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REVIEW

Objectively measured walkability and active transport and weight-related outcomes in adults: a systematic review

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Abstract

Objectives The aim of this study was to investigate which GIS-based measures of walkability (density, land-use mix, connectivity and walkability indexes) in urban and suburban neighbourhoods are used in research and which of them are consistently associated with walking and cycling for transport, overall active transportation and weight-related measures in adults.

Methods A systematic review of English publications using PubMed, Science Direct, Active Living Research Literature Database, the Transportation Research Information Service and reference lists was conducted. The search terms utilised were synonyms for GIS in combination with synonyms for the outcomes.

Results Thirty-four publications based on 19 different studies were eligible. Walkability measures such as gross population density, intersection density and walkability indexes most consistently correlated with measures of physical activity for transport. Results on weight-related measures were inconsistent.

Conclusions More research is needed to determine whether walkability is an appropriate measure for predicting weight-related measures and overall active transportation. As most of the consistent correlates, gross population density, intersection density and the walkability indexes have the potential to be used in planning and monitoring.

Keywords Walkability · Density · Land-use mix · Connectivity · Body weight · Physical activity for transport

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Introduction

Physical inactivity and obesity are important public health problems that are related to the increasing burden of non-communicable diseases (WHO 2006). One promising strategy for increasing physical activity and preventing overweight and obesity is the creation of healthy living environments (WHO 2006). Research findings have demonstrated that there is an association between the built environment in residential neighbourhoods and physical activity (Saelens et al. 2003b) and obesity (Papas et al. 2007).

Different disciplines, such as urban and transport planning, leisure and health studies, have contributed to a better theoretical understanding of the associations between the built environment and health (Sallis 2009). For example, urban and transport planners have developed theoretical concepts of community design, such as walkability (Sallis 2009). In the field of health research, there has been an increase in the use of the concept of walkability.

Leslie et al. (2007) defined walkability as “the extent to which characteristics of the built environment and land use may or may not be conducive to residents in the area walking for either leisure, exercise or recreation, to access services, or to travel to work”. With this definition, Leslie et al. (2007) continued the research traditions of Frumkin et al. (2004) and Frank et al. (2003). Walkability has two fundamental aspects: proximity to destinations and connectivity (Frank et al. 2003; Frumkin et al. 2004). Proximity is determined by the concepts of density and land-use mix (Frumkin et al. 2004; Leslie et al. 2007). Density measures the “quantity of people, households or jobs distributed over a unit of area” (Frumkin et al. 2004), while land-use mix can be seen as a complement to density and is “a measure of how many types—offices, housing, retail, entertainment, services, and so on—are located in a given area” (Frumkin et al. 2004). In mixed neighbourhoods, the distance to different utilitarian destinations will be short and convenient for walking (Saelens et al. 2003b). Connectivity describes the street linkage among destinations. It “measures the directness of the pathway between households, shops and places of employment and is based on the design of the street network” (Leslie et al. 2007).

Based on the concepts of density, land-use mix and connectivity described above, Frank et al. (2005) developed a walkability index by adding up the normalised scores of each walkability measure (Frank et al. 2005). This index was extended by adding the *ratio of total commercial building floor area to the total commercially used land area (FAR)* to measures of density, land-use mix and connectivity (Frank et al. 2006).

There are different ways to measure the built environment and walkability. Brownson et al. (2009) differentiated perceived measures derived from questionnaires, observational measures derived from audits, and objective measures derived from geographic information systems (GIS). Research using characteristics of walkability that are objectively measured by GIS has increased more recently, but a wide variety of different measures has been used. For this reason, Brownson et al. (2009) stated that the validity, reliability, comparability and usefulness for research and practice of GIS-based measures still needs to be examined. One approach to address this issue is to review the different GIS-based walkability measures and examine how strongly these measures are associated with health determinants and outcomes.

In order to improve the precision of theoretical models, research must be conducted to explore the correlation between specific environmental factors and specific health determinants and outcomes (Giles-Corti et al. 2005). Since the walkability concept was developed in the field of transportation planning, it has focused on environments that determine transport-related physical activity (Saelens et al. 2003b). For this reason, walkability must be examined in relation to transport-related walking, cycling and physical activity.

