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REVIEW ARTICLE

Built environment attributes and their influence on walkability

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ABSTRACT

Walking is a sustainable mode of transport and a healthy way of doing physical activity. Walkability is a concept that has gained enormous popularity in recent years due to its potential to promote more sustainable urban environments and healthy lifestyles. This paper provides a literature review to analyze the influence of built environment attributes on walkability. The Scopus and Web of Science databases were chosen to survey the peer-reviewed documents published up to June 2020. A total of 132 documents were selected by the search. The review of these 132 documents showed that various built environment attributes were differently analyzed and assessed. More specifically, the search identified 32 built environment attributes that were assessed by using 63 measures. Intersection density, residential density and land use mix were the most used attributes for assessing walkability, namely by using objective methods, such as ratios and spatial score tools. In turn, attributes related to streetscape design and security were much less adopted in walkability assessments. This paper provides additional insights into how built environment attributes influence walkability and identifies gaps and issues that should be analyzed in-depth in the future. The review could be helpful for researchers and urban planners in developing walkability studies and in defining policies to improve walkability.

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Active modes; built environment attributes; pedestrians; sustainable mobility; walkability; walking

1. Introduction

Walkability is a multi-dimensional concept that can be broadly defined as the extent to which the built environment (BE) is pedestrian friendly and enables walking (Habibian & Hosseinzadeh, 2018; Taleai & Amiri, 2017). Walkability is often evaluated by considering a changeable number of BE attributes. However, there is no consensus on how to measure walkability and how to analyze the several BE attributes related to walkability (Shashank & Schuurman, 2019).

BE is the physical support of all activities, services and infrastructures found in urban spaces. Described by multiple attributes, the BE is increasingly recognized as a key driver of walking and physical activity (Jacobs et al., 2020; Liao et al., 2020). BE features can be managed through suitable planning policies and, therefore, actions to improve walkability are often associated to the quality of the BE. Consequently, the quality of the walking environment has become an essential element of urban planning and design (Wang & Yang, 2019).

Interest in walkability usually relies on two main topics. In the environmental domain, walking is seen as a sustainable mode of transport that should be used whenever possible, mainly for short trips, to reduce the negative impacts of motorized vehicles such as traffic emissions, noise, and congestion (Ellis et al., 2016; Ribeiro & Hoffimann, 2018; Taleai & Amiri, 2017). In the health domain, walking is a way of doing physical activity that helps to prevent various diseases. Physical inactivity is a leading risk factor for premature mortality and various health problems associated to sedentary lifestyles, such as obesity, diabetes, cancer (Chandrabose et al., 2019; Creatore et al., 2016; Glazier et al., 2014; Howell et al., 2019), depression (Berke et al., 2007; James et al., 2017), among others.

Due to the overall importance of walkability, the topic has often been reviewed in recent years. For example, Wong et al. (2011) reviewed 14 studies to examine the relationships between objective BE features and active school transportation in children and adolescents; Wang et al. (2016) analyzed BE barriers to walking and cycling; Cerin et al. (2007) examined the influence of BE on enhancing the levels of physical activity and active travel in older adults; Hall and Ram (2018) analyzed studies on walkability published in North America that were constructed with the Walk Score, a tool which combines distance to destination, block length, and intersection density; and Wang and Yang (2019) reviewed the literature associating walkability with GIS.

In addition to the aforementioned studies, in this paper, a literature review is carried out on the influence of BE attributes on walkability, covering all the subject areas, regardless of the country and scale of analysis (microscale or mesoscale) and the measures and methods adopted to assess

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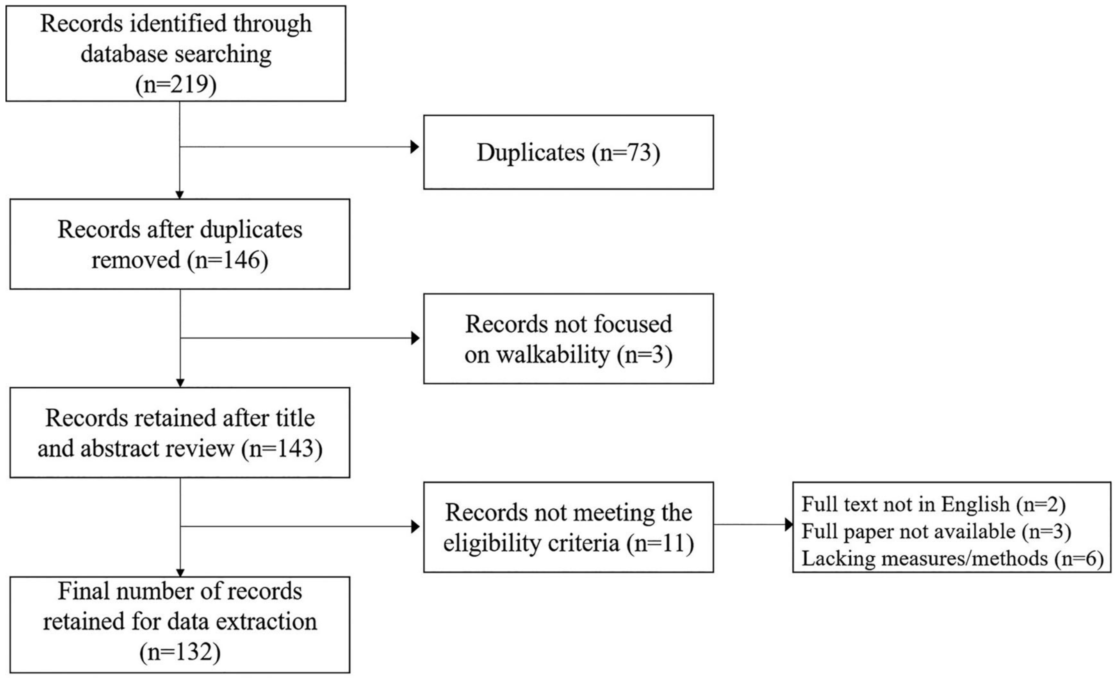

Figure 1. Flow diagram of literature review.
Source: Scopus and Web of Science databases. Diagram built on http://www//worditout.com

walkability. The goal was to analyze the influence of BE attributes on walkability, especially to understand which BE attributes were used for assessing walkability and how such attributes were measured and analyzed. The review presented in this paper could be helpful for the following reasons. First, the study assesses the existing publications associating BE attributes with walkability. Second, the paper shows clusters, gaps and overlaps of research on BE attributes that influence walkability. Third, by identifying these gaps and shortcomings, the paper is useful for guiding needs and opportunities for future research on walkability. Finally, this study can be helpful for researchers and planners to define a theoretical framework for evaluating the conditions provided to pedestrians and to support the definition of pedestrian-friendly policies.

2. Methodology

PRISMA (Preferred Reporting Items for Systematic Review and Meta-Analysis) guidelines were followed to carry out the review (Moher et al., 2009), resulting in the four-phase flow diagram shown in Figure 1.

The literature review focused on articles published in two electronic bibliographic databases: Scopus and Web of Science. These two search tools have been widely used for performing reviews and are considered consistent repositories to search for scientific publications (Arellana et al., 2020; Hall & Ram, 2018; Yang et al., 2020). As the aim of this review was to analyze the influence of BE attributes on walkability, the search was carried out by using the following criteria in the title, abstract and keywords: "walkability" and "built environment" and "walkability attribute" or synonyms of "attribute", including "criteria", "indicator", "indices", "index", "measure", "score" and "variable". The search was limited to peer-reviewed documents written in English, published as journal articles, conference papers and book chapters. In terms of time frame, the search covered the documents published from the inception of the electronic bibliographic databases to June 30, 2020. The following step consisted of assessing the eligibility of the returned documents. Titles, abstracts and keywords were manually reviewed in order to determine which of these publications predominantly deal with the influence of BE attributes on walkability. Duplicated publications, documents without full texts and documents where walkability appeared just as a subtopic or as a label were excluded.

A data extraction form was then developed to organize the information from the full paper review. Data extracted from full studies included: article title, authors, year of publication, publication title, study location, built environment attributes used, measures of walkability adopted, methods used for measuring walkability and key findings. When walkability measures and methods could not be retrieved or were not clearly described, responses to the foregoing were categorized as not available.

3. Overview of the selected articles

The review covered 132 documents published between 2005 and June 2020. The oldest documents found were published in 2005 (Frank et al., 2005; Leslie et al., 2005), but the searched topic gained increasing attention as more than half of the documents were published in the last five years.

Approximately 89% of the documents were published as articles in a total of 79 journals. The two subject areas with more publications were Health and Medicine (32%) and Social Sciences (21%). The 132 documents were prepared by 160 authors from 38 countries from the five continents.

Figure 2. Authors' keyword density diagram.

