

Review

Health benefits of cycling: a systematic review

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Accepted for publication 23 December 2010

The purpose of this study was to update the evidence on the health benefits of cycling. A systematic review of the literature resulted in 16 cycling-specific studies. Cross-sectional and longitudinal studies showed a clear positive relationship between cycling and cardiorespiratory fitness in youths. Prospective observational studies demonstrated a strong inverse relationship between commuter cycling and all-cause mortality, cancer mortality, and cancer morbidity among middle-aged to elderly subjects. Intervention studies among working-age adults indicated consistent improvements in cardiovascular fitness and some improvements in cardiovascular risk factors due to commuting cycling. Six studies showed a consistent positive dose–response gradient

between the amount of cycling and the health benefits. Systematic assessment of the quality of the studies showed most of them to be of moderate to high quality. According to standard criteria used primarily for the assessment of clinical studies, the strength of this evidence was strong for fitness benefits, moderate for benefits in cardiovascular risk factors, and inconclusive for all-cause mortality, coronary heart disease morbidity and mortality, cancer risk, and overweight and obesity. While more intervention research is needed to build a solid knowledge base of the health benefits of cycling, the existing evidence reinforces the current efforts to promote cycling as an important contributor for better population health.

Recent research on physical activity and health provides continuing, consistent, and increasingly specific evidence to support the importance of physical activity for public health. The review of the scientific evidence undertaken by the Physical Activity Guidelines Advisory Committee (2008) presents the most comprehensive summary of current knowledge. In children and adolescents, there is strong evidence for improved cardiorespiratory endurance and muscular fitness, favorable body composition, improved bone health, and improved cardiovascular and metabolic health biomarkers. In adults, there is strong evidence for: lower risk of early death, heart disease, stroke, type-2 diabetes, high blood pressure, adverse blood lipid profiles, metabolic syndrome, colon and breast cancers; prevention of weight gain; weight loss when combined with diet; improved cardiorespiratory and muscular fitness; prevention of falls; reduced depression; and better cognitive function in older adults.

Cycling is a form of physical activity that effectively taxes the cardiorespiratory and metabolic functions of the whole body in a wide range of intensities and thus lends itself to many potential health benefits. Theoretically, cycling can result in

most of the above-mentioned health benefits. It is therefore no surprise that cycling has been recognized as an important potential means to promote public health (e.g. Bassett et al., 2008; Bauman & Rissel, 2009).

Many recent studies on active commuting combine walking and cycling (e.g. Wagner et al., 2001; Hu et al., 2003; Hu et al., 2005; Nakanishi & Suzuki, 2005; Barengo et al., 2006; Wennberg et al., 2006; Abu-Omar & Rutten, 2008; Bassett et al., 2008; Lindström, 2008; Gordon-Larsen et al., 2009). These studies have shown that active commuting reduces the risk of cardiovascular events, type-2 diabetes, hypertension and adiposity, and improves fitness. Hamer and Chida (2008) reported a meta-analysis of studies on active commuting and cardiovascular risk. The analysis included eight studies and 15 separate risk ratios. The integrated overall risk ratio for cardiovascular outcomes was 0.89 [95% confidence interval (CI) 0.81–0.98], with a somewhat greater reduction among women (RR = 0.87, 95% CI 0.77–0.98) than among men (RR = 0.91, 95% CI 0.80–1.04). Because walking and cycling for transportation have been treated together in these studies, cycling-specific health outcomes cannot be extracted.

However, as commuting cycling is normally of higher physiological intensity than walking (Oja et al., 1991), it is likely that these kinds of health benefits can be expected to accrue from regular commuting cycling. Nevertheless, cycling-specific evidence is needed to demonstrate the definitive health-enhancing significance of cycling.

Three recent reviews provide some evidence on the cycling-specific health benefits. An Ogilvie et al. (2004) systematic review focused on intervention studies with the aim of changing walking and cycling behavior. The reviewers concluded that active commuting provides health and functional benefits in the short term, but there is no evidence to show clear effects at the population level. However, as only one study out of 22 provided cycling-specific health effects, this review provides only limited evidence regarding the health effects of cycling.

In his review on active commuting, Shephard (2008) found three prospective studies and one cross-sectional study that provided cycling-specific data. He concluded that these empirical data showed mixed results with respect to gender and age in that the health benefits may be more pronounced among women than among men, and among older men than among young men. As this was a descriptive review of selected studies without a systematic review process, the conclusions remain limited.

Andersen and Cooper (2010) reviewed three cohort studies and two cross-sectional studies and provided unpublished data from two cross-sectional studies in an effort to quantify the health benefits of cycling especially among children and youth. They concluded that in children, cycling to school is associated with a better fitness level and better cardiovascular risk factor profile compared with passive commuters and walkers.

Cycling-related injuries are often thought to supersede the preventive health benefits. As a response to a report showing increased cycling-related injuries in Australia, Bauman and Rissel (2009) argued that the cycling-induced benefits for chronic disease prevention, obesity reduction, and improved mental health are substantial and that the benefit-to-risk ratio is overwhelmingly positive. Recently, de Hartog et al. (2010) compared the health benefits against the risks due to traffic accidents and inhaled air pollution on mortality, when shifting from car to bicycle in urban commuting. They estimated that the gained life expectancy due to increased physical activity was many-fold larger (3–14 months gained) than the lost life expectancy due to increased air pollution (0.8–40 days lost) and increased traffic accidents (5–9 days lost).

As indicated by this brief overview, there is promising yet limited evidence on cycling-specific health benefits. Considering the significant public health

potential of cycling, especially regular commuting cycling, we systematically reviewed the current evidence on the health benefits of cycling in order to inform public health efforts to promote cycling for better population health.

Methods

Literature search

A systematic search and appraisal of published observational and intervention studies that have examined the relation between cycling and health was conducted. Published and peer-reviewed articles in English and German language journals were identified from electronic databases and from reference lists of articles available to the authors.

Search terms “Bicycling or Bicycle and Health or Mortality or Morbidity” were combined for each of the seven electronic databases, and the search resulted in a total of 3534 hits as follows: BioMed Central 171, Google Scholar1000, Pubmed Central 968, Scopus 973, SPORT Discus 175, TRIS online 124, Web of Science 123.

Inclusion criteria and selection process

Based on the article titles and abstracts, when available, the identified reports were initially evaluated for inclusion/exclusion using the following inclusion criteria:

- Observational or intervention studies published in peer-reviewed journals.
- Subjects: No age or gender limits.
- Quantitative measures of cycling for any purpose (stationary cycling excluded).
- Measures of mortality or morbidity (including disease risk factors) and/or measures of health and function (e.g. fitness).

