Chapter 2
A History of Physical Activity Measurement in Epidemiology

Roy J. Shephard

Abstract Although Hippocrates is often considered the father of epidemiology, John Snow also played an important role with his studies of cholera epidemics in Victorian London. A detailed study of relationships between physical activity and the prevention of chronic disease did not begin until the mid-twentieth century, with Jeremy Morris in London, and Henry Taylor and Ralph Paffenbarger in the U.S. leading investigations of the epidemic of ischaemic heart disease. Occupation or athletic status was initially used to classify the habitual physical activity of study participants, but as daily energy expenditures diminished at most work sites, interest shifted to questionnaire and diary assessments of leisure activity. Other options to classify the habitual activity of subjects included occasional quasi-experimental assignments to exercise programmes, determinations of aerobic fitness, and a study of "natural experiments" where community activity patterns were known to have diminished. Such initiatives generally distinguished active from inactive individuals, but attempts to determine the intensity and volume of exercise that was undertaken often yielded unrealistically large values. The introduction of modern pedometer/accelerometers at first seemed to promise accurate, objective assessments of habitual activity. Although quite successful in assessing standardized activities such as steady walking, the newer monitors have shown much less consistency in measuring the wide range of activities encountered in normal daily living. Future research may focus upon some combination of activity monitoring with global position-sensing and posture detecting devices.

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2.1 Introduction

The term epidemiology means literally "*what is upon the people*." From the classical period of ancient Greece, physicians such as Hippocrates (460–370 BCE) have sought to find a logic underlying human illness and disease. Rather than blaming the random act of an angry God, the more discerning physicians have sought to explain and treat illness in terms of adverse external influences. For Hippocrates, the answer lay in restoring the internal balance of the four humours he saw as underlying the structure of our universe (air, fire, water, and earth) [1, 2]. Exposure to an unusual climate, an excess of moisture or noxious vapours were seen as external factors that could upset this delicate balance. Thus, Hippocrates noted that malaria and yellow fever were prevalent in swampy areas, although it was not until 1900 that Walter Reed linked these diseases to the breeding grounds of the mosquito rather than to unhealthy miasmata that were emerging from the swamps [1].

Even in Classical times, a small proportion of physicians, philosophers and other opinion-makers had formed a vague idea that moderate exercise was good for the health of the average citizen [2], but until about 70 years ago, there was no attempt to explore the epidemiology of physical inactivity; no one had defined the health benefits of a physically active lifestyle, and no one had attempted to specify the minimal amount of daily exercise that was needed for good health. In the mid-twentieth century, epidemiologists such as Jeremy Morris in England, and Ralph Paffenbarger and Henry Taylor in the United States began to address this challenge.

The present chapter first considers the apparent epidemic of cardiovascular disease that stimulated this new interest in the epidemiology of physical activity. It relates early ground-breaking initiatives, and traces through to the present day how changing methods of classifying an individual's habitual physical activity have helped to elucidate both the likely range of health benefits associated with regular exercise and the optimal weekly dose of physical activity.

2.2 The Cardiac Epidemic

Much early epidemiology was concerned with the causes of acute disease, as exemplified by the observations of Hippocrates on malaria and yellow fever, and more recently by John Snow's (1813–1858 CE) study of a cholera epidemic in the area served by the Broad Street pump in Central London [3]. However, there had been occasional ventures into the epidemiology of chronic disease. Paracelsus (1493–1541 CE) had demonstrated a geographic relationship between the mineral content of drinking water and the development of goiter, and Snow had himself proposed a chronic epidemiology project. The latter author had written an article in the Lancet suggesting that the adulteration of commercial bread was a probable cause of rickets [4], and he proposed testing this by a comparison of bone health between families baking their own bread and those purchasing it from bakers.

One new feature of epidemiology in the mid-twentieth century was its exploration of the idea that personal lifestyle could be among the adverse external influences predisposing to chronic disease. This concept was first applied to ischaemic heart disease, and subsequently to lung cancer, obesity, diabetes mellitus and other chronic conditions. The issue that persuaded "Jerry" Morris to begin his study of the epidemiology of physical activity was his perception that during the 1940s, an epidemic of cardiovascular disease affecting middle-aged adults was sweeping across England and Wales.

Morris cited the impression of many clinicians [5–8] that coronary heart disease was becoming ever more common and was being seen in younger patients. He thus examined the statistics of the Registrar General for England and Wales for the period 1931–1948 [9]. The statistics for older men (aged 50–54 and 60–64 years) showed a progressive increase in the number of deaths attributed to acute ischaemic heart disease (including coronary atheroma or atherosclerosis, and coronary, ischaemic or atherosclerotic heart disease). In contrast, deaths attributed to chronic myocardial disease showed little change over this same period (Fig. 2.1). Among women of comparable age, deaths attributed to coronary vascular disease were much less frequent, but nevertheless they also showed an increase in acute cardiovascular mortality. Morris [9] concluded cautiously "*If the increase is real, in whole or in part....causes may be discoverable in changing ways of living, in people who are changing in a changing environment.*" He also cautioned "*It is extremely difficult to determine how much of the apparent increase of coronary heart disease*

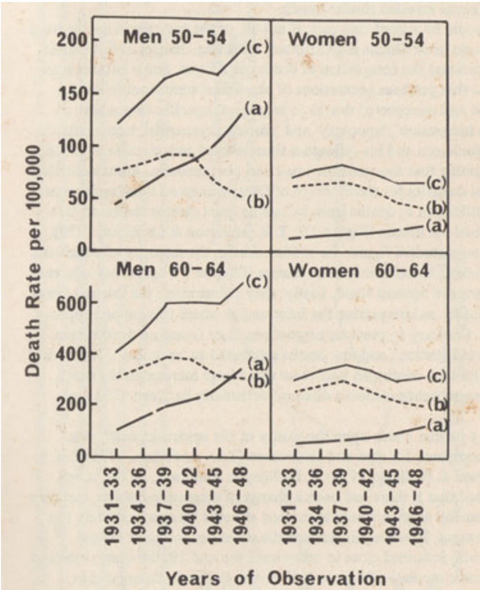

Fig. 2.1 Annual death rates for age and sex specific groups of the English and Welsh populations, as recorded by the Registrar General for the year 1931–1948 CE. (a): Acute ischaemic heart disease (coronary arterial disease plus angina, including coronary atheroma or atheroslerosis and coronaryt, ischaemic or arteriosclerotic hear disease); (b): chronic myocardial disease (including late deaths from myocardial infarction); (c): sum of (a) + (b). Based on the analysis of Morris [9]

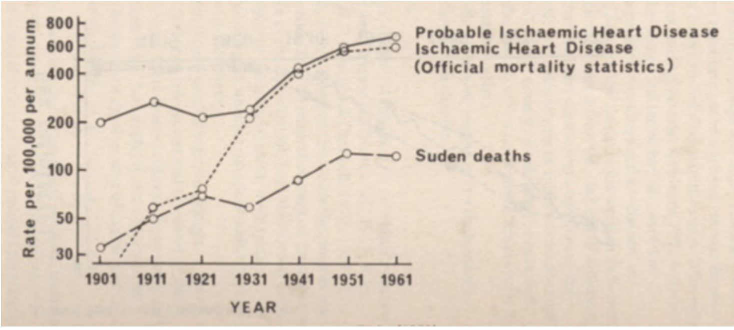

Fig. 2.2 Deaths from ischaemic heart disease in the province of Ontario, as analyzed by Anderson and LeRiche [10].The figure illustrates the official mortality data for ischaemic heart disease (comprising angina pectoris, coronary thrombosis, myocardial infarction and arteriosclerotic heart disease) in men aged 45–64 years, the probable incidence of ischaemic heart disease (based upon a reinterpretation of the original death certificates), and the incidence of sudden death (adjusted for certificates providing no information on the duration of illness). Note that death rates are expressed on a logarithmic scale

represents greater prevalence and how much is due to better diagnosis or changing fashions in diagnosis." Nevertheless, the Registrar General's statistics were supported by a doubling in the number of sudden deaths due to ventricular rupture from 1932 to 1949, and data for recent coronary thrombosis and acute myocardial infarction from the necropsy room of the London Hospital from 1907–1914 to 1944–1949 showed a six to sevenfold overall increase, with the steepest increase occurring around the time of the first World War.

Terence Anderson and Harding LeRiche, working in the Department of Epidemiology and Biometrics at the University of Toronto, decided to explore the generality of the epidemic, using Canadian mortality data [10]. Vital statistics for the Province of Ontario showed a similar trend to that observed by Morris, with an increase in deaths from cardiovascular disease from 1931 to 1961 (Fig. 2.2). However, Anderson and LeRiche recognized the problem that in the early 1900s, some practitioners may have ascribed ischaemic heart disease deaths to such vague causes as "*acute indigestion,*" "*apoplexy*," or "*chronic myocardial degeneration*." They reasoned that there could be much less room for error in the reporting of sudden death, and since most cases of sudden death were due to ischaemic heart disease, the substantial increase of sudden deaths from 1931 to 1961 suggested that the cardiac epidemic was a real phenomenon. They next re-examined the original death certificates, finding that no deaths were in fact recorded as "acute indigestion," and very few had been classed as "apoplexy." Sex ratios provided a final argument against explaining the apparent epidemic in terms of misdiagnoses. If there had been simply a change in diagnostic labels, sex ratios should have remained close to unity throughout. However, statistics for Canada, England and Wales and the U.S. all showed a sharp surge in cardiovascular disease in men, beginning around 1920 (Fig. 2.3) [11].