However, 59% of these publications result from studies carried out only in three countries: USA, Australia and Canada. The 132 documents contain about 600 keywords. From these, as shown in Figure 2, "built environment" (it appeared in 66 documents), "walkability" (56), "physical activity" (29), "GIS" (24), and "walking" (23) were the most used keywords.

The eligible studies have some differences in terms of their topics (Table 1). Briefly, the most representative studies (41%) were focused on evaluating the impacts of BE attributes and walkability on health and physical activity. Then, 20% of the studies described objective assessments of BE attributes and their influence on walkability, while 15% reported walkability indexes and evaluations. Less representative were the travel behavior/active travel studies (8%) and the documents based on subjective evaluations of BE attributes (7%). The remaining studies included comparative analysis of objective and subjective evaluations on walkability and the development of audit tools for assessing walkability.

4. Results and analysis of the selected documents

Due to the extensive details from the reviewed documents and to avoid writing a very long paper, a few decisions were made to simplify the summary tables while presenting the most critical information. Firstly, some documents included several measures, making it impossible to report all the detailed findings in this article due to word limitations. In such cases, we aggregated and simplified the information. For example, the various types and number of amenities used were summarized in single attributes such as "amenity density" and "distance to amenities". Secondly, the various BE attributes identified in the review were inserted into seven main categories according to their characteristics (Figure 3). For example, attributes such as "traffic volume", "traffic speed", "speed limit", "number of lanes", "traffic accidents" and "traffic calming devices" were classified into the category "safety and security". The seven categories are: i) land use density; ii) land-use diversity, iii) accessibility; iv) street network connectivity; v) pedestrian facility and comfort; vi) safety and security; and vii) streetscape design.

The selected categories were inspired and retrieved from the Neighborhood Environment Walkability Scale defined by Saelens et al. (2003), which became a widely used tool to assess BE attributes (Leslie et al., 2005; Nichani et al., 2019; Qureshi & Ho, 2014). These categories, the respective attribute measures and methods are presented in Tables 2 to 8, which summarize the main findings of this review. This organization was adopted to better represent the key results while balancing the space limitations of this paper. Finally, for studies using mixed approaches (objective, self-reported, audit), we decided to describe how each BE attribute was individually assessed.

4.1. Land use

Land use was often operationalized using diversity and density attributes. It was shown that neighborhoods with high population density and diverse land uses were more likely to facilitate walking (Habibian & Hosseinzadeh, 2018).

Table 1. Main topics of research resulting from the review.

Main topics of research	Examples
Impacts of BE attributes and walkability on health	Braun et al., 2016; Chandrabose et al., 2019; Creatore et al., 2016; Hankey et al., 2012; Howell et al., 2019; artschmit et al., 2020; Koohsari et al., 2020; Pereira et al., 2020.
Impacts of BE attributes and walkability on physical activity	Bracy et al., 2014; De Sa & Ardern, 2014; Edwards & Dulai, 2018, Frank et al., 2005; Lovasi et al., 2011; Mayne et al., 2017.
Objective evaluations of BE attributes and their influence on walkability	Bhadra et al., 2015; Chen et al., 2019; Frank et al., 2005; Huang et al., 2019; Liao et al., 2020; Yin, 2017.
Subjective evaluations of BE attributes and their influence on walkability	Arellana et al., 2020; Kaczynski, 2010; Oyeyemi et al., 2017, 2019; Pelclová et al., 2013.
Development of walkability assessment indexes/evaluations	Frank et al., 2010; Giles-Corti et al., 2014; Lee et al., 2020; Lefebvre-Ropars et al., 2017; Rundle et al., 2019; Shammas & Escobar, 2019.
Travel behavior/active travel	Christiansen et al., 2014; Koohsari et al., 2016; Moran et al., 2017; Moran et al., 2018; Ramezani et al., 2019.
Comparative use of objective and subjective evaluations of walkability	Gebel et al., 2009; Koohsari et al., 2015; Larranaga et al., 2019; Leslie et al., 2005; Moura et al., 2017; Qureshi & Ho, 2014; Ye et al., 2017.
Audit tools for assessing walkability	Scanlin et al., 2014.

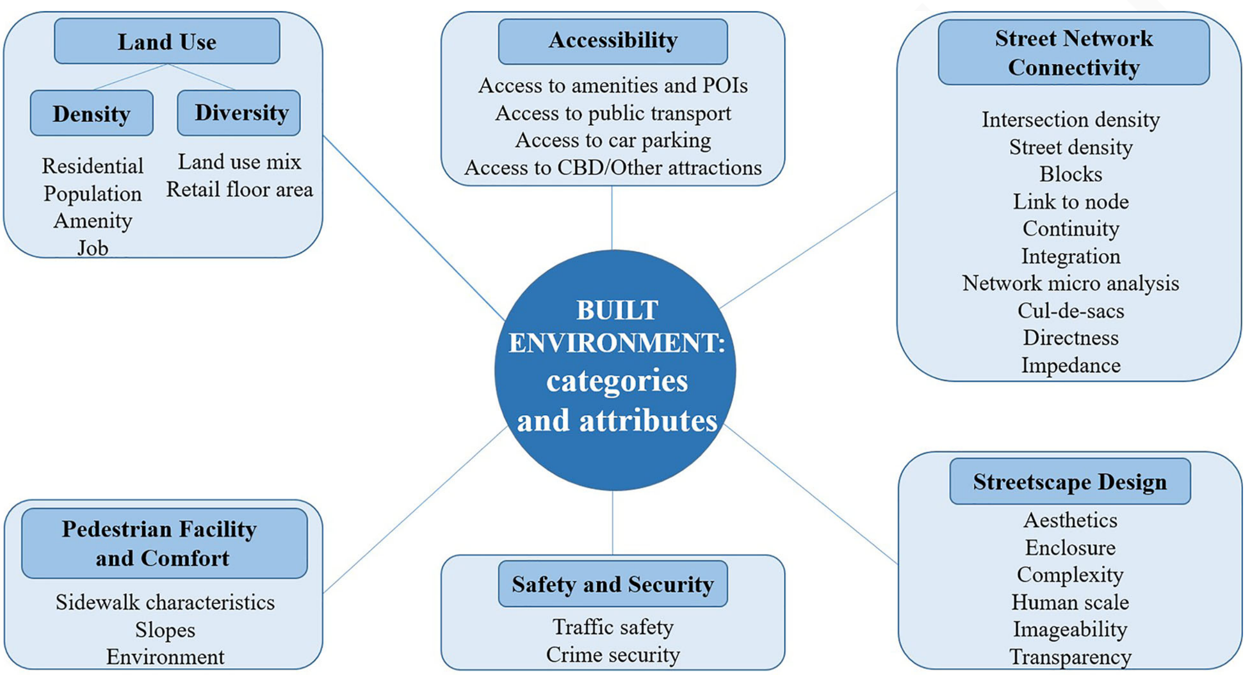

Figure 3. Built environment categories and attributes returned from the review.

4.1.1. Land use density

Land use density refers to the concentration of land uses within an area. According to the review, land use density has been mostly analyzed by using objective measures, especially residential/population densities through density ratios (Table 2). The review also showed that land use density attributes are amongst the most used in walkability.

Findings indicated that high residential/population densities are often significantly correlated with walking and physical activity (Clark et al., 2014; Frank et al., 2005; Huang et al., 2019; Mayne et al., 2013; Ribeiro & Hoffimann: 2018). In fact, areas with high population and residential densities are not only attractive for retail and services, but also for walking as they reduce the distance and time of travel between residences and destinations (Bhadra et al., 2015; Mayne et al., 2013). Nonetheless, in Vancouver (Canada), Pouliou et al. (2014) found a negative association between physical activity and residential density due to individual reasons (age, gender). In the UK, Kenyon and Pearce (2019) found that street connectivity and destination accessibility were more conducive to walking than high residential density.

The density of amenities (parks, schools, shops, services) has also been widely used. Areas with high amenity density are more conducive for walking and for physical activity (Buck et al., 2015; Kerr et al., 2014). However, other authors found a weak association between amenity density and walking (Li et al., 2018), while this attribute overlooks the quality provided by the amenities (Adu-Brimpong et al., 2017).

4.1.2. Land use diversity

Land use diversity shows the degree to which there is a mix of land uses within an area (Tsiompras & Photis, 2017). The search showed that land use diversity was mostly evaluated by considering two main attributes: land use mix and retail floor area (Table 3). Both attributes have been mostly assessed by using objective measures, such as entropy

Table 2. Land use density attributes, measures and methods.

