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Built environment attributes and their influence on walkability

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Built environment attributes and their influence on walkability

Fernando Fonseca, Paulo J. G. Ribeiro, Elisa Conticelli, Mona Jabbari, George Papageorgiou, Simona Tondelli, and R. U. I Antonio Rodrigues Ramos

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REVIEW ARTICLE

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environment attributes; pedestrians; sustainable

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2 3 Built environment attributes and their influence on walkability 4 O14 Fernando Fonseca^a (b), Paulo J. G. Ribeiro^a, Elisa Conticelli^b, Mona Jabbari^a, George Papageorgiou^c, 5 6 Simona Tondelli^b, and R. U. I Antonio Rodrigues Ramos^a 🝺 7 ^aCivil Engineering, University of Minho Centre for Territory Environment and Construction, Guimarães, Portugal; ^bDepartment of 8 O1 Architecture, University of Bologna, Bologna, Italy; ^cEuropean University Cyprus, Nicosia, Cyprus 9 10 11 ABSTRACT 12 13 14 15 16 17 18 19 2021 22 23 24 25 26 27 28 1. Introduction 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 CONTACT Fernando Fonseca 🖾 ffonseca@civil.uminho.pt 🗈 Civil Engineering, University of Minho Centre for Territory Environment and Construction, Campus 56 O2 de Azurém, Guimarães, 4800-058, Portugal 57 © 2021 Taylor & Francis Group, LLC

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.

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 85 way of doing physical activity that helps to prevent various 86 diseases. Physical inactivity is a leading risk factor for pre-87 mature mortality and various health problems associated to 88 sedentary lifestyles, such as obesity, diabetes, cancer 89 (Chandrabose et al., 2019; Creatore et al., 2016; Glazier 90 et al., 2014; Howell et al., 2019), depression (Berke et al., 91 92 2007; James et al., 2017), among others.

Due to the overall importance of walkability, the topic ⁹³ has often been reviewed in recent years. For example, Wong ⁹⁴ et al. (2011) reviewed 14 studies to examine the relationships between objective BE features and active school transporta-96 tion in children and adolescents; Wang et al. (2016) ana-97 lyzed BE barriers to walking and cycling; Cerin et al. (2007) 98 examined the influence of BE on enhancing the levels of 99 physical activity and active travel in older adults; Hall and 100 101Ram (2018) analyzed studies on walkability published in North America that were constructed with the Walk Score, 103 a tool which combines distance to destination, block length, 104 and intersection density; and Wang and Yang (2019) 105 reviewed the literature associating walkability with GIS.

106 In addition to the aforementioned studies, in this paper, 107a literature review is carried out on the influence of BE 108 attributes on walkability, covering all the subject areas, 109 regardless of the country and scale of analysis (microscale or 110 mesoscale) and the measures and methods adopted to assess 111

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mobility: walkabil-

ity; walking





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 162 electronic bibliographic databases: Scopus and Web of 163 Science. These two search tools have been widely used for 164 performing reviews and are considered consistent reposito-165 ries to search for scientific publications (Arellana et al., 166 2020; Hall & Ram, 2018; Yang et al., 2020). As the aim of 167 this review was to analyze the influence of BE attributes on 168 walkability, the search was carried out by using the follow-169 ing criteria in the title, abstract and keywords: "walkability" 170 and "built environment" and "walkability attribute" or syno-171 nyms of "attribute", including "criteria", "indicator", 172 "indices", "index", "measure", "score" and "variable". The 173

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. 174

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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.228
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Figure 2. Authors' keyword density diagram.

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Print

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 320 density" and "distance to amenities". Secondly, the various 321 BE attributes identified in the review were inserted into 322 seven main categories according to their characteristics 323 (Figure 3). For example, attributes such as "traffic volume", 324 "traffic speed", "speed limit", "number of lanes", "traffic 325 accidents" and "traffic calming devices" were classified into 326 the category "safety and security". The seven categories are: 327 i) land use density; ii) land-use diversity, iii) accessibility; iv) 328 street network connectivity; v) pedestrian facility and com-329 fort; vi) safety and security; and vii) streetscape design.

The selected categories were inspired and retrieved from 331 the Neighborhood Environment Walkability Scale defined 332 by Saelens et al. (2003), which became a widely used tool to ³³³ assess BE attributes (Leslie et al., 2005; Nichani et al., 2019; ³³⁴ Qureshi & Ho, 2014). These categories, the respective attri-bute 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 $_{348}$ population density and diverse land uses were more likely to $_{349}$ facilitate walking (Habibian & Hosseinzadeh, 2018). $_{350}$

4 🕞 F. FONSECA ET AL.

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



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

4.1.1. Land use density 391

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Land use density refers to the concentration of land uses 392 within an area. According to the review, land use density 393 has been mostly analyzed by using objective measures, espe-394 cially residential/population densities through density ratios 395 (Table 2). The review also showed that land use density 396 attributes are amongst the most used in walkability. 397

Findings indicated that high residential/population den-398 sities are often significantly correlated with walking and 399 physical activity (Clark et al., 2014; Frank et al., 2005; 400 Huang et al., 2019; Mayne et al., 2013; Ribeiro & 401 Hoffimann: 2018). In fact, areas with high population and 402 residential densities are not only attractive for retail and 403 services, but also for walking as they reduce the distance 404 and time of travel between residences and destinations 405 (Bhadra et al., 2015; Mayne et al., 2013). Nonetheless, in 406 Vancouver (Canada), Pouliou et al. (2014) found a negative 407 association between physical activity and residential density 408 due to individual reasons (age, gender). In the UK, Kenyon 409

and Pearce (2019) found that street connectivity and destination accessibility were more conducive to walking than high residential density.