Altogether 3456 articles were excluded, most of them because they focused on bicycle helmet use, cycling injuries and accidents, or on physical activity in general and not on cycling specifically, or they were laboratory studies performed on a bicycle ergometer (see Fig. 1). Seventy-eight potentially relevant papers were found and accessed. Two authors (P. O., S. T.) independently evaluated them against the inclusion criteria. In two cases, the judgments differed; the final classification was reached by consensus. This resulted in further exclusion of 70 studies and eight initially eligible studies. Ten other studies were identified from outside the search, and the resulting 18 papers were retrieved in full text for detailed evaluation. After exclusion of two more papers according to the unanimous judgment of the two authors, 16 studies remained for the review.

Data extraction

The studies included were divided evenly among four authors (B. G., A. B., P. K., and B. R.-N.) who extracted the data according to a common table format including information on study identification, purpose, sample and subjects, exposure measures, outcome measures, and results. Studies were divided into three groups (cross-sectional studies, prospective observational and case-control studies, and intervention studies) and harmonized in terms of the style and level of details by two authors (P. O., S. T.). This ensured that the metrics for exposure and outcome measures and for the results were equally specific across the studies.

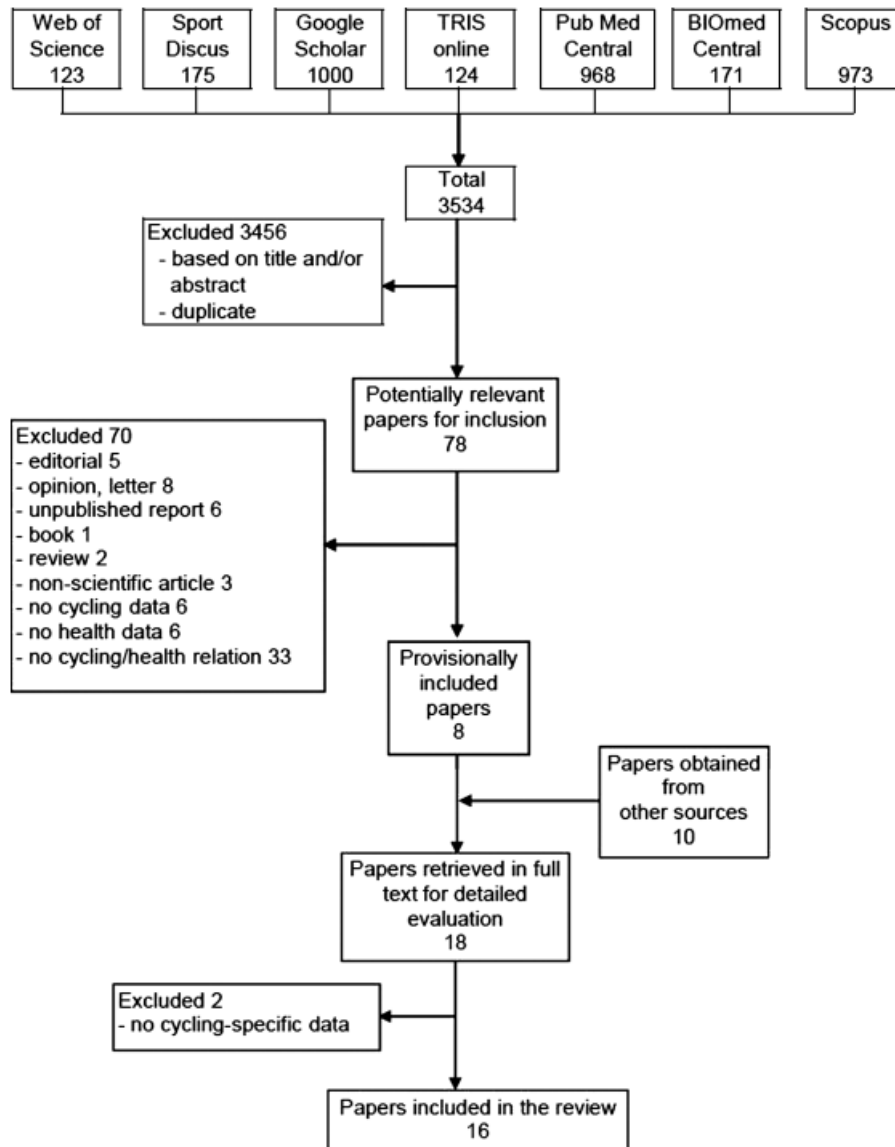


Fig. 1. Flow chart of the literature search.

Quality assessment and strength of the evidence

The quality of the included studies was assessed according to a standardized tool, the Quality Assessment Tool for Quantitative Studies (Effective Public Health Practice Project, 2008), which appraises the methodological rigor of the studies included. It consists of six components: (1) the extent to which study participants are representative of the target population, (2) study design, (3) control of confounding factors, (4) blinding of outcome assessors and participants, (5) reliability and validity of the data-collection tools, and (6) the number of withdrawals and drop-outs. The fourth criterion was considered not applicable for cross-sectional studies, and the first and the fourth criteria not applicable for intervention studies. The reason for considering blinding not applicable for intervention studies was that in such studies with physical activity intervention the assessors (i.e. researchers) and the participants are very likely to know the outcome of the randomization.

For all studies, each component was rated as “strong,” “moderate,” or “weak” according to standard criteria. The component ratings were used to obtain an overall rating: “strong” when there was no weak component rating, “moderate” when

there was one weak component rating, and “weak” when there were two or more weak component ratings. This quality assessment was performed independently by two authors (P. O, S. T), followed by a consensus judgment where there was disagreement between the initial assessments.

To assess the strength of the evidence, a rating system based on previously defined best evidence synthesis (De Bourdeaudhuij et al., 2010) was used. This system rates the strength of the evidence as follows.

Strong evidence: (1) at least two randomized-controlled trials (RCT) of high quality or (2) one RCT of high quality and at least two RCTs of medium quality. Effects must be consistent for both cases.

Moderate evidence: (1) one RCT of medium quality and at least one RCT of low quality or (2) one RCT of medium quality and at least one controlled trial (CT) of high quality or (3) at least three CTs of high quality or (4) one CT of high quality and at least three CTs of medium quality. Effect must be consistent for all cases.

Limited evidence: (1) more than one RCT of low quality or (2) one CT of medium quality and two CTs of low quality or

(3) two CTs of low quality and at least two before–after, cohort, or longitudinal studies. Effect must be consistent for all cases.

Inconclusive evidence: (1) only one study or (2) multiple before–after, cohort, or longitudinal studies or (3) contradictory effects.