Attributes	Measures	Methods	References
Residential density	Residential density	Ratio: number of residences/dwellings per specific land area	Adams et al., 2014, 2015; Awuor & Melles, 2019; Bhadra et al., 2015; Bödeker, 2018; Boulange et al., 2018; Bracy et al., 2014; Cerin et al., 2007; Chandrabose et al., 2019; Christiansen et al., 2014; Colley et al., 2019; Cook et al., 2013; Creatore et al., 2016; De Sa & Ardern, 2014; Deng et al., 2020; Dias et al., 2020; Dygryn et al., 2010; Esteban-Cornejo et al., 2016; Fan et al., 2018; Foster et al., 2019; Frank et al., 2005, 2010; Gebel et al., 2009; Giles-Corti et al., 2014; Glazier et al., 2014; Hill et al., 2012; Howell et al., 2019; Huang et al., 2019; Kenyon & Pearce, 2019; Kerr et al., 2013, 2014; Koohsari et al., 2016, 2018; Kozo et al., 2012; Laatikainen et al., 2018; Learnihan et al., 2011; Lee et al., 2020; Macdonald et al., 2016; Marshall et al., 2009; Mayne et al., 2013, 2017, Mayne et al., 2019; McDonald et al., 2012; Mooney et al., 2020; Moran et al., 2017, 2018; Oliver et al., 2015; Pouliou et al., 2014; Qureshi & Ho, 2014; Ramezani et al., 2019; Reyer et al., 2014; Ribeiro & Hoffimann, 2018; Roberts et al., 2015; Rubín et al., 2015; Shashank & Schuurman, 2019; Taleai & Amiri, 2017; Todd et al., 2016; Van Dyck et al., 2012; Wang et al., 2017; Ye, 2020; Ye et al., 2017; Zhou et al., 2020.
		Survey: perceived residential density/ types of residences in an area	Gebel et al., 2009; Kaczynski, 2010; Leslie et al., 2005; Nichani et al., 2019; Oyeyemi et al., 2017, 2019; Pelclová et al., 2013; Qureshi & Ho, 2014; Tsiompras & Photis, 2017; Van Dyck et al., 2012; Ye, 2020; Ye et al., 2017.
Population density	Population density	Ratio: number of persons per unit area	Braun et al., 2016; Buck et al., 2015; Chen et al., 2019; Clark et al., 2014; Creatore et al., 2016; Cruise et al., 2017; Deng et al., 2020; Glazier et al., 2014; Habibian & Hosseinzadeh, 2018; Hanibuchi et al., 2012; Hankey et al., 2012; Howell et al., 2019; James et al., 2017; James et al., 2015; King, 2008; Koohsari et al., 2016, 2018; Lamíquiz & Domínguez, 2015; Lefebvre-Ropars et al., 2017; Li et al., 2018; Liao et al., 2020; Lovasi et al., 2011; McCormack et al., 2019; Nichani et al., 2020; Oluyomi et al., 2014; Orstad et al., 2018; Robinson et al., 2018; Rundle et al., 2019; Sehatzadeh et al., 2011; Shammas & Escobar, 2019; Sugiyama et al., 2019; Tamura et al., 2019; Vargo et al., 2012; Williams et al., 2018.
Amenity density	Amenity density (including urban parks)	Ratio: number of amenities per unit area	Adams et al., 2014, 2015; Braun et al., 2016; Buck et al., 2015; Chandrabose et al., 2019; Chen et al., 2019; Colley et al., 2019; Deng et al., 2020; Glazier et al., 2014; Golan et al., 2019; Hanibuchi et al., 2012; Howell et al., 2019; Huang et al., 2019; James et al., 2015, 2017; Kenyon & Pearce, 2019; Kerr et al., 2014; Lamíquiz & Domínguez, 2015; Lefebvre-Ropars et al., 2017; Li et al., 2018; Liao et al., 2020; McDonald et al., 2012; Nichani et al., 2020; Orstad et al., 2018; Pereira et al., 2020; Pouliou et al., 2014; Reisi et al., 2019; Rundle et al., 2019; Todd et al., 2016; Vargo et al., 2012; Wang et al., 2017; Ye, 2020; Ye et al., 2017; Zhou et al., 2020.
		Ratio: urban park/green area per capita	Pereira et al., 2020.
		Street audit scoring method	King, 2008; Scanlin et al., 2014.
		Survey: perceived presence of amenities in an area	Larranaga et al., 2019.
Building density	Building density	Ratio: building cover per unit area	Robinson et al., 2018.
Job density	Job density	Ratio: number of jobs per unit area	Huang et al., 2019; Lamíquiz & Domínguez, 2015; Mooney et al., 2020; Pereira et al., 2020; Sehatzadeh et al., 2011; Vargo et al., 2012.

equations and ratios to show the prevalence and distribution of various land uses.

Land use mix was often measured by using an entropy equation to obtain the proportional abundance of specific uses in an area, giving a score ranging from 0 (single use) to 1 (even distribution among various uses). Other well-reported measures include the percentage and the number of specific land uses in an area. The number and type of land uses considered was strongly changeable. The widely replicated index of Frank et al. (2010) was based on five uses (residential, retail, recreational, office and institutional), but the review identified studies using a number ranging from three (Taleai & Yameqani, 2018) to 17 land uses (Hanibuchi et al., 2012). The analyzed documents globally showed that mixed land uses providing nonresidential activities (shops, restaurants, offices, banks, etc.) are correlated to

Table 3. Land use diversity attributes, measures and methods.

Attributes	Measures	Methods	References
Land use mix	Diversity of land uses	Entropy indexes indicating the distribution of different land uses in an area	Adams et al., 2014, 2015; Awuor & Melles, 2019; Bhadra et al., 2015; Bödeker, 2018; Boulange et al., 2018; Bracy et al., 2014; Buck et al., 2015; Cerin et al., 2007; Christiansen et al., 2014; Clark et al., 2014; Cruise et al., 2017; Deng et al., 2020; Dygryn et al., 2010; Esteban-Cornejo et al., 2016; Fan et al., 2018; Frank et al., 2005, 2010; Gebel et al., 2009; Giles-Corti et al., 2014; Habibian & Hosseinzadeh, 2018; Hankey et al., 2012; Kerr et al., 2013, 2014; Koohsari et al., 2015, 2016, 2018; Kozo et al., 2012; Laatikainen et al., 2018; Learnihan et al., 2011; Leslie et al., 2005; Marshall et al., 2009; Mayne et al., 2013, 2017, 2019; Moran et al., 2017; Oliver et al., 2015; Oluyomi et al., 2014; Pouliou et al., 2014; Ramezani et al., 2019; Reyer et al., 2014; Ribeiro & Hoffimann, 2018; Robinson et al., 2018; Rubín et al., 2015; Sehatzadeh et al., 2011; Shashank & Schuurman, 2019; Taleai & Amiri, 2017; Taleai & Yameqani, 2018; Tamura et al., 2019; Todd et al., 2016; Van Dyck et al., 2012; Zhou et al., 2020.
		Ratio: fraction/percentage of specific land uses per unit area	Cook et al., 2013; Foster et al., 2019; Hill et al., 2012; Jacobs et al., 2020; King & Clarke, 2015; Laatikainen et al., 2018; Leslie et al., 2005; Liao et al., 2020; Lovasi et al., 2011; Moran et al., 2017, 2018; Qureshi & Ho, 2014; Ramezani et al., 2019; Roberts et al., 2015; Wang et al., 2017.
		Ratio: streets having a specific use/ total streets	Lee et al., 2020.
		Number/count of specific land uses in an area	Bracy et al., 2014; Hanibuchi et al., 2012; Lovasi et al., 2011; Pereira et al., 2020; Robinson et al., 2018; Shammas & Escobar, 2019.
		Street audit scoring method	Adu-Brimpong et al., 2017; Cambra & Moura, 2020; Moura et al., 2017.
		Survey: perceived land uses mix in a specific area	Gebel et al., 2009; Kaczynski, 2010; Koohsari et al., 2015; Leslie et al., 2005; Nichani et al., 2019; Pelclová et al., 2013; Qureshi & Ho, 2014; Tsiompras & Photis, 2017; Van Dyck et al., 2012; Ye, 2020; Ye et al., 2017.
Retail floor area	Net retail use	Ratio: retail building floor area per unit area	Adams et al., 2015; Awuor & Melles, 2019; Bhadra et al., 2015; Bödeker, 2018; Bracy et al., 2014; Christiansen et al., 2014; Clark et al., 2014; Cook et al., 2013; Cruise et al., 2017; Dygryn et al., 2010; Esteban-Cornejo et al., 2016; Frank et al., 2010; Gebel et al., 2009; Kerr et al., 2013; Koohsari et al., 2016, 2018; Kozo et al., 2012; Laatikainen et al., 2018; Learnihan et al., 2011; Marshall et al., 2009; Mayne et al., 2013; Moran et al., 2017; Reyer et al., 2014; Todd et al., 2016; Wang et al., 2017.
		Survey: perceived retail use	Gebel et al., 2009.
	Gross retail use	Ratio: gross retail area per unit area	Cerin et al., 2007; Moran et al., 2018; Ramezani et al., 2019.

pedestrian-friendly environments and high levels of physical activity (Frank et al., 2005; Kaczynski, 2010; Lovasi et al., 2011), and walking (Carlson et al., 2018; Clark et al., 2014; Fan et al., 2018). However, some authors also found negative associations, namely in European and Asian cities (Buck et al., 2015; Habibian & Hosseinzadeh, 2018; Liao et al., 2020). But even in the USA, Tamura et al. (2019) showed that active people prefer less populated and mixed areas for recreational walking.