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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

462 Land use diversity shows the degree to which there is a mix 463 of land uses within an area (Tsiompras & Photis, 2017). The 464 search showed that land use diversity was mostly evaluated 465 by considering two main attributes: land use mix and retail 466 floor area (Table 3). Both attributes have been mostly 467 assessed by using objective measures, such as entropy 468

Attributes	Measures	Methods	References	529
Residential	Posidential	Patio: number of residences/dwellings	Adams et al. 2014, 2015: Awyor & Melles, 2019: Bhadra	520
density	density	per specific land area	et al., 2015: Bödeker, 2018: Boulange et al., 2018: Bracy	530
actional	density		et al., 2014; Cerin et al., 2007; Chandrabose et al., 2019;	221
			Christiansen et al., 2014; Colley et al., 2019; Cook et al.,	532
			2013; Creatore et al., 2016; De Sa & Ardern, 2014; Deng	533
			et al., 2020; Dias et al., 2020; Dygryn et al., 2010;	534
			Esteban-Cornejo et al., 2016; Fan et al., 2018; Foster	534
			et al., 2019; Frank et al., 2005, 2010; Gebel et al., 2009; Ciles Certi et al., 2014; Clarier et al., 2014; Hill et al.	520
			2012: Howell et al. 2019: Huang et al. 2019: Kenvon &	530
			Pearce, 2019: Kerr et al., 2013, 2014: Koohsari et al.,	55
			2016, 2018; Kozo et al., 2012; Laatikainen et al., 2018;	538
			Learnihan et al., 2011; Lee et al., 2020; Macdonald et al.,	539
			2016; Marshall et al., 2009; Mayne et al., 2013, 2017,	540
			Mayne et al., 2019; McDonald et al., 2012; Mooney et al.,	54
			2020; Moran et al., 2017, 2018; Oliver et al., 2015; Reulieu et al., 2014; Ourochi & Ho. 2014; Ramozani	51
			et al. 2019: Rever et al. 2014: Ribeiro & Hoffimann	542
			2018; Roberts et al., 2015; Rubín et al., 2015; Shashank	54:
			& Schuurman, 2019; Taleai & Amiri, 2017; Todd et al.,	544
			2016; Van Dyck et al., 2012; Wang et al., 2017; Ye, 2020;	545
			Ye et al., 2017; Zhou et al., 2020.	546
		Survey: perceived residential density/	Gebel et al., 2009; Kaczynski, 2010; Leslie et al., 2005;	547
		types of residences in an area	Nichani et al., 2019; Oyeyemi et al., 2017, 2019; Peiciova et al. 2013: Oureshi & Ho. 2014: Tsiompras & Photis	5/15
			2017: Van Dyck et al., 2012: Ye, 2020: Ye et al., 2017.	540
Population	Population	Ratio: number of persons	Braun et al., 2016; Buck et al., 2015; Chen et al., 2019; Clark	545
density	density	per unit area	et al., 2014; Creatore et al., 2016; Cruise et al., 2017;	550
			Deng et al., 2020; Glazier et al., 2014; Habibian &	551
			Hosseinzadeh, 2018; Hanibuchi et al., 2012; Hankey	552
			et al., 2012; Howell et al., 2019; James et al., 2017;	553
			2018: Lamíquiz & Domínguez 2015: Lefebyre-Ropars	554
			et al., 2017; Li et al., 2018; Liao et al., 2020; Lovasi et al.,	554
			2011; McCormack et al., 2019; Nichani et al., 2020;	550
			Oluyomi et al., 2014; Orstad et al., 2018; Robinson et al.,	336
			2018; Rundle et al., 2019; Sehatzadeh et al., 2011;	557
			Shammas & Escobar, 2019; Sugiyama et al., 2019;	558
			et al. 2018	559
Amenity density	Amenity density	Ratio: number of amenities per	Adams et al., 2014, 2015; Braun et al., 2016; Buck et al.,	560
, ,	(including urban	unit area	2015; Chandrabose et al., 2019; Chen et al., 2019; Colley	561
	parks)		et al., 2019; Deng et al., 2020; Glazier et al., 2014; Golan	501
			et al., 2019; Hanibuchi et al., 2012; Howell et al., 2019;	304
			Huang et al., 2019; James et al., 2015, 2017; Kenyon & Poarce, 2010; Kerr et al., 2014; Lamíquiz & Domínguez	563
			2015: Lefebyre-Ropars et al. 2017: Li et al. 2018: Liao	564
			et al., 2020: McDonald et al., 2012: Nichani et al., 2020:	565
			Orstad et al., 2018; Pereira et al., 2020; Pouliou et al.,	566
			2014; Reisi et al., 2019; Rundle et al., 2019; Todd et al.,	567
			2016; Vargo et al., 2012; Wang et al., 2017; Ye, 2020; Ye	565
		Datia weber wash (maan ana	et al., 2017; Zhou et al., 2020.	500
		Ratio: urban park/green area	Pereira et al., 2020.	305
		Street audit scoring method	King, 2008: Scanlin et al., 2014	570
		Survey: perceived presence of	Larranaga et al., 2019.	571
		amenities in an area		572
Building density	Building density	Ratio: building cover	Robinson et al., 2018.	573
		per unit area		57/
loh	Job density	Ratio: number of jobs	Huang et al., 2019; Lamiguiz & Domínguez, 2015; Mooney	514
doncitu	·····	nor unit area	at al. 2020; Davaira at al. 2020; Cabateradab at al. 2011	574

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

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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 wellreported measures include the percentage and the number of specific land uses in an area. The number and type of

578 land uses considered was strongly changeable. The widely 579 replicated index of Frank et al. (2010) was based on five 580 uses (residential, retail, recreational, office and institutional), 581 but the review identified studies using a number ranging 582 from three (Taleai & Yameqani, 2018) to 17 land uses 583 (Hanibuchi et al., 2012). The analyzed documents globally 584 showed that mixed land uses providing nonresidential activ-585 ities (shops, restaurants, offices, banks, etc.) are correlated to 586

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

Attributes	Measures	Methods	References
and use nix	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.
		Patio: fraction/percentage	2012; Zhou et al., 2020.
		of specific land uses per unit area	Jacobs et al., 2013, Poster 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
letail floor rea	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;
		\sim	Laatikainen et al., 2018; Learnihan et al., 2011; Marshall et al., 2009; Mayne et al., 2013; Moran et al., 2017; Rever et al., 2014: Todd et al. 2016; Wang et al. 2017
	Crock retail	Survey: perceived retail use	Gebel et al., 2007. How et al. 2010. Democratis et al. 2010.
	Gross retail use	natio: gross retail area per unit area	Cerini et al., 2007; Moran et al., 2018; Kamezani et al., 2019.

628 pedestrian-friendly environments and high levels of physical 629 activity (Frank et al., 2005; Kaczynski, 2010; Lovasi et al., 630 2011), and walking (Carlson et al., 2018; Clark et al., 2014; 631 Fan et al., 2018). However, some authors also found negative 632 associations, namely in European and Asian cities (Buck 633 et al., 2015; Habibian & Hosseinzadeh, 2018; Liao et al., 634 2020). But even in the USA, Tamura et al. (2019) showed 635 that active people prefer less populated and mixed areas for 636 recreational walking. 637

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The retail floor area attribute indicates the amount of 638 available space for parking. This attribute was frequently cal-639 culated as a ratio (retail building floor area per retail land 640 areas). Areas with low retail density often have more space 641 available for car parking, while areas with high retail density 642 usually have less unused land and space for parking, which 643 are more attractive for walking (Learnihan et al., 2011; 644 Sehatzadeh et al., 2011). The retail floor area was correlated 645

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.