No evidence: more than one study with consistent non-significant effect.

The assessment of the strength of the evidence was conducted independently by two authors (P. O., S. T.), followed by a consensus judgment where there was disagreement between the initial assessments.

Results

General findings

Cross-sectional studies

Four recent large-scale cross-sectional studies were identified for the review: two in children and youth and two in adults (Table 1).

Cooper et al. (2006) studied the relationship between travel mode to school and cardiovascular fitness (measured by maximal power output relative to body weight in a cycle ergometer test) among >900 Danish school children at the ages of 9 and 15 years. Compared with passive commuters, the fitness of the 9-year-old cyclists was 5% better among the girls and 7% better among the boys. The 15-year-old cycling girls had 11% higher fitness than the passive commuters, and the cycling boys had 7% higher fitness than the walkers. Taken together, the cyclists were nearly five times as likely as the walkers and the passive commuters to be in the top quartile of fitness. Besides the large representative sample, the strengths of this study include a maximal cycle ergometer test for the assessment of cardiovascular fitness and the use of accelerometry for the assessment of out-of-school commuting physical activity as well as carefully adjusted statistical models.

Another large study of Danish adolescents was reported by Andersen et al. (2009). They studied the relationship between the modes of transport to school and different aspects of fitness. The cyclists had up to 6% higher maximal aerobic power (estimated from maximal power output), up to 16% higher isometric back muscle endurance, 10% higher dynamic abdominal muscle endurance, and 6% better flexibility than the walkers and the passive travellers. These differences were independent of leisure-time physical activity. There were no differences between the cyclists and the passive commuters in upper and lower trunk muscle power and in dynamic arm muscle endurance. The strengths of this study include the large representative sample of subjects, standard set of multi-component fitness tests, and appropriate statistical treatment of the data.

An Australian cross-sectional study analyzed the relationship between the modes of transport to work

and overweight and obesity from the data of a health survey among adults in New South Wales (Wen & Rissel, 2008). A strong inverse relationship was found between cycling to work and the likelihood of overweight and obesity among men. No such relationship was found in women, which may have been due to few women cycling to work. The large representative sample size and the relatively high response rate (68%) lend strength to the results. On the other hand, the self-reported height and weight introduce a systematic error in the data, although this is likely to result in a conservative estimate of the level of the relationship between cycling and overweight and obesity.

Huy et al. (2008) reported a cross-sectional study on the relationship between cycling in everyday life and self-reported health and medical risk factors among 50–70-year-old men and women in Germany. Bicycle use was significantly related to subjective health among women when controlling for sporting activity. The number of self-reported medical risk factors was associated with bicycle use among men adjusting for sports activity. The self-report of bicycle use, health, and medical risk factors may limit the robustness of the results.

Prospective cohort and case–control studies

Eight prospective studies were found through the literature search (Table 2).

One of the most-cited prospective cycling studies reported pooled data from three epidemiological surveys from Copenhagen, Denmark (Andersen et al., 2000). This study addressed physical activity during leisure-time, work, sports, and cycling to work. The cohorts included 13 375 women and 17 265 men, with a mean follow-up time of 14.5 years. The analysis of bicycling to work consisted of 783 women and 6171 men. The relative risk of all-cause mortality of the cyclists was 0.72 (95% CI 0.57–0.91) compared with non-cyclists after adjustment for multiple confounders including leisure-time physical activity.

The study by Tanasescu et al. (2002) is one of the few prospective cohort studies where specific forms of physical activity have been analyzed in relation to health outcomes. A cohort of 44 452 US men was followed for 12 years for new cases of coronary heart disease (CHD). The data allowed relative risk analysis for walking, running, jogging, rowing, cycling, swimming, racquet sports (tennis and racquet ball), and weight training. When the analysis was adjusted for age, several CHD risk factors, and other types of physical activity, running, rowing, walking (pace), and weight training showed risk reduction, but jogging, swimming, racquet sports, and cycling did not. Cycling was classified into four classes according to

Table 1. Summary of cross-sectional studies on cycling and health

Author, year, country	Purpose	Sample and subjects	Exposure measures	Outcome measures	Results
Andersen, 2009, Denmark	Association between active transport to school and different aspects of fitness	Representative sample of school children in Denmark, 545 boys, 704 girls, 15–19 years old	Self-reported mode of transport to school: passive transport (motorcycle, car, bus, train), walking, cycling	Maximal aerobic power (estimated from maximal power output in progressive cycle ergometer test until volitional maximum), dynamic and isometric trunk muscle endurance, leg extensor strength, dominant arm strength, trunk flexibility, and agility	Cyclists had 4.6–5.9% higher aerobic power, 10–16% higher isometric muscle endurance, 10% higher dynamic abdominal muscle endurance, 6% better flexibility than walkers and passive travellers
Cooper, 2006, Denmark	Association between the transport mode to school and cardiovascular fitness	Proportional cluster sample of 25 schools in the region of Odense, 529 children 9.7 ± 0.5 years, 390 adolescents 15.5 ± 0.4 years, gender not reported	Self-reported mode of transport to school: travel mode (car or motorcycle, bus or train, bicycle, on foot) and duration (<5, 5–15, 15–30, 30 min to 1 h, > 1 h) Total physical activity by accelerometry	Maximal power output per kilogram body weight in progressive cycle ergometer test until volitional maximum	Children and adolescents who cycled to school were significantly more fit than those who walked or travelled by motorized transport (5.4–12.7% in children, 1.1–15.2% in adolescents) and they were nearly five times as likely [odds ratio (OR) = 4.8, 95% confidence interval (CI) 2.8–8.4, controlled for other physical activity] to be in the top quartile of fitness
Huy, 2008, Germany	Association between transport cycling and perceived general health, cardiovascular disease, orthopedic disease, and medical risk factors	Representative population sample of Baden-Württemberg, 982 men and 1020 women, 50–70 years old	Self-reported cycling for transport at least once a week over the past 12 months	Perceived general health on a scale 1–5, self-reported cardiovascular disease (arteriosclerosis, coronary artery disease, angina pectoris, myocardial infarction, cardiac dysrhythmia, aortic aneurysm, stroke/transient ischemic attacks, peripheral arterial occlusive disease), self-reported orthopedic disease (osteoarthritis of the hip or knee joints, arthritis of the joints or spine, osteoporosis, back pain), self-reported medical risk factors (high cholesterol, high blood pressure, diabetes, overweight)	Cycling for transport positively associated with general health among women (OR = 1.59, 95% CI = 1.19–2.12, controlled for age, education, and sporting activity) Cycling for transport negatively associated with medical risk factors overall (OR = 0.82, CI = 0.67–1.00, controlled for age, gender, education, and sporting activity) and among men (OR = 0.62, CI = 0.46–0.85, controlled for age, education, and sporting activity)
Wen, 2007, Australia	Associations between various modes of transport to work and overweight and obesity in men and women	A representative subset of New South Wales (Australia) health survey, 3810 men and 3022 women in the workforce	Self-reported modes of transport to work (driving, public transport, walking, bike) Body mass index derived from self-reported height and weight and classified into underweight (<18.5), normal weight (18.5–24.9), overweight (25–29.9), and obese (≥ 30)	Overweight and obese, obese	Men who cycled to work were significantly less likely to be overweight and obese (OR = 0.49, 95% CI 0.31–0.76, adjusted for level of physical activity, age, marital status, level of education, main language spoken at home), and obese (OR = 0.34, 95% CI 0.13–0.87, same adjustment as above) than those driving. No association among women