The retail floor area attribute indicates the amount of available space for parking. This attribute was frequently calculated as a ratio (retail building floor area per retail land areas). Areas with low retail density often have more space available for car parking, while areas with high retail density usually have less unused land and space for parking, which are more attractive for walking (Learnihan et al., 2011; Sehatzadeh et al., 2011). The retail floor area was correlated to walkability (Frank et al., 2010), but findings indicated that this attribute is difficult to implement due to the lack of parcel-level data (Adams et al., 2014; Ellis et al., 2016; Fan et al., 2018). Todd et al. (2016) also concluded that the retail floor area was less relevant for pedestrians than other BE attributes, such as public transport density and intersection density.

4.2. Accessibility

Accessibility reflects the distance/proximity to key amenities and public transport (Cervero et al., 2009). In addition to these, the distance to car parks and to the city center and other attractions, such as the coast, were also identified as accessibility attributes (Table 4).

Distance to amenities was found to be the most adopted attribute within this context. It was frequently measured as

Table 4. Accessibility attributes, measures and methods.

Attributes	Measures	Methods	References
Access to amenities and points of interest	Distance to amenities	Distance between one or more amenities and a specific point/area	An et al., 2019; Berke et al., 2007; Boulange et al., 2018; Braun et al., 2016; Creatore et al., 2016; Hollenstein & Bleisch, 2016; Kartschmit et al., 2020; Kerr et al., 2014; Liao et al., 2020; McDonald et al., 2012; Qureshi & Ho, 2014; Robinson et al., 2018; Williams et al., 2018.
		Walk Score	Sugiyama et al., 2019; Williams et al., 2018.
		Survey: perceived access/ distance to various amenities	Arellana et al., 2020; Carlson et al., 2018; Koohsari et al., 2020; Orstad et al., 2018; Oyeyemi et al., 2017, 2019; Pelclová et al., 2013; Roberts et al., 2015; Tsiompras & Photis, 2017.
	Neighborhood Destination Accessibility Index	Index showing the intensity of neighborhood destination in an area	Oliver et al., 2015.
Access to public transport	Distance to stops/ stations	Distance between the stop and a selected point/area	Boulange et al., 2018; Pereira et al., 2020; Riggs & Sethi, 2020; Taleai & Amiri, 2017; Watson et al., 2020.
		Survey: perceived distance/ access to stops/stations	Arellana et al., 2020; Van Dyck et al., 2012.
	Density of public transport stops	Ratio: number of stops per unit area	Adams et al., 2014, 2015; An et al., 2019; Buck et al., 2015; Chen et al., 2019; Deng et al., 2020; Fan et al., 2018; Kartschmit et al., 2020; Lee et al., 2020; Lovasi et al., 2011; McDonald et al., 2012; Reisi et al., 2019; Rundle et al., 2019; Todd et al., 2016; Vargo et al., 2012.
		Street audit scoring method	Adu-Brimpong et al., 2017.
Access to car park	Car parks and setbacks	Ratio: area of car parks/ total area	Herrmann et al., 2017.
		Number of car parks	An et al., 2019; Golan et al., 2019.
		Survey: perceptions about car parks in specific areas	Nichani et al., 2019; Qureshi & Ho, 2014; Van Dyck et al., 2012; Ye, 2020; Ye et al., 2017.
Access to city center/CBD and other attractions	Distance to CBD/city center	Distance between the CBD and residential areas	An et al., 2019; Foster et al., 2019; Habibian & Hosseinzadeh, 2018; Lamíquiz & Domínguez, 2015.
	Distance to the coast	Distance between residential areas and the coast	Kerr et al., 2014.

the network distance between the considered amenities and specific points, such as residential areas and schools. Many studies were also supported on individual perceptions related to the access to amenities. This review showed that total walking time is significantly correlated with short distances to destinations (Berke et al., 2007; Kerr et al., 2014; Vargo et al., 2012). Access to amenities was associated with less sedentary lifestyles (Oyeyemi et al., 2019) and with moderate to high levels of physical activity (Cerin et al., 2007). Abundant evidence also showed that distance plays a critical role in the likelihood of children walking to school (Macdonald et al., 2016; Moran et al., 2017; Williams et al., 2018). Inversely, Kerr et al. (2014) found that park distance was not related to walking or to physical activity. And Talen and Koschinsky (2014) also argued that the proximity to amenities does not always mean the opportunity to use them due to various socioeconomic and individual variables, such as age and income.

Access to public transport was also a frequently used attribute, meaning that stops should be near enough to be reached by walking (Table 4). It is widely recognized that the shorter the distance to a stop, the higher the walking activity and the greater the odds are of walking to public transport (Boulange et al., 2018; Riggs & Sethi, 2020). Many distances have been used to represent pedestrian catchment areas for public transport stations, which are usually comprised between 300 to 900 meters (An et al., 2019; Boulange et al., 2018; Habibian & Hosseinzadeh, 2018). However, distance is not the only critical factor for using public transport. For example, An et al. (2019) showed that the number of transport stops in an area was more important than the distance. For that reason, many authors measured the access to public transport through the density of public transport stops/stations (Table 4). Areas with high public transport stop densities were positively correlated to walking (Buck et al., 2015; Kerr et al., 2014) and to active people (Buck et al., 2015; McDonald et al., 2012; Todd et al., 2016).

As can be concluded from Table 4, access to car parks, city centers and other urban attractions were much less analyzed attributes. Results suggest that the distance to these destinations does not have a decisive influence on walkability.

4.3. Street network connectivity

Street network connectivity can be understood as the directness and availability of alternative routes between destinations (Ellis et al., 2016). Street network connectivity increases walkability in two ways: more interconnected streets provide more potential routes for walking and shorter distances to destinations (Tsiompras & Photis, 2017). Street connectivity is often described by measurable properties of the street network, but there is no accepted

Table 5. Street network connectivity attributes, measures and methods.