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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 703 attribute within this context. It was frequently measured as 704

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; McDonalc et al., 2012; Qureshi & Ho, 2014; Robinson et al., 2018; Williams et al., 2018.
		Walk Score Survey: perceived access/ distance to various amenities	Sugiyama et al., 2019; Williams et al., 2018. 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.
	Density of public transport stops	Survey: perceived distance/ access to stops/stations Ratio: number of stops per unit area	Arellana et al., 2020; Van Dyck et al., 2012. 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.,
Access to car park	Car parks and setbacks	Street audit scoring method Ratio: area of car parks/ total area Number of car parks Survey: perceptions about	2016; Vargo et al., 2012. Adu-Brimpong et al., 2017. Herrmann et al., 2017. An et al., 2019; Golan et al., 2019. Nichani et al., 2019; Qureshi & Ho, 2014; Van Dyck
Access to city center/CBD and other attractions	Distance to CBD/city center Distance to the coast	car parks in specific areas Distance between the CBD and residential areas Distance between residential areas and the coast	et al., 2012; Ye, 2020; Ye et al., 2017. An et al., 2019; Foster et al., 2019; Habibian & Hosseinzadeh, 2018; Lamíquiz & Domínguez, 2015 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.

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Access to public transport was also a frequently used 755 attribute, meaning that stops should be near enough to be 756 reached by walking (Table 4). It is widely recognized that 757 the shorter the distance to a stop, the higher the walking 758 activity and the greater the odds are of walking to public 759 transport (Boulange et al., 2018; Riggs & Sethi, 2020). Many 760 distances have been used to represent pedestrian catchment 761 areas for public transport stations, which are usually com-762 prised between 300 to 900 meters (An et al., 2019; Boulange 763

et al., 2018; Habibian & Hosseinzadeh, 2018). However, dis-796 tance is not the only critical factor for using public trans-797 port. For example, An et al. (2019) showed that the number 798 of transport stops in an area was more important than the 799 distance. For that reason, many authors measured the access 800 to public transport through the density of public transport 801 stops/stations (Table 4). Areas with high public transport 802 stop densities were positively correlated to walking (Buck 803 et al., 2015; Kerr et al., 2014) and to active people (Buck 804 et al., 2015; McDonald et al., 2012; Todd et al., 2016). 805

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As can be concluded from Table 4, access to car parks, 806 city centers and other urban attractions were much less ana- 807 lyzed attributes. Results suggest that the distance to these 808 destinations does not have a decisive influence on 809 810 walkability. 811

4.3. Street network connectivity

814 Street network connectivity can be understood as the direct-815 ness and availability of alternative routes between destinations (Ellis et al., 2016). Street network connectivity $\frac{317}{817}$ increases walkability in two ways: more interconnected 818 streets provide more potential routes for walking and 819 shorter distances to destinations (Tsiompras & Photis, 820 2017). Street connectivity is often described by measurable 821 properties of the street network, but there is no accepted 822

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

Attributes	Measures	Methods	References
ntersection density	Intersection	Ratio: number of street intersections	Adams et al., 2015; Awuor & Melles, 2019; Bödeker, 2018;
	density	of three or more legs and the	Boulange et al., 2018; Bracy et al., 2014; Chandrabose
		land area	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., 2 <mark>01</mark> 6; 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	Ratio: number of all intersections and	An et al., 2019; Bhadra et al., 2015; Braun et al., 2016; Buck
	density	the	et al., 2015; Cerin et al., 2007; Chen et al., 2019; De Sa &
	(all legs)	land area	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	Cerin et al., 2007; Gebel et al., 2009; Koohsari et al., 2015;
		intersection density	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	King & Clarke, 2015; Lefebvre-Ropars et al., 2017; McDonald
		per true intersections	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	Braun et al., 2016; Ellis et al., 2016; Habibian &
		intersections	Hosseinzadeh, 2018; Williams et al., 2018.
Cul-de-sacs	Cul-de-sac	Ratio: number of cul-de-sacs per	Habibian & Hosseinzadeh, 2018; Lamíquiz & Domínguez,
	density	unit area	2015; Sehatzadeh et al., 2011; Van Dyck et al., 2012;
			Ye, 2020.
		Survey: perceived presence of cul-	Qureshi & Ho, 2014; Kaczynski, 2010; Ye, 2020; Ye
		de-sacs	et al., 2017.
· ·		Street audit scoring method	Wang et al., 2017.
street	Street density	Ratio: total length of	Deng et al., 2020; Habibian & Hosseinzadeh, 2018; King &
density		street segments per	Clarke, 2015; Koohsari et al., 2020; Li et al., 2018;
		unit area	Sehatzaden et al., 2011; Tamura et al., 2019; Williams
			et al., 2018; Ye, 2020; Ye et al., 2017.
ontinuity	Sidewalk/	Katio: connected sidewalks/	Lee et al., 2020.
	Footpath	total sidewalks	
	continuity	Katio: least topological length/	Cambra & Moura, 2020; Moura et al., 2017.
		Euclidean distance	
		Kernel density estimation	Shashank & Schuurman, 2019.
Directness	Route	Footpath distance between	Ellis et al., 2016.
	directness	two points	M
		Ratio: shortest path/	moura et al., 2017.
		Euclidean distance	511:
	Pedshed analysis	Walkable catchments between two	Ellis et al., 2016.
		points (%)	511:
	Metric reach	Walkable catchments between two	Ellis et al., 2016.
_		points (km)	
ntegration	Topological	Space Syntax	Koohsari et al., 2016, 2018; Lamíquiz & Domínguez, 2015;
	analysis		McCormack et al., 2019; Sugiyama et al., 2019.
		Directional change analysis (> 20°)	Ellis et al., 2016.
Network	Network	Centrality, betweenness,	Yamagata et al., 2019.
micro analysis	micro analysis	angularity, convexity	

941 method for assessing it (Ellis et al., 2016). The search 942 showed that street network connectivity has been described 943 by a considerable number of different attributes of the 944 street/footpath network mostly by calculating ratios, such as 945 intersection and street densities (Table 5).