To date, most reviews have used a broad theoretical understanding of the built environment (Bauman and Bull 2007; Ewing and Cervero 2010; Saelens and Handy 2008; Saelens et al. 2003b) rather than focusing on one specific conceptual approach. Furthermore, most of these reviews have summarised the findings of studies using different methods of measuring the built environment and using walking or physical activity as outcome measures. A review that focuses on GIS-based walkability and looks at active transport as a health determinant and weight-related outcomes can contribute to the improvement of the specificity of environmental models and to the development of a minimal set of comparable and replicable measures. Therefore, the aim of our review was to investigate which GIS-based measures of walkability in urban and suburban neighbourhoods are used in research, and which of them are consistently associated with active transport and weight-related outcomes in an adult population.

Methods

The methods of the review were specified in advance and documented in a protocol (for access, contact first author). The protocol was approved by the ethics committee of the local medical university (No. 21-504 ex 08/09). The reporting of the review was guided by the PRISMA statement for reporting systematic reviews (Liberati et al. 2009).

We used the walkability definitions of Leslie et al. (2007), Frumkin et al. (2004), and Frank et al. (2003), and included the walkability index as developed by Frank et al. (2005, 2006). The exposure definition of this review did not explicitly include FAR. Nevertheless, publications using the walkability index with FAR were included. Furthermore, the publications included had to use GIS to measure walkability in the residential neighbourhood.

Publications were included if their outcome measures were walking for transport, cycling for transport or overall active transportation (combining walking and cycling for transport or active transportation such as non-motorised trips) or weight-related measures (body mass index as a continuous variable or as a categorical variable, i.e., overweight, obesity, overweight or obesity, waist circumference and waist-to-height ratio).

To be eligible, publications had to provide information on at least three out of five predefined quality criteria (i.e. response rate, representativeness, validity/reliability of outcome measure, sample size, description of data) for cross-sectional studies, and four out of six (i.e. description of study participants, similarity between groups, validity/reliability of outcome measure, amount of follow-up, sample size, similarity of group treatment) for longitudinal studies. The authors customised the quality criteria from a framework for appraising a survey and quality criteria for the critical appraisal of observational studies (Petticrew and Roberts 2008). Furthermore, publications were only included if the study had an available abstract, was accessible via scientific literature or the internet and was published in English. No publication date restrictions were imposed.

To ensure a homogenous and comparable group, the population was restricted to healthy, white adults, older than 19 years, living in suburban or urban neighbourhoods. Research suggests that different factors explain active transport and weight-related outcomes in population subgroups such as in different racial/ethnic groups or in less healthy groups (Frank et al. 2009a; Forsyth et al. 2009; Oakes et al. 2007; Sallis and Glanz 2009).

A MeSH and a text word search were conducted limited to humans, English language and all adults aged 19 years of age and older in PubMed as well as in Science Direct, Transportation Research Information Service and Active Living Research Database. The search used a combination of synonyms for walkability, geographic information systems and active transport and weight-related outcomes (for access to the search protocol contact first author). The search was conducted in August 2010. Both the reference lists of all of the included publications and the reference lists of recently published reviews (Brownson et al. 2009; Ewing and Cervero 2010) related to physical activity and travel were also scanned.

One author (GG) conducted the eligibility assessment, and a second author (DvD) performed an unblinded cross-check for eligibility of the full texts. Disagreements were resolved by consensus.

A data extraction sheet was developed, piloted and adapted (data extraction form available from first author). GG extracted the data from the included publications, and DvD did the cross-check. Disagreements were resolved by discussion between the first two authors.

The criteria used in the quality assessment tools were tailored for the review based on a pre-existing appraisal framework for surveys and quality criteria for observational studies (Petticrew and Roberts 2008). The criteria focused on assessing the selection of the sample, measurement and data issues (Petticrew and Roberts 2008). The criteria and the scoring items were cross checked with established quality assessment tools for quantitative studies (EPHPP 2009a, b; Effective Practice Institute 2011) GG rated all included texts, and DvD performed the cross-check (see Online Resource, Appendix 1).

The exposure measures were categorised into measures of density, land-use mix and street connectivity based on measures described by Forsyth et al. (2006, 2007).