Attributes	Measures	Methods	References
Intersection density	Intersection density	Ratio: number of street intersections of three or more legs and the land area	Adams et al., 2015; Awuor & Melles, 2019; Bödeker, 2018; Boulange et al., 2018; Bracy et al., 2014; Chandrabose et al., 2019; Christiansen et al., 2014; Clark et al., 2014; Colley et al., 2019; Cook et al., 2013; Creatore et al., 2016; Cruise et al., 2017; Dygryn et al., 2010; Ellis et al., 2016; Fan et al., 2018; Foster et al., 2019; Frank et al., 2010; Gebel et al., 2009; Giles-Corti et al., 2014; Glazier et al., 2014; Habibian & Hosseinzadeh, 2018; Hanibuchi et al., 2012; Hankey et al., 2012; Hill et al., 2012; Howell et al., 2019; James et al., 2015, 2017; Kenyon & Pearce, 2019; Kerr et al., 2013; Kerr et al., 2014; Koohsari et al., 2015, 2016, 2018; Kozo et al., 2012; Laatikainen et al., 2018; Learnihan et al., 2011; Leslie et al., 2005; Liao et al., 2020; Macdonald et al., 2016; Mayne et al., 2013, 2017, 2019; Nichani et al., 2020; Oliver et al., 2015; Oluyomi et al., 2014; Orstad et al., 2018; Pereira et al., 2020; Qureshi & Ho, 2014; Ramezani et al., 2019; Ribeiro & Hoffimann, 2018; Rubín et al., 2015; Rundle et al., 2019; Sehatzadeh et al., 2011; Todd et al., 2016; Van Dyck et al., 2012; Vargo et al., 2012; Zhou et al., 2020.
	Intersection density (all legs)	Ratio: number of all intersections and the land area	An et al., 2019; Bhadra et al., 2015; Braun et al., 2016; Buck et al., 2015; Cerin et al., 2007; Chen et al., 2019; De Sa & Arden, 2014; Deng et al., 2020; Dias et al., 2020; Esteban-Cornejo et al., 2016; Frank et al., 2005; Huang et al., 2019; King & Clarke, 2015; Lee et al., 2020; Lovasi et al., 2011; Marshall et al., 2009; McDonald et al., 2012; Moran et al., 2017, 2018; Pouliou et al., 2014; Reyer et al., 2014; Roberts et al., 2015; Robinson et al., 2018; Shammas & Escobar, 2019; Shashank & Schuurman, 2019; Taleai & Amiri, 2017; Wang et al., 2017; Williams et al., 2018; Ye et al., 2017.
		Map visual inspection	King, 2008.
		Survey: perceived intersection density	Cerin et al., 2007; Gebel et al., 2009; Koohsari et al., 2015; Larranaga et al., 2019; Nichani et al., 2019; Tsiompras & Photis, 2017; Van Dyck et al., 2012; Ye, 2020; Ye et al., 2017.
	Block length/size	Ratio: length of roads per true intersections	King & Clarke, 2015; Lefebvre-Ropars et al., 2017; McDonald et al., 2012; Roberts et al., 2015; Williams et al., 2018; Ye, 2020.
		Street block walkability scores	Tribby et al., 2016.
		Survey: perceived length	Oyeyemi et al., 2017, 2019.
	Link to node ratio	Ratio: street segments to intersections	Braun et al., 2016; Ellis et al., 2016; Habibian & Hosseinzadeh, 2018; Williams et al., 2018.
Cul-de-sacs	Cul-de-sac density	Ratio: number of cul-de-sacs per unit area	Habibian & Hosseinzadeh, 2018; Lamíquiz & Domínguez, 2015; Sehatzadeh et al., 2011; Van Dyck et al., 2012; Ye, 2020.
		Survey: perceived presence of cul-de-sacs	Qureshi & Ho, 2014; Kaczynski, 2010; Ye, 2020; Ye et al., 2017.
		Street audit scoring method	Wang et al., 2017.
Street density	Street density	Ratio: total length of street segments per unit area	Deng et al., 2020; Habibian & Hosseinzadeh, 2018; King & Clarke, 2015; Koohsari et al., 2020; Li et al., 2018; Sehatzadeh et al., 2011; Tamura et al., 2019; Williams et al., 2018; Ye, 2020; Ye et al., 2017.
Continuity	Sidewalk/ Footpath continuity	Ratio: connected sidewalks/ total sidewalks	Lee et al., 2020.
		Ratio: least topological length/ Euclidean distance	Cambra & Moura, 2020; Moura et al., 2017.
		Kernel density estimation	Shashank & Schuurman, 2019.
Directness	Route directness	Footpath distance between two points	Ellis et al., 2016.
		Ratio: shortest path/ Euclidean distance	Moura et al., 2017.
	Pedshed analysis	Walkable catchments between two points (%)	Ellis et al., 2016.
	Metric reach	Walkable catchments between two points (km)	Ellis et al., 2016.
Integration	Topological analysis	Space Syntax	Koohsari et al., 2016, 2018; Lamíquiz & Domínguez, 2015; McCormack et al., 2019; Sugiyama et al., 2019.
		Directional change analysis (> 20°)	Ellis et al., 2016.
Network micro analysis	Network micro analysis	Centrality, betweenness, angularity, convexity	Yamagata et al., 2019.
Impedance	Impedance	Network spatial analysis	Kartschmit et al., 2020.

method for assessing it (Ellis et al., 2016). The search showed that street network connectivity has been described by a considerable number of different attributes of the street/footpath network mostly by calculating ratios, such as intersection and street densities (Table 5).

According to the review, intersection density was the most used attribute to describe how connected a street network is (Table 5). This attribute has been widely measured as the number of road intersections of three or more links in an area, but many authors also considered the ratio of all street intersections in an area. Intersection density was associated with physical activity and walking (Buck et al., 2015; Cruise et al., 2017; Frank et al., 2005) and was described by Ellis et al. (2016) as the best measure of street network connectivity. Some studies also found that intersection density may have less influence on walkability. For instance, Moran et al. (2018) concluded that routes with fewer intersections (lesser crossings) are more likely to be selected by pedestrians due to safety reasons. While some studies showed a positive association between intersection density and walking to public transport (Nichani et al. (2019), other authors found the opposite. For example, in Shanghai, An et al. (2019) concluded that intersection density was not positively associated with walking to train stations. Well-connected streets and the diversity of land uses in the city center decreased the number of train passengers and increased walking and cycling.

Some other attributes and measures are derived from street intersection, such as block length, link to node ratio and cul-de-sac (or T-intersection) density. From these, cul-de-sacs are recognized as leading to poor connectivity as they represent non-grid street patterns and dead-ends (Sehatzadeh et al., 2011).

Street density, described as the total length of street segments per unit area, was adopted in some studies, but also with diverse results. While some authors showed that street density promotes active travel (Cervero et al., 2009), other studies indicated less influence of this attribute on walkability. More specifically, Tamura et al. (2019) found that high street density areas were characterized by less physical activity levels, because people avoid walking in areas with many crossings. Sehatzadeh et al. (2011) also found that street density does not have a significant effect on walking but showed a positive association with the number of household cars.

A restricted number of authors argue that connectivity should be analyzed by considering the real pedestrian network, instead of using the street/road network (Ellis et al., 2016; Tsiompras & Photis, 2017). Using road-networks not only ignores the fact that some routes are unsuitable and undesirable for walking, but also footpaths and informal paths, such as footbridges and paths through parks, which are primarily used by pedestrians (Cruise et al., 2017; Tribby et al., 2016). For that reason, some authors focused on evaluating footpath networks, by analyzing aspects such as the sidewalk continuity and footpath directness between specific points. However, these attempts have been limited, mostly because disaggregated footpath data are difficult to obtain.

Finally, some authors also evaluated how street networks are integrated. Integration relies on the topological representation of the built environment: a more integrated street segment requires fewer turns to reach a destination from other streets within the network (McCormack et al., 2019). By using space syntax for measuring street integration, some authors, such as McCormack et al. (2019) found a positive association between topological distance and walking for transport. However, this attribute was found to weakly described connectivity and walking when applied to small and dense urban areas, where turns are the norm (Ellis et al., 2016; Lamíquiz & Domínguez, 2015).

4.4. Pedestrian facility and comfort

This category includes the following three pedestrian facility and comfort attributes: sidewalk characteristics, slopes and environmental conditions at the street level.

According to the review, the presence and density of sidewalks in an area, the width and overall characteristics of sidewalks and the presence of obstructions on sidewalks were the most extensively measured attributes (Table 6). The overall findings indicate that a sidewalk with sufficient width, without obstructions, in a good condition and designed according to the desired pedestrian level of service, is safe and convenient for pedestrians (Vargo et al., 2012; Wang et al., 2016). More specifically, the existence and percentage of sidewalks were consistently correlated with walking (Vargo et al., 2012). Narrow sidewalks with obstacles reduce the walkability of an area (Tsiompras & Photis, 2017), while sidewalks in a poor condition are considered a barrier for walking (Larranaga et al., 2019), especially for elderly and impaired people (Moura et al., 2017). In turn, street furniture and support facilities (benches, water fountains, etc.) have been rarely included in the evaluation of walkability. Inversely to the previous categories, many of these attributes, especially the condition of the sidewalk surface, presence and density of sidewalks and sidewalk obstructions, have been mostly evaluated by performing street audits and questionnaires. This type of objective data is difficult to obtain and, for that reason, sidewalk data are often replaced by street network (Shashank & Schuurman, 2019).

Slopes are another attribute included in this category. Slopes affect the walking speed and time, the comfort and safety of walking, as well as the energy and effort required for walking (Kerr et al., 2013; Taleai & Yameqani, 2018). Nonetheless, the review showed that slopes were only considered by a relatively reduced number of authors. Evidence indicated that slopes have a strong impact on walkability. For example, in Porto Alegre, Brazil, topography was found to be one of the most important barriers for walking (Larranaga et al., 2019); in Bogota, Colombia, high slopes were correlated with walking for public transport (Kerr et al., 2013); and in Lisbon, Portugal, some of the less walkable areas found by Moura et al. (2017) were also characterized by high slopes.

Table 6. Pedestrian facility and comfort attributes, measures and methods.