Table 2. Summary of prospective observational and case-control studies on cycling and health

Author, year, country	Purpose	Sample and subjects	Exposure measures	Outcome measures	Results
Andersen, 2000, Denmark	Relationship between levels of physical activity during work, leisure-time, cycling to work, and sports participation and all-cause mortality	Representative sample of Danish women ($n = 13\,375$) and men ($n = 17\,265$) 20–90 years of age of whom 783 women and 6171 men had information on cycling to work	Self-reported cycling to work, average cycling time 3 h/week	All-cause mortality during 15.1 (± 6.6) years of follow-up	RR of all-cause mortality 0.72 [95% confidence interval (CI) 0.57–0.91] of cyclists vs non-cyclists adjusted for age, sex, educational level, leisure-time physical activity, body mass index (BMI), blood lipid levels, smoking, blood pressure
Besson, 2008, United Kingdom	Association of overall and domain-specific physical activity on all-cause and cause-specific mortality	Epic-Norfolk population-based cohort ($n = 25\,639$) of whom physical activity data for 14 905 who attended second health check; 1 02 964 person-years of follow-up	Self-reported physical activity during the past year: in and around home, during work, active transport, recreational physical activity, total physical activity, all in MET h/week Cycling for transport in minute per week classified into: non-cyclists, up to 30 min/week, over 30 min/week	All-cause mortality, cardiovascular mortality, cancer mortality, other causes mortality adjusted for baseline age, gender, social class, alcohol consumption, smoking status, history of diabetes, history of cancer, history of cardiovascular disease (CVD) and stroke, and other physical activity	Hazard ratios for all-cause mortality: non-cyclists 1.0, up to 30 min/week 1.02 (0.77–1.35), over 30 min/week 1.01 (0.76–1.36), $P_{\text{trend}} 0.3908$ Hazard ratios for cardiovascular mortality: non-cyclists 1.0, up to 30 min 0.81 (0.47–1.40), over 30 min/week 0.72 (0.39–1.33), $P_{\text{trend}} 0.7960$
Cooper, 2008, Denmark	Association between change in transport to school from non-cycling to cycling and cardiorespiratory fitness	Representative sample of 310 girls and 279 boys in third grade (mean age 9.7 years) in Odense of whom 214 girls and 170 boys were re-examined after 6 years	Self-reported travel mode (car or motorcycle, bus or train, bicycle, on foot) and travel time (<5, 5–15, 15–30, 30 min to 1 h, > 1 h) to school:	Cardiorespiratory fitness as maximal power output per kilogram body weight during progressive bicycle ergometer test to volitional maximum	Among those who changed from non-cycling to cycling fitness improved by 6% in girls and by 21% in boys. Models including skinfolds, baseline CRF, and travel mode explained 60% of the variance of CRF in girls and 65% in boys.
Hoeveraar-Blom, 2010, the Netherlands	Association between leisure-time physical activity and fatal and nonfatal CVD incidence	Representative sample of 7451 men and 8991 women 20–65 years of age from three Dutch municipalities	Self-reported weekly gardening (yes/no), cycling (yes/no), sports (yes/no), and walking (less vs more than 3.5 h/week)	Incidence of fatal and nonfatal CVD during an average follow-up of 9.8 years	Inverse association with CVD for cycling hazard ratio (HR) 0.82, 95% CI 0.71–0.95] and sports (HR 0.74, 95% CI 0.64–0.87) controlled for age, sex, other physical activities, smoking, alcohol consumption, educational level, BMI, total and HDL cholesterol and systolic blood pressure, but not for walking or gardening OR of colon cancer 0.41, 95% CI 0.21–0.83 (adjusted for age, education, family income, marital status, total energy intake, intake of red meat, carotene, fiber, occupational physical activity, leisure-time physical activity, and walking) among men cycling > 120 min/day vs those cycling
Hou, 2004, China	Association between physical activity and BMI with colon cancer in a case-control design	30- to 74-year-old residents of 10 districts constituting urban Sanghai Cases: 931 (469 women, 462 men) newly diagnosed colon cancer cases during 22 months Controls: 1552 controls matched by age and sex	Self-reported (interview) commuting physical activity means (bus, walking, cycling), number of days per week, and minutes spent for round trip to and from work per day at different age periods over lifetime	Newly diagnosed colon cancer cases	

Table 2. (continued)

Author, year, country	Purpose	Sample and subjects	Exposure measures	Outcome measures	Results
Lusk, 2010, United States	Association of walking and bicycle riding and weight change	18 414 women 25–42 years of age in the US Nurses' Health Study II	Self-reported average weekly time spent walking and cycling	Estimated weight (self-report) change for 30 min/day increase in walking and cycling during 16 years of follow-up	<30 min/day, and 0.44, 95% CI 0.12–0.89 (same adjustment as with men plus number of pregnancies and menopausal status) among women Significant weight change – 1.81 kg (95% CI – 2.05 to – 1.56) for 30 min/day increase in brisk walking and – 1.59 kg (95% CI – 2.0 to – 1.08) for 30 min/day increase in bicycling but not for increase in slow walking (all adjusted for baseline age, weight and height, other physical activities, alcohol intake, sugar-sweetened beverage intake, energy-adjusted trans fat, energy-adjusted fiber intake, oral contraceptive use, smoking, parity and antidepressant intake)
Mathews, 2007, China	Association of exercise, walking and cycling for transportation, and non-exercise physical activity with mortality	40- to 70-year-old female residents of seven communities in urban Shanghai 75 221 women enrolled and 67 143 left for analysis	Self-reported (interview) time spent in cycling to and from work and cycling for other reasons (during the 5-year period before the interview) transformed to MET h/day	All-cause mortality during 5.7 years of follow-up.	HR of all-cause mortality 0.66 (95% CI 0.66–1.07) (adjusted for age, marital status, education, household income, smoking, alcohol drinking, number of pregnancies, oral contraceptive use, menopausal status, other types of physical activity, and several chronic medical conditions) of those cycling most vs non-cyclists
Tanasescu, 2002, United States	Association between the amount, type, and intensity of physical activity and risk of coronary heart disease (CHD)	40- to 75-year-old male US health professionals (dentists, optometrists, pharmacists, pediatricists, osteopaths, and veterinarians) 44 452 men enrolled	Self-reported (questionnaire) cumulative average hours per week (0, <0.5, 0.5–1, ≥ 1) spent in cycling during the past year assessed for 2-year follow-up intervals	Incident nonfatal myocardial infarction or fatal CHD during a 12-year follow-up.	Non-significant RR of CHD 0.91–0.98 (95% CI 0.75–1.10) with increasing amount of cycling/week vs no cycling, adjusted for age, weaker association with multivariate adjustment