946 According to the review, intersection density was the 947 most used attribute to describe how connected a street net-948 work is (Table 5). This attribute has been widely measured 949 as the number of road intersections of three or more links 950 in an area, but many authors also considered the ratio of all 951 street intersections in an area. Intersection density was asso-952 ciated with physical activity and walking (Buck et al., 2015; 953 Cruise et al., 2017; Frank et al., 2005) and was described by 954 Ellis et al. (2016) as the best measure of street network con-955 nectivity. Some studies also found that intersection density 956 may have less influence on walkability. For instance, Moran 957 et al. (2018) concluded that routes with fewer intersections 958 (lesser crossings) are more likely to be selected by pedes-959 trians due to safety reasons. While some studies showed a 960 positive association between intersection density and walking 961 to public transport (Nichani et al. (2019), other authors 962 found the opposite. For example, in Shanghai, An et al. 963 (2019) concluded that intersection density was not positively 964 associated with walking to train stations. Well-connected 965 streets and the diversity of land uses in the city center 966 decreased the number of train passengers and increased 967 walking and cycling. 968

Some other attributes and measures are derived from 969 street intersection, such as block length, link to node ratio 970 and cul-de-sac (or T-intersection) density. From these, culde-sacs are recognized as leading to poor connectivity as 972 they represent non-grid street patterns and dead-ends (Sehatzadeh et al., 2011).

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974 Street density, described as the total length of street seg-975 ments per unit area, was adopted in some studies, but also 976 with diverse results. While some authors showed that street 977 density promotes active travel (Cervero et al., 2009), other 978 studies indicated less influence of this attribute on walkabil-979 ity. More specifically, Tamura et al. (2019) found that high 980 street density areas were characterized by less physical activ-981 ity levels, because people avoid walking in areas with many 982 crossings. Sehatzadeh et al. (2011) also found that street 983 density does not have a significant effect on walking but 984 showed a positive association with the number of house-985 hold cars. 986

A restricted number of authors argue that connectivity 987 should be analyzed by considering the real pedestrian net-988 work, instead of using the street/road network (Ellis et al., 989 2016; Tsiompras & Photis, 2017). Using road-networks not 990 only ignores the fact that some routes are unsuitable and 991 undesirable for walking, but also footpaths and informal 992 paths, such as footbridges and paths through parks, which 993 are primarily used by pedestrians (Cruise et al., 2017; Tribby 994 et al., 2016). For that reason, some authors focused on eval-995 uating footpath networks, by analyzing aspects such as the 996 sidewalk continuity and footpath directness between specific 997 points. However, these attempts have been limited, mostly 998 because disaggregated footpath data are difficult to obtain. 999

Finally, some authors also evaluated how street networks 1000 are integrated. Integration relies on the topological represen- 1001 tation of the built environment: a more integrated street seg- 1002 ment requires fewer turns to reach a destination from other 1003 streets within the network (McCormack et al., 2019). By 1004 using space syntax for measuring street integration, some 1005 authors, such as McCormack et al. (2019) found a positive ¹⁰⁰⁶ association between topological distance and walking for 1007 transport. However, this attribute was found to weakly ¹⁰⁰⁸ described connectivity and walking when applied to small 1009 and dense urban areas, where turns are the norm (Ellis 1010 1011 et al., 2016; Lamíquiz & Domínguez, 2015). 1012

4.4. Pedestrian facility and comfort

1015 This category includes the following three pedestrian facility 1016 and comfort attributes: sidewalk characteristics, slopes and 1017 environmental conditions at the street level. 1018

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According to the review, the presence and density of 1019 sidewalks in an area, the width and overall characteristics of 1020sidewalks and the presence of obstructions on sidewalks 1021 were the most extensively measured attributes (Table 6). 1022 The overall findings indicate that a sidewalk with sufficient 1023width, without obstructions, in a good condition and 1024 designed according to the desired pedestrian level of service, 1025 is safe and convenient for pedestrians (Vargo et al., 2012; 1026 Wang et al., 2016). More specifically, the existence and per- 1027 centage of sidewalks were consistently correlated with walk- 1028 ing (Vargo et al., 2012). Narrow sidewalks with obstacles 1029 reduce the walkability of an area (Tsiompras & Photis, 1030 2017), while sidewalks in a poor condition are considered a 1031 barrier for walking (Larranaga et al., 2019), especially for 1032 elderly and impaired people (Moura et al., 2017). In turn, 1033 street furniture and support facilities (benches, water foun- 1034 tains, etc.) have been rarely included in the evaluation of 1035 walkability. Inversely to the previous categories, many of 1036 these attributes, especially the condition of the sidewalk sur- 1037 face, presence and density of sidewalks and sidewalk 1038 obstructions, have been mostly evaluated by performing 1039street audits and questionnaires. This type of objective data 1040is difficult to obtain and, for that reason, sidewalk data are 1041& ¹⁰⁴² often replaced by street network (Shashank 1043 Schuurman, 2019). 1044

Slopes are another attribute included in this category. 1045 Slopes affect the walking speed and time, the comfort and safety of walking, as well as the energy and effort required 1046 for walking (Kerr et al., 2013; Taleai & Yameqani, 2018). 1048 Nonetheless, the review showed that slopes were only con-1049 sidered by a relatively reduced number of authors. Evidence 1050 indicated that slopes have a strong impact on walkability. 1051 For example, in Porto Alegre, Brazil, topography was found 1052 to be one of the most important barriers for walking 1053 (Larranaga et al., 2019); in Bogota, Colombia, high slopes 1054 were correlated with walking for public transport (Kerr 1055 et al., 2013); and in Lisbon, Portugal, some of the less walk- 1056 able areas found by Moura et al. (2017) were also character- 1057 ized by high slopes. 1058