Attributes	Measures	Methods	References
Sidewalk characteristics	Presence and density of sidewalks	Ratio: streets having at least one sidewalk/ total streets	Lee et al., 2020; Vargo et al., 2012.
		Ratio: sum of sidewalks' length per area /road length	Chen et al., 2019; Clark et al., 2014; Huang et al., 2019; Laatikainen et al., 2018; Williams et al., 2018.
		Dichotomous scoring method	Hollenstein & Bleisch, 2016.
		Survey: perceived presence of sidewalks	Kaczynski, 2010; Orstad et al., 2018; Pelclová et al., 2013; Roberts et al., 2015; Van Dyck et al., 2012 Ye et al., 2017.
	Sidewalk width	Average sidewalk width along the street	Reisi et al., 2019.
		Ratio: streets having wide sidewalks/ total streets having sidewalks	Lee et al., 2020.
		Street audit scoring method	Moura et al., 2017; Seagle et al., 2008.
		Survey: perceived sidewalk width	Arellana et al., 2020; Larranaga et al., 2019; Tsiompras & Photis, 2017.
	Support facilities and furniture	Number of pedestrian facilities	Reisi et al., 2019.
		Street audit scoring method	Moura et al., 2017; Scanlin et al., 2014.
	Condition of the sidewalk surface	Ratio: number of requests for clean-up sidewalks per unit area	Golan et al., 2019.
		Ratio: street having trashes/ total streets	Lee et al., 2020; Lovasi et al., 2011.
		Street audit scoring method	Adu-Brimpong et al., 2017; Cambra & Moura, 2020; King, 2008; Moura et al., 2017; Scanlin et al., 2014; Seagle et al., 2008; Wang et al., 2017.
		Survey: perceived condition and quality of the pedestrian facility	Arellana et al., 2020; Carlson et al., 2018; Cerin et al., 2007; Cook et al., 2013; Larranaga et al., 2019; Leslie et al., 2005; Nichani et al., 2019; Oyeyemi et al., 2017, 2019; Qureshi & Ho, 2014; Tsiompras & Photis, 2017; Ye et al., 2017.
	Sidewalk obstructions	Number of obstacles along sidewalks	Reisi et al., 2019.
		Street audit scoring method	King, 2008; Scanlin et al., 2014.
		Survey: perception of obstacles on sidewalks	Arellana et al., 2020; Nichani et al., 2019; Qureshi & Ho, 2014; Tsiompras & Photis, 2017; Van Dyck et al., 2012; Ye, 2020; Ye et al., 2017.
Slopes	Average slope	Digital elevation model analysis	Deng et al., 2020; Golan et al., 2019; Taleai & Yameqani, 2018.
		Ratio: streets having flat sidewalks/ total streets having sidewalks	Lee et al., 2020.
		Difference between the maximum and minimum elevation	Fan et al., 2018.
		Street audit scoring method	King, 2008; Moura et al., 2017; Scanlin et al., 2014; Wang et al., 2017.
		Survey: perceived street slopes	Larranaga et al., 2019; Nichani et al., 2019; Qureshi & Ho, 2014; Ye, 2020; Ye et al., 2017.
Environment	Greenness level	Normalised Difference Vegetation Index (satellite imagery)	Nichani et al., 2020; Robinson et al., 2018; Taleai & Amiri, 2017; Taleai & Yameqani, 2018; Tamura et al., 2019.
	Street tree density	Ratio: streets with trees/ total streets	Lee et al., 2020.
		Ratio: thousands of trees per km^2	Lovasi et al., 2011.
		Area covered by trees/green areas	Reisi et al., 2019.
		Survey: perceived presence of trees	Arellana et al., 2020; Cook et al., 2013; Nichani et al., 2019.
	Tree canopy cover	Proportion of the total area of trees/ average tree cover	Awuor & Melles, 2019; Herrmann et al., 2017.
	Tree shading	Street audit scoring method	King, 2008; Scanlin et al., 2014.
	Sun/shade level	3D spatial analysis (GIS)	Shammas & Escobar, 2019; Taleai & Amiri, 2017.
	Land Surface Temperature	Remote sensing	Taleai & Yameqani, 2018.
	Noise level	Spatial analysis from noise maps	Shammas & Escobar, 2019.
		Ratio: streets having noise from factories and other sources /total streets	Lee et al., 2020.
	Air pollution	Outdoor exposure to air pollutants by using air pollution models and concentrations	Awuor & Melles, 2019; Hankey et al., 2012; Howell et al., 2019; James et al., 2015; Pereira et al., 2020.

The environmental conditions at street level is the third attribute included in this category. In the analyzed documents, the greenness level and street tree density were the two most used measures for describing the environment at street level. According to the review, street trees were found to be positively associated with physical activity (Lovasi et al., 2011; Tamura et al., 2019), healthy pedestrian routes (Taleai & Yameqani, 2018) and more pleasant walkable areas (Herrmann et al., 2017). The presence and level of tree shading have been considered by some authors as they influence the pedestrian comfort. Street trees are also known for causing some negative impacts as they may create obstructions and deformations on sidewalks, and they may reduce the sidewalk. These negative aspects linked to street trees were globally not found in the searched literature.

Finally, pedestrian exposure to air pollution and noise, especially from traffic, have recently been analyzed by some authors. Walking in more polluted areas can result in higher inhalation of polluted air, which could have public health

Table 7. Safety and security attributes, measures and methods.

Attributes	Measures	Methods	References
Traffic safety	Risk of accidents	Ratio: pedestrian-automobile injuries per thousand residents	Lovasi et al., 2011.
		Survey: perceived risk of traffic accidents	Larranaga et al., 2019.
	Vehicular traffic exposure	Ratio: length of roads by the average traffic volume	Williams et al., 2018.
		Ratio: busy or large streets by all the streets	Lee et al., 2020.
		Maximum traffic speed limit per area	Golan et al., 2019; Williams et al., 2018.
		Ratio: vehicles/day (traffic volume)	Lovasi et al., 2011.
		Traffic density on nearest street	Robinson et al., 2018.
		Number of potential vehicle conflict points	Reisi et al., 2019.
		Dichotomous scoring method	Hollenstein & Bleisch, 2016.
		Street audit scoring method	Cambra & Moura, 2020; King, 2008; Moura et al., 2017; Scanlin et al., 2014; Seagle et al., 2008.
		Survey: perceived traffic safety	Arellana et al., 2020; Bracy et al., 2014; Carlson et al., 2018; Cerin et al., 2007; Esteban-Cornejo et al., 2016; Leslie et al., 2005; Nichani et al., 2019; Oyeyemi et al., 2017, 2019; Pelclová et al., 2013; Qureshi & Ho, 2014; Van Dyck et al., 2012; Ye, 2020; Ye et al., 2017.
	Traffic calming for pedestrian safety	Ratio: number of traffic calming devices/facilities per area	Reisi et al., 2019; Williams et al., 2018.
		Ratio: streets having any traffic calming device/total streets	Lee et al., 2020.
		Ratio: formal intersection/total street crossings	Moura et al., 2017.
		Dichotomous scoring method	Hollenstein & Bleisch, 2016.
		Street audit scoring method	King, 2008; Wang et al., 2017.
		Survey: perceived presence of traffic calming devices	Arellana et al., 2020; Bracy et al., 2014; Carlson et al., 2018; Esteban-Cornejo et al., 2016.
Crime security	Crimes and social incivilities	Ratio: homicides per number of residents	Lovasi et al., 2011.
		Crime density: Number of crimes in an area/ number of crimes per 1000 inhabitants	Deng et al., 2020; Foster et al., 2019; Golan et al., 2019; King, 2008; Liao et al., 2020.
		Survey: perception of criminality/ crime security in an area	Arellana et al., 2020; Bracy et al., 2014; Carlson et al., 2018; Cerin et al., 2007; Esteban-Cornejo et al., 2016; Foster et al., 2019; Leslie et al., 2005; Nichani et al., 2019; Orstad et al., 2018; Oyeyemi et al., 2017, 2019; Pelclová et al., 2013; Qureshi & Ho, 2014; Van Dyck et al., 2012; Ye, 2020; Ye et al., 2017.
	Police stations/officers	Ratio: number of police officers per inhabitants	Larranaga et al., 2019.
		Survey: perception of police stations	Arellana et al., 2020; Larranaga et al., 2019.
	Visual surveillance systems	Survey: perceived security resulting from the presence of surveillance systems	Arellana et al., 2020; Moayedi et al., 2013.
	Street lighting	Ratio: street lightings/ total length of streets	Lee et al., 2020.
		Number/count of street lighting	Reisi et al., 2019.
		Street audit scoring method	Scanlin et al., 2014; Seagle et al., 2008.
		Survey: perceived street lightning	Kaczynski, 2010.
	Graffiti, broken windows	Ratio: number of reported incidences per unit area	Golan et al., 2019.
		Ratio: streets having graffiti/ total streets	Lee et al., 2020.
		Street audit scoring method	Scanlin et al., 2014.
		Survey: perception of graffiti on buildings	Arellana et al., 2020.
	Unwanted people and dogs	Ratio: number of requests per unit area	Golan et al., 2019.
		Street audit scoring method	King, 2008; Scanlin et al., 2014.
	Home security practices	Street audit scoring method	King, 2008.
	Pedestrian volume/ Conviviality	Street audit scoring method	Cambra & Moura, 2020.
		Survey: perception of pedestrian flow	Arellana et al., 2020; Cook et al., 2013; Ye, 2020; Ye et al., 2017.

impacts (Pereira et al., 2020), while high noise levels have been identified as a source of discomfort and stress (Colley et al., 2019; James et al., 2017). Some studies indicated that high walkable areas are correlated with exposure to air pollutants (James et al., 2015; Marshall et al., 2009). However, the review indicated that walkability and pollution have been mostly assessed independently, which requires more research in this field.

Table 8. Streetscape design attributes, measures and methods.