the weekly volume in hours: 0, >0–<0.5, 0.5–1, >1. This narrow classification may explain the lack of association between cycling and CHD risk.

The association between commuting physical activity and risk of colon cancer among Chinese women and men was reported by Hou et al. (2004). The study used a case–control design, including over 900 cases and over 1500 controls. The colon cancer risk was reduced consistently with an increasing weekly time spent on cycling ($P_{\text{trend}} < 0.001$ for both men and women). The risk reduction was >50% for those who cycled >2 h/day [odds ratio (OR) = 0.41, 95% CI 0.21–0.83 for men, OR = 0.44, 95% CI 0.12–0.89 for women] compared with those who cycled <30 min/day. Recall of the past cycling behavior in this study is believed to be accurate, because cycling is prevalent in China and it is regularly performed as a daily activity. It was reported that the commuting cycling rates were relatively constant over two decades of time.

Matthews et al. (2007) studied the association of walking for transportation, cycling for transportation, exercise, and non-exercise physical activity with mortality [all causes, cardiovascular diseases (CVD), cancer, other causes] among Chinese women. Almost 70 000 40- to 70-year-old women were followed for an average of 5.7 years. Physical activity was classified based on MET h/day and the cycling classes for the analysis were 0, 0.1–3.4, and >3.4 MET h/day (the middle class equals to from a few minutes to slightly >1 h of moderate-intensity daily cycling). Compared with non-cyclists, the risk of dying from all causes was 0.79 for women in the middle class and 0.66 for women in the highest class (overall statistically significant decreasing trend, $P_{\text{trend}} = 0.018$) when the analyses were adjusted for multiple confounders including other types of physical activity. The corresponding risks for cancers were 0.82 and 0.55 ($P_{\text{trend}} = 0.048$), respectively. The risk of cardiovascular mortality and mortality from other causes was also lower among cycling than non-cycling women, but the differences were statistically non-significant. The obvious strength of this study is the very large cohort size. Also, the high prevalence of cycling in this region provides sufficient analytical power and robustness of the results.

Cooper et al. (2008) conducted a 6-year-long observational longitudinal study among Danish school children, who were 9.7 years old at the onset, and analyzed the association between the change of the transport mode to school and the cardiorespiratory fitness in 322 children. The longitudinal analysis showed that fitness improved significantly among those who changed from non-cycling to cycling during the follow-up (6% increase in girls and 21% increase in boys). Starting to cycle to school and maintaining cycling were significant predictors of

fitness among both girls and boys. Models including skinfolds, baseline fitness, and travel mode explained 60% of the overall variance in the follow-up fitness in girls and 63% in boys. A potential confounder might have been physical activity outside of school travel. However, it was shown that other physical activity (measured by an accelerometer) was not consistently higher in those cycling to school compared with other subjects.

Data from the Epic-Norfolk population-based cohort study in the United Kingdom were used to study the relationships between total and domain-specific physical activity and mortality (Besson et al., 2008). Of the original cohort of 25 639 men and women, who were recruited from participating general practice lists, 14 905 attended a second health check in 1998–2000 and reported domestic, occupational, commuting, and recreational physical activity during the past year. Cycling for transport in minutes per week was derived from questions on how people commute from home to work and their usual mode of transport. The cohort was followed for all-cause, cardiovascular, and cancer mortality until 2006. Adjusted hazard ratios for both all-cause and cardiovascular mortality were non-significant across the cycling categories of no cycling, up to 30 min/week, and over 30 min/week. This narrow range of weekly cycling may explain the non-significant result.

A Dutch study examined the association between cycling, sports, walking, and gardening with CVD morbidity in a 10-year prospective follow-up design (Hoevenaer-Blom et al., 2010). Almost all subjects were engaged in walking (97%), three-quarters in cycling, and about half in gardening or sports. Walking and gardening were not related to CVD incidence, but cycling and sport participation were inversely related. The adjusted hazard ratio (\pm 95% CI) was 0.82 (0.71–0.95) for cyclists compared with non-cyclists, and 0.74 (0.64–0.87) for sports participants compared with non-sports participants.

Data from the large US Nurses' Health Study II (Lusk et al., 2010) were used to explore the relationship of bicycling and walking with weight gain during a 16-year follow-up among pre-menopausal women. At baseline, about half of the subjects reported at least some cycling and 13% at least 10 min cycling per day. An increase of 30 min/day cycling compared with no activity during the follow-up resulted in a significant decrease in weight (–1.59 kg, 95% CI –2.09 to –1.08). However, only 1.2% of the women attained the increase of 30 min/day in cycling. The benefits of cycling were significantly stronger among overweight and obese women [body mass index (BMI) \geq 25] compared with lean women (BMI < 25). Less weight gain was seen among women who took up cycling during the follow-up (–0.74 kg, 95% CI –1.41 to –0.07). Conversely, women who

decreased their bicycling gained more weight (+2.13 kg, 95% CI +0.35 to +3.98).

Intervention studies

Four intervention studies were identified through the literature search (Table 3).

Oja et al. (1991) conducted a RCT on the effects of work commuting walking and cycling on cardiovascular fitness and selected disease risk factors. The subjects were healthy inactive men ($n = 38$) and women ($n = 30$) who were randomly allocated into an intervention and a control group. The intervention comprised regular walking or cycling to and from work for 10 weeks. Cycling took place on average 3.75 day/week for about 30 min one-way duration and at a measured intensity of 65% of $\dot{V}O_{2\max}$. Maximal aerobic power increased on average by 7% (net change) among the cyclists. Measures of physiological strain decreased during standard submaximal bicycle ergometer work representing 85% of $\dot{V}O_{2\max}$. The net change in blood lipids variables between the active and the control group showed an increase in HDL cholesterol ($P = 0.06$), and no significant changes in total cholesterol, triglycerides, and the total to HDL-cholesterol ratio. The observed differences were independent of gender. This study controlled for subject selection, treatment, attrition, and the main outcome detection, thus providing robust results. The duration of the study (2×10 weeks) was probably too short for the detection of clear changes in blood lipids.