The measures of density were *gross population density*, *employment density and housing unit density* (Forsyth et al. 2007). Land-use mix was classified into the *entropy index* and the *Herfindahl–Hirschman index* (Forsyth et al. 2006). The measures of street connectivity included *block size*, *intersection density*, *ratio of four or three-way intersections to all intersections* and the *number of (all kind of) intersections*. In addition, the *composite measures/walkability indexes* category was used. The indexes were constructed from measures of density, land-use mix and street connectivity only, or in combination with a FAR value.

The outcomes were classified into four categories: walking for transport, cycling for transport, overall active transportation and weight-related measures.

In the results Table 1, we distinguished between good and fair quality studies on one hand, and all included studies on the other hand. In order to narrow the discussion down to the best available evidence, our discussion in the

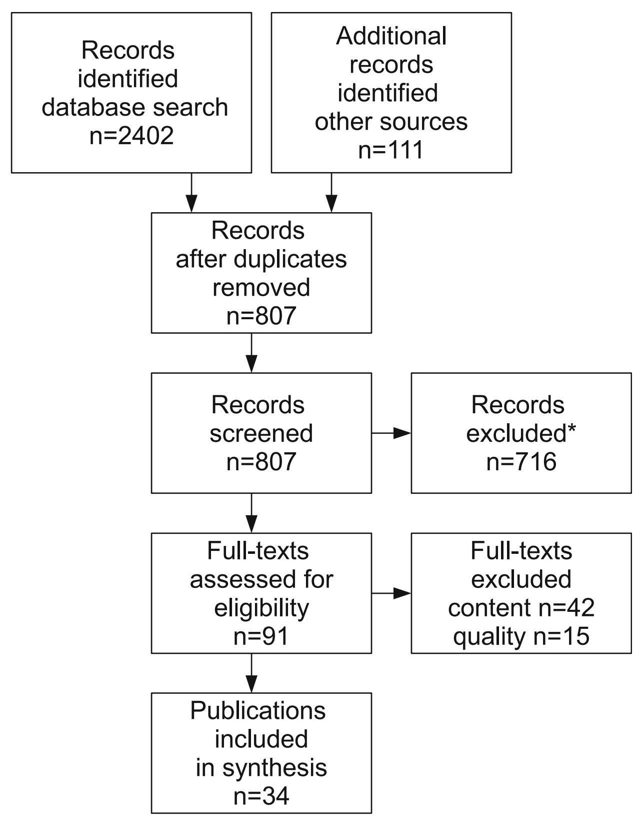

Fig. 1 Literature selection process. *Asterisk* indicates the main reasons for exclusion: exposure not measured by geographic information systems, exposure or outcome not identical with our definitions, children as the researched population, not accessible publications, no abstract available, publications not reporting results of primary studies or reporting results of testing validity and reliability of walkability instruments

Table 1 Number of studies reporting significant associations in relation to all included studies (reference numbers of publications in parentheses)