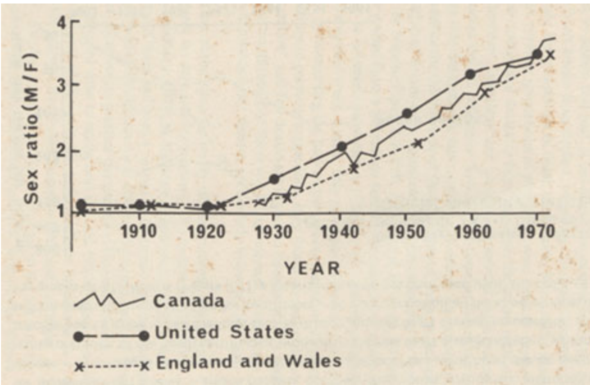

Fig. 2.3 The sex ratio (male/female) for all forms of heart disease in adults aged 45–64 years. Data for Canada, England and Wales and the United States. Based on an analysis of Anderson [11]

The reality of the cardiac epidemic thus seems established. However, its etiology is less certain. Shephard [12] made a detailed analysis of changes in ways of living over the twentieth century, looking specifically at such factors as hypertension, occupational stress, cigarette smoking, habitual physical activity, cholesterol levels, consumption of refined carbohydrates, diabetes, and obesity. Associations were sought between changes in each of these factors and the course of the epidemic. A growing prevalence of cigarette smoking during this era was one undesirable aspect of personal lifestyle; heavy smoking doubled the risk of a fatal heart attack [13], but it did not seem a strong enough influence to account for the epidemic in its entirety. A decline of habitual physical activity during the 1940s did not seem a major contributing factor, at least in England and Wales. Relatively few Britishers owned cars prior to World War II, and during the war most people had no access to petrol for the operation of private vehicles. Moreover, in the Britain of Morris's era, there had been little attempt to modernize industry or to reduce the energy expenditures of employees. Leisure habits also had shown little change; although public television broadcasting had officially begun in 1936, the majority of the population was unable to purchase a television receiver until the mid 1950s.

Given that the secular trend to a decline in habitual physical activity had yet to occur in Britain, it is a little surprising that Morris and his fellow epidemiologists developed an interest in potential relationships between habitual physical activity and cardiovascular disease. Nevertheless, over the next decade their efforts were rewarded by a clear demonstration that physical inactivity was a substantial risk factor for cardiovascular disease.

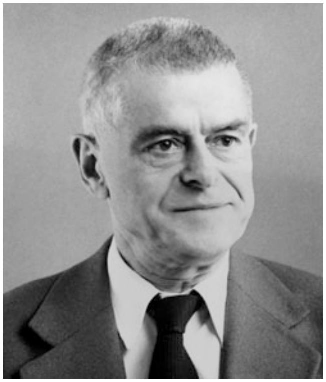

Fig. 2.4 "Jerry" Morris (1910–2009 CE), was an epidemiologist at the London School of Hygiene and Tropical Health and an early explorer of the relationships between physical inactivity and chronic ill-health. *Source*: LSHTH Blog

2.3 The Occupational Epidemiology of Physical Activity and Health

Although a proportion of physicians had long commended moderate physical activity as good for health, a serious examination of relationships between habitual physical activity and the prevention of chronic disease was not initiated until the late 1940s, with the classical epidemiological studies of Jerry Morris [14], Ralph Paffenbarger [15, 16] and Henry Taylor [17] on the role of regular physical activity in the prevention of cardiovascular disease.

Their early investigations were based upon comparisons of health experience between groups of workers with presumed differences of occupational energy expenditure. Statistics that were examined included total death rates, sudden death rates, deaths from ischaemic heart disease, the annual incidence of myocardial infarction, the annual incidence of angina, and combinations of these statistics.

2.3.1 Jeremiah Noah Morris

"Jerry" Morris (1910–2009 CE) was the son of Jewish refugees from Poland (Fig. 2.4). He had grown up in poverty in the slums of Glasgow, and this experience shaped his lifelong interest in the social determinants of health. After graduating in Medicine from University College London, he joined the Medical Research Council's Social Medicine Research Unit, which he brought to the London School of Hygiene and Tropical Medicine. He became a keen proponent of incorporating what he termed "vigorous getting about" into daily living.

He initiated studies on the epidemiology of physical activity by comparing cardiovascular data for London bus-drivers (who sat in their driver's seats for at least 90 % of their shifts) with similar figures for the bus conductors, who in that era had to collect fares from passengers on both decks of their vehicle every few minutes; the conductors climbed 500–750 steps every working day [18]. In a

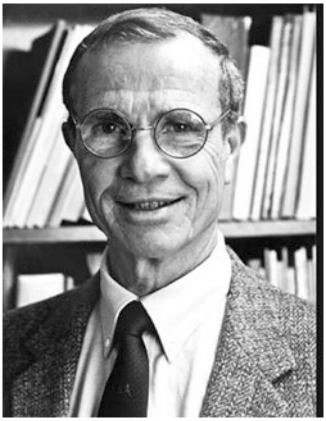

Fig. 2.5 Ralph Paffenbarger (1922–2007 CE) was a U.S. epidemiologist who carried out landmark studies on the relationships between activity and cardiovascular health on San Francisco long-shore workers and Harvard Alumni. Photograph reproduced by kind permission of Stanford School of Medicine's Office of Communication & Public Affairs

massive sample of 31,000 male workers aged 35–65 years, Morris found that the respective annual incidences of coronary arterial disease were 2.7/1000 for the drivers and 1.9/1000 for the conductors. Moreover, in the conductors who did eventually develop chronic cardiovascular disease, it occurred at a later age than in the drivers, often presenting as angina rather than a heart attack, and it was less likely to be fatal (30 vs. 50 %).

Morris next examined an even larger sample of 110,000 employees of the British post-office. He again observed a gradation of cardiovascular disease incidence with the presumed physical demands of employment. The lowest rates were seen in postal carriers who cycled or walked to deliver the mail; rates were higher in workers who engaged in less demanding physical activity (counter-hands, postal supervisors, and higher grade postal staff) and the highest rates were seen in totally sedentary workers (telephone operators, clerks and executives). Respective annual rates for the incidence of coronary arterial disease were 1.8/1000, 2.0/1000, and 2.4/1000, and annual case fatality rates were 0.6/1000, 0.9/1000 and 1.2/1000 in the three groups of workers. But as with the London Transport employees, the annual incidence of angina pectoris was highest in the most active group (0.7/1000), with rates of 0.4/1000 and 0.5/1000 for the other two categories of employees [18].

2.3.2 Ralph Paffenbarger

Ralph Paffenbarger (1922–2007 CE) (Fig. 2.5) was the son of a physician. He completed medical training at Northwestern University, and then took a Ph.D. degree in Epidemiology at Johns Hopkins University in Baltimore. After spending time teaching at Harvard and the University of California at Berkeley, he joined Stanford University, where he taught health research and policy. He was himself a committed exerciser, and engaged in many marathon and ultramarathon events.

His first study on the epidemiology of physical activity involved a group of 3263 San Francisco longshore workers who had undergone multiple health screenings over a 16-year period of employment. He classified these workers in terms of their presumed energy expenditure per shift, distinguishing a group of workers who each day expended 4 MJ more than their peers. The "heavy" workers, thus identified, had lower coronary artery disease death rates than other dock workers (59 vs. 80 incidents per 10,000 person-years of work) [15]; moreover, these differences persisted after statistical adjustment of the data for other coronary risk factors (smoking habits, weight for height and blood pressure).

A further analysis of data for the same population distinguished heavy workers (energy expenditures averaging 7.8 MJ/day), moderately heavy workers (expenditures of 6.1 MJ/day) and light workers (expenditures of 3.6 MJ/day). Again, the data showed a gradation of cardiac risk between the three categories of worker, with age-adjusted coronary arterial disease death rates of 26.9 vs. 46.3 vs. 49.0 deaths per 10,000 person-years of work; protection of the heavy workers was particularly marked in terms of sudden deaths (5.6 vs. 19.9 vs. 15.7 deaths per 10,000 person-years) [16].

A final report on the longshore workers looked at the 22-year health experience of this population. It distinguished men who engaged in bursts of high intensity activity (29 kJ/minute) with those with the lowest energy expenditures on the waterfront (4 kJ/minute). Advances in computer technology now allowed adjustment of the data for multiple co-variates (age, race, systolic blood pressure, smoking, glucose intolerance and ECG status). After making such adjustments, the sedentary group had twice the risk of sustaining a fatal myocardial infarction when compared with the highly active group [19].

2.3.3 Henry Longstreet Taylor

Henry Taylor (1912–1983 CE) (Fig. 2.6) was one of a group of distinguished physiologist-epidemiologists who spent much of his career in Ancel Key's

Fig. 2.6 Henry Longstreet Taylor (1912–1983 CE) was one of a group of distinguished physiologist-epidemiologists who spent much of his career in Ancel Key's *Laboratory of Physiological Hygiene* at the University of Minnesota. He studied the relationship between occupational physical activity and cardiovascular health in a large sample of railroad workers. *Source*: The Physiologist, 27(1), p. 22, 1984, used with courtesy from the American Physiological Society

Laboratory of Physiological Hygiene at the University of Minnesota. He gave serious consideration to the possibility of conducting a randomized controlled trial of exercise in the primary prevention of heart disease, but he reluctantly concluded that such an experiment was not practicable because of its complexity, magnitude and the number of confounding factors.

Like Morris and Paffenbarger, Taylor thus approached the epidemiology of physical activity in terms of workers with differing occupational energy expenditures. He chose as his subjects railroad employees, classifying them as clerks (85,112 person-years), switchmen (61,630 person-years) and section workers (44,867 person-years) [17]. Although the clerks were clearly sedentary, and greater energy expenditures were required by the other two groups of workers, no precise estimates of occupational energy demands were made. All subjects were white males aged 40–64 years who had worked for the railroad company for at least 10 years. Age-adjusted death rates for the three categories of employee were, respectively, 11.8/1000, 10.3/100 and 7.6/1000 for all-cause mortality, and 5.7/1000, 3.9/1000, an 2.8/1000 for deaths ascribed to arteriosclerotic heart disease. Sub-maximal treadmill tests were subsequently carried out on many of the study participants, using as a laboratory a converted Pullman car that travelled around the U.S. [20]; unfortunately, these findings were not related to the occupational categories identified by Henry Taylor.

