td>
</tr>
<tr>
<td>P value for trend</td>
<td>0.04</td>
<td></td>
</tr>
</tbody>
</table>

Data from a 5-year longitudinal study of seniors living in the community of Nakanojo, Japan, based on a quartile classification of accelerometer-recorded 24-hour activity patterns averaged across the duration of the study.[6] Activity levels are the mean ± SD of daily step counts and minutes of activity at an intensity > 3 METs; risks adjusted for baseline osteosonic index, age, body mass, years since menopause (in the women), calcium intake, smoking habits, and alcohol intake are expressed relative to those in the fourth activity quartile, with 95% confidence limits.
Other aspects of psychological health, particularly a greater health-related quality of life, are seen among individuals falling into the second quartile of habitual activity (5,000–7,000 steps/d, 7.5–15 min/d of activity at an intensity > 3 METs). Activity in the third quartile (7,000–8,000 steps/d, 15–20 min/d at an intensity > 3 METs) is linked to various manifestations of physical health (a good gait speed, muscle strength, physical fitness, a decreased risk of arteriosclerosis as indicated by lower arterial pulse wave velocities, a decreased risk of osteoporotic fractures as indicated by a favorable calcaneal osteoporotic index, and a decreased risk of sarcopenia as indicated by a muscle mass/height² ratio falling less than 1 SD below the mean for young adults). Finally, metabolic health (manifestations of the metabolic syndrome, including hypertension and hyperglycemia) is significantly less evident in the most active quartile (> 8,000 steps/d, > 20 min/d at an intensity > 3 METs; Fig. 1); presumably this association reflects the taking of a sufficient volume of physical activity to reduce obesity.

Some earlier studies suggested that correlations with cardiovascular health were greater for high attained levels of treadmill-measured aerobic fitness than for questionnaire assessments of habitual activity, and it was speculated that this might be because fitness levels give a more reliable indication of habitual activity than questionnaire data. We looked at associations between 1 objective measure of cardiovascular health (pulse wave velocity), a simple assessment of attained fitness (peak walking speed) and accelerometer measurements of physical activity in elderly individuals, and using the more accurate and objective measure of activity patterns, the association was closer for the accelerometer data than for the fitness assessment.

The accelerometer is not well adapted to the detection of the isometric activity that would sustain and increase muscle mass, but the average accelerometer is not set to record the intensities of impact needed to sustain bone mass, but the person who engages in regular aerobic activity is more likely to stimulate bone calcification than the person who is inactive.

Although accelerometers might be thought to have the potential to yield more precise information on physical activity dose/response relationships than physical activity questionnaires, in general the potential of objective monitors has not yet been realized, in part because samples have been small, and this has forced observers to use surrogate measures of poor health. Thus, pulse wave velocities have served as indices of atherosclerosis, and osteosonic indices for a single region of the body have been substituted for the incidence of clinical fractures in the assessment of osteoporosis.

**Economic consequences of physical inactivity**

A number of questionnaire-based studies have previously compared health-care costs between active and inactive individuals, showing that a major economic burden is associated with a sedentary lifestyle. However, it is unrealistic to expect that most sedentary individuals will suddenly be persuaded to switch from inactivity to an optimal level of physical activity, and an analysis based on the accelerometer data now allows an assessment of the economic impact of a more modest change in behavior (Table 2).

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**TABLE 2.**

Average annual per capita direct costs due to 9 chronic medical conditions, classified by physical activity quintile (figures expressed in 2009 Canadian dollars, based on the data of Aoyagi and Shephard[13] for senior citizens living in the community of Nakanojo, Japan).

<table>
<thead>
<tr>
<th>Medical Condition and Cost of Treatment in Individuals with the Diagnosis</th>
<th>Activity Quartile 1 (2,000–5,000 steps/d, 2.5–7.5 min/d)</th>
<th>Activity Quartile 2 (5,000–7,000 steps/d, 7.5–15 min/d)</th>
<th>Activity Quartile 3 (7,000–9,000 steps/d, 15–25 min/d)</th>
<th>Activity Quartile 4 (&gt; 9,000 steps/d, &gt; 25 min/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dependent (20,513), (%)</td>
<td>$14,974 (73)</td>
<td>$0 (0)</td>
<td>$0 (0)</td>
</tr>
<tr>
<td></td>
<td>Depression (2,497), (%)</td>
<td>$150 (6)</td>
<td>$100 (4)</td>
<td>$50 (2)</td>
</tr>
<tr>
<td></td>
<td>Osteoporosis (1,991), (%)</td>
<td>$358 (18)</td>
<td>$259 (13)</td>
<td>$159 (8)</td>
</tr>
<tr>
<td></td>
<td>Fractures ($503), (%)</td>
<td>$75 (15)</td>
<td>$55 (11)</td>
<td>$35 (75)</td>
</tr>
<tr>
<td></td>
<td>Hypertension ($2,115), (%)</td>
<td>$1,015 (48)</td>
<td>$761 (36)</td>
<td>$508 (24)</td>
</tr>
<tr>
<td></td>
<td>Diabetes mellitus ($3,894), (%)</td>
<td>$623 (16)</td>
<td>$467 (12)</td>
<td>$312 (8)</td>
</tr>
<tr>
<td></td>
<td>Hyperlipidemia ($1,919), (%)</td>
<td>$365 (19)</td>
<td>$269 (14)</td>
<td>$173 (9)</td>
</tr>
<tr>
<td></td>
<td>Ischemic heart disease ($3,613), (%)</td>
<td>$434 (12)</td>
<td>$253 (7)</td>
<td>$72 (2)</td>
</tr>
<tr>
<td></td>
<td>Cerebrovascular disease ($2,694), (%)</td>
<td>$404 (12)</td>
<td>$242 (7)</td>
<td>$81 (2)</td>
</tr>
<tr>
<td>Total across 9 conditions</td>
<td>$18,398</td>
<td>$2,406</td>
<td>$1,390</td>
<td>$650</td>
</tr>
</tbody>
</table>