A similar randomized-controlled study was conducted in the Netherlands focusing on cardiorespiratory performance measures (Hendriksen et al., 2000). Working-age women ($n = 35$) and men ($n = 87$) were randomized into intervention and control groups. The 6-month randomized intervention phase consisted of cycling to and from work amounting to three times per week for 8.5 km each way and at an intensity of approximately 60% of $\dot{V}O_{2\max}$. In the intervention group, maximal power output (W_{\max}) increased by 13% in both men and women and $\dot{V}O_{2\max}$ by 6% in men, while there was no change in W_{\max} and a 5–10% decrease in $\dot{V}O_{2\max}$ among the controls. This study showed results consistent with those of Oja et al. (1991). The improvement in $\dot{V}O_{2\max}$ was less than in the Oja and colleagues study, which may be explained by the lower cycling intensity.

A Belgian research group reported two papers from a non-randomized cycling intervention study lasting for 1 year (de Geus et al., 2008, 2009). The intervention group consisted of 65 middle-aged men and women, and the control group had 15 comparable subjects. The intervention consisted of cycling to and from work on average 2.5 day/week, and 14 km

or 45 min/day. Over the 1-year intervention, there was a non-significant 5% increase in maximal power output and a 1% decrease in relative $\dot{V}O_{2\max}$, while in the control group the respective changes were 2% and -7% . The net changes (differences between the group changes over time) were statistically significant for maximal power output and relative $\dot{V}O_{2\max}$, and they were more pronounced at 6 months, mainly due to the decreases in the control group. There were no net changes in anthropometric, blood, and quality-of-life variables. The relatively small non-significant effects of commuting cycling in this study compared with the studies of Oja et al. (1991) and Hendriksen et al. (2000) may be explained by the fact that the cycling dose was smaller in terms of the weekly frequency and the daily cycling time.

Dose–response of cycling and health outcomes

In order to understand the type and volume of cycling needed for health benefits, the shape of the relationship between the dose of cycling and the health outcomes needs to be described. Six reviewed studies provided information on the relationship between multiple levels of cycling exposure and the extent of the change in health outcomes.

The RCT by Hendriksen et al. (2000) provided a three-dimensional plot with decreasing initial fitness and single trip distance against the relative change of maximal work output (W_{\max}). The plot showed a consistent increase in $\%W_{\max}$ with decreasing the initial fitness and increasing the trip distance for men. High initial fitness ($W_{\max}/\text{kg} = 4.6$) with a short cycling distance (4 km one way) resulted in a zero change, and low initial fitness ($W_{\max}/\text{kg} = 2.2$) with a long cycling distance (28 km one way) resulted in almost a 30% improvement. For all participants, there was a diminishing return with increasing single trip distance; an increase in the distance from 3 to 6 km produced more gain in fitness than increasing the distance from 15 to 18 km.

The intervention study by de Geus et al. (2009) also looked at the dose–response between the amount of weekly cycling and the fitness changes. Consistent statistically significant correlations were found between the total weekly energy expenditure of cycling and the change in peak $\dot{V}O_{2\max}$ for both men ($r = 0.57$ for L/min, $r = 0.47$ for mL/kg/min) and for women ($r = 0.44$ for L/min, $r = 0.39$ for mL/kg/min). The relationship between the total weekly volume of cycling and the change in $\dot{V}O_{2\max}$ (L/min) explained 26% and 18% of the variance in fitness among men and women, respectively. The gain in $\dot{V}O_{2\max}$ became positive at approximately 1000 and 1500 kcal/week of energy expended for women and men, respectively.

The study on cycling and mortality among Chinese women (Matthews et al., 2007) measured the daily

Table 3. Summary of intervention studies on cycling and health

Author, year, country	Design	Purpose	Subjects	Intervention	Outcome measures	Results
De Geus, 2008, Belgium	Non-randomized intervention trial	Influence of cycling to work on cardiorespiratory fitness, coronary heart disease risk factors and health-related quality of life in untrained healthy adults	92 men and women 30–65 years old enrolled, divided into intervention group ($n = 74$) and control group ($n = 18$), 65 intervention subjects and 15 controls completed	Cycling to work at least 3 times/week for 1 year, one way distance 2–15 km	Body mass (BM) and body mass index (BMI) Maximal external power (W_{max}) and maximal aerobic power (VO_{2max}) in progressive bicycle ergometer test until volitional maximum Uric acid, TG, TC, LDL, VLDL, HDL, CRP Systolic and diastolic blood pressure, quality of life according to SF-36 Health Status Survey all at 0, 6, and 12 months	No changes in BMI, BMI W_{max} , VO_{2max} ; all: significant increase over time in the intervention group compared with the control group W_{max} , VO_{2max} men: no change VO_{2max} women: increase over time in the intervention group compared with the control group (due to decrease in control group) no net changes in blood variables, no net changes in quality of life variables
De Geus, 2009, Belgium	Non-randomized intervention trial	Effects of cycling to work on cardiorespiratory fitness and the dose-response thereof in untrained healthy adults	Same as de Geus (2008)	Same as de Geus (2008)	W_{max} and VO_{2max} as in de Geus (2008) Correlation between cycling dose (kcal/week, min/week) and cardiorespiratory response (W_{max} , VO_{2max})	Effects on cardiorespiratory performance same as in de Geus (2008) Statistically significant correlations between cycling dose kcal/week and VO_{2max} in the total group (0.42–0.36), in men (0.53–0.47) and in women (0.44–0.39), correlation for cycling dose minute per week statistically significant in total group (0.40–0.33) W_{max} change at 6 months: cycling group men 12.6%, women 12.8%; control group men –0.4%, women 1.3% VO_{2max} change at 6 months: cycling group men 6.1%, women –2.2%; control group men –5.4%, women –12.1% at 12 months both W_{max} and VO_{2max} levelled off in the cycling group, and increased in the control group to the same extent as in the cycling group during the first 6 months There was a clear inverse dose-response between initial fitness and increase in W_{max} and direct dose-response between single-trip distance and increase in W_{max} among men
Hendriksen, 2000, The Netherlands	Randomized-controlled trial (during the first 6 months)	Effects of commuter cycling on cardiorespiratory fitness in working age men and women	35 women 87 men 25–56 years old randomized into intervention ($n = 57$) and control group ($n = 58$)	Cycling to and from work with minimum one-way distance of 3 km at least 3 times/week for one year (intervention group) and for six months (control group)	Maximal power output (W_{max}) and maximal aerobic power (VO_{2max}) in progressive bicycle ergometer test until volitional maximum Measured at 0, 6, and 12 months	Absolute and relative VO_{2max} and maximum treadmill time increased statistically significantly (7%, 7%, 13%, respectively) VE and LA at 85% standard work decreased statistically significantly (10%, 21%, respectively)
Oja, 1991, Finland	Randomized-controlled trial	Effects of walking and cycling to and from work on maximal and submaximal cardiorespiratory fitness in healthy women and men	38 men and 30 women 20–65 old randomized into an intervention ($n = 35$) and a control group ($n = 33$), cycling intervention group ($n = 26$)	Cycling to work and back on average 3.75 day/week and 10 km one-way distance at intensity of 65% of VO_{2max} for 10 weeks	VO_{2max} and maximum time in progressive treadmill test until volitional maximum heart rate, minute ventilation (VE), respiratory quotient (RQ) and blood lactate (LA) at fixed 85 and 65% of maximum work load	