2.3.4 Conclusions from Occupational Comparisons

Morris was convinced the evidence from his occupational comparisons pointed towards a beneficial effect of physical activity, advancing the hypothesis the "*men doing physically active work have a lower mortality from coronary heart disease in middle age than men in less active work*" [18]. However, the job-classification approach initially encountered strong skepticism from the medical establishment.

One obvious issue was the self-selection of active vs. sedentary employment. A follow-up analysis at London Transport demonstrated that bus drivers began their employment with a larger trouser and jacket size than the conductors, implying that they had a greater initial body fat content [21]. Nevertheless, at a 10-year follow-up, rates of sudden death in the drivers were twice as high as those in the conductors, irrespective of their initial physique [22]. A subsequent multivariate analysis examined the contribution of other risk factors to the development of cardiac disease. It found that systolic blood pressure and serum cholesterol levels accounted for 75 % of new cases. Blood pressure and lipid levels were lower in the conductors than in the drivers, but for any given systemic blood pressure, the risk of cardiovascular disease was almost twice as great in the drivers as in the conductors [23].

Paffenbarger's occupational comparisons were complicated somewhat by job reclassifications secondary to cardiac symptoms; those with angina frequently transferred out of heavy work, and he noted that the risk of a heart attack was greatest in those whose occupational energy expenditure had decreased over a

4-year observation period [19]. However, Taylor suggested that there was little problem of reclassification amongst his railroad workers, because sedentary employees belonged to a different union that did not welcome track workers. Despite the potential challenges of self-selection of active employment, reclassification of active workers as cardiac disease develops, and differences of social class and leisure activities between sedentary and active workers, the occupational studies point strongly towards benefit from engaging in physically demanding employment. However, they do not define the intensity and volume of effort needed for better health.

The interest of epidemiologists shifted from occupational classifications to assessments of leisure-time activity during the latter part of the twentieth century, in part because mechanization was eroding the physical demands of much traditional heavy industry, in part because there seemed the greatest scope for public health intervention in terms of augmenting the voluntary leisure activity of sedentary individuals, and in part because analyses of leisure behaviour could be made on groups having a similar socio-economic status. Options for assigning an individual to an active leisure category became reports of athletic status, assignment to the experimental group in quasi-experimental studies, questionnaire self-reports of vigorous leisure activity, and demonstrations of a high level of aerobic fitness. In some instances, it was also possible to examine associations between changes in reported physical activity or fitness and health status.

2.4 Athletic Status and Health

2.4.1 Comparisons Between Athletes and the General Population

Many Victorian physicians had fears that participation in athletic competition would create what they regarded as the dangerous condition of "athlete's heart" [2]. Epidemiological studies intended to disprove this view (Table 2.1) commonly compared the overall and/or cardiovascular death rates of former athletes with the experience of the general population [48–50], or the death rates that Actuaries established for people purchasing life insurance. Almost all of such comparisons have favoured the athletes. A recent meta-analysis based upon a total of 2807 competitors (707 of whom were women) showed an all-cause standardized mortality ratio of 0.67 for the athletes, with no evidence of publication bias; six studies reported data for cardiovascular disease, with a mortality ratio of 0.73 favouring the athletes [48].

During much of the era under consideration, athletes (as university graduates or high-earning professional competitors) had access to better health-care and a considerable socio-economic advantage over the general population. Furthermore, they were usually selected initially in terms of physique, often showing differences

Table 2.1 Comparison of overall and/or cardiovascular (CV) death rates between athletes and the general population

Author	Populations	Athletes	Comment
Anderson [24]	808 Yale University athletes 1855–1905 vs. Actuarial tables	Athletes favoured	Death rate 52 % of actuarial table, 46 % of American table
Baron et al. [25]	3439 National football league players playing from 1959 to 1988 vs. general population	Athletes favoured	All-cause mortality 0.53, CV mortality 0.68
Belli et al. [26]	24,000 professional Italian soccer players, 1960–1996 vs. general population	Athletes favoured	CV mortality 0.83 (all-cause mortality 1.00)
Cooper et al. [27]	100 Australian oarsmen vs. Actuarial tables	Athletes favoured	Mortality ratio 75.4 %
Dublin [28]	4976 Athletes from 10 U.S. Colleges, 1890–1905 vs. actuarial table	Athletes favoured	Mortality 93.2 %, 91.5 % relative to two Actuarial tables; BUT greater advantage in non-athletic honours graduates
Gaines and Hunter [29]	808 Yale athletes vs. actuarial tables	Athletes favoured	Death rate 49 % of expected by actuarial table, 44 % relative to American table
Gajewski and Poznanska [30]	2113 Polish Olympic competitors (414 F) during twentieth century vs. gender adjusted Polish urban population	Athletes favoured	All-cause mortality 0.51
Hartley and Llewellyn [31]	767 Oxford and Cambridge oarsmen 1829–1928 vs. Actuarial tables	Athletes favoured	Mortality ratio 76.7–93.5 % in four comparisons
Hill [32]	3424 British County or University cricketers, 1800–1888 vs. English Life Tables	Athletes favoured	Significant advantage in terms of number dying before given age in all comparisons
Kalist and Peng [33]	2641 S. Major league baseball players born 1945–1964	Athletes favoured	All-cause mortality 0.31
Karvonen et al. [34]	396 Champion skiers vs. general Finnish population	Athletes favoured	3–4 year advantage of longevity
Kujala et al. [35]	2009 Finnish international competitors 1920–1965 vs. general population	Athletes favoured	All-cause mortality 0.74, CV mortality 0.72
Marijon et al. [36]	786 Tour de France competitors, 1947–2012 vs. general French male population	Athletes favoured	All-cause mortality 0.59, CV mortality 0.67
Menotti et al. [37]	700 M, 283 F Italian track and field athletes vs. Italian life tables	Athletes favoured	All-cause mortality 0.73 (M), 0. 48 (F)
Metropolitan Life [38]	6753 Baseball players 1876–1973 vs. insured population	Athletes favoured	Mortality ratio 1876–1900, 72 %
Meylan [39]	152 university rowers 1852–1892 vs. standard mortality tables	Athletes favoured	2.9 year advantage of life expectancy

(continued)

Table 2.1 (continued)

Author	Populations	Athletes	Comment
Morgan [40]	251 Oxford and Cambridge rowers 1829–1859 vs. Farr's English life tables	Athletes favoured	Death rate 64 % of expected, 2.0 year advantage of life expectancy
Reed and Love [41]	4991 West Point military academy officers 1901–1916 vs. Actuarial tables	Officers favoured	0.25–1.25 year advantage of longevity
Schmid [42]	400 Czechoslovak athletes, 1861–1900 vs. general population of non-athletes	Athletes favoured	Longevity advantage of 8.66–1.44 years
Schnohr [43]	297 Danish athletes vs. general population	Athletes favoured	To age 50 year mortality 0.69 of expected; CV deaths 34.7 %, expected 36.7 %
Schnohr et al. [44]	4658 Joggers vs. other Copenhagen residents	Athletes favoured	Relative risk of death in persistent joggers 0.37
Taioli [45]	5389 Italian professional soccer players 1975–2003 vs. population statistics	Athletes favoured	All-cause mortality 0.68, CV disease 0.41
Wakefield [46]	State high school basketball champions vs. general male population of Indiana	Athletes favoured;	16.3 % of deaths due to cardiac or renal disease, BUT mortality 69 % of general population; 13.3 % of age-matched deaths due to cardiac or renal disease
Waterbor et al. [47]	985 baseball players 1911–1915 vs. general population	Athletes favoured	All-cause mortality 0.94 (0.88–1.00)

of body build relative to the average person, and at least in the case of endurance athletes they were generally non-smokers.

2.4.2 University Athletes and Their Academic Peers

Some studies of athletic status and health have drawn comparisons between those winning "letters," as representatives of their university, and other individuals who were attending the same institution in the same era, but did not distinguish themselves as athletes (Table 2.2). This approach largely overcame the issue of a differing socio-economic status in the comparison group, and perhaps in consequence the advantage of the athletes was less clearly demonstrated.

Rook [58] compared the mortality experience of members of Cambridge University athletic teams with a random sample of students and with "intellectuals" marked by academic distinction in their final examinations. He found no significant inter-group difference in average age at death, although the percentage of cardiovascular deaths was marginally lower in the athletes than in the other students. Rook commented that those involved in muscular sports ("heavy" sportsmen) had a

Table 2.2 Comparison of deaths from cardiovascular disease between athletes and other similar populations

Author	Population	Athletes	Non-athletes
Abel and Kruger [51]	Baseball players debuting between 1900 and 1939 vs. other baseball players	Top athletes favoured	4.8 year advantage of life expectancy
Dublin [28]	4976 Athletes from 10 U.S. Colleges, 1890–1905 vs. non-lettermen	Intellectuals favoured	2 year greater life expectancy than athletes or other graduates
Greenway and Hiscock [52]	686 students earning athletic letters vs. other graduates	Controls favoured	Mortality 93 % of expected in athletes, 83 % of expected in other graduates
Montoye et al. [53, 54]	628 Pre-1938 University of Michigan lettermen vs. other graduates	Non-athletes tended to be favoured	2 year difference in age at death (non-significant)
Paffenbarger et al. [55]	63 Univ. of Pennsylvania and Harvard lettermen 1921–1950 vs. other graduates	Athletes favoured	Coronary death ratio 0.6
Polednak and Damon [56]	Harvard major athletes (letter winners) vs. minor athletes, vs. non-participating students	Minor athletes and non-athletes tended to be favoured relative to major athletes	40.0 % of deaths due to cardiovascular disease, no significant inter-group difference in age at death
Prout [57]	172 Harvard and Yale crews 1882–1902 vs. other graduates	Athletes favoured	6.3 year advantage in age at death
Rook [58]	Cambridge University athletes vs. "intellectuals" and random Cambridge students	36.4 % of deaths due to cardiovascular disease, NO significant difference in average age at death	39.9 % of "intellectuals," 41.4 % of random students died of cardiovascular disease

slight disadvantage relative to endurance competitors ("light" sportsmen), the latter living some 1.7 years longer. He further noted that the literature provided little support for the idea that University athletes gained a large amount of weight when their competitive career was over.