1059 Table 6. Pedestrian facility and comfort attributes, measures and methods.

1059	Table 6. Pedes	trian facility and comfort attributes, i	measures and methods.		111
1060	Attributes	Measures	Methods	References	111
1061	Sidewalk	Presence and	Ratio: streets having at least one sidewalk/	Lee et al., 2020; Vargo et al., 2012.	112
1062	characteristics	density of sidewalks	total streets	Chan at al. 2010; Clark at al. 2014; Huang at al. 2010;	112
1063			/road length	Laatikainen et al., 2018; Williams et al., 2018.	112
1064			Dichotomous scoring method	Hollenstein & Bleisch, 2016.	112
1065			Survey: perceived presence of sidewalks	Kaczynski, 2010; Orstad et al., 2018; Pelclová et al., 2013;	1124
066				Roberts et al., 2015; Van Dyck et al., 2012 Ye	112
067		Sidewalk width	Average sidewalk width along the street	Reisi et al., 2019.	112
1068			Ratio: streets having wide sidewalks/ total	Lee et al., 2020.	112
1060			streets having sidewalks		112
1009			Street audit scoring method	Moura et al., 2017; Seagle et al., 2008.	1120
1070			Survey: perceived sidewalk width	Photis 2017	112
10/1		Support facilities	Number of pedestrian facilities	Reisi et al., 2019.	1130
1072		and furniture	Street audit scoring method	Moura et al., 2017; Scanlin et al., 2014.	113
073		Condition of the sidewalk surface	Ratio: number of requests for clean-up	Golan et al., 2019.	1132
1074			sidewalks per unit area Ratio: street baying trashes/ total streets	lee et al. 2020. Lovasi et al. 2011	113.
1075			Street audit scoring method	Adu-Brimpong et al., 2017; Cambra & Moura, 2020; King,	1134
1076			<u> </u>	2008; Moura et al., 2017; Scanlin et al., 2014; Seagle	113
1077				et al., 2008; Wang et al., 2017.	1130
1078			Survey: perceived condition and	Arellana et al., 2020; Carlson et al., 2018; Cerin et al., 2007; Cook et al. 2013: Larranaga et al. 2019: Leslie et al.	113
079			quality of the pedesthan facility	2005; Nichani et al., 2019; Oveyemi et al., 2017, 2019;	113
1080				Qureshi & Ho, 2014; Tsiompras & Photis, 2017; Ye	1130
1081				et al., 2017.	114
1082		Sidewalk	Number of obstacles along sidewalks Street audit scoring method	Keisi et al., 2019. King 2008: Scanlin et al. 2014	11/
1002		obstructions	Survey: perception of obstacles	Arellana et al., 2020; Nichani et al., 2019; Qureshi & Ho,	114
1003			on sidewalks	2014; Tsiompras & Photis, 2017; Van Dyck et al., 2012;	114.
1004	Classes	A	Disited elevention and determined	Ye, 2020; Ye et al., 2017.	114.
1085	Slopes	Average slope	Digital elevation model analysis	Deng et al., 2020; Golan et al., 2019; Taleal & Yamegani 2018	1144
1086			Ratio: streets having flat sidewalks/ total	Lee et al., 2020.	114:
1087			streets having sidewalks		1140
1088			Difference between the maximum and	Fan et al., 2018.	114'
1089			minimum elevation Street audit scoring method	King 2008: Moura et al. 2017: Scaplin et al. 2014: Wang	1148
1090			Street addit sconing method	et al., 2017.	114
1091			Survey: perceived street slopes	Larranaga et al., 2019; Nichani et al., 2019; Qureshi & Ho,	1150
1092	F	Community land		2014; Ye, 2020; Ye et al., 2017.	115
1093	Environment	Greenness level	(satellite imagery)	Nichani et al., 2020; Kobinson et al., 2018; Taleai & Amiri, 2017: Taleai & Yamegani, 2018: Tamura et al., 2019	1152
1094		Street tree density	Ratio: streets with trees/ total streets	Lee et al., 2020.	115
095			Ratio: thousands of trees per km ²	Lovasi et al., 2011.	1154
1096			Area covered by trees/green areas	Reisi et al., 2019.	115
1097		Tree canony cover	Proportion of the total area of trees/	Areliana et al., 2020; COOK et al., 2013; Nichani et al., 2019. Awuor & Melles 2019: Herrmann et al. 2017	115
1008		nee earlopy cover	average tree cover		115
1000		Tree shading	Street audit scoring method	King, 2008; Scanlin et al., 2014.	115
1100		Sun/shade level	3D spatial analysis (GIS)	Shammas & Escobar, 2019; Taleai & Amiri, 2017.	1150
1100		Land Surface Temperature Noise level	Remote sensing Spatial analysis from poise maps	raiear & Yameqani, 2018. Shammas & Escobar 2019	115
1101			Ratio: streets having noise from factories	Lee et al., 2020.	116
1102			and other sources /total streets		116
1103		Air pollution	Outdoor exposure to air pollutants by using	Awuor & Melles, 2019; Hankey et al., 2012; Howell et al.,	1162
1104			air pollution models and concentrations	2019; James et al., 2015; Pereira et al., 2020.	116.
105					11/

1107 The environmental conditions at street level is the third 1108 attribute included in this category. In the analyzed docu-1109 ments, the greenness level and street tree density were the 1110 two most used measures for describing the environment at 1111 street level. According to the review, street trees were 1112 found to be positively associated with physical activity 1113 (Lovasi et al., 2011; Tamura et al., 2019), healthy pedestrian 1114 routes (Taleai & Yameqani, 2018) and more pleasant walk-1115 able areas (Herrmann et al., 2017). The presence and level 1116 of tree shading have been considered by some authors as 1117

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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 trees globally found the street were not in 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

References

Table 7. Safety and security attributes, measures and methods. Attributes Measures Methods Traffic Risk of accidents Ratio: pedestrian-automobile injuries Lovasi et al., 2011. safety per thousand residents Survey: perceived risk of Larranaga et al., 2019. traffic accidents Vehicular traffic exposure Ratio: length of roads by the average