Attributes	Measures	Methods	References
Esthetics	Esthetics of the BE	Street audit scoring method	King, 2008; Scanlin et al., 2014; Wang et al., 2017.
		Survey: perceived esthetic features of the neighborhood	Arellana et al., 2020; Carlson et al., 2018; Cerin et al., 2007; Kaczynski, 2010; Larranaga et al., 2019; Leslie et al., 2005; Oyeyemi et al., 2017, 2019; Pelclová et al., 2013; Qureshi & Ho, 2014; Van Dyck et al., 2012; Ye, 2020; Ye et al., 2017.
Enclosure	Streets enclosure	Line-of-sight (3 D spatial analysis)	Taleai & Amiri, 2017; Yin, 2017.
		Survey: perceived enclosure	Arellana et al., 2020.
	Visible landmarks	Street audit scoring method	Cambra & Moura, 2020; Moura et al., 2017.
Complexity	Building design diversity	Line-of-sight (2 D) and proportion of sky (3 D) spatial analysis	Yin, 2017.
		Survey: perceived building design complexity	Cook et al., 2013.
	Housing diversity	Ratio: number of housing typologies by mesh-blocks in an area	Boulange et al., 2018.
Human scale	Human scale of the BE	Spatial analysis: line-of-sight (2 D) and proportion of sky (3 D)	Yin, 2017.
	Building height	Average building height (m)	Moran et al., 2018.
Imageability	Imageability of the BE	Line-of-sight (2 D) and proportion of sky (3 D) spatial analysis	Yin, 2017.
Transparency	Building/Façade transparency	Line-of-sight (2 D) and proportion of sky (3 D) spatial analysis	Yin, 2017.
		Street audit scoring method	Moura et al., 2017.

4.5. Safety and security

Within the context of walkability, safety refers to pedestrians being protected from motorized traffic, while security refers to pedestrians being protected from crime and incivilities (Foster et al., 2019; Williams et al., 2018). As shown in Table 7, both attributes have been widely used for describing walkability, by using several measures, part of them based on self-reported perceptions of traffic safety and security from crime.

Traffic safety has been measured by the risk of having accidents, vehicular traffic exposure and by the adoption of traffic calming measures. Findings from the review indicated that high traffic volume was found to be a barrier to walking (Moran et al., 2017), the risk of accidents was associated with less physical activity (Lovasi et al., 2011), while areas providing safety conditions were associated with less sedentary time (Oyeyemi et al., 2019). Moreover, Golan et al. (2019) found that vehicular traffic was a major cause for concern, and several participants in their study in San Francisco tended to avoid major streets with many traffic lanes and high traffic volumes or high-speed limits. Inversely, Oyeyemi et al. (2017) concluded that, in Nigeria, traffic safety was not associated to walking for transport, while other studies carried out in in some American and European cities showed that traffic safety was not associated to active transport (Van Dyck et al., 2012). While in African cities people are more used to dealing with traffic conflicts (Oyeyemi et al., 2017), the adoption of traffic calming measures in the cities studied by Van Dyck et al. (2012) overall improved the perception of traffic safety.

Crime security was measured by considering various features directly linked to BE, such as street lighting, the presence of buildings with broken windows and graffiti, as well as indirect aspects such as homicide rates and the presence of police officers (Table 7). Because crime security data is difficult to obtain, many authors performed street audits and questionnaires to collect data and the pedestrian perceptions about crime security. Findings indicated that high perceived crime was associated with reduced use of public transport (Foster et al., 2019; Oyeyemi et al., 2017), less physical activity (Nichani et al., 2019), reduced walking to school (Esteban-Cornejo et al., 2016), and increased risk of obesity (Suglia et al., 2016). Particularly in some Latin American and Asian countries, security against crime was found to be a main problem deterring people from walking (Arellana et al., 2020; Larranaga et al., 2019; Moayedi et al., 2013). Contrarily, some authors also identified a lower connection between security and walking (Carlson et al., 2018), walking for public transport (Cerin et al., 2007) and physical activity (Bracy et al., 2014). These contradictory findings about the influence of safety and security on walking could be related to specificities of the case studies analyzed. More research may be necessary for clarifying the influence of these attributes in walkability.

4.6. Streetscape design

Streetscape is a term used to describe micro and street level features of the built environment and is usually defined by various perceptual qualities of the urban environment (Yin, 2017). The search showed that streetscape design has been measured by six attributes: esthetics (the most used), human scale, enclosure, complexity, transparency and imageability (Table 8). Streetscape design features have a significant impact on walking and on creating comfortable walking environments (Yin, 2017). More specifically, esthetics was positively associated with walking (Pelclová et al., 2013; Van Dyck et al., 2012). It was also considered a strong determinant of a recreational physical activity (Kaczynski, 2010; Nichani et al., 2019) and was found to be a more relevant attribute for females than for males (Golan et al., 2019). However, there are also contradictory findings. For example, in studies conducted by Carlson et al. (2018) and Oyeyemi et al. (2017), esthetics was not associated with recreational walking and physical activity. Oyeyemi et al. (2017) justified the contradictory finding by the fact that African people have lower expectations about esthetics in their cities.

As shown in Table 8, the assessment of design attributes was mostly based on subjective evaluations, especially through questionnaires conducted to find out about the pedestrians' perceptions. It is recognized that streetscape design data is often available, difficult to assess and requires intensive fieldwork/audits (King & Clarke, 2015; Shammas & Escobar, 2019). Nonetheless, some authors also performed objective evaluations by using ratios, such as the building height, and GIS-based approaches. For instance, Yin (2017) developed 2 D and 3 D GIS approaches for measuring five street-level design qualities objectively (imageability, enclosure, human scale, transparency, and complexity). She found significant correlations between the measured features and pedestrian volume.

5. Discussion

The review showed that the ways to assess walkability are as varied as the number of researchers that measure it. Walkability was evaluated by considering a changeable number of attributes, at different scales, often providing different and sometimes contradictory results. Ways of describing walkability were also found very variable and supported by different methods such as land use indexes (Frank et al., 2005; Golan et al., 2019; Habibian & Hosseinzadeh, 2018; Mayne et al., 2019), remote sensing and multi-criteria evaluations (Taleai & Yameqani, 2018), multi-level approaches (Clark et al., 2014; Pouliou et al., 2014; Zhou et al., 2020), topological relationships (Koohsari et al., 2016; McCormack et al., 2019), GIS evaluation tools (Shammas & Escobar, 2019; Yin, 2017), among others. In part, this is related to the different subject areas that work with walkability, reflecting the different authors' sensibility, skills and type of data available. On the other hand, the diversity of results and approaches can reflect the different walkable conditions provided by cities, different urban morphologies and specific issues and problems. Considering this and for each one of the seven categories analyzed, the following subsections provide a critical assessment of the findings obtained and some recommendations for future works.

5.1. Street network connectivity: Around 84% of the reviewed documents included street network connectivity attributes. These approaches are mostly based on road-based network systems, which may not be the most reliable and comprehensive process to assess the connectivity of a pedestrian network. Some studies suggest that evaluations based on footpath networks may provide a more robust basis for assessing the walkability. Attempts to solve this problem have mostly been performed in Europe and Asia, where measures such as footpath continuity, route directness, cul-de-sac density and street density have been analyzed (Cruise et al., 2017; Ellis et al., 2016; Habibian & Hosseinzadeh, 2018). Moreover, some problems associated to the use of intersection density were scarcely discussed. For example, intersection density could be greatly affected by the size of the analyzed area (Shashank & Schuurman, 2019), while areas with high intersection densities have more pedestrian crossings, which are associated with pedestrian crash frequency and risk (Moran et al., 2018). Some studies also suggest that routes with fewer intersections are more likely to be selected by pedestrians (Moran et al., 2018). Therefore, these aspects should be more explored in future works.

5.2. Land use density: these attributes were found in 81% of the revised documents. Density attributes have been particularly adopted in North America, Australia and Europe. But while in Australia, about 95% of these evaluations were merely supported on population/residential densities, in the USA and Europe, about 30% of the evaluations included amenity density. Nonetheless, from the overall attributes identified, population/residential densities were the most consistently associated with walking (Dias et al., 2020; Giles-Corti et al., 2014; Huang et al., 2019) and physical activity (Nichani et al., 2020; Tamura et al., 2019). However, it has been argued that there might be optimum threshold values beyond whose higher residential densities have a negative impact as sidewalks become crowded (Khanal & Babiano, 2016). This could be an interesting line of future research, as densities are changeable from country to country. Australian and North American cities have lower densities when compared to European and Asian cities, which have more compact and dense urban structures. This also means that the replication of land use density measures from Australian and North American indexes may not be appropriate and may require changes as already carried out by some authors. For example, Fan et al. (2018) modified the scale of assessing the residential density proposed by Frank et al. (2005) from 1 km to 100 m to fit the high residential density of Chinese cities. Also the scores assigned to residential density in Neighborhood Environment Walkability Scale for China are much higher than those assigned in Australian and in the USA due to the higher densities of the Chinese cities (Ye, 2020).