Other studies from Scandinavia found a several year advantage of longevity in endurance athletes relative to the general population [34]. However, it remained unclear whether this was because they continued to undertake a large volume of habitual physical activity, or whether their advantage was attributable to other characteristics of the endurance competitor such as an ectomorphic body build and abstinence from cigarettes. The potential influence of initial selection was seen in a comparison between Baseball Hall of Famers and other baseball players [51],

Fig. 2.7 Henry J. Montoye of the University of Michigan, Ann Arbor, MI, conducted a major longitudinal study of cardiovascular disease in athletes, and made major contributions to questionnaire analyses of habitual physical activity

with the top baseball players having a substantial health advantage over other less successful league players.

An extensive study conducted by Henry J. Montoye (Fig. 2.7) and his colleagues at the University of Michigan showed that athletic "*Letter Holders*" tended to have a shorter lifespan than their peers who had attended the same university, but had not participated in inter-collegiate athletics [53, 54]. This could suggest a negative effect of sport participation upon cardiovascular health. However, further investigation of this data suggested two alternative explanations. Many of the *Letter-Holders* at the University of Michigan had been football players, a sport where a mesomorphic body build not only gave them a physical edge over lighter opponents, but also predisposed them to cardiovascular disease in middle age. Moreover, by the time that they had reached middle age, many of the former *Letter-Holders* were engaging in no more physical activity than their peers and had gained some 10 kg of body mass since leaving the university.

2.4.3 Conclusions from Studies Based on Athletes

Unfortunately, a variety of factors conspire to limit the conclusions about physical activity and health that can be drawn from comparisons between former athletes and their supposedly sedentary peers. The initial selection of the athlete is based upon a specific body build and outstanding sport-specific fitness. Most studies have obtained little information on the exercise habits of the athletes after they ceased competition, and by middle age some former competitors have allowed themselves to become more sedentary and obese than their non-athletic peers. Finally, top athletes differ in temperament from the general population, and thus have an above average death rate from such causes as motor vehicle collisions, homicides and suicides.

Fig. 2.8 In 1969–1970 CE, the late Hugues Lavallée initiated a quasi-experimental study that examined the impact of five additional hours of physical education per week upon the fitness and health of 546 primary school students in Trois Rivières, Québec

2.5 Exercise Group Assignment in Quasi-experimental Studies of Fitness and Health

No one has disputed the assertion of Henry Taylor that it is impractical to carry out a true randomized controlled study looking at the long-term effects of physical activity upon various facets of fitness and health. However, several quasi-experimental studies have attempted to explore this question.

2.5.1 The Trois Rivières Regional Study

In terms of experimental design, perhaps the most convincing of the quasi-experimental studies was initiated by the late Hugues Lavallée (Fig. 2.8). Between 1970 and 1977, 546 children attending two state primary schools (one urban, and one rural) in the Trois Rivières region of Quebec were assigned to either an experimental programme (an additional 1 hour per day of vigorous physical education, taught by an enthusiastic physical education professional), or the standard control programme (where students received only minimal physical education, taught by their home-room teacher) [59]. Student assignment was based simply on the year of school enrolment; alternate years followed the experimental or the control programme at the same school, with the same teaching staff; the only inter-group difference in treatment was that 14 % of the academic teaching time was replaced by physical activity instruction for students who were assigned to the experimental group. Students continued in their assigned group throughout their 6 years in primary school, the only exceptions being a few pupils who skipped one grade, or who failed a year. By the age of 10–12 years, children in the experimental group showed the expected gains of aerobic fitness, muscular strength and physical performance relative to control students, but there was little inter-group difference of health experience while students were attending the primary school.

An attempt was made to re-evaluate participants 25–35 years later. At this stage, there were still a few inter-group differences of lifestyle (the experimental group still tended to greater habitual physical activity and had a smaller proportion of smokers); however, bone density was similar for the two groups [60]. Possibly, differences in the incidence of cardiovascular disease or cancer might have been seen if the study could have continued further, until the subjects were aged 50 or 60 years. However, even in a city such as Trois Rivières, where the population has a relatively limited mobility, it would be difficult to maintain contact with an adequate proportion of the original subjects in order to establish significant lifetime differences in health experience. In most North American cities, mobility is much greater, and few of the original sample would be available for testing after an interval of 40–50 years. Moreover, although the experimental programme was effective in enhancing the immediate fitness of the students in Trois Rivières, it would be necessary to extend modification of the academic programme throughout the critical adolescent years in order to ensure that there was still a substantial inter-group difference of lifestyle when the subjects were adults.

2.5.2 Quasi-experimental Assignment to a Work-Site Fitness Programme

A second potential option for a quasi-experimental study is to introduce an effective work-site fitness programme to one major company, and to select as a control a closely comparable company at a nearby location, where similar evaluations can be made, with the promise of an equivalent fitness programme at a later date. The control group are unlikely to accept a delay of more than a year in development of their fitness programme, and anticipation of this event could compromise their control status. Further, most companies are unlikely to agree to a programme that focuses uniquely upon exercise; typically, advice is given on other health issues such as obesity, stress, and substance abuse. Further, programme attendance is voluntary, and despite attractive incentives, less than a third of employees may be following the programme at the end of the first year of its operation. In one quasi-experimental work-site fitness study in Toronto, we were able to demonstrate that there was a small reduction in health care costs over the first year of programme operation [61], but a fitness programme was provided to the control company at the end of the year, so it would not have been possible to evaluate long-term effects upon health.

2.5.3 Conclusions

Although quasi-experimental studies allow an examination of short and medium term influences of increased physical activity upon fitness and health, population mobility and poor long-term compliance with the assigned regimen have to date precluded use of this approach in examining the impact of increased physical activity upon the incidence of chronic ill-health.

2.6 Questionnaire and Diary Assessments of Leisure Activity

The physical activity questionnaire has long been the main tool of the chronic disease epidemiologist. Its main attraction is that it can easily be applied to large population samples. However, the limitations of such methodology have also long been appreciated [62, 63].

2.6.1 Types of Instrument

The questionnaires available to epidemiologists have ranged from very simple forms, requiring only two or three responses from users [64–66], to complex instruments 20 or more pages in length encompassing every conceivable type of physical activity [67–69]. The latter have sometimes been completed using cue sheets to remind subjects of less common sources of energy expenditure, and often a trained assistant has been needed to make nuanced interpretations of responses. The latter requirement immediately negates the primary virtues of the questionnaire approach: simplicity and low cost, and the act of interpretation could bias the data. One alternative or complement to the questionnaire is an activity diary. Morris [70] had his sample of civil servants complete sheets noting their activities every 5 minutes during a Friday and a Saturday. The need to complete such a record can in itself modify activity patterns, particularly by restricting the number of changes in activity over the course of a day [70].

Most investigators have recognized the limitations of human memory, particularly in older individuals. Thus questionnaires have generally asked about activity performed during the previous week or the previous month. This is problematic in countries with a continental climate, since outdoor activities are decreased by rainfall and extremes of warm or cold weather [71–73]. Ideally, responses should be obtained over the various seasons of the year, but few observers have taken this precaution.

In terms of some chronic conditions such as cancers, the relevant time-frame of preventive physical activity is much longer than a month or even a year. A few questionnaires have covered the entire life span [68, 74–76]. Friedenrich et al. [75] used trained interviewers and an anchored calendar as a memory aid; with this approach, they found that the 6–8 week reliability when estimating lifetime hours per week of physical activity was relatively good (intra-class correlation coefficients for occupational activity, 0.87; for domestic activity, 0.77; for exercise or sports participation, 0.72; and for all forms of activity, 0.74). A 1-year re-evaluation of female U.S. College graduates [77] achieved similar intra-class correlation coefficients (vigorous activities, 0.86; moderate activities, 0.80; recreational activities, 0.87; domestic activities, 0.78; total activities, 0.82). Both of these studies were conducted on well-educated subjects, and it is less clear that a comparable reproducibility could be achieved with the poorly educated, or with recent immigrants who have a poor understanding of the English language and differing cultural norms of physical activity. Indeed, even with Harvard Alumni, the reliability coefficient for the questionnaire used by Paffenbarger and his associates was 0.72 over a 1-month interval, dropping to 0.3–0.4 when the recall period was 8–12 months [78].

2.6.2 Types of Information Collected

There is little argument that leisure questionnaires can draw a relatively accurate binary distinction between active and inactive individuals [70, 79–83]. However, many investigators have attempted to collect a much greater range of information from their questionnaires, including the intensity and the total volume of physical activity performed in a typical week.

2.6.2.1 Intensity of Physical Activity

Many questionnaires have ignored brief or low intensity bursts of physical activity, although in the context of modern sedentary society, the cumulative impact of short periods of activity could conceivably be important to health. Thus, Blair et al. [84] took no account of activities if they were less intense than brisk walking, or lasted for less than 10 minutes. Likewise, a questionnaire developed by Gaston Godin (Fig. 2.9) [64] asked "how many times on the average do you do the following types of exercise for more than 15 minutes. . ."