2		Vehicular traffic exposure	Ratio: length of roads by the average	Williams et al., 2018.	124
3			Ratio: busy or large streets by all	lee et al. 2020	124
4			the streets		124
5			Maximum traffic speed limit per area	Golan et al., 2019; Williams et al., 2018.	124
6			Ratio: vehicles/day (traffic volume)	Lovasi et al., 2011.	124
7			Iraffic density on nearest street	Robinson et al., 2018. Reisi et al., 2019	124
8			conflict points		124
0			Dichotomous scoring method	Hollenstein & Bleisch, 2016.	12/
0			Street audit scoring method	Cambra & Moura, 2020; King, 2008; Moura et al., 2017;	12-
1				Scanlin et al., 2014; Seagle et al., 2008.	124
1			Survey: perceived traffic safety	Areliana et al., 2020; Bracy et al., 2014; Carison et al., 2018; Cerin et al. 2007: Esteban-Corneio et al. 2016: Leslie	12:
2				et al., 2005: Nichani et al., 2019: Ovevemi et al., 2017.	12:
3				2019; Pelclová et al., 2013; Qureshi & Ho, 2014; Van	125
4				Dyck et al., 2012; Ye, 2020; Ye et al., 2017.	12:
5		Traffic calming	Ratio: number of traffic calming	Reisi et al., 2019; Williams et al., 2018.	12:
6		for pedestrian	devices/facilities per area Ratio: streets having any traffic	lee et al 2020	125
7		Surcey	calming device/total streets		124
8			Ratio: formal intersection/total	Moura et al., 2017.	12
0			street crossings		12.
2 0			Dichotomous scoring method	Hollenstein & Bleisch, 2016.	12.
0			Survey: perceived presence of traffic	Arellana et al. 2020: Bracy et al. 2014: Carlson et al. 2018:	12.
1			calming devices	Esteban-Corneio et al., 2016.	120
2	Crime	Crimes and social incivilities	Ratio: homicides per number	Lovasi et al., 2011.	120
3	security		of residents		120
4			Crime density: Number of crimes in	Deng et al., 2020; Foster et al., 2019; Golan et al., 2019;	120
5			1000 inhabitants	King, 2008; Liao et al., 2020.	120
6			Survey: perception of criminality/	Arellana et al., 2020; Bracy et al., 2014; Carlson et al., 2018;	120
7			crime security in an area	Cerin et al., 2007; Esteban-Cornejo et al., 2016; Foster	120
8				et al., 2019; Leslie et al., 2005; Nichani et al., 2019;	12
0				Orstad et al., 2018; Oyeyemi et al., 2017, 2019; Pelclova	120
9				Ye 2020: Ye et al. 2017	120
0		Police stations/officers	Ratio: number of police officers per	Larranaga et al., 2019.	120
1			inhabitants	5	12
2			Survey: perception of police stations	Arellana et al., 2020; Larranaga et al., 2019.	12'
3		Visual surveillance systems	Survey: perceived security resulting	Arellana et al., 2020; Moayedi et al., 2013.	12'
4			surveillance systems		127
5		Street lighting	Ratio: street lightings/ total length	Lee et al., 2020.	127
6			of streets		12
7			Number/count of street lighting	Reisi et al., 2019.	12
0			Street audit scoring method	Scanlin et al., 2014; Seagle et al., 2008. Kastynski, 2010	12
0		Graffiti, broken windows	Ratio: number of reported incidences	Golan et al., 2019.	12
9		diama, broken vindows	per unit area		12
0			Ratio: streets having graffiti/	Lee et al., 2020.	12'
1			total streets	• · · · · · · · · · · · · · · · · · · ·	128
2			Street audit scoring method	Scanlin et al., 2014.	128
3			on huildings	Areliana et al., 2020.	128
4		Unwanted people and dogs	Ratio: number of requests per	Golan et al., 2019.	128
2			Street audit scoring method	King, 2008; Scanlin et al., 2014.	128
6		Home security practices	Street audit scoring method	King, 2008.	128
7		Pedestrian volume/ Conviviality	Street audit scoring method	Cambra & Moura, 2020.	12
			Survey: perception of pedestrian flow	Arellana et al., 2020; Cook et al., 2013; Ye, 2020; Ye	128
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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 1291 have been mostly assessed independently, which requires 1292 more research in this field.

1295 Table 8. Streetscape design attributes, measures and methods

Attributes	Measures	Methods	References
Esthetics	Esthetics of the BE	Street audit scoring method Survey: perceived esthetic features of the neighborhood	King, 2008; Scanlin et al., 2014; Wang et al., 2017. 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) Survey: perceived enclosure	Taleai & Amiri, 2017; Yin, 2017. 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	Line-of-sight (2 D) and proportion of	Yin, 2017.
	transparency	sky (3 D) spatial analysis	
		Street audit scoring method	Moura et al., 2017.

4.5. Safety and security 1317

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1318 Within the context of walkability, safety refers to pedestrians 1319 being protected from motorized traffic, while security refers 1320 to pedestrians being protected from crime and incivilities 1321 (Foster et al., 2019; Williams et al., 2018). As shown in 1322 Table 7, both attributes have been widely used for describing 1323 walkability, by using several measures, part of them based 1324 on self-reported perceptions of traffic safety and security 1325 from crime. 1326

Traffic safety has been measured by the risk of having 1327 accidents, vehicular traffic exposure and by the adoption of 1328 traffic calming measures. Findings from the review indicated 1329 that high traffic volume was found to be a barrier to walking 1330 (Moran et al., 2017), the risk of accidents was associated 1331 with less physical activity (Lovasi et al., 2011), while areas 1332 providing safety conditions were associated with less seden-1333 tary time (Oyeyemi et al., 2019). Moreover, Golan et al. 1334 (2019) found that vehicular traffic was a major cause for 1335 concern, and several participants in their study in San 1336 Francisco tended to avoid major streets with many traffic 1337 lanes and high traffic volumes or high-speed limits. 1338 Inversely, Oyeyemi et al. (2017) concluded that, in Nigeria, 1339 traffic safety was not associated to walking for transport, 1340 while other studies carried out in in some American and 1341 European cities showed that traffic safety was not associated 1342 to active transport (Van Dyck et al., 2012). While in African 1343 cities people are more used to dealing with traffic conflicts 1344 (Oyeyemi et al., 2017), the adoption of traffic calming meas-1345 ures in the cities studied by Van Dyck et al. (2012) overall 1346 improved the perception of traffic safety. 1347

Crime security was measured by considering various fea-1348 tures directly linked to BE, such as street lighting, the pres-1349 ence of buildings with broken windows and graffiti, as well 1350 as indirect aspects such as homicide rates and the presence 1351 of police officers (Table 7). Because crime security data is 1352 difficult to obtain, many authors performed street audits 1353

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.

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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.

1418 As shown in Table 8, the assessment of design attributes 1419 was mostly based on subjective evaluations, especially 1420 through questionnaires conducted to find out about the 1421 pedestrians' perceptions. It is recognized that streetscape 1422 design data is often available, difficult to assess and requires 1423 intensive fieldwork/audits (King & Clarke, 2015; Shammas 1424 & Escobar, 2019). Nonetheless, some authors also performed 1425 objective evaluations by using ratios, such as the building 1426 height, and GIS-based approaches. For instance, Yin (2017) 1427 developed 2D and 3D GIS approaches for measuring five 1428 street-level design qualities objectively (imageability, enclos-1429 ure, human scale, transparency, and complexity). She found 1430 significant correlations between the measured features and 1431 pedestrian volume. 1432

5. Discussion

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1435 The review showed that the ways to assess walkability are as 1436 varied as the number of researchers that measure it. 1437 Walkability was evaluated by considering a changeable num-1438 ber of attributes, at different scales, often providing different 1439 and sometimes contradictory results. Ways of describing 1440 walkability were also found very variable and supported by 1441 different methods such as land use indexes (Frank et al., 1442 2005; Golan et al., 2019; Habibian & Hosseinzadeh, 2018; 1443 Mayne et al., 2019), remote sensing and multi-criteria evalu-1444 ations (Taleai & Yameqani, 2018), multi-level approaches 1445 (Clark et al., 2014; Pouliou et al., 2014; Zhou et al., 2020), 1446 topological relationships (Koohsari et al., 2016; McCormack 1447 et al., 2019), GIS evaluation tools (Shammas & Escobar, 1448 2019; Yin, 2017), among others. In part, this is related to 1449 the different subject areas that work with walkability, reflect-1450 ing the different authors' sensibility, skills and type of data 1451 available. On the other hand, the diversity of results and 1452 approaches can reflect the different walkable conditions pro-1453 vided by cities, different urban morphologies and specific 1454 issues and problems. Considering this and for each one of 1455 the seven categories analyzed, the following subsections pro-1456 vide a critical assessment of the findings obtained and some 1457 recommendations for future works. 1458