Exposure measures	Walking for transport		Cycling for transport	Overall active transportation		Weight related measures	
	Publications[a] of good ($n = 4$) and fair quality ($n = 9$)	All included publications[a] ($n = 16$)	All included publications[a] ($n = 3$) (good ($n = 1$) and fair quality ($n = 2$))	Publications[a] of good ($n = 0$) and fair quality ($n = 2$)	All included publications[a] ($n = 5$)	Publications[a] of good ($n = 4$) and fair quality ($n = 11$)	All included publications[a] ($n = 20$)
Density							
Gross population density	1 of 1 (10, 23) [for men, but not for women (10)]	1 of 1 (8, 10, 23) [for men, but not for women (10)]	–	–	2 of 2 (16, *17*)	2 of 2 (*4,* 28) [for men, but not for women (*4*)]	2 of 2 (*4,* 28) [for men, but not for women (*4*)]
Employment density	1 (*8*) of 1 (*8*, 9)	1 (*8*) of 1 (*8*, 9)	–	–	1 of 1 (16)	–	–
Housing unit density	2 of 2 (*8*, 14)	3 of 3 (*8*, 14, ***18***)	–	–	–	2 of 2 (***14***, 26) [for men and for women (***14***)]	2 of 2 (***14***, 26) [for men and for women (***14***)]
Others	1 of 1 (8)	1 of 1 (8)	–	–	–	–	–
Land use mix							
Entropy index	2 (11,19) of 4 (5, 9, 11, 19) [for men and for women (11)]	2 (11,19) of 4 (5, 9, 11, 19) [for men and for women (11)]	–	–	–	4 of 4 (*4*, 11, 19, *26*) [2 of 2 for men (*4*, 11), 1 (11) of 2 for women (*4*)]	4 of 4 (*2*, *4*, 11, 19, *26*) [2 of 2 for men (*4*, 11), 1 (11) of 2 for women (*4*, 11)]
Herfindahl–Hirschman index	0 of 1 (9)	0 of 1 (9)	–	–	–	–	0 of 1 (7)
Others	2 (5, 14) of 3 (5, 9, 14)	3 (3, 5, 14) of 4 (3, 5, 9, 14)	–	–	–	2 of 2 (*14*, 27, 28) [for men, but not for women (*14*)]	2 of 2 (*14*, 27, 28) [for men, but not for women (*14*)]
Connectivity							
Block size	0 of 2 (10, 23, 30) [not for men, and not for women (10)]	1 (3) of 4 (3, 10, 18, 23, 30) [not for men, and not for women (10)]	–	–	1 of 1 (16)	0 of 1 (30)	0 of 1 (30)
Intersection density	3 of 3 (9, 11, 14, 19) [for men and for women (11)]	3 of 3 (9, 11, 14, 19) [for men and for women (11)]	–	–	1 of 1 (16)	2 (*11, 14*, *26*) of 3 (*11, 14*, *26*, 27) [for men, but not for women (*11, 14*)]	3 (*11, 14*, *21, 26*) of 4 (*11, 14*, *21, 26*, 27) [for men, but not for women (*11, 14*)]
Ratio of four- or three-way intersections to all intersections	1 of 1 (**9**)	2 of 2 (3, **9**)	–	–	–	–	–
Number of intersections	–	–	–	–	1 of 1 (6)	1 of 1 (***4***, *31*, **34**) [1 of 1 for men (***4***, 31), 1 (*31*) of 1 for women (4, *31*)]	1 of 1 (***4***, *31*, **34**) [1 of 1 for men (***4***, *31*), 1 (*31*) of 1 for women (4, *31*)]
Others	0 of 1 (30)	0 of 1 (30)	–	0 of 1 (22)	0 of 1 (22)	1 of 1 (30)	2 of 2 (*7*, 30)

Table 1 continued

Exposure measures	Walking for transport		Cycling for transport	Overall active transportation		Weight related measures	
	Publications[a] of good ($n = 4$) and fair quality ($n = 9$)	All included publications[a] ($n = 16$)	All included publications[a] ($n = 3$) (good ($n = 1$) and fair quality ($n = 2$))	Publications[a] of good ($n = 0$) and fair quality ($n = 2$)	All included publications[a] ($n = 5$)	Publications[a] of good ($n = 4$) and fair quality ($n = 11$)	All included publications[a] ($n = 20$)
Composite measures/walkability indexes							
Housing unit density, entropy index, intersection density	1 of 1 (32, 33)	1 of 1 (32, 33)	1 of 1 (32, 33)	–	–	1 (*26*) of 2 (*26*, 33)	1 (*26*) of 2 (*26*, 33)
Housing unit density, entropy index, intersection density, FAR	2 of 2 (*24*, 29)	3 of 3 (13, *24*, 29)	1 of 1 (25)	1 of 1 (12)	1 of 1 (12)	2 of 2 (12, *15*, *29*) [for men, but not for women (15)]	2 of 2 (12, 13, *15*, *29*) [for men, but not for women (15)]
Others	–	–		–	–	0 of 1 (20)	0 of 2 (1, 20) [not for men, and not for women (1)]

Italic mixed results, **bold** including associations in unexpected direction, *FAR* ratio of total commercial building floor area to the total commercially used land area

[a] The publication corresponding to the reference number can be found in the Online Resource. Since some publications reported data from the same study, there can be more publications than observations

results section focuses on the findings of good and fair quality studies. In the results table, information from the same study that was reported in more than one publication was treated as one observation. Furthermore, the results were differentiated by sex in the results table and by age in the accompanying text.