Physical activity compendia [85, 86] have been used to convert reported activities such as walking, jogging or cycling to approximate energy expenditures, although unfortunately secular changes in technology such as the introduction of ultra-lightweight bicycles have progressively reduced the actual energy costs of activities relative to the values indicated in compendia [87]. Accurate information on pace is also critical to any estimate of the intensity of energy expenditures, and many of the activities listed in the compendia were assessed on fit young adults rather than on sedentary older people who may be heavier, but tend to move much

Fig. 2.9 Gaston Godin is a exercise psychologist and physiologist at Laval University, Quebéc. He developed a simple physical activity questionnaire with scores having a good correlation with the individual's level of attained aerobic fitness

more slowly. In terms of health, the relative intensity of effort is also more important than absolute energy expenditures [88]. Subjective descriptions of the intensity of effort (light, moderate or hard) depend on age, physical fitness, culture and the duration of activity [89], the stoicism of the subject [90], and sometimes on the social desirability of the response [91]. It may thus be best to tie descriptors of intensity to physiological anchors such as breathlessness [92] or the onset of sweating [64].

2.6.2.2 Duration of Physical Activity

It remains unclear whether a single exercise session must have a minimum duration in order to induce health benefits. Objective monitoring has allowed the analysis of the effects of the total volume of physical activity and the effects of its segmentation. Very few people of the general population engage in the recommended 30 minutes of daily aerobic exercise [93, 94], but it has been suggested that they might obtain similar benefit by taking three 10 minute sessions of physical activity per day [95]; possibly, every step counts! Sixteen studies of fractionated activity [94] have as yet failed to resolve this issue, although it remains important to the design and interpretation of physical activity questionnaires.

2.6.2.3 Aspects of Exercise Other than Aerobic Activity

With a few exceptions [96, 97], physical activity questionnaires have focussed uniquely upon participation in aerobic exercise. However, current public health recommendations also call for resistance and flexibility exercises, plus activities to enhance bone structure and improve balance [93, 94]. Most questionnaires have also neglected the environmental context in which activity is performed, although it is now recognized that high temperatures can increase the energy cost of activities [89, 98, 99], and that extremes of temperature reduce programme compliance. Further, favourable psychological reactions such as a reduction of stress are more likely if activity is taken in a pleasant natural environment [100].

2.6.3 Reliability and Validity of Information Obtained from Questionnaires

2.6.3.1 Reliability

The reliability of questionnaires has commonly been expressed as intra-class test-retest correlation coefficients. Results have been most reliable in groups marked by intelligence and/or a high socio-economic status (for example, senior civil servants [101]; Harvard alumnae [102]; members of an exclusive fitness club [103]; and nursing graduates [104]). The consistency of reported activity was also greatest if a single stereotyped activity such as walking was the predominant form of physical activity. Test-retest correlations were higher for reports of strenuous physical activity (>0.7) than for reports of moderate or low intensity activity [105]. Data from the Canada Fitness Survey of 1982 also suggested that intensity was reported less reliably than the frequency or duration of physical activity [106].

2.6.3.2 Validity

Although many questionnaires can sort a population into active and inactive categories, doubt has been cast upon the validity of more detailed and quantitative interpretations. The lack of validity is highlighted by discrepancies between the substantial proportions of Canadian National and Provincial populations reporting activity patterns that meet current physical activity guidelines, and the very low proportion of active individuals that are seen by casual observers in most North American cities [69, 71, 107–111]. Serious systematic errors seem inherent in many questionnaire studies [112, 113]. Thus, three surveys conducted by the U.S. National Center for Health Statistics provided widely divergent estimates of the prevalence of limited physical activity among women of child-bearing age (from 3.9 to 39 % [114]). Likewise, estimates of the prevalence of moderate physical activity have varied widely from one survey to another, depending on such issues as the use of cue cards and the exact form of the questions asked [115, 116]. The problem reflects in part the ever-diminishing average level of physical activity in most populations. Questionnaires that were appropriate to discern the occupational and leisure activities of earlier generations lack the sensitivity to quantitate the very limited energy expenditures required by modern society [62].

Response options in even the most elaborate questionnaires have frequently omitted important component activities of a typical day, such as care for an ailing parent or grandchildren. Memory has also been a problem (particularly for older people). On the other hand, subjects have commonly exaggerated their activity patterns, partly to satisfy observer expectations (particularly if a physical activity programme has been prescribed for them [71, 117–119]). Because of over-estimation of times spent in various activities, some respondents have indicated total day lengths much greater than 24 hours, and it has then been necessary to introduce an arbitrary downward scaling in the duration of reported activities [71, 120].

Direct comparisons between questionnaire estimates and external criteria have shown discouragingly large errors, even when assessing something as simple as the daily walking distance [78, 91, 121]. Thus, the College Alumnus Questionnaire data suggested a daily walking distance of 1.4 km vs. the 4.2 km that was scored on a pedometer [121]. Even more alarming, for each km of walking distance that was reported, a 48-hour activity diary suggested that subjects had actually walked 5.3 km [78]. A recent study of elderly Japanese (where walking was the predominant form of physical activity) found moderate and statistically significant correlations of questionnaire responses with pedometer/accelerometer measures of daily step count, minutes of activity <3 METs and minutes >3 METS ($r = 0.41$, 0.28 and 0.53, respectively), but in this community the reported total energy expenditures relative to the objective pedometer/accelerometer measurements were over-estimated by a factor of three [122]. One reason for over-estimating the duration of activities is that subjects often include such items as travel to a gymnasium, periods of passive instruction, changing, showering, and socializing in their estimates of the time that they have devoted to physical activity [123].

Formal assessments of the validity of questionnaires have been made relative to doubly-labelled water (DLW) estimates of overall energy expenditures, pedometer/accelerometer data, and physiological indices such as aerobic fitness and obesity. All of these objective measures have their limitations. DLW measurements are costly, and thus can be applied only to small samples; moreover, they only provide an average of energy expenditures over a 2-week period, which is necessarily heavily weighted by low intensity activities. Correlation coefficients with DLW were 0.68 for the Baecke index, 0.64 for the Tecumseh questionnaire, and 0.68 (women) and 0.79 (men) for the physical activity scale for the elderly [124, 125]. Coefficients of correlation between pedometer/accelerometer scores or physiological status and reports of strenuous activity are typically in the range 0.4–0.5 [105, 126]. Among 10 questionnaires [105], the closest correlations with the directly measured maximal oxygen intake (0.56) were for the Minnesota [82] and Godin/Shephard [64] questionnaires.

Relatively simple questionnaires [64, 127–130] seem at least as valid as complex forms, although there is often a poor correlation between the data obtained from simple and complex questionnaires (0.14–0.41) [131, 132]. The questionnaire of Godin and Shephard [64] required three-option responses to two simple questions; in well-educated individuals, the most satisfactory univariate item was the report of performing strenuous physical activity over the previous 7 days (2-week reliability coefficient of 0.94, a correlation of 0.98 with an age and sex-adjusted step test prediction of maximal oxygen intake, and an 0.74 correlation with an age and sex-adjusted skinfold prediction of body fat content).

2.6.3.3 Conclusions on the Reliability and Validity of Questionnaires

The general direction of relationships between physical activity and health was probably indicated correctly in most questionnaire-based surveys. However, the demonstration of substantial systematic errors in most questionnaire responses has inevitably cast a pall of doubt upon the quantitative epidemiological research carried out over the past 50 years. Moreover, the lack of precision in questionnaire data may well have attenuated the apparent strength of relationships with health, making correlations statistically insignificant [133, 134].

2.6.4 Population Studies of Leisure Activity Using Questionnaires and Activity Diaries

As examples of analyses of leisure activity using questionnaires and diaries, we may instance in Britain a study of executive-class civil servants [70] and a regional analysis drawn from 25 representative medical practices across Britain [135]. From the U.S., we will consider the experience of Seventh-Day Adventists Harvard alumni [81], and U.S. railroad workers. Many of these studies not only identified active individuals, but also attempted to assess the intensity, duration and volume of habitual physical activity. In particular, attempts were made to predict the minimum intensity [70, 101, 136], the relative intensity [137] and the total weekly volume of effort needed [138] to prevent heart attacks in various age groups.

2.6.4.1 Executive-Class Civil Servants

Between 1968 and 1970, Morris and his associates [70] undertook a study of 16,682 male executive-class civil servants aged 40–64 years. Participants recorded on a Monday their recollection of leisure activities undertaken at 5-minute intervals on the preceding Friday and Saturday. Without knowledge of clinical histories, three observers then noted for each participant periods >5 minutes per day that had been ascribed to active recreation, keeping fit, or vigorous getting about (activities demanding near maximal effort), bouts of heavy work reported as lasting >15 minutes (gardening, building or moving heavy objects) and stair climbing. All of these activities were thought to demand at least peak energy outputs >31 kJ/minute, and thus could be considered as heavy work. Reported vigorous physical activity in each of the first 214 of the sample who sustained a clinical attack of ischaemic heart disease was compared with that of two matched peers who had not sustained a heart attack (Table 2.3). Those sustaining the heart attack were less likely to have been active than their peers. Protection was also seen for fatal heart attacks in all of the categories of physical activity that were analyzed. However, no such differences were seen with respect to reports of moderate activity, or for total

Table 2.3 Frequency of vigorous physical activity reported by 214 executive-class civil servants sustaining a first clinical attack of myocardial infarction relative to the frequency of attacks observed in matched controls [70]

Type of physical activity	Matched controls (n = 428)	Men sustaining heart attack (n = 214)	Expected number in those sustaining attack
Active recreation	15	5	7.5
Keeping fit	15	3	7.5
Vigorous getting about	18	1	9
Heavy work	73	17	36.5
Climbing >500 stairs/day	8	0	4
Total reporting vigorous activity	111	23	55.5

activity (which included much light activity). When participants were grouped by age, the benefit of habitual physical activity seemed similar for those aged 40–49 years and for those aged 60–64 years. Further, the data provided no evidence that early symptoms had previously impeded physical activity in those sustaining a first heart attack. Those engaging in much vigorous exercise seemed to gain more benefit (risk ratio 0.18) than those doing some vigorous exercise (risk ratio 0.42–0.55). The identification of those engaging in any vigorous physical activity also proved relatively consistent from March or September 1969 (38 individuals) to November 1971 (31 individuals). The one issue that could not be excluded was that participation in vigorous physical activity was serving as a marker of some other unidentified personal characteristic.