5.3. Land use diversity: these attributes, essentially land use mix, were also identified in more than a half of the reviewed documents. The presence of specific uses, such as retail, recreational, office and institutional, have been associated with walking and physical activities. However, many of these findings come from North American and Australian cities (Carlson et al., 2018; Clark et al., 2014; Frank et al., 2005, 2010; Lovasi et al., 2011). In Europe and Asia, some authors found a weak association between walking and land use mix/retail floor area (Buck et al., 2015; Habibian & Hosseinzadeh, 2018; Liao et al., 2020). The reason relies again on different urban morphologies: urban areas in North America and Australia are characterized by a lower degree of land use mix when compared with European/Asian cities (Liao et al., 2020). For that reason, the replication of land use mix measures from Australian and North American indexes may not be appropriate. Some authors developed indexes and tools by adapting attributes and weights of variables widely used in the American context to better fit the context of European and Asian cities (Grasser et al., 2017; Habibian & Hosseinzadeh, 2018; Stockton et al., 2016; Ye, 2020). For example, in a study carried out in Austria, Grasser et al. (2017) used larger street network buffers than those used in North America (1500 meters instead of 1000 meters), because European inhabitants usually walk more.

5.4. Pedestrian facility and comfort: these attributes reflect the physical conditions provided to pedestrians, showing how safe, attractive and convenient the routes can be. Besides being identified in 42% of the publications analyzed, many walkability evaluations were made without including pedestrian facility and comfort attributes (Ribeiro & Hoffimann, 2018; Rundle et al., 2019; Watson et al., 2020). The non-inclusion of pedestrian facility and comfort could lead to an over-estimation of walkability (Larranaga et al., 2019), while some studies have shown that measuring sidewalk width and slope instead of using other widely used attributes might address wider concerns about walkability (Shashank & Schuurman, 2019). Interestingly, the review showed that pedestrian facility and comfort attributes were more representative in studies conducted in South America and Asia (27% and 18% of all attributes, respectively). In these regions, evaluations were focused on the sidewalk characteristics. In turn, the exposure of pedestrians to noise and air pollution and their health implications were predominantly conducted in Canada, Europe and in the USA. However, pedestrian exposure to pollutants is apparently an under-researched area on walkability considering the relative low number of studies found.

5.5. Accessibility: these attributes appeared in 41% of the publications analyzed. In this category, access to amenities was the most used attribute in Europe, Australia and Canada (60% of the accessibility attributes), while access to public transport was more relevant in South America and in the USA (about 50%). According to the review, accessibility was often calculated by considering linear distances from specific dots, such as bus stops and residential areas. It is recognized that Euclidian distances do not reflect the real walkable distance that is often longer (Kartschmit et al., 2020). In this review, the number of studies using street network distances to analyze accessibility was very restricted (Adams et al., 2014; Ribeiro & Hoffimann, 2018). Furthermore, Ellis et al. (2016) were the only authors that used the real footpath network to measure route directness between locations. Thus, future accessibility evaluations should consider the use of real walkable distances and the use of real pedestrian network.

5.6. Safety and security: these attributes were more representative in South America (39%), Africa (29%) and, to a lesser extent, in the USA (16%). The review indicated that crime security was a main concern in South America (70% of the safety and security attributes), Asia (55%), USA (53%) and Africa (50%). In Europe and Canada, focus has been on traffic safety (around 70%), and not crime security. Findings regarding the influence of safety and security on walking were particularly inconsistent among the documents analyzed. For example, traffic safety was not related to walking for transport in Africa, because people are more used to dealing with traffic conflicts (Oyeyemi et al., 2017), while in countries such as Canada (Williams et al., 2018), USA (Lovasi et al., 2011) and Israel (Moran et al., 2017), traffic safety has a strong negative impact on walking. Identically, security from crime is a strong deterrent to walking in South America and Africa (Arellana et al., 2020; Oyeyemi et al., 2017), but was not associated with walking to public transport in countries such as Canada (Nichani et al., 2019) and Australia (Cerin et al., 2007). The inconsistencies may rely not only on the different safety conditions provided by the cities, but also on individual perceptions which are sometimes dissociated from the real conditions (Foster et al., 2019; Golan et al., 2019). In addition, it was concluded that safety and security were frequently not included in BE analysis and walkability indexes. The potential barrier effect of roads and community severance are other limitations identified in this review. Community severance is a concept linked to the physical separation promoted by roadways, which also causes other undesirable visual and esthetics impacts for pedestrians. These aspects were not found in the analyzed literature.

5.7. Streetscape design: these attributes were much less used to assess walkability. They globally correspond to less than 5% of the attributes measured. Design attributes are difficult to evaluate due to the lack of streetscape data (microscale attributes) and objective assessment methods. For these reasons, streetscape design attributes were mostly based on subjective evaluations. More research is necessary to provide additional evidence on the influence of streetscape design attributes on walkability and to improve objective methods for measuring design features, such as complexity and imageability.

5.8. Geographical differences: the review clearly indicated that walkability has become a widely researched topic in developed countries. In developing countries, the influence of BE attributes on walkability has not received enough attention. Further, cities in developing countries have their own characteristics, such as crime security and traffic safety issues, sidewalk invasion, poor planning and maintenance (Arellana et al., 2020), as well as different land-use, street patterns and eco-social parameters (Taleai & Yameqani, 2018). Thus, the use of BE attributes and measures usually adopted in developed countries could be particularly difficult and inappropriate for developing countries. Furthermore, the review demonstrated that in developed countries, BE attributes have been predominantly measured objectively, while in South America and Africa, subjective evaluations have prevailed. These differences may not only reflect the lack of objective BE data that is often found in developing countries (Khanal & Babiano, 2016; Taleai & Yameqani, 2018), but also still insufficient access to tools, skills and funds that prevent these countries from carrying out more research and using more objective methods and data.

5.9. Recommendations for future works: from the outcomes of this review and to create more comprehensive and holistic approaches regarding the influence of BE attributes on walkability and to plan and design more suitable pedestrian routes and spaces, the following aspects should be considered in future research and planning practices:

- Use real walkable distances rather than Euclidian-buffer distances to assess accessibility attributes.
- Evaluate street network connectivity and accessibility by considering the real pedestrian network (including footpaths, pedestrian crossings, bridges and tunnels) rather than the street network, which does not entirely correspond to the pedestrian environment.
- Include safety issues on street network connectivity evaluations. Areas with many intersections represent more pedestrian crossings, which are associated with pedestrian crash frequency and risk.
- Analyze the environmental impacts in-depth caused by motorized traffic (fumes, noise, pollution) on pedestrian behavior, health and comfort.
- Evaluate the influence of the barrier effect and community severance caused by roads on pedestrians under the topic of traffic safety domain.
- Provide further evidence about the impact of safety and security in walkability.
- Develop methods for measuring more objective design (and security) attributes, such as complexity and imageability.
- Include more streetscape attributes (pedestrian facility and comfort as well as streetscape design features) in walkability indexes and walkability assessments.
- Further research should be particularly conducted in developing countries to strengthen the evidence on the influence of BE attributes on walkability in these countries.

6. Conclusion

The present study provided a broad review of 132 documents retrieved from a search made in the Scopus and Web of Science databases exploiting the associations between walkability and BE attributes. The aim was to understand how the influence of BE attributes on walkability have been analyzed and measured to offer general guidance for researchers and urban planners about selecting attributes and measures for policies to improve walkability. The review was a challenge considering the number of documents analyzed and the wide use of the concept of walkability in various scientific disciplines, which have their own view of the concept.

Many attributes, measures and methods have been developed over the last years to evaluate their influence on walkability. A total of 32 built environment attributes and 63 measures were identified and analyzed. The review showed that street network connectivity, land use density and land use diversity were the three categories more analyzed, while intersection density, residential/population density land use mix were the BE attributes more used to measure walkability. In turn, attributes related to streetscape design were much less identified.

The number and diversity of attributes, measures and methods used, the lack of standardized practices and the inconsistencies in some results can make difficult the evaluation on how BE attributes influence walkability. Development of new measures and refinement of existing measures will certainly continue in the future. Thus, more studies should be conducted to evaluate the impact of BE associated with heterogeneous urban environments on walkability in more depth and to follow the continued evolution in this field.

This review has some limitations. First, the documents were selected according to the search rules described in the methodology. There may certainly be other relevant studies in the literature that were not included in this review. Second, because of the number of papers analyzed and the variety of attributes, measures and methods used, only the major findings were presented in this review instead of adopting a meta-analysis in a comprehensive way. Third, the review was limited to publications on Scopus and Web of Science, which excludes publications in other databases. Finally, the review was based on documents written in English. Contributions published in other widely spoken languages were not considered.

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