Results

Figure 1 details the publication selection process. Twenty-five of the excluded full texts did not fulfill the inclusion criteria for the definition of exposure. Thirteen publications were excluded because their outcome measures differed from the definitions used in the review. Four publications were excluded because the focus was on Hispanics and/or black populations ($n = 2$), or because the geographical scale was the community route or a city ($n = 2$).

Fifteen publications were excluded for quality reasons. None of these 15 publications reported on the response, the representativeness and the validity/reliability of the outcome measure.

Appendix 2 (see Online Resource) contains an overview of the publication characteristics. Thirty-three publications had a cross-sectional design (Berke et al. 2007; Bodea et al. 2008; Boer et al. 2007; Brown et al. 2009; Cerin et al. 2007; Chatman 2009; Coombes et al. 2010; Forsyth et al. 2007, 2008, 2009; Frank et al. 2004, 2006, 2007, 2008, 2009a; Huang et al. 2009; Kitamura et al. 1997; Lee and Moudon 2006; Li et al. 2008; Lopez 2007; McGinn et al. 2007; Oakes et al. 2007; Owen et al. 2007, 2010; Pouliou and Elliott 2010; Rundle et al. 2007, 2009; Sallis et al. 2009; Scott et al. 2009; Smith et al. 2008; Van Dyck et al. 2010a, b; Zick et al. 2009), and one had a prospective design (Li et al. 2009). No study with an experimental design was found.

Nineteen different projects formed the data base for the 34 publications included.

As exposure measures, 11 publications used density, 12 used land-use mix, 19 used street connectivity and 11 used a walkability index. Most of the publications included (20 out of 34) used weight-related measures as an outcome. In two of the publications included, the authors investigated the relationship between walkability and waist-to-height ratio (Van Dyck et al. 2010a) or waist circumference (Li et al. 2009). All of the other papers reported BMI as a continous or categorical variable.

In 16 of the publications included, the authors explored the relationship between walkability and walking for transport. Fewer publications reported on the relationship between walkability and overall active transportation ($n = 5$) or cycling for transport ($n = 3$).

Half of the publications ($n = 17$) used a buffer as the geographical scale to determine neighbourhood. Most of the articles reported results from the US ($n = 27$).

Based on the quality assessment tool (EPHPP 2009a, b; Petticrew and Roberts 2008), eight publications were rated to be good quality, 16 fair quality, and 10 poor quality (see Online Resource, Appendix 1). In almost all publications (31 of 34), analyses were conducted including covariates such as age, sex or some measure of socio-economic status.

Results of good and fair-quality publications

Table 1 shows the number of studies reporting significant associations in relation to all included studies differentiated by walkability and outcome measures.

Walking for transport

Five out of six publications on density and walking were of good or fair quality and reported data from two study projects. Based on data from the Twin City Walking Study, Forsyth et al. (2008, 2009) and Oakes et al. (2007) demonstrated a positive association between *gross population density* and walking. Forsyth et al. (2009) also conducted a subgroup analysis by race and sex. For all respondents and for only white respondents, both research teams reported a greater odds ratio of walking of 1.9 in high-density areas compared to low-density areas. Based on data from the SMARTRAQ study, Frank et al. (2008) reported that *housing unit density* was the strongest predictor of walking for transport. In the Twin City Walking Study, Forsyth et al. (2008) found statistical significant but mainly minor correlations between *housing unit density* and walking for transport at different geographical scales. However, these correlations were not adjusted for potential confounders.

Five (out of six) publications on land-use mix and walking were of good or fair quality and reported results from five study projects. In four studies, the *entropy index* was used to measure land-use mix. Two of these studies showed a positive association between the *entropy index* and walking for transport. Li et al. (2008) used data from the Portland Neighborhood Environment and Health Study to show that a one-unit increase in the *entropy index* was associated with 5.8 times more walking for transport and 1.5 times more walking for errands in an elderly population. Frank et al. (2004) found a similar pattern in the data from the SMARTRAQ study, where they found a significant positive association in men and women. However, analysis from the Twin City Walking Study (Forsyth et al. 2008) and from the PLACE study (Cerin et al. 2007) found no significant correlations between the *entropy index* and walking for transport.