This study thus confirmed the association of regular vigorous physical activity with a low risk of cardiac disease, as seen in the occupational studies, and it made the first tentative steps towards identifying the required intensity and volume of activity. By 1980, participants in the study had sustained 1138 first clinical episodes of coronary heart disease, but the general conclusion that vigorous habitual activity protected against heart attacks, particularly fatal incidents, remained unchanged [139].

A second and somewhat similar study was launched in 1976 [101]; this followed 9376 healthy male executive civil servants initially aged 45–64 years for an average of 9 years. During this period, there were 474 heart attacks. Some 9 % of employees reported that over the preceding 4 weeks that they had often participated in vigorous sports, undertaken considerable amounts of cycling, and/or rated their walking pace as >6.4 km/hour, they experienced less than a half as many non-fatal and fatal heart attacks as their peers. However, no protection against cardiac disease was observed unless the sport or exercise was reported as vigorous (Table 2.4), and no protection was obtained from sports participation at a younger age.

Table 2.4 Relationship of participation of male executive class civil servants in sport to age-adjusted risk of coronary heart disease, based on data of Morris and associates [101]

Episodes of sports play in past 4 weeks	Vigorous sports (>31 kJ/minute)		Non-vigorous sports (<31 kJ/minute)	
	Cases/1000 man-year	Relative risk	Cases/1000 man-year	Relative risk
None	5.8	1.00	5.4	1.00
1–3	4.5	0.78	5.9	1.09
4–7	4.1	0.71	5.9	1.09
8–11	2.1	0.36	3.5	0.65
>12			6.8	1.26

2.6.4.2 Coronary Disease and Physical Activity in Regional Medical Practice

Shaper and Wannamethee [135] followed 7735 men initially aged 40–59 years for an average of 8 years. Their sample was drawn from 24 medical practices that were considered as representative of socio-economic conditions across Britain. Nurses administered to all participants a questionnaire that included questions on physical activity (walking, recreational activity, cycling and sport activity).

A six-level gradation of physical activity was calculated arbitrarily from the reported frequency and intensity of each of these forms of activity. The relative risk of coronary heart disease over the 8 years was adjusted for age, body mass index, social class and smoking status. Setting the risk of inactive subjects at 1.00, values for patients placed in the other five categories were: occasional physical activity, 0.8; light activity, 0.8; moderate activity, 0.4; moderately vigorous activity, 0.4, and vigorous activity 0.8. Although there was considerable statistical overlap between groups, in contrast to the views of Morris, there was a suggestion that vigorous activity might give a poorer prognosis than moderate or moderately vigorous activity. However, when a similar analysis was made for the relative risk of stroke among men initially aged 45–59 years, the best prognosis was seen in those men who reported undertaking vigorous physical activity [140].

2.6.4.3 Seventh-Day Adventist Men

Linsted and his colleagues [141] followed a group of 9484 male Seventh-Day Adventist men for an average of 26 years. There were 4000 deaths over this period. A self-administered lifestyle questionnaire completed at entry to the study allowed the categorization of participants as inactive, moderately active, or highly active. The all-cause mortality rate for the three groups was calculated for each of five decades (Table 2.5). In late middle-age, the moderate and highly active groups had a substantial advantage, but as age advanced, there was a crossover, with the highly active men having a poorer prognosis after the age of 78 years, and the moderately

Table 2.5 All-cause mortality (deaths/1000 man-years) of Seventh-Day Adventist males, classified by age group and reported activity category (based on the data of Linsted et al. [141])

Age category (years)	Inactive	Moderately active	Very active
50–59	4.0	2.4	2.5
60–69	11.2	8.4	9.1
70–79	36.6	27.4	33.5
80–89	85.1	81.9	94.1
90–99	169.6	152.5	156.5

Table 2.6 Relationships between questionnaire estimates of weekly leisure energy expenditures in U.S. male railroad workers, coronary heart disease mortality and all-cause mortality, as seen over 17–20 year follow-up (based on the data of Slattery et al. [142])

Reported leisure energy expenditure (MJ/week)	Relative risk of CHD mortality	Relative risk of all-cause death
15.1	1.00	1.00
5.7	1.05	1.04
2.3	1.11	1.08
0.2	1.28	1.21

active faring worse than the inactive after 95 years of age. As in the study of Shaper and Wannamethee, there was little suggestion that the very active had a better prognosis than those who were moderately active in any of the age decades that were analyzed.

2.6.4.4 U.S. Railroad Workers

The U.S. railroad study [142] followed the population recruited by Henry Taylor, a sample of 3032 white male employees. Subjects completed the very detailed Minnesota Leisure-time activity questionnaire in order to determine each individual's participation in more than 50 activities; the reported frequency, duration and hours per week of involvement in each of these activities were noted, and an estimate of the person's weekly leisure activity energy expenditures was calculated from responses (Table 2.6). Over a 17–20 year follow-up, the data showed a small trend towards an increased risk of death both from coronary heart disease and from all-causes among those who were taking less leisure-time exercise than the most active group, after statistical adjustment of the data for age, cigarette smoking, blood pressure and serum cholesterol level (but surprisingly, not for differences of occupational activity); the adverse effect of physical inactivity was statistically significant for all-cause but not for coronary deaths.

2.6.4.5 Harvard Alumni

Paffenbarger and his associates [138] questioned 11,864 initially healthy male Harvard alumni on their exercise habits, noting the number of city blocks walked, the number of stairs climbed, and the intensity and duration of any sport involvement during a typical week. Arbitrary rates of energy expenditure were ascribed to each of these activities to provide an estimate of the individual's gross leisure energy expenditure. Over an 11- to 15-year follow up, there were 1413 deaths, 45 % of these being due to cardiovascular disease and 32 % to cancer. Setting the risk of cardiovascular disease in the least active group as 1.00, an age-adjusted benefit was seen from walking (<5 vs. >15 km/week, 0.67), stair-climbing (<20 vs. >55 flights/week, 0.75), sports (none vs. moderate sports play >4.5 METs, 0.63), and a large total energy expenditure (<2 to 8 vs. 8 to >14 MJ/week, 0.70). The data were interpreted as showing a need to spend more than 8 MJ/week to enhance cardiovascular prognosis, although in fact risk ratios did not differ greatly between participants with expenditures of 2–4 MJ/week (0.63) and 12–14 MJ/week (0.68).

A further 8-year follow-up of the same population was undertaken in 1985, examining health outcomes in relation to changes in moderate sport involvement and weekly energy expenditures >8 MJ. The baseline risk was set as failing to meet the 8 MJ/week standard in either 1962–1966 or in 1977. The risk tended to an insignificant increase if activity had diminished over the 8 years, but in those whose activity had risen, the cardiac risk had dropped to approximately the same level as seen in those who had remained active throughout the 8 years (for moderate sports, 0.71 vs. 0.69, and for weekly energy expenditures >8 MJ, 0.74 vs. 0.79).

2.6.4.6 Relative Risk Assessment

I-M Lee and associates [137] noted that whereas earlier analyses of Harvard alumni data had called for a weekly leisure energy expenditure of >8 MJ, the usual public health recommendation of 30 minutes of moderate physical activity (>3 METS) on most days generated a weekly energy expenditure of no more than 4 MJ. They highlighted the further problem that specifying an absolute energy expenditure took little account of the relative stress that such a requirement imposed upon a fit young adult relative to an unfit elderly individual. They thus investigated the usefulness of assessing the relative intensity of effort, even in people who were currently failing to meet minimum public health recommendations for weekly physical activity.

A sample of 7337 men with an initial age averaging 66 years used the Borg scale to report their perceived intensity of effort when exercising. Over a 7-year follow-up, the risks of coronary heart disease relative to men who perceived their efforts as weak were 0.86, 0.69 and 0.72 for those rating their effort as moderate, somewhat strong and strong respectively. Moreover, this statistically significant trend was shown even among individuals with total energy expenditures of less than 4 MJ/week, and among those never engaging in activities >3 METS.

2.6.4.7 Conclusions

The questionnaire study of leisure activities provides strong support for the concept that regular exercise protects against both coronary vascular disease and all-cause deaths. However, disagreement remains concerning the optimal intensity and volume of effort. While some authors argue that activity must be vigorous to improve cardiac health, other studies suggest that particularly in older people moderate activity may be preferable to vigorous effort. Likewise, although some studies have argued the need for a weekly leisure energy expenditure as large as 8 MJ, others have found benefit from much smaller amounts of vigorous activity, particularly in the elderly.

2.7 Aerobic Fitness Assessments

Given the substantial uncertainties and errors inherent in questionnaire assessments of habitual physical activity, Steve Blair (Fig. 2.10) and his associates at the Aerobics Fitness Center in Dallas [143] suggested that it might be better to classify the activity behaviour of subjects in terms of an objectively measurable outcome, such as a high level of maximal oxygen intake. Certainly, physiological data have greater precision than questionnaire reports, although a part of a high maximal oxygen intake may reflect body build and genetic endowment rather than participation in vigorous physical activity. Moreover, the type of fitness assessment made in many laboratories (including the Cooper Aerobics Center) has been the endurance time during a progressive treadmill test, and this value is strongly influenced not only by habitual physical activity, but also by obesity.

Fig. 2.10 Steve Blair for many years directed epidemiological research for the Cooper Aerobics Center in Dallas Texas. He conducted many noteworthy studies of relationships between the fitness of clients and their subsequent health

2.7.1 Review Evidence

A review of 67 articles published between 1990 and 2000 showed consistent evidence of greater longevity and a reduced risk of coronary heart disease, cardiovascular disease, stroke and colon cancer in the more active members of a subject-sample, whether judged from questionnaire reports or measurements of aerobic fitness [143]. Commonly, much of the benefit appeared to occur at low levels of physical activity. It was not entirely clear from this review whether questionnaire assessments of physical activity or fitness assessments provided the better indication of prognosis. Nevertheless, gradients of health benefit were generally steeper for fitness than for questionnaire data, and if habitual activity was included in a multivariate analysis of the treadmill data, there appeared to be a residual effect of aerobic fitness.