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**Cause and effect.** Accelerometer-based findings typically point to associations between low levels of physical activity and various aspects of chronic ill-health. But as with most questionnaire data, one cannot infer causation. In some instances, even the direction of the observed association is unclear. This is particularly true of reports that depression is less frequent among active individuals; although the arousing effect of exercise can enhance an individual’s mood state, people who are anxious or depressed are also less likely to engage in physical activity.

Studies of Japanese seniors have related the likelihood of developing sarcopenia or osteoporosis to accelerometer measurements of physical activity collected over a 5-year follow-up.[11,12] Here, the inference of a causal relationship is stronger (Table 1). A multivariate Cox proportional hazards model adjusted for baseline osteoporotic index, age, body mass, years since menopause (in the women), calcium intake, smoking habits, and alcohol intake shows a substantially greater risk that the osteoporotic index will drop below the fracture threshold in the 2 least active quartiles of the population sample, with significant evidence of a dose-related trend in both men and women, whether physical activity is assessed in terms of step counts or minutes of moderate activity per day.
The annual health cost per dependent senior was estimated at $20,513, and with 73% of people in the least active group being dependent, the average cost of dependency for individuals in this group was $14,974. Even among the dependent category, only 6% were affected by depression, and because the cost of treating depression was estimated at $2497, the sum assigned to those in this quintile was 6% of $2497, or $150. Proceeding in the same manner for other 7 diseases listed, the total health costs for each individual in the least active category was $18,398, but this total dropped dramatically across the 4 activity quartiles to a figure of only $3342 in the most active individuals. It was thus possible to calculate the substantial likely health benefits if a small proportion (say 10%) of the population could be persuaded to increase their habitual activity sufficiently to move themselves upward by 1 activity category.

Along similar lines, an analysis of accelerometer data for elderly patients in the United Kingdom showed that whether measured in terms of steps/day or minutes of moderate/vigorous physical activity, various indications of health care usage (new diagnoses, consultations, prescriptions, hospital admission days and secondary care referrals) showed a substantial negative gradient in relation to a 3-level categorization of the individual’s habitual physical activity.

There is plainly a need to extend such objective economic analyses to younger age groups, but because most chronic diseases are less prevalent in younger individuals, this will require the study of larger sample sizes, a development that will be facilitated as data analysis is increasingly automated.

Although current data suggest a potential for fiscal savings from encouraging greater physical activity, the savings may not be realized in practice. Firstly, although active people are generally more healthy, it is less certain how far an increase of physical activity can reverse established disease. And even if the incidence of 1 or more illnesses can be reduced by participation in a regular exercise program, it will be necessary to explore how large a fraction of patients benefit, lag periods, and the persistence of any favorable response. Moreover, hospitals and physicians are unlikely to relish a reduction in their incomes; thus, their response to an improved health experience will likely be a reallocation of resources to some other health need. Finally, a high proportion of medical expenses are generated in the final year of life, and it remains to be demonstrated how health promotional programs can change physical activity patterns at this stage of life. Probably, the greatest gain from a change in lifestyle will be a reduction of dependency, which is the major element in the list of potentially modifiable costs (Table 2).

**Contribution of personal monitors to exercise and rehabilitation programs**

Long-term compliance with programs of exercise rehabilitation is often poor, with drop-out rates of 50% or more over 6 months of observation. Various forms of reminder such as regular telephone calls or electronic messaging have been used in attempts to boost compliance, and it has also been suggested that the wearing of a simple objective monitor might be a helpful tactic in encouraging motivation. One obvious advantage of a personal monitor relative to alternative forms of motivation is that an exerciser can vary a walking route, or indeed substitute other forms of physical activity and still be aware of the weekly volume of activity that has been performed.