Seven out of nine publications, based on data from four study projects, used connectivity and were rated to be of good or fair quality. Analysing data from three different studies, four papers demonstrated a positive association between *intersection density* and walking. In the Portland Neighborhood Environment and Health Study, Li et al. (2008) observed that a one-unit increase in *intersection density* was associated with an increase in walking for transport and for errands by 20 and 11 %, respectively, in an elderly population (Li et al. 2008). Evidence from the Twin City Walking (Forsyth et al. 2008) and from the SMARTRAQ study (Frank et al. 2004, 2008) supported these results.

Four fair-quality publications representing data from three study projects found a correlation between a composite measure of walkability and walking. In BEPAS, researchers found significant positive associations between the *walkability index* (based on *housing unit density*, *entropy index* and *intersection density*) and the weekly minutes of walking for transport (Van Dyck et al. 2010a, b). Van Dyck et al. (2010a, b) reported that residents of highly walkable neighbourhoods walked 80 min per week (which is on average 210 %) more than residents of low-walkable neighbourhoods.

Two studies operationalised walkability as an index of *housing unit density*, *the entropy index*, *intersection density* and *FAR*. In NQLS, Sallis et al. (2009) observed that respondents in high-walkable areas walked 31 min per week more than respondents in low-walkable areas (Sallis et al. 2009). In PLACE, according to Owen et al. (2007), 4.2 % of the variance in the weekly frequency of walking was explained by the *walkability index*. However, they found no association in PLACE between the sum of weekly minutes of walking and walkability (Owen et al. 2007).

Cycling for transport

Two studies that dealt with cycling for transport found positive associations between different composite measures and cycling for transport. From BEPAS, Van Dyck et al. (2010a, b) reported a positive association between cycling and the *walkability index* based on *housing unit density*, *the entropy index* and *intersection density*. In PLACE, Owen et al. (2010) used the same *walkability index* extended with *FAR*. They observed that residents of high-walkable areas were 1.8 times more likely to bike for transport than residents in low-walkable areas.

Overall active transportation

In five publications, the researchers examined the association between walkability and overall active transportation. Two of the five were rated to be of fair quality and reported on data from two study projects. In NQLS, Frank et al. (2006) found a correlation between an increase in the *walkability index* and an increase in minutes of walking (Frank et al. 2006).

Weight-related outcomes

Four studies were included that examined the association between density and weight-related measures. The two studies on *gross population density* and weight-related outcomes were of good or fair quality and found significant negative associations. However, Brown et al. (2009) only observed a negative association with obesity in men. The associations with *gross population density* and overweight or BMI in women were not statistically significant. Rundle et al. (2009) found a reduction in obesity and overweight prevalence ratio between residents in the highest and the lowest *gross population density* areas. Two studies on *housing unit density* were of good or fair quality. Pouliou and Elliott (2010) observed a decrease in BMI with each unit increase in *housing unit density* in Toronto and Vancouver. In SMARTRAQ, inconsistent evidence was found (Frank et al. 2008). Frank et al. (2008) found a negative association between *housing unit density* and overweight in men, but not in women. *Housing unit density* was not associated with obesity in men and was even positively associated with obesity in women.

Seven of the nine publications that used land-use mix as a walkability measure were rated to be of good or fair quality and reported on data from five different study projects. In four good or fair quality studies, the *entropy index* was used to investigate the association with weight-related outcomes. In SMARTRAQ and in the Portland Neighborhood Environment and Health Study, significant negative associations were found (Frank et al. 2004; Li et al. 2008). Frank et al. (2004) reported a 12.2 % reduction in the odds of being obese, while Li et al. (2008) reported a 25 % reduction in the overweight or obesity prevalence associated with a one-unit increase in the *entropy index*. Mixed results were reported based on data from the Canadian Community Health Survey (Pouliou and Elliott 2010) and from the Salt Lake County drivers register (Brown et al. 2009).