2.7.2 Cooper Aerobics Center Data

Blair and his colleagues made treadmill assessments of aerobic fitness levels in 10,244 men and 3120 women, subsequently following them for an average of 8 years. The age-adjusted relative risk of death over this period was expressed relative to the experience of the group in the lowest quintile of fitness. For men, the values for the four higher quintiles were 0.40, 0.42, 0.34 and 0.29, respectively, and for the women, the corresponding figures were 0.52, 0.31, 0.15 and 0.22 [103].

A further analysis of 9777 men from this sample looked at the impact of a change in fitness level over an average interval of 4.9 years in terms of health experience in the following 5.1 years [144]. The highest age-adjusted death rate was seen in those who were unfit at both examinations (12.2/1000 man-years), and the lowest rate was found in men who were fit at both examinations (4.0/1000 man-years). The men whose fitness improved between the two evaluations showed a 44 % decrease in their death rate, to 6.8/1000 man-years; the risk decreased by some 7.9 % for each minute increase in their treadmill endurance time.

2.7.3 Canada Fitness Survey Data

In addition to asking subjects to complete a detailed physical activity questionnaire which yielded rather questionable results, participants in the original Canada Fitness Survey undertook a simple step test in their own homes, under the supervision of a health professional. A 7-year follow-up of 2174 male and female participants distinguished individuals who reached recommended, minimum acceptable and unacceptable age and sex-linked standards of performance on the step test [145]. In terms of all-cause deaths, the crude risk-ratios for the two groups with less than recommended fitness levels were 1.3 and 3.0, and after adjusting data for age, sex, body mass index and smoking status, the corresponding ratios were 1.6 and 2.7.

Subjects were also classed into four categories in terms of their habitual physical activity (very active, active, moderately active and inactive), as reported in the questionnaires, but both crude and adjusted risk ratios for the three lower categories of physical activity were too variable to discern any trends.

2.7.4 Conclusions

Classification of subjects by fitness level rather than reported physical activity gives a steeper gradient of subsequent health experience, suggesting that fitness data have greater accuracy than questionnaire responses. This is particularly evident in the findings of the Canadian Fitness Survey, where a simple step test showed a clear gradient of subsequent mortality, but this gradient was not seen in analysis of responses to a lengthy questionnaire.

2.8 Natural Experiments

In a few instances, there is good evidence that secular change has altered the energy expenditures of a community (generally in a downward direction), thus allowing comparisons of health experience when activity was high with the current experience, when activity is much less frequent and less intensive. Striking instances of a secular reduction of habitual physical activity have occurred over the past several decades among indigenous populations such as the Inuit [146] and North American Indians [147], in association with epidemic increases in the prevalence of obesity and type 2 diabetes mellitus. However, the etiology of these epidemics is complex, as there has also been a shift from country foods such as fish and caribou to store products with a high carbohydrate content, and the diagnosis of illness has also been more complete with greater access to medical care.

2.9 The Objective Monitoring of Human Activity in Epidemiology

During the past decade, the development of inexpensive and relatively accurate objective monitors has challenged the accuracy of what seemed sophisticated questionnaire-based estimates of habitual physical activity. Questionnaires appear to have been under- or over-estimating energy expenditures by factors of two or even three [121, 122, 148, 149]. After brief comments on studies based upon pulse monitors and the Kofranyi-Michaelis respirometer, we will look at the potential information yield from the objective monitoring of body movement patterns, using odometers, pedometers and accelerometers.

2.9.1 Pulse Monitoring

Potential methods for the field monitoring of heart rate have included ECG telemetry or tape-recording, ear-lobe photo cells, and electrochemical integration of pulse signals.

The latest type of telemetric pulse-rate recorders [150, 151] can transmit an ECG signal from a chest band to a wrist-watch type recorder or a nearby laboratory; although useful in athletic training, the need to maintain effective chest electrode contact has limited use of this approach in epidemiology.

Ear-lobe photo cells [152] have also been used mainly in short-term industrial studies rather than in epidemiology; slippage of the earpiece was a strong argument against epidemiological use.

In contrast, Wolff's electrochemical integrator [153] was developed specifically for epidemiological studies, including the International Biological Programme and Morris's studies of bus drivers and conductors. The ECG was used to drive a chemical reaction, and the average heart rate for the day could be estimated in the laboratory by passing a current in the reverse direction. Evolution of this instrument introduced multiple electrochemical cells, so that heart rates could be counted in selected target ranges [154], but problems remained from poor electrode contacts and erroneous counts [155]; in the study of more than 5000 London Transport workers (above), successful heart rate recordings were reported on only 10 subjects. Other wrist-band devices that accumulated ECG signals [156, 157] suffered from similar problems.

Even if these technical difficulties could be overcome, the theoretical basis for use of heart rate monitoring to monitor the intensity of physical activity is dubious. Data interpretation rests upon the existence of a relatively linear relationship between heart rate and oxygen consumption from 50 to 100 % of an individual's maximal aerobic effort [158]. There are many limitations to exploitation of this relationship: the slope of the line varies with the age, sex, physical fitness and posture of the subject, and it differs radically between arm and leg work. Moreover, the slope is increased by static effort, anxiety, and exposure to a hot environment or high altitudes [159]. Finally, in the context of population studies of physical activity, most of modern daily activity demands less than 50 % of maximal aerobic effort, an intensity of exercise where the relationship is non-linear.

2.9.2 Kofranyi-Michaelis Respirometer

The Kofranyi-Michaelis respirometer measures a subject's respiratory minute volume by a mechanical gas meter, and small aliquots of expired gas are collected in a balloon for subsequent chemical analysis [160]. The device has proven useful in determining the average energy cost of specified types of physical activity, in publishing compendia that show the energy demands of various common activities [161], and in demonstrating that Inuit engaged in various types of traditional hunting developed high energy expenditures on the days when they were hunting [146]. However, only a limited number of observations are possible with such a respirometer, and the information must be combined with direct observation of the subjects, diary records or questionnaire responses to form a picture of total energy expenditures over a typical week.

2.9.3 Odometers

The odometer may have been invented by Archimedes of Syracuse (287–212 BCE), although its use to measure walking distances was first described by Vitruvius in Book X of *de Architectura*, around 27 BCE. The device allowed the accurate placement of milestones on Roman roads, ensuring that armies covered an appropriate distance on their daily marches.

More recently, car odometers have been used to measure walking distances on city streets, thus allowing cardiologists to prescribe physical activity for their patients [162]. For example, a patient might be advised to walk a measured distance of two level miles in 40 minutes at least five times a week. This would equate to a pace of 4.8 km/hour, equivalent to an oxygen consumption of about 1.25 L/minute, or to a net weekly increase in energy expenditure of about 4 MJ. If a person's main source of leisure activity was deliberate walking or active commuting, a similar measurement of times and distances could be exploited to determine his or her active energy expenditures.

2.9.4 Pedometers

2.9.4.1 Early History

Invention of the pedometer has been ascribed to Leonardo da Vinci (1452–1519). One beautiful early instrument in Southern Germany has been dated to 1590 CE (Fig. 2.11). da Vinci's underlying purpose in designing the pedometer was military—he suggested that it should be used to make accurate maps of contested territory [163].

Reintroduction of the pedometer has been traced to the Swiss watchmaker Abraham-Louis Perrelet (1729–1826). He invented a watch that rewound itself from the impulses generated by 15 minutes of brisk walking, and a logical extension of this device was an instrument that measured the number of steps taken, allowing the distance walked to be estimated from the average stride length. Thomas

Fig. 2.11 An early pedometer from Southern Germany (1590 CE). *Source*: http://en.wikipedia.org/wiki/Pedometer#History

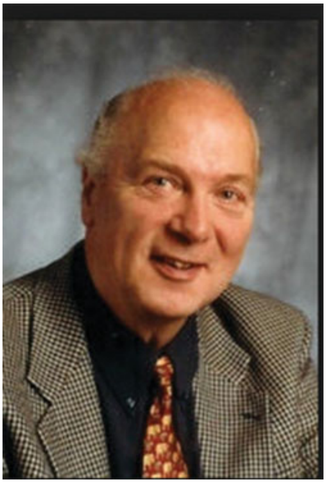

Fig. 2.12 Han Kemper evaluated the traditional type of pedometer, based on a pocket watch mechanism. He found that sometimes it counted two steps rather than one during jogging, and that it failed to record at all during slow walking

Jefferson (US President, 1801–1809) [164] brought the pedometer to North America, using it to monitor the length of his 2-hour daily walks.

Some mechanical instruments that were produced in the 1950s followed the concept of Perrelet, using the step impulse to activate a watch escapement, advancing the dial reading by a single unit. Designers have nevertheless experienced difficulty in choosing an appropriate loading of the escapement, so that only one "escape" is allowed per step. Han Kemper (Fig. 2.12) and Verschuur demonstrated that the greater force associated with jogging sometimes advanced the dial by two units rather than one, and steps might not be counted at all during very slow walking [165]. An accurate response to slow gaits and minor movements is plainly important in our sedentary and aging society.

Miscounts tended to be exacerbated if a belt-worn pedometer was tilted from the vertical, as when assessing an obese person [166]. There have thus been claims that a recently developed "Step-watch Activity Monitor" detects movements more accurately if it is worn on the ankle rather than a waist belt [167], and some investigators regard this as the current criterion instrument for assessing the activity of free-living individuals.

2.9.4.2 Pedometer/Accelerometers

There is a growing consensus that the errors inherent in the original watch-type pedometer are too large for accurate epidemiological work [168, 169]. The Seiko and Epson companies began developing a digital timepiece prior to the Tokyo Olympic Games (1964), and a liquid crystal display (LCD) was adapted to display accumulated step-impulses as the Yamasa Tokei (Keiki) company marketed the manpo-kei, or "10,000 steps meter" in 1965 CE. In modern electronic pedometers, a lever arm moves with each stride, making an electrical contact or compressing a piezo-electric crystal, and the electrical impulse thus generated is recorded as a step. The user can input an estimated stride length, so that the instrument displays a figure for the distance travelled; however, a person's stride length is quite variable, and it is probably better to report simply the number of steps taken.