5.1. Street network connectivity: Around 84% of the 1459 reviewed documents included street network connectivity 1460 attributes. These approaches are mostly based on road-based 1461 network systems, which may not be the most reliable and 1462 comprehensive process to assess the connectivity of a pedes-1463 trian network. Some studies suggest that evaluations based 1464 on footpath networks may provide a more robust basis for 1465 assessing the walkability. Attempts to solve this problem 1466 have mostly been performed in Europe and Asia, where 1467 measures such as footpath continuity, route directness, cul-1468 de-sac density and street density have been analyzed (Cruise 1469 et al., 2017; Ellis et al., 2016; Habibian & Hosseinzadeh, 1470 2018). Moreover, some problems associated to the use of 1471

intersection density were scarcely discussed. For example, 1472 intersection density could be greatly affected by the size of 1473 the analyzed area (Shashank & Schuurman, 2019), while 1474 areas with high intersection densities have more pedestrian 1475 crossings, which are associated with pedestrian crash fre- 1476 quency and risk (Moran et al., 2018). Some studies also sug- 1477 gest that routes with fewer intersections are more likely to 1478 be selected by pedestrians (Moran et al., 2018). Therefore, 1479 these aspects should be more explored in future works.

5.2. Land use density: these attributes were found in 81% 1481 of the revised documents. Density attributes have been par- 1482 ticularly adopted in North America, Australia and Europe. 1483 But while in Australia, about 95% of these evaluations were ¹⁴⁸⁴ merely supported on population/residential densities, in the 1485 USA and Europe, about 30% of the evaluations included ¹⁴⁸⁶ amenity density. Nonetheless, from the overall attributes 1487 identified, population/residential densities were the most ¹⁴⁸⁸ consistently associated with walking (Dias et al., 2020; Giles- ¹⁴⁸⁹ Corti et al., 2014; Huang et al., 2019) and physical activity 1490 (Nichani et al., 2020; Tamura et al., 2019). However, it has ¹⁴⁹¹ been argued that there might be optimum threshold values ¹⁴⁹² beyond whose higher residential densities have a negative ¹⁴⁹³ impact as sidewalks become crowded (Khanal & Babiano, 1494 1495 2016). This could be an interesting line of future research, 1496 as densities are changeable from country to country. Australian and North American cities have lower densities 1497 1498 when compared to European and Asian cities, which have 1499 more compact and dense urban structures. This also means 1500 that the replication of land use density measures from 1501 Australian and North American indexes may not be appro-1502 priate and may require changes as already carried out by 1503 some authors. For example, Fan et al. (2018) modified the 1504 scale of assessing the residential density proposed by Frank 1505 et al. (2005) from 1 km to 100 m to fit the high residential 1506 density of Chinese cities. Also the scores assigned to resi-1507 dential density in Neighborhood Environment Walkability 1508 Scale for China are much higher than those assigned in 1509 Australian and in the USA due to the higher densities of the 1510 Chinese cities (Ye, 2020). 1511

5.3. Land use diversity: these attributes, essentially land 1512 use mix, were also identified in more than a half of the 1513 reviewed documents. The presence of specific uses, such as $\frac{1510}{1514}$ retail, recreational, office and institutional, have been associ-1515 ated with walking and physical activities. However, many of $\frac{11}{1516}$ these findings come from North American and Australian 1517 cities (Carlson et al., 2018; Clark et al., 2014; Frank et al., 1518 2005, 2010; Lovasi et al., 2011). In Europe and Asia, some 1519 authors found a weak association between walking and land 1520 use mix/retail floor area (Buck et al., 2015; Habibian & 1521 Hosseinzadeh, 2018; Liao et al., 2020). The reason relies 1522 again on different urban morphologies: urban areas in 1523 North America and Australia are characterized by a lower 1524 degree of land use mix when compared with European/ 1525 Asian cities (Liao et al., 2020). For that reason, the replica-1526 tion of land use mix measures from Australian and North 1527 American indexes may not be appropriate. Some authors 1528 developed indexes and tools by adapting attributes and 1529 weights of variables widely used in the American context to 1530 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.

1538 5.4. Pedestrian facility and comfort: these attributes 1539 reflect the physical conditions provided to pedestrians, 1540 showing how safe, attractive and convenient the routes can 1541 be. Besides being identified in 42% of the publications ana-1542 lyzed, many walkability evaluations were made without 1543 including pedestrian facility and comfort attributes (Ribeiro 1544 & Hoffimann, 2018; Rundle et al., 2019; Watson et al., 1545 2020). The non-inclusion of pedestrian facility and comfort 1546 could lead to an over-estimation of walkability (Larranaga 1547 et al., 2019), while some studies have shown that measuring 1548 sidewalk width and slope instead of using other widely used 1549 attributes might address wider concerns about walkability 1550 (Shashank & Schuurman, 2019). Interestingly, the review 1551 showed that pedestrian facility and comfort attributes were 1552 more representative in studies conducted in South America 1553 and Asia (27% and 18% of all attributes, respectively). In 1554 these regions, evaluations were focused on the sidewalk 1555 characteristics. In turn, the exposure of pedestrians to noise 1556 and air pollution and their health implications were pre-1557 dominantly conducted in Canada, Europe and in the USA. 1558 However, pedestrian exposure to pollutants is apparently an 1559 under-researched area on walkability considering the relative 1560 low number of studies found.

1561 5.5. Accessibility: these attributes appeared in 41% of the 1562 publications analyzed. In this category, access to amenities 1563 was the most used attribute in Europe, Australia and 1564 Canada (60% of the accessibility attributes), while access to 1565 public transport was more relevant in South America and in 1566 the USA (about 50%). According to the review, accessibility 1567 was often calculated by considering linear distances from 1568 specific dots, such as bus stops and residential areas. It is 1569 recognized that Euclidian distances do not reflect the real 1570 walkable distance that is often longer (Kartschmit et al., 1571 2020). In this review, the number of studies using street net-1572 work distances to analyze accessibility was very restricted 1573 (Adams et al., 2014; Ribeiro & Hoffimann, 2018). 1574 Furthermore, Ellis et al. (2016) were the only authors that 1575 used the real footpath network to measure route directness 1576 between locations. Thus, future accessibility evaluations 1577 should consider the use of real walkable distances and the 1578 use of real pedestrian network. 1579

5.6. Safety and security: these attributes were more repre-1580 sentative in South America (39%), Africa (29%) and, to a 1581 lesser extent, in the USA (16%). The review indicated that 1582 crime security was a main concern in South America (70% 1583 of the safety and security attributes), Asia (55%), USA (53%) 1584 and Africa (50%). In Europe and Canada, focus has been on 1585 traffic safety (around 70%), and not crime security. Findings 1586 regarding the influence of safety and security on walking 1587 were particularly inconsistent among the documents ana-1588 lyzed. For example, traffic safety was not related to walking 1589

1590 for transport in Africa, because people are more used to 1591 dealing with traffic conflicts (Oyeyemi et al., 2017), while in 1592 countries such as Canada (Williams et al., 2018), USA 1593 (Lovasi et al., 2011) and Israel (Moran et al., 2017), traffic 1594 safety has a strong negative impact on walking. Identically, 1595 security from crime is a strong deterrent to walking in 1596 South America and Africa (Arellana et al., 2020; Oyeyemi 1597 et al., 2017), but was not associated with walking to public transport in countries such as Canada (Nichani et al., 2019) 1598 1599 and Australia (Cerin et al., 2007). The inconsistencies may 1600 rely not only on the different safety conditions provided by 1601 the cities, but also on individual perceptions which are 1602 sometimes dissociated from the real conditions (Foster et al., 1603 2019; Golan et al., 2019). In addition, it was concluded that 1604 safety and security were frequently not included in BE ana-1605 lysis and walkability indexes. The potential barrier effect of 1606 roads and community severance are other limitations identi-1607 fied in this review. Community severance is a concept linked 1608 to the physical separation promoted by roadways, which 1609 also causes other undesirable visual and esthetics impacts for 1610 pedestrians. These aspects were not found in the ana-1611 lyzed literature. 1612

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.

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1623 5.8. Geographical differences: the review clearly indicated 1624 that walkability has become a widely researched topic in 1625 developed countries. In developing countries, the influence 1626 of BE attributes on walkability has not received enough 1627 attention. Further, cities in developing countries have their 1628 own characteristics, such as crime security and traffic safety 1629 issues, sidewalk invasion, poor planning and maintenance 1630 (Arellana et al., 2020), as well as different land-use, street 1631 patterns and eco-social parameters (Taleai & Yameqani, 1632 2018). Thus, the use of BE attributes and measures usually 1633 adopted in developed countries could be particularly difficult 1634 and inappropriate for developing countries. Furthermore, 1635 the review demonstrated that in developed countries, BE 1636 attributes have been predominantly measured objectively, 1637 while in South America and Africa, subjective evaluations 1638 have prevailed. These differences may not only reflect the 1639 lack of objective BE data that is often found in developing 1640 countries (Khanal & Babiano, 2016; Taleai & Yameqani, 1641 2018), but also still insufficient access to tools, skills and 1642 funds that prevent these countries from carrying out more 1643 research and using more objective methods and data. 1644

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 1649 pedestrian routes and spaces, the following aspects should 1650 be considered in future research and planning practices: 1651

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- Use real walkable distances rather than Euclidian-buffer distances to assess accessibility attributes.
- 1654 Evaluate street network connectivity and accessibility by 1655 considering the real pedestrian network (including foot-1656 paths, pedestrian crossings, bridges and tunnels) rather 1657 than the street network, which does not entirely corres-1658 pond to the pedestrian environment.
- 1659 Include safety issues on street network connectivity eval-1660 uations. Areas with many intersections represent more 1661 pedestrian crossings, which are associated with pedestrian 1662 crash frequency and risk. 1663
 - Analyze the environmental impacts in-depth caused by motorized traffic (fumes, noise, pollution) on pedestrian behavior, health and comfort.
- 1666 • Evaluate the influence of the barrier effect and commu-1667 nity severance caused by roads on pedestrians under the 1668 topic of traffic safety domain.
- 1669 • Provide further evidence about the impact of safety and 1670 security in walkability. 1671
 - 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 attributes influence of BE on walkability in these countries.

6. Conclusion

1685 The present study provided a broad review of 132 docu-1686 ments retrieved from a search made in the Scopus and Web 1687 of Science databases exploiting the associations between 1688 walkability and BE attributes. The aim was to understand 1689 how the influence of BE attributes on walkability have been 1690 analyzed and measured to offer general guidance for 1691 researchers and urban planners about selecting attributes 1692 and measures for policies to improve walkability. The review 1693 was a challenge considering the number of documents ana-1694 lyzed and the wide use of the concept of walkability in vari-1695 ous scientific disciplines, which have their own view of 1696 the concept. 1697

Many attributes, measures and methods have been devel-1698 oped over the last years to evaluate their influence on walk-1699 ability. A total of 32 built environment attributes and 63 1700 measures were identified and analyzed. The review showed 1701 that street network connectivity, land use density and land 1702 use diversity were the three categories more analyzed, while 1703 intersection density, residential/population density land use 1704 mix were the BE attributes more used to measure walkabil-1705 ity. In turn, attributes related to streetscape design were 1706 much less identified. 1707

The number and diversity of attributes, measures and 1708 methods used, the lack of standardized practices and the 1709 inconsistencies in some results can make difficult the evalu- 1710 ation on how BE attributes influence walkability. 1711 Development of new measures and refinement of existing 1712 measures will certainly continue in the future. Thus, more 1713 studies should be conducted to evaluate the impact of BE 1714 associated with heterogeneous urban environments on walk- 1715 ability in more depth and to follow the continued evolution 1716 1717 in this field.

This review has some limitations. First, the documents 1718 were selected according to the search rules described in the 1719 methodology. There may certainly be other relevant studies 1720 in the literature that were not included in this review. 1721 Second, because of the number of papers analyzed and the 1722 variety of attributes, measures and methods used, only the ¹⁷²³ major findings were presented in this review instead of 1724 adopting a meta-analysis in a comprehensive way. Third, the ¹⁷²⁵ review was limited to publications on Scopus and Web of 1726 Science, which excludes publications in other databases. ¹⁷²⁷ 1728 Finally, the review was based on documents written in 1729 English. Contributions published in other widely spoken 1730 languages were not considered. 1731

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ORCID

Fernando Fonseca (D) http://orcid.org/0000-0003-2336-175X R. U. I Antonio Rodrigues Ramos (D) http://orcid.org/0000-0002-6690-5940

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