Eight out of 10 publications that used connectivity were of good or fair quality and represented data from five study projects. In four different study projects, significant associations were found. However, from three of these four studies associations in an unexpected direction or mixed results were reported. From the three studies investigating the association between *intersection density* and weight-related measures, Rundle et al. (2007) found no associations; while Pouliou and Elliott (2010) reported negative associations in Vancouver, but not in Toronto. Data from the SMARTRAQ study showed only a negative association of *intersection density* with BMI or obesity in men (Frank et al. 2004, 2008). Three publications used *number of intersections* as a walkability measure at different geographical scales based on weight-related data from the Salt Lake County drivers register. (Brown et al. 2009; Smith et al. 2008; Zick et al. 2009) They reported mixed results and some associations in the unexpected direction.

Six out of the eight publications that used a composite measure of walkability were of good or fair quality and reported results from five study projects. In two studies, researchers calculated a *walkability index* based on *housing unit density*, the *entropy index* and *intersection density*. Pouliou and Elliott (2010) reported a negative association with BMI in Vancouver, but not in Toronto. Van Dyck et al. (2010a) found no direct association with BMI and waist-to-height-ratio in BEPAS. In the NQLS and SMARTRAQ study, a *walkability index* based on *housing unit density*, the *entropy index* and *intersection density* and *FAR* was used. In the SMARTRAQ study, Frank et al. (2009a) found a significant negative association between walkability and BMI for men, but not for women (Frank et al. 2009a). In the NQLS, the results were also inconsistent. Sallis et al. (2009) observed that the odds of having a BMI $\geq$ 25 (i.e. being obese or overweight) were 1.4 times higher in low-walkable neighbourhoods than in high-walkable neighbourhoods. But they reported no significant association between the *walkability index* and obesity (BMI $\geq$ 30) and BMI. On the other hand, using the same database, Frank et al. (2006) reported a decrease in BMI by 0.11 with each unit increase in *walkability index*.

Discussion

Available evidence on walking for transport showed the most consistent results. In particular, walkability measures such as *gross population density*, *housing unit density*, *intersection density* and the *walkability indexes* were factors that consistently promoted walking. These results are supported by a meta-analysis from the transport field. (Ewing and Cervero 2010) The associations between density (Saelens and Handy 2008; Saelens et al. 2003a) and walkability (Bauman and Bull 2007) and walking for transport have also been supported by other reviews. But the evidence on connectivity as a correlate of walking for transport has been questioned (Saelens and Handy 2008). In our review, there was a mixed picture when considering all connectivity measures, but supporting evidence when looking specifically at *intersection density*. While we found inconsistent evidence on the *entropy index,* (Saelens and Handy (2008) and Saelens et al. (2003b) concluded that land-use mix showed a consistent positive association with walking for transport. Ewing and Cervero (2010) concluded in their meta-analysis that other measures of land-use mix (such as distance to store or jobs-housing balance) are stronger correlates of walking for transport than the *entropy index*.

The information on cycling for transport and overall active transportation was scarce. The main reason for the scarcity of studies that used cycling as an outcome measure is that most studies included were conducted in the US, where cycling is not common. The available evidence on cycling for transport, however, was of good and fair quality and supported *walkability indexes* as correlates of cycling. In addition, other reviews have concluded that walkability is related to cycling and active transportation (Saelens et al. 2003a; Sallis et al. 2004).

The articles included on overall active transportation were mainly of poor quality and identified the *walkability index* as the best promoting factor of overall active transportation, which is consistent with findings of other reviews (Sallis et al. 2004).

Most of the publications in our review used weight-related measures as an outcome, but the results were inconsistent and showed associations in the unexpected direction. However, *gross population density*, the *entropy index* and the *walkability index* as negative correlates of weight-related outcomes are supported by the review of Feng et al. (2009).

Despite the associations shown between walkability measures and physical activity for transport and weight-related outcomes, there is some concern related to self-selection into neighbourhoods. Some of the studies included assessed the impact of self-selection on the association between walkability measures and physical activity for transport and weight-related outcomes. In PLACE, self-selection was a significant moderator of the association between walkability and weekly minutes of walking for transport, but not between walkability and frequency of walking for transport (Owen et al. 2007). In NQLS and SMARTRAQ, the association between walkability measures and walking for transport (Frank et al. 2007) and weight-related measures (Frank et al. 2007; Sallis et al. 2009) remained significant even after adjusting for self-selection. This confirms the findings from the review of Cao et al. (2009), who reported that a significant influence of the built environment on travel remained, even after accounting for self-selection (Cao et al. 2009).