The difficulty of setting an appropriate sensitivity to record one impulse per step has also not been entirely overcome. However, devices such as the Kenz Lifecorder incorporate a filter that limits the range of recorded accelerations, thus reducing false counts from incidental movements. Sophisticated types of equipment also allow electronic storage of information for up to 200 days, and some instruments can estimate the minute-by-minute energy expenditures from the force of impulses [170, 171].

2.9.4.3 Reliability and Validity

Most reports suggest that modern electronic pedometer/accelerometers are more reliable than the older mechanical watch-type pedometers. Reliability has been assessed by fitting two instruments to the left and right-hand sides of a person's waist belt [172, 173]; good reliability has been seen with devices such as Yamax, Kenz, Omron, New Lifestyle and Digiwalker recorders [173, 174].

When one instrument was shaken on a test rig, the correlation with the actual number of oscillations was 0.996; the threshold acceleration for this particular device was 2 m/s^2, with a coefficient of variation of 1.5 % [172]. Pedometer/accelerometers also respond accurately to a consistent movement pattern such as level walking. The 24-hour step count determined with one pedometer/accelerometer had an intramodal reliability of 0.998 and the error relative to 500 actual paces taken on a level 400 m track was only -0.2 ± 1.5 steps [175]. Of five instruments tested, the Yamax device gave the best estimates for both moderate and slow walking speeds; the average systematic error over a distance of 4.8 km being about 2 % [173]. At a walking speed of 4.8 km/hour, most of 10 commercially available pedometer/accelerometers were able to estimate treadmill walking distances to within ±10 % and gross energy expenditures to within ±30 % of the actual value [175, 176]. As with the older mechanical pedometers, activity tended to be under-estimated at speeds below 4.8 km/hour [177]; at 3.2 km/hour, readings from the Kenz Lifecorder and the Actigraph were, respectively, 92 ± 6 % and 64 ± 15 % of the true values [178]. Other validation assessments have compared step counts with impulses recorded by a heel-mounted resistance pad (an error of 460 ± 1080 steps/day [172]), with the directly measured oxygen consumption during treadmill walking at speeds of 3–9 km/hour (a Pearson correlation coefficient of 0.97 and a mean difference in estimated energy expenditures ranging from −3.2 to +0.1 kJ/minute [179]), and with 24-hour metabolic chamber data that included some treadmill walking and running (more substantial errors of 9 % for total energy expenditure and 8 % for physical activity energy expenditure [180]).

Although many of these trials suggest that modern pedometer/accelerometers have a reasonable validity, inaccuracies are introduced by slow walking speeds, a short stride length and abnormalities of gait [181]. Moreover, errors are increased on moving from the laboratory to free-living conditions [182], as subjects choose their own activity patterns rather than walking over a fixed course at a fixed pace. Both pedometers and accelerometers respond poorly to cycling, skating, load-carrying, household chores, and other non-standard activities [183]. Further, they take no account of energy expended when climbing hills or making movements against external resistance, and artifacts may arise when traveling over bumpy ground in a car [184].

In general, the current generation of pedometer/accelerometers functions reasonably well when assessing old people, whose main source of physical activity is moderate walking. However, attempts to garner information on younger adults remains much more questionable, and sometimes the conversion of step counts to energy expenditures using dubious and secret equations has under-estimated doubly-labelled water measurements by as much as 30–60 % [185].

2.9.4.4 Uni-axial Accelerometers

Uni-axial accelerometers measure the acceleration forces exerted upon small weights rather than summing a series of electrical contacts. But given the similarity of principle to the modern pedometer/accelerometer, it is not surprising that the performance of accelerometers is generally comparable [175]. Moreover, the interpretation of accelerometer data remains controversial. Different accelerometers integrate movements over intervals ranging from 1 to 15 seconds. Also, complex (and sometimes secret) equations are often used to interpret the data. Thus, the Actical instrument includes a three-part algorithm: (1) below an inactivity threshold, the individual is credited with an energy expenditure of 1 MET; (2) a walk/run regression equation is used when the inactivity threshold is exceeded but the coefficient of variation (CV) of impulses over four consecutive 15-second epochs is $<13\,\%$; and (3) a third, lifestyle regression equation is used when the inactivity threshold is exceeded and the CV of impulses is $>13\,\%$ [186].

2.9.4.5 Tri-axial Accelerometers

Tri-axial accelerometers measure forces in three planes, and thus can theoretically capture a wider range of body movements than uni-axial devices (Chap. 3). Park et al. [187] found differences of score between the two types of device even during walking, with uni-axial devices underestimating step counts and/or metabolic equivalents, particularly during slow walking (55 m/minute). Further, the accuracy of both types of accelerometer was affected by step frequency at any given walking speed.

One type of tri-axial accelerometer (the DynaPort Move Monitor) includes an algorithm to evaluate gaits and postures [188]. A quadratic discriminant analysis and a Hidden-Markov model are used to infer activity patterns in another tri-axial accelerometer (the MTI Actigraph) [189]. However, these algorithms were established on small samples, and their generality remains to be established. Moreover, the interpretation of tri-axial data under free-living conditions is as yet too complex for most epidemiological surveys.

2.9.4.6 Conclusions

To date, most pedometer and accelerometer studies have used relatively small samples, and have not been continued long enough to provide statistically significant information on clinical outcomes such as the onset of cardiovascular disease or sudden death, although this situation is now changing. As yet, it has been necessary to examine relationships between the recorded activity patterns and precursors of disease such as attained fitness levels [190], metabolic risk factors [191–193] or a deterioration of arterial elasticity [194]. Interestingly, the outcome of one study of arterial elasticity shows a greater correlation with measured habitual activity than with attained fitness. This is in contrast with the conclusion from questionnaire data, probably because the pedometer/accelerometer provides a measure of habitual physical activity which is at least as valid and accurate as the estimate of aerobic fitness [195].

2.10 New Directions in Objective Monitoring

Given problems in using objective monitors under free-living conditions, some investigators have looked at the benefits of altering the placement of accelerometers. Information has also been paired with data collected from global positioning systems (GPS), and multi-phasic devices have recorded audio signals, light intensity, barometric pressure, humidity and environmental temperatures. As yet, most of these devices are too costly and complicated for epidemiological use.

2.10.1 Accelerometer Placement

Accelerometers have sometimes been mounted on places other than the subject's waist belt. One commercial accelerometer known as the "footpod" has been attached to the foot, recording the impact associated with each stride. Another innovation has been the attachment of a small inertia-sensing device to the ear lobe. This monitor records information on both posture and linear acceleration that is introduced into an algorithm predicting energy expenditures. An initial report has claimed a good correlation with the directly measured oxygen consumption when performing 11 daily activities; the investigators also claimed success in identifying the nature of the activities that were being undertaken [196].

2.10.2 GPS Devices

Some recent studies have combined GPS and accelerometer data [197]. The GPS is helpful in detecting artifacts arising from travel in vehicles. However, the sampling rate is insufficient to detect very rapid movements. Moreover, the quality of the device is critical when recording data in urban areas with tall buildings [198], and the signal is lost when travelling on underground trains.

2.10.3 Multiphasic Devices

Multiphasic devices seek to enhance the interpretation of objective monitors when examining non-standard movements [199]. Corder et al. [200] claimed some improvement in the estimation of children's energy expenditures when they supplemented accelerometry with ECG data. Haskell et al. [159] combined 3-lead ECG data with information captured by uni-axial accelerometers mounted on the wrist and the thigh. When using this arrangement, the correlation with directly measured oxygen consumption across a range of activities (0.73) was not particularly impressive, and the absolute error in measurements of oxygen consumption remained a substantial 5.2 mL/(kg minute).

One recent multi-phasic device (the Multi-sensor Board) combines a tri-axial accelerometer with GPS, audio, light, barometric pressure, temperature and humidity recording [134]. Supposedly, this device can determine the proportion of activity taken out of doors, local versus distant travel, the vibrations resulting from car journeys, and the possible influence of weather conditions upon movement patterns.

The Sensewear arm band is another multi-phasic device. It incorporates information from two accelerometers with heat flux, skin temperature, and galvanic skin response data [201–204]. The manufacturers claim that this instrument can distinguish activities performed by the upper and lower limbs, and that it takes account of hill climbing, load carriage and non-ambulatory activity. However, one trial found a 24–56 % under-estimation of directly measured energy expenditures during skating, and another trial found significant under-estimation of energy expenditures during high-speed running (40 %) and cycling (25–50 %) [205]. Other studies of the Sensewear arm band have found 16–43 % over-estimates of energy expenditure in children [206] and large individual errors relative to indirect calorimetry in adults [207]. Much seems to depend on the algorithm that is used [208], and it remains a challenge to find formulae appropriate for the interpretation of multi-phasic data on all subjects and all circumstances.

2.11 Conclusions

Estimation of the intensity and total volume of weekly energy expenditures has become practicable for epidemiologists with the replacement of questionnaires by relatively low cost objective monitoring devices. Step counting has become progressively more sophisticated, with an ability to classify the intensity of impulses and accumulate activity data over long periods. Pedometer/accelerometers yield quite precise data for standard laboratory exercise, and in groups where steady, moderately paced walking is the main form of energy expenditure they can provide very useful epidemiological data. Nevertheless, such instruments remain vulnerable to external vibration and they fail to reflect adequately the energy expenditures incurred in hill climbing and isometric activity, as well as many of the everyday activities of children and younger adults. Multi-phasic devices hold promise as a means of assessing atypical activities, but appropriate and universally applicable algorithms have as yet to be developed. Moreover, the equipment is at present too costly and complex for epidemiological use.

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