TG, triglyceride; TC, total cholesterol; LDL, low-density lipoprotein cholesterol; VLDL, very-low-density lipoprotein cholesterol; HDL, high-density lipoprotein; CRP, C-reactive protein.

amount of cycling in MET-hours and classified the subjects into three classes: 0 (reference), 0.1–3.4, and ≥ 3.5 MET-hours. The hazard ratio for all-cause mortality decreased from 1 to 0.79 (95% CI 0.61–1.01) to 0.66 (95% CI 0.40–1.07) ($P_{\text{trend}} = 0.018$), and for cancer from 1 to 0.82 (95% CI 0.59–1.14) to 0.55 (95% CI 0.27–1.11) ($P_{\text{trend}} 0.048$).

The Chinese study on cycling and colon cancer (Hou et al., 2004) measured daily cycling in minutes and classified it into four categories: <30 , 30–60, >60 –120, >120 min. The OR for colon cancer in men decreased from 1 to 0.81 (95% CI 0.78–1.21) to 0.52 (95% CI 0.42–0.89) to 0.41 (95% CI 0.21–0.83) ($P_{\text{trend}} < 0.001$). The respective values for women were from 1 to 0.76 (95% CI 0.82–1.71) to 0.54 (95% CI 0.34–0.91) to 0.44 (95% CI 0.12–0.89) ($P_{\text{trend}} \leq 0.001$).

The dose–response relationship between the amount of weekly cycling and sports participation and CVD incidence was studied by Hoevenaar-Blom et al. (2010). Cycling for up to 3.5 h/week was protective compared with non-cycling, but cycling for ≥ 3.5 h/week did not provide additional protection. Sports participation for up to 3.5 h/week resulted in a 23% reduction in the risk of CHD incidence and ≥ 3.5 h/week participation resulted in a further reduction to 34%. Participation in both cycling and sports reduced the risk still further to 36% compared with those who engaged in neither cycling nor sports. The adjusted hazard ratio decreased stepwise from 1.0 of those who were engaged in neither cycling nor sports to approximately 0.82 of

those who cycled but did no sports, to approximately 0.72 of those doing sports but no cycling, and to approximately 0.63 of those doing both cycling and sports.

In the Nurses' Health Study II (Lusk et al., 2010), there was an inverse stepwise decrease in weight change as a function of increased cycling time from 0 to ≤ 5 to ≥ 15 to >15 min/day. Conversely, weight gain increased with decreasing cycling time.

In the studies by Hendriksen et al. (2000) and by de Geus et al. (2008, 2009), the cycling interventions lasted for 1 year. In the former study, the original intervention group continued to cycle 6 more months after the randomized initial 6-month period, and the control group started to cycle. The fitness measures showed consistent increases during the first 6 months of cycling, followed by a levelling off during the consequent 6 months in both studies, suggesting a ceiling effect with this volume and intensity of commuting cycling.

Quality of the studies and strength of the evidence

The quality of the reviewed studies was variable. As can be seen in Table 4, two of the cross-sectional studies were rated as “moderate” and two as “weak.” The included prospective observational studies were of mixed quality: global rating “strong” for three studies, “moderate” for three studies, and “weak” for two studies. The intervention studies were of high quality: all were rated “strong.” Two of them were considered as RCTs (Oja et al., 1991;

Table 4. Quality assessment of the included studies according to the EPHP tool

Study	Component rating						Global rating*
	Representativeness	Design	Confounders	Blinding	Methods	Drop-outs	
<i>Cross-sectional studies</i>							
Andersen, 2009	Moderate	Weak	Strong	NA	Moderate	Strong	Moderate
Cooper, 2006	Moderate	Weak	Strong	NA	Moderate	Strong	Moderate
Huy, 2008	Moderate	Weak	Strong	NA	Weak	Weak	Weak
Wen, 2008	Moderate	Weak	Strong	NA	Weak	Moderate	Weak
<i>Prospective observational studies</i>							
Andersen, 2000	Weak	Moderate	Strong	Moderate	Moderate	Weak	Weak
Besson, 2008	Weak	Moderate	Strong	Moderate	Moderate	Strong	Moderate
Cooper, 2008	Moderate	Moderate	Strong	NA	Moderate	Weak	Moderate
Hoevenaar-Blom, 2010	Moderate	Moderate	Strong	Moderate	Strong	Strong	Strong
Hou, 2004	Strong	Moderate	Strong	Moderate	Moderate	Moderate	Strong
Lusk, 2010	Strong	Moderate	Strong	Weak	Moderate	Strong	Moderate
Matthews, 2007	Strong	Moderate	Strong	Moderate	Moderate	Strong	Strong
Tanasescu, 2002	Weak	Moderate	Strong	Weak	Moderate	Strong	Weak
<i>Intervention studies</i>							
de Geus, 2008	NA	Moderate	Strong	NA	Strong	Strong	Strong
de Geus, 2009	NA	Moderate	Strong	NA	Strong	Strong	Strong
Hendriksen, 2000	NA	Strong	Strong	NA	Strong	Strong	Strong
Oja, 1991	NA	Strong	Strong	NA	Strong	Strong	Strong

*Strong, no weak component rating; moderate, one weak component rating; weak, two or more weak component ratings.

NA, not applicable; EPHP, Effective Public Health Practice Project (see details in the text).

Hendriksen et al., 2000) and two (de Geus et al., 2008, 2009) as controlled clinical trials, according to the tool's criteria.