An important objective of any health professional is to encourage self-motivation and when using a personal monitor, much depends on whether the activity target is set by the health professional or the patient. Further, the benefit from any type of feedback depends heavily on how it is interpreted (feedback from a professional, a member of a peer group, or simply from a computer assessment of the data). One study of patients with diabetes mellitus was surprised to find no significant advantage of a pedometer relative to a thorough counseling program. A second investigation found a substantial increase of daily step-counts in those wearing activity monitors but only if trial participants were set targets that were adjusted upward on a frequent basis.

Research on the motivational use of activity monitors is to date quite limited, and it has examined only short periods of wear. The more important issue is whether objective monitoring provides a long-lasting change in activity patterns.

**The importance of monitoring sedentary habits**

Sedentary time is typically defined as periods of the day when a person is sitting or lying and the rate of energy expenditure is less than 1.5 METs. A systematic review of questionnaire studies examining sedentary behaviors in terms of indices such as hours spent television watching or working at a desk found significant correlations with various types of chronic ill-health, even after adjusting the data for questionnaire estimates of habitual physical activity. However, it remains less clear whether a specific adverse health effect is associated with prolonged periods of sitting, or whether the estimation of sedentary time is merely accounting for a part of the variance in total physical activity not detected by a weak questionnaire assessment of active movement.

Modern accelerometers can be programmed to record and analyze not only patterns of physical activity but also patterns of sedentary behavior. However, current designs of accelerometers do not provide a conclusive answer as to whether sedentary time has an independent impact upon health. As with questionnaire-based analyses, the measurements of sedentary behavior may in part be serving as an indicator of activities not otherwise measured by the accelerometer. If further research confirms a specific adverse health effect of sedentary behavior, it will be necessary to study whether its effect is uniform across individuals having different levels of active behavior.

**Continuing research issues**

There remains a need to define more clearly which intensities of physical activity have epidemiologic interest at various ages. For the elderly, it is probably appropriate to focus on activities demanding an energy expenditure in the range 3–6 METs, but there is a need for agreement on the higher intensities that should be monitored in younger individuals.

Much of the existing research with objective monitors is cross-sectional and is based on short periods of wear (4–7 days), often with removal of the equipment at night. There remains scope to repeat existing research, making longer and more representative 24-hour periods of data collection, and monitoring health outcomes on a longitudinal rather than a cross-sectional basis. There is also a need to move beyond demonstrating gross differences in outcomes between quartiles of physical activity and to study sufficient samples that clear dose–response relationships can be established, including thresholds and ceilings of response.

Questionnaire-based research has suggested that the accumulation of 10-minute periods of physical activity may offer as much health benefit as longer bouts of exercise. However, little information has been accumulated on the possible cumulative benefit of very short periods such as the 1–2 minute bursts of activity typical of spontaneous play in children. The accelerometer is well adapted for monitoring activity patterns over longer periods.
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to studying the effectiveness of different temporal distributions of physical activity, and there is growing evidence that even in older adults cardiovascular risks may be negatively associated with activity bouts having a duration < 10 minutes.

Potential future developments in objective activity monitors

Future design developments may overcome some of the limitations associated with the present generation of objective activity monitors. Currently, if such devices are worn on the hips or at the belt, they markedly underestimate energy expended in such activities as cycling, weight-lifting, and swimming. This limitation could be largely overcome by the simultaneous recording of posture, using some form of inclinometer. Moreover, no information is currently obtained on the context in which exercise is taken; this could be very helpful to those who are seeking to enhance physical activity, and simultaneous GPS recording could provide the necessary data. Others have sought to extend the accuracy of equipment by simultaneous recording the ECG signal, skin temperature, the galvanic skin response, sweating, and environmental temperatures. However, at present multi-phasic equipment that samples body posture, exercise location, and other additional variables is too complex and costly for epidemiological use.

At present, the careful use of accelerometers is labor intensive, limiting sample sizes and the duration of monitoring of subjects. However, the growing potential for the automation of both analysis and the checking of records should facilitate large-scale surveys, allowing epidemiologists to switch from correlating output with indirect indicators of disease (such as the use of pulse wave velocity as a surrogate of cardiovascular disease) to the use of clinical incidents such as myocardial infarction and strokes.

Conclusions

Application of objective physical activity monitors (particularly modern designs of accelerometer) have confirmed the significant relationships between habitual patterns of physical activity and the risks of chronic disease, as established by the use of activity questionnaires. However, it is not clear that the output of existing monitors is linearly related to the volume of health-significant physical activity, and there is a failure to measure some important sources of human energy expenditure. The limitations imposed by a significant unit cost of monitors and the complexities of data checking and analysis have also limited research to fairly small and usually cross-sectional studies. Thus, the nature and causality of dose–response relationships has yet to be clarified, and possible thresholds and ceilings of response have yet to be identified. Future technical developments allow larger scale longitudinal objective studies, with a greater realization of the potential inherent in objective monitoring.

Disclosure

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