The socio-economic characteristics of the individual and of the neighbourhood are also potential confounding factors when looking at the association between walkability and active transport and weight-related outcomes (Saelens et al. 2003b). Most of the publications included in our review are controlled for socio-economic status on an individual level, and about one-third are also controlled for socio-economic characteristics on the neighbourhood level. In BEPAS (Van Dyck et al. 2010a) and PLACE (Owen et al. 2007), no interactions in relation to walking for transport on the neighbourhood level were reported. In NQLS (Sallis et al. 2009), a significant walkability and income interaction was found. After adjusting for the socio-economic characteristics of the area, the association between walkability and walking for transport remained for all groups, although the association was stronger for high-income neighbourhoods (Sallis et al. 2009). Furthermore, in NQLS other health-related outcomes, such as weight-related measures, social cohesion, or quality of life, were analysed. No interaction between walkability and income at the neighbourhood level was found for these outcomes (Sallis et al. 2009).

Overall, the evidence on walkability as a correlate of physical activity for transport and weight-related outcomes seems to be weak due to the following reasons. First, almost all of the publications included had a cross-sectional design. Second, most of the publications were rated to be of poor or fair quality. Third, we discovered a lack of prospective studies designed to explore causal links between walkability and the reviewed outcomes.

It is difficult to evaluate the strength of associations due to the broad range of measures used in the reviewed studies. It seems that a rather small proportion of variance in outcomes was explained by walkability. Nevertheless, the contribution to population health can be essential (Owen et al. 2004), as environmental changes have the potential to effect whole populations over a long period of time. The evidence of the association between walkability and walking for transport appears to be stronger than for the other reviewed outcomes.

Most of the studies were conducted in the US, and the applicability of the results to other countries has to be considered with caution. It is important to conduct similar studies in other countries and to attempt to validate the walkability measures across countries (Frank et al. 2009b). In particular, more European research needs to be undertaken to identify the associations between walkability and cycling. A common set of environmental measures should be used to enable replication in various populations and to facilitate pooled analysis (Sallis and Glanz 2009). Based on our results, this common set should include *gross population density*, *intersection density* and *the walkability index*. Even though the results on the *entropy index* were less clear, we would recommend including the *entropy index*. This inclusion can contribute first to a standardisation of operationalising the index and second to a clearer picture on the consistency of results. Furthermore, associations should be reported in a standardised way. This research should be conducted using a collaborative, cross-disciplinary approach and based on a clear theoretical basis.

One step forward is the IPEN project (www.ipenproject.org). Among others, IPEN aims to improve comparability of GIS-based walkability measures by including a large variety of built environment characteristics. The possibility to use a common GIS protocol across culturally- and environmentally-different countries worldwide will be explored.

Only a few studies differentiated their results by sex, even though our findings suggest that there are major differences in the walkability correlates for men and women. A large number of studies did not report the age range. Future studies should stratify their results by sex and should provide full information on the age range of the population examined. Furthermore, studies focusing on the elderly would provide deeper insights into the walkability correlates of health for this important population group.

This review is the first of its kind to examine different GIS-based walkability measures and their associations with physical activity for transport and weight-related outcomes. The value of the review was increased by the distinct focus on the theoretical construct of walkability, and by the differentiation of results based on comparable exposure measures. Compared to other reviews, more specific conclusions can be drawn.

However, some limitations have to be taken into account. First, one person selected titles and abstracts. Second, only publications in English were included in the review which might lead to language bias. Third, the quality assessment procedure was based on an adapted tool and on rather simple criteria. Fourth, our team did not include researchers from the urban planning or transport field. A multidisciplinary team might have made a difference in terms of the design and execution of the review.

Conclusions

The findings suggest that GIS-based walkability measures are relevant indicators that should be considered for monitoring environmental determinants of public health. *Gross population density*, *intersection density* and *walkability indexes* were consistently correlated with walking for transport and can be considered as the best available GIS based measures of walkability regarding walking for transport. Based on a small, but good quality evidence base, the *walkability indexes* were the best available GIS based measures in relation to biking for transport. No reasonable robust conclusions can be drawn on the best measures in relation to overall active transport and weight-related outcomes.

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Conflict of interest The authors declare that they have no conflict of interest.

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