The chosen rating method for the assessment of the strength of the evidence (De Bourdeaudhuij et al., 2010) revealed:

- strong evidence for cardiorespiratory fitness benefits in adults (two high-quality RCTs and one high-quality controlled clinical trial);
- moderate evidence for benefits in cardiovascular risk factors in adults (one high-quality RCT and one weak-quality cross-sectional study);
- inconclusive evidence for reduction in all-cause mortality (one high-quality and one weak-quality prospective longitudinal study, and one moderate-quality prospective longitudinal study with no effect), in CHD morbidity or mortality (one high-quality prospective longitudinal study, and one moderate-quality and one weak-quality prospective longitudinal study with no effect), in cancer risk (one high-quality prospective longitudinal study), and in overweight and obesity (one moderate-quality prospective longitudinal study and one weak-quality cross-sectional study) in adults;
- inconclusive evidence for improvement in subjective health (one weak-quality cross-sectional study) and in quality of life (one CT with no effect) in adults;
- inconclusive evidence for cardiorespiratory fitness benefits in adolescents (one moderate-quality prospective longitudinal study and two moderate-quality cross-sectional studies).

Discussion

This systematic review of published scientific literature on the health effects of cycling identified 16 studies reporting cycling-specific results. Overall, all but two studies showed that cycling provided a health benefit. Cross-sectional and longitudinal studies showed a consistent and substantial positive relationship between cycling and cardiorespiratory fitness in children and adolescents. All but two prospective cohort studies demonstrated a consistent inverse relationship between commuter cycling and all-cause and CVD/CHD mortality, and cancer mortality and morbidity among middle-aged to elderly adults. All intervention studies indicated clear improvements in cardiovascular fitness, and one study showed improvements in cardiovascular risk factors due to regular commuting cycling. After the submission of the paper, the authors learned about a Norwegian non-randomized uncontrolled intervention study on health-related physiological effects of commuter cycling (Tjelta et al., 2010). They found a

16% increase in $\dot{V}O_{2max}$ and a 15% increase in HDL-cholesterol. These findings are consistent with the three intervention studies included in this review.

These studies suggest that there is a clear positive dose–response relationship between the amount of cycling and health outcomes: fitness improvement increases and the risk of all-cause mortality, CVD and colon cancer morbidity, and incidence of overweight and obesity decrease with increasing amount of daily cycling.

Commuter cycling of a few kilometers' single-trip distance substantially improves the cardiorespiratory performance of low-fitness adults. With increasing distance, the improvement can reach 30%. The improvement is less but still significant and progressive among medium- and high-fitness adults (Hendriksen et al., 2000). The thresholds for cardiorespiratory fitness improvements of 1000 kcal/week cycling for women and 1500 kcal/week for men, as suggested by de Geus et al. (2009), would translate to approximately 170 and 250 min/week, respectively, at moderate-intensity (6 METs) cycling.

The reduction in the risk of all-cause mortality becomes larger with increasing daily cycling; compared with non-cyclists, there is an approximate 20% risk reduction with less than an hour's daily moderate-intensity cycling and more than a 30% risk reduction with about 100 min of such daily cycling among women (Matthews et al., 2007). The cancer risk decreases similarly with increasing cycling. For cancer mortality, the risk reduction is about 20% with 1 h daily cycling and >40% with about 100 min of moderate-intensity daily cycling among women (Matthews et al., 2007). Also, the risk of incident colon cancer becomes smaller with increasing daily cycling. Moderate-intensity (~ 6 METs) cycling of <1 h/day reduces the risk by about 20%, by about 45% with 90 min of cycling, and even more with at least 2 h cycling among both men and women (Hou et al., 2004).

Cycling also protects against CVD risk in a dose–response manner. Cycling up to or >3.5 h/week reduces the CVD risk by about 20%, but >3.5 h/week of combined cycling and sport reduces the risk by almost 40% (Hoevenaer-Blom et al., 2010).

Systematic assessment of the quality of the studies showed most of them to be of moderate to high quality. In particular, all intervention studies were rated high in quality. The rating of the strength of this evidence revealed that, based on the standard rating system used primarily for the assessment of clinical studies, the evidence for cardiorespiratory fitness benefits in adults is strong, and moderate evidence shows benefits in cardiovascular risk factors. For all-cause mortality, CHD morbidity and mortality, cancer risk, and overweight and obesity the evidence for benefits is considered inconclusive.

This rating system yields high scores for evidence generated in clinical trials and is less useful for rating epidemiological study evidence. With only two RCTs available for the review (and they focused mainly on cardiorespiratory fitness as the outcome), the rating of the strength of the evidence for other health outcomes remains mostly inconclusive according to this rating method. However, the relatively large number of studies focusing on cycling-specific health outcomes, the largely high quality of the studies, the consistency of the findings, and the dose–response nature of the health effects suggest that with high probability regular cycling has significant health impact, and thus substantial potential to benefit public health. In comparison, the Physical Activity Guidelines Advisory Committee (2008) review on the health benefits of physical activity was based largely on observational epidemiological evidence, which was then used to define national physical activity recommendations.

Conclusions

Overall, this review and evaluation of studies on cycling and health revealed relatively large numbers and diverse types of cycling-specific studies. They were consistent in showing a positive relationship between cycling and health and functional benefits in young boys and girls and improvements in cardiorespiratory fitness and disease risk factors as well as significant risk reduction for all-cause and cancer mortality and for cardiovascular, cancer, and obesity morbidity in middle-aged and elderly men and women. The rigid clinical-type rating of this evidence showed it to be at best of strong to moderate strength and mostly inconclusive, although the bulk of the evidence comes from large prospective epidemiologi-

cal studies, which are usually used as sufficient indication for public health policy actions. While more robust research is needed to build a solid evidence base of the health benefits of cycling, the existing state of knowledge reinforces the current public health efforts to promote cycling as an important contributor to improving population health.

Perspectives

Cycling represents a potentially powerful way to meet the recommended levels of physical activity for many populations. It is important to base current and future interventions on up-to-date evidence of the health benefits specific to cycling. Until recently, the knowledge of the health benefits of cycling has been mostly based on studies of commuting physical activity. As cycling was typically addressed together with walking, it was not possible to tease out the cycling-specific health effects. This review identified several new studies focusing on cycling-specific health outcomes. These studies are mostly of good quality. The findings, which demonstrate a consistent dose–response for improved function and health, provide strong support for the promotion of cycling for public health.

Key words: physical activity, bicycling, commuter cycling, function, disease.

Acknowledgements

The work was partially supported by Fonds Gesundes Österreich.

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