



Review article

Systematic review on quantifying pedestrian injury when evaluating changes to the built environment

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ABSTRACT

Modifying the built environment to make communities more walkable remains one strategy to promote physical activity. These modifications may have the added benefit of reducing the risk of pedestrian injury; however, there is a gap in the physical activity literature regarding how best to measure pedestrian injury. Examining the measures that have been used and related data sources can help inform the use of pedestrian injury data to evaluate whether safety is optimized as walking increases. We conducted a systematic review of the literature to identify studies that evaluated changes to the built environment that support walking and measures impacts on pedestrian injury as a measure of safety. We searched PubMed, PsycInfo, and Web of Science to identify peer-review studies and websites of fifteen organizations to document studies from the grey literature published in English between January 1, 2010 and December 31, 2018. Our search identified twelve studies that met the inclusion criteria. The few studies that measured changes in pedestrian injury used crash data from police reports. Injury frequency was often reported, but not injury severity, and no studies reported injury risk based on walking exposure. We conclude that few studies have measured pedestrian injury in the context of creating more walkable communities. Future research would benefit from using well-characterized measures from existing studies to support consistency in measurement, and from more longitudinal and evaluation research to strengthen the evidence on additional benefits of walkability. Increased collaborations with injury prevention professionals could bolster use of valid and reliable measures.

1. Introduction

Despite the known benefits of physical activity, according to the U.S. Centers for Disease Control and Prevention only half of adults and a quarter of adolescents meet the aerobic physical activity guidelines (U.S. Department of Health and Human Services, 2018; U.S. Centers for Disease Control and Prevention, 2008). The U.S. Surgeon General in 2015 issued *Step It Up! The Surgeon General's Call to Action to Promote Walking and Walkable Communities (Call to Action)*, which highlighted walking as an important public health strategy for promoting physical activity (U.S. Department of Health and Human Services, 2015). Globally, walking is promoted as an accessible and cost-effective way of being active (World Health Organization, 2021).

To increase walking, the U.S. Community Preventive Services Task Force recommends implementation of built environment interventions combining transportation system interventions (e.g., traffic calming) and land use and environmental design (Community Preventive Services Task Force, 2016). These modifications to the built environment are likely to impact safety, so pedestrians feel safe while walking. Several studies examining walkable communities have measured safety, often operationalized as perceived safety, and using crime data to objectively measure safety (Suarez-Balcazar et al., 2020; Dong, 2017).

In addition to safety concerns from crime, unsafe roads are another important dimension of safety. Early estimates of motor vehicle traffic fatalities in the U.S. for the first half of 2021, indicate that over 20,000 people died in crashes; this number was 18.4% higher than the same

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period in 2020 and the largest number of projected fatalities in the same period since 2006 (U.S. Department of Transportation, 2021). According to the World Health Organization, roughly 1.3 million people die annually from road traffic crashes; more than half of these deaths are among “vulnerable” road users including pedestrians (World Health Organization, 2021).

Studies of how to measure pedestrian injury are common in the injury and transportation literatures (U.S. Department of Health and Human Services, 2015; Smart Growth America, 2019) but less frequent in the physical activity and chronic disease literatures. Providing physical activity and public health professionals insight on measures that have been used and related data sources can help inform the use of pedestrian injury data to evaluate whether safety is optimized as walking increases. The need to improve the measurement of pedestrian injury is especially timely as jurisdictions around the world expand Safe Street offerings in response to the COVID-19 pandemic (Smart Growth America; Berigan et al., 2019). As fitness centers closed around the world due to safety concerns, localities implemented temporary changes to slow traffic or close roads altogether to provide access to outdoor physical activity. These actions increased attention to ensuring roads are safe for all users of ages and abilities, with questions arising about how best to monitor the impacts as deliberations occur about sustaining these changes.

This systematic review responds to this need to measure changes and examines how pedestrian injury (as an indicator of safety) is measured in studies that evaluate built environment interventions that support walking. Because prior reviews exist that have summarized the impacts of built environment interventions on physical activity (Smith et al., 2017; Sallis et al., 2020), we did not aim to comprehensively synthesize the evaluation data from these interventions. The intent of this review was to focus on the measurement components; thus, we briefly summarized the findings from the studies that were included in this review. We conclude with implications for the field and highlight a need for increased collaborations between those working to promote physical activity and injury prevention professionals to bolster the use of valid and reliable injury measures.

2. Materials and methods

2.1. Data sources

This paper was part of a larger project examining the additional potential benefits of walkable communities, one of which was safety. Peer-reviewed articles that described changes to the built environment to promote walking and walkable communities were identified by searching PubMed, PsycInfo, and Web of Science. The lead author on this paper, an injury prevention researcher, developed the initial list of search terms, which was finalized by study team members and with guidance from a National Collaborative on Childhood Obesity Research (NCCOR) Working Group for this project. Keywords for the search included (walkab* OR pedestrian OR pedestrians) combined with “pedestrian safety” OR “pedestrian injury” OR “pedestrian injuries” OR “pedestrian injured” OR “traffic accident” OR “traffic accidents” OR accidents, traffic OR “accident prevention” OR collision OR crash. Because of the interdisciplinary nature of this search, topic-specific journals (e.g., Transportation Research Record, Injury Prevention) were also searched to ensure that all relevant articles were captured. Sources from the grey literature were identified by searching websites of 15 relevant nongovernmental organizations using the terms “benefits of walkability” and “benefits of walkable” (Table 1). Public databases that catalogue grey literature from government agencies were also searched.

Using Mesh terms and title/abstract tags, a search of PubMed yielded 2,654 references for this specific review, Psycinfo yielded 825 results, and Web of Science yielded 913 results, for a total of 2,654 references that were initially identified. A search of the websites for the 15 organizations yielded 19 documents from the grey literature for potential

Table 1
Grey Literature Sources.

Sources	Website
Active Living Research	https://www.activelivingresearch.org/
America Walks	https://americawalks.org/
American Planning Association	https://www.planning.org/
American Public Health Association	https://www.apha.org/
American Society of Civil Engineers	https://www.asce.org/
American Society of Landscape Architects	https://www.asla.org/
American Sociological Association	https://www.asanet.org/
Association of Pedestrian and Bicycle Professionals	https://www.apbp.org/
Institute of Transportation Engineers	https://www.ite.org/
National Academies/IOM	https://www.nationalacademies.org/hmd/health-and-medicine-division
National Association of City Transportation Officials	https://nacto.org/
National Recreation and Park Association	https://www.nrpa.org/
Smart Growth America	https://smartgrowthamerica.org/
Transportation Research Board	https://www.nationalacademies.org/trb/transportation-research-board
Urban Land Institute	https://uli.org/

inclusion.

2.2. Study selection

The titles and abstracts of all potential sources were screened by trained research assistants (RAs) for relevancy based on inclusion and exclusion criteria, developed in consultation with the Working Group. To capture the most recent literature, eligible articles were published between January 1, 2010 and December 31, 2018 and in English. Studies had to define pedestrian injury as resulting from an “unintentional motor vehicle traffic crash with one or more vehicles or pedal-cycles (or bicycles)” (Injury Surveillance Workgroup 8 (ISW8), 2017). Studies had to quantify pedestrian injury rates, risk, occurrence, or severity in relation to a specific intervention designed to make communities more walkable. These interventions were identified from the extant literature and feedback from the expert panel. Non-specific characterizations (e.g., “safe routes to schools”) of interventions were excluded; however, studies that evaluated specific interventions implemented as part of Vision Zero, a multidisciplinary approach to achieve zero fatalities and severe injuries on the road by addressing roadway design, speeds, pedestrian and driver behaviors, technology and policies, were eligible for inclusion (International Transport Forum, 2016; Kim et al., 2017). Studies that jointly examined walking and biking to promote active transportation were also excluded unless specific interventions to improve walkability and quantifiable impacts of the intervention’s impact on pedestrian injury were reported. In these instances, only data for the impacts on pedestrian injury were collected. These narrow inclusion criteria were applied to isolate the specific intervention studies that were sought to meet the intent of this review, which was a focus on measurement and data sources.

RAs screened the titles and abstracts of 2,336 references and after removing duplicates (628), 1,708 sources remained. The text for these sources was reviewed to identify articles for potential inclusion. A total of 1,677 of the 1,708 sources were removed that were descriptive studies, did not quantify injury prevention in the context of walkable communities, or did not provide enough transparency about how pedestrian injury was measured; the lead author of this study confirmed that these articles should be excluded. The 31 remaining articles were reviewed and only intervention and quasi-experimental studies that evaluated changes in the built environment that were salient for walkable communities were collected. Interventions that were relevant for walkable communities were defined based on qualitative judgment from the review team. The present study focuses on the 12 articles that met inclusion criteria (10peer-reviewedarticlesandtwostudiesfromthegreyliterature). Fig. 1

illustrates the study selection process.

2.3. Data extraction

All included documents were uploaded into Endnote. A data extraction tool was developed and piloted to ensure consistency in the abstraction approach. Inter-rater reliability was determined by calculating percent agreement across the research assistants and was 86%. Key study details were captured using an Excel document. Although the overall quality of each individual article was not given a methodological rating, limitations related to measurement and data of included studies were noted and are outlined in the Discussion.

3. Results

Table 2 includes a summary of the 12 studies, including the intervention and measures used to quantify pedestrian injury. The methods used to measure pedestrian injury are also summarized below and are grouped by the type of intervention examined. Although this paper focuses on how pedestrian injury is measured, we also briefly summarize the findings from the 12 studies.

3.1. Pedestrian countdown signals

Three studies evaluated pedestrian countdown timer signals (PCS) and impacts on pedestrian-motor vehicle collisions (PMVC). All three studies used data from police reports to evaluate the effects of PCS on

pedestrian safety. Huitema et al used monthly crash data obtained from the Detroit DOT over a 10-year period (2001–2010) and information related to installation from the local Traffic Engineering Division (Huitema et al., 2014). They used an interrupted time series design to study new PCS installed at 449 intersections in Detroit (Huitema et al., 2014). Pulugurtha et al. used police reports collected by the local DOT in Charlotte to examine PMVCs that occurred at intersections before and after installation of PCS (during 2003–2004) (Pulugurtha et al., 2010). Richmond et al. used ArcGIS to examine crash data, from police reports (2000 to 2009), to compare pre- to post-PCS installation in Toronto, Canada (Richmond et al., 2014). This study also measured injury severity, which was included in the police reports and categorized based on the Toronto Police Service injury classification: no injury; minimal injury (no medical attention); minor injury (emergency department treatment only); major injury (hospital admission); and fatal injury (Richmond et al., 2014).

Results of these 3 studies were mixed, which may relate to the different ways pedestrian injury was measured. Huitema et al found pedestrian crashes decreased 70% at sites with PCS as compared to control sites (Huitema et al., 2014). Pulugurtha et al. found the mean number of PMVCs decreased by 13% after PCS installation, although this value was not statistically significant, and found a significant decrease in all crashes, which was seen at 68% of the signalized intersections (Pulugurtha et al., 2010). Richmond et al. found a 26% increase in the rate of PMVCs following PCS installation, including collisions with pedestrians crossing in the right-of-way crossing. This increase was present for both minor/minimal injury and major/fatal injury (Richmond et al.,

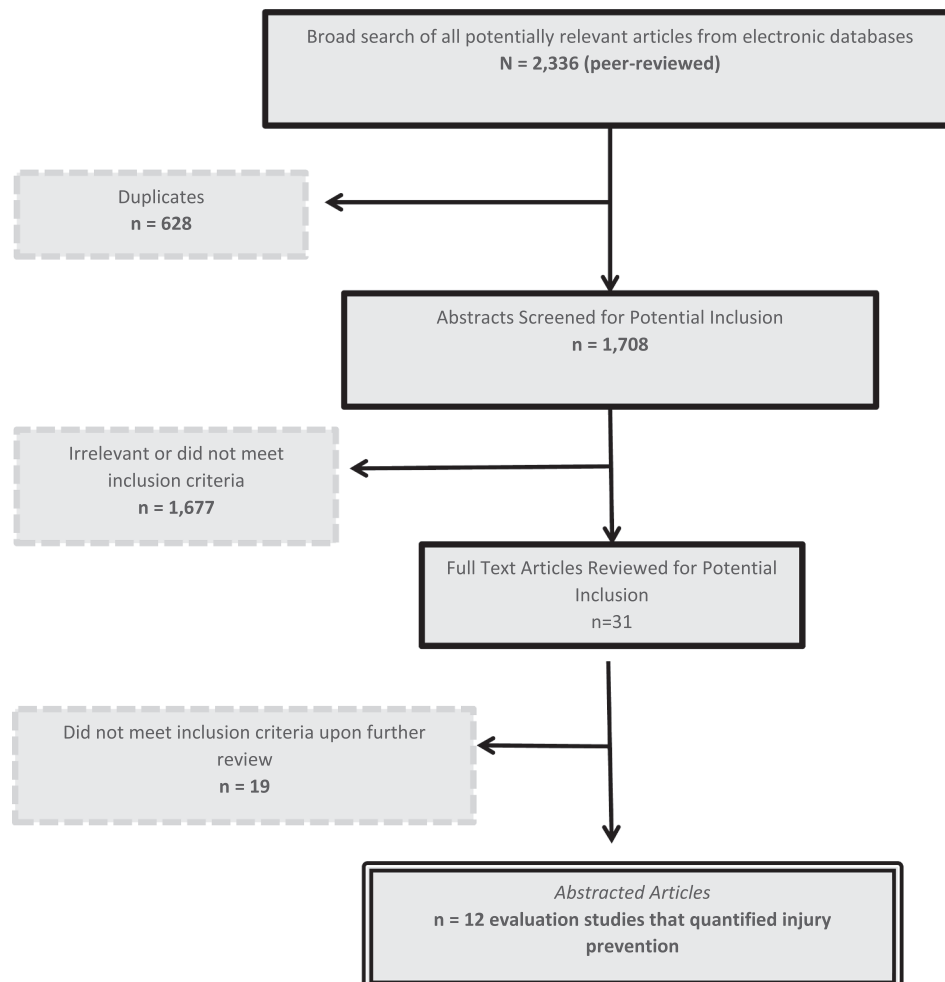


Fig. 1. Article Selection Flow Chart.

Table 2
Summary of Measures of Injury and Findings Related to Injury and Walkability (n = 12 included studies).

Author, Year of Publication, Location of Study	Intervention Description	Measures of Pedestrian Injury	Data Sources	Injury-Related findings
(Huiteima et al., 2014; Smart Growth America. Complete Streets + COVID-19) Detroit, MI	Pedestrian Countdown Signals (PCS) PCS installed at 449 intersections in Detroit	Incidence of pedestrian motor vehicles crashes (PMVCs), frequency	Monthly crash data, City DOT	As the number of PCS sites in this unit increased, the overall trend for crashes decreased. At full implementation, pedestrian crashes decreased 70% at sites with PCS as compared to control sites. The degree of linear relationship between PCS penetration and crash frequency, as measured by the Pearson correlation coefficient, was -5.1 ($p < 0.001$). Overall, the introduction of PCS reduced pedestrian crashes to approximately one third of the pre-intervention level.
(Pulugurtha et al., 2010; Berigan et al., 2019) Charlotte, NC	PCS	All crashes, including PMVCs, frequency	Local police reports	10,250 crashes occurred at 106 intersections between 2003 and 2004. After installation of PCS signals, the mean number of all crashes declined 21% (statistically significant). A 13% decrease in the mean number of PMVCs after installation of the signals was observed, although this value was not statistically significant.
(Richmond et al., 2014; Smith et al., 2017) Toronto, Canada	PCS	PMVC, rate Injury severity was categorized based on Toronto Police Service injury classification: no injury; minimal injury (no medical attention); minor injury (emergency department treatment only); major injury (hospital admission); and fatal injury	Local police reports	A 26% increase in the rate of collisions, pre- to post-PCS installation (incidence rate ratio [IRR] = 1.26; 95% CI, 1.11–1.42; $p < 0.001$) was observed. There were statistically significant increases in the rate of collisions, post-PCS installation, for minor/minimal injury (IRR = 1.25; 95% confidence interval [CI], 1.09–1.42; $p = 0.001$) and major/fatal injury (IRR = 1.51; 95% CI, 1.06 to 2.16; $p = 0.023$). There was a statistically significant increase in collision rate with pedestrian crossing in right-of-way crossing (IRR = 1.19; 95% CI, 1.03–1.38; $p = 0.019$) and nonsignificant increases in non-right-of-way crossing (IRR = 1.30; 95% CI, 0.98–1.74; $p = 0.078$).
(Zegeer et al., 2017; Sallis et al., 2020) 14 U.S. cities	Pedestrian Crossings Four pedestrian crossing treatments—rectangular rapid-flashing beacon (RRFB), pedestrian hybrid beacon (PHB), pedestrian refuge island (RI), and advance yield or stop markings and signs (AS)—at unsignalized intersections	PMVCs, frequency (used a weighted average of the crashes before and after intervention)	Local police reports, pedestrian counts collected to reflect pedestrian density	All four treatment types were associated with reductions in pedestrian crash risk, compared with the reductions at untreated sites. PHBs were associated with the greatest reduction of pedestrian crash risk (55% reduction), followed by RRFBs (47% reduction; this is the only intervention the authors note was based on a small sample), RIs (32% reduction), and AS (25% reduction).
(Guo et al., 2016; Injury Surveillance Workgroup 8 (ISW8), 2017) Nanning, China	Pedestrian Crossings Parallelogram-shaped pavement markings at mid-block pedestrian crosswalks	All crashes, including PMVCs, frequency	Local police reports	The presence of parallelogram-shaped pavement markings reduced vehicle–pedestrian crashes at pedestrian crosswalks by 24.9% (95% CI, 10.1–30.8%). However, the model results also showed that the presence of parallelogram-shaped pavement markings increased rear-end crashes at pedestrian crosswalks by 5.4% (95% CI, 0–11.2%).
(Rothman et al., 2015; International Transport Forum, 2016) Toronto, Canada	Pedestrian Crossings School crossing guards	PMVCs, frequency	Local police reports	27,827 PMVCs were observed during the study period. Data from 2003 to 2011 were examined to determine the risk of crashes after crossing guards were deployed in school zones. During this time, 260 PMVCs occurred at locations where 58 crossing guards were present. Repeated measures analysis using adjusted Poisson regression found PMVC rates remained unchanged at guard

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Table 2 (continued)

Author, Year of Publication, Location of Study	Intervention Description	Measures of Pedestrian Injury	Data Sources	Injury-Related findings
(Nadesan-Reddy and Knight, 2013; Kim et al., 2017) Durban, South Africa	Speed humps	PMVCs, frequency	Local police reports	locations after implementation (IRR 1.02; 95% CI, 0.74–1.39). PMVCs in one neighborhood accounted for 163 (38%) collisions in the 2 years prior to speed humps being installed. PMVCs decreased by 41% (n = 96) following the intervention. In the other area, there were 553 PMVCs (12% of the total) before and 455 PMVCs after the installation of speed humps, a reduction of 18%. Both neighborhoods showed a statistically significant decrease in the median PMVC rate post-installation [(pre 1.4, Interquartile Range (IQR) 0.3–4.4 v. post 1, IQR 0.4–4.4) and (pre 2.4, IQR 0.9–3.9 v. post 1.4, IQR 0–2.1)]. 27,827 PMVCs, with 1344 collisions along 409 roadways with speed humps, were observed. PMVC incidence rates/meters of road/month decreased after installation of speed humps (IRR 0.78 95 % CI 0.66, 0.91). Winter, collector roads (versus local), pre-amalgamated city center and increased land use mix were associated with more collisions. The association between speed humps and PMVC rates decreased more for children (IRR 0.57, 95 % CI 0.41, 0.79) than for adults (IRR 0.80, 95 % CI 0.68, 0.95). Before (2010) and after (2011–2012) data were compared. . Analysis of the after-treatment data identified 59 wrong-way incidents compared to 17 incidents observed in 2011 and no incidents in 2010. *Note: Review of the vehicle speed data highlighted a need for traffic calming especially during nigh periods when speeds were elevated. The authors note that the shared space implementation contributed to a significant reduction of operating speeds for most vehicles. With the decrease in vehicle volumes in the postimplementation scenarios, the risk of crash involvement was reduced based on crash prediction models.
(Rothman et al., 2015; Huitema et al., 2014) Toronto, Canada	Speed humps	PMVCs, rate Characterized season, built environment (besides speed humps), road type, neighborhood, and land use	Local police reports and city-level data on environment	The following interventions were associated with a significant reduction in PMVCs: all-pedestrian phase signal, increasing pedestrian crossing time, and high visibility crosswalks.
(Karnadacharuk et al., 2014; Pulugurtha et al., 2010) Auckland, New Zealand	Shared space intervention that utilized a public road space where all road users were encouraged by design to occupy legally, interact, and share the same public space with little physical segregation (e.g., traffic control devices)	Number of injuries or fatal PMVCs Safety observation data were collected via video during a 3-day period deemed to reflect usual travel levels.	NZ Transport Agency	
(Chen et al., 2013; Richmond et al., 2014) NYC, New York	13 safety countermeasures implemented in NYC to reduce pedestrian-vehicle conflicts, exposure, and speed. Intersection-based: all pedestrian phase high visibility crosswalk increasing pedestrian crossing time left-turn bay left-turn phase signal installation split phase timing Segment-based: bike lane bus lane pedestrian fencing road diet speed hump speed limit reduction	All crashes: (vehicle-vehicle collisions and pedestrian-vehicle collisions) Analysis combined crashes with injuries and fatalities, frequency	Police and driver report data maintained by New York State Department of Motor Vehicles (NYSDMV) and New York State Department of Transportation (NYSDOT)	
(NYC DOT, 2012; Zegeer et al., 2017) NYC, New York	Neighborhood traffic calming, dedicated bus lanes, and economic expansion (i.e., additional business)	All crashes including PMVCs and injuries	Not described	New pedestrian safety islands led to a 35% decrease in injuries to all street users on one main avenue and a 58% decrease on an adjacent main avenue. Traffic calming successfully decreased speeding in either direction, between 29% and 32%, which resulted in a 67% decrease in pedestrian crashes. Dedicated bus lanes

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Table 2 (continued)

Author, Year of Publication, Location of Study	Intervention Description	Measures of Pedestrian Injury	Data Sources	Injury-Related findings
(Seattle DOT, 2017; Guo et al., 2016) Seattle, WA	Speed limit reductions (30mph to 25mph), lane reductions (4 to 3), transit improvements, signal timing adjustments with additional pedestrian interval, and paint and posts to enhance sight lines	All crashes including PMVCs	Local police reports	and separate dedicated signal phases for pedestrians led to a 12% increase in bus ridership and a 37% decrease in injury crashes. Before treatment (2005 and 2014), there were nearly 3,600 total collisions along the Rainier Street corridor. After treatment (6-month period in 2015), on average, there was one crash per day that took 45 min to clear. Regarding the data on pedestrians, collisions in the Rainier Street corridor decreased 15% overall, with injury collisions decreased by 30% and pedestrian collisions decreased by 9%.

2014).

3.2. Pedestrian crossings

Three studies evaluated pedestrian crossings and injuries, all using local crash data from police reports. Zegeer et al. studied four different pedestrian crossing treatments at unsignalized intersections in 14 cities across the U.S.: rectangular rapid-flashing beacon (RRFB), pedestrian hybrid beacon (PHB), pedestrian refuge island (RI), and advance yield or stop markings and signs (AS) (Zegeer et al., 2017). Outcomes included pedestrian crashes and other crash types that occurred at each site and data were collected from local police reports. Guo et al. examined the effects of parallelogram-shaped pavement markings on crashes at unsignalized mid-block pedestrian crosswalks (Guo et al., 2016). The study compared six sites in a treatment group (with parallelogram-shaped pavement markings) with six sites in a comparison group (without parallelogram-shaped pavement markings). Traffic police department data were obtained and used to characterize crashes as property damage only, injury crashes, or fatal crashes. Finally, Rothman et al. examined the role of school crossing guards at a pedestrian crossing (Rothman et al., 2015). They utilized a quasi-experimental study design to examine all age collision counts near newly implemented guards before and after implementation. Collision data was extracted from routinely collected pedestrian motor vehicle collision reports from the local police department.

Overall, these three studies documented improvements in pedestrian safety related to these interventions, although findings were somewhat mixed. Zegeer et al. observed that all four pedestrian crossing treatments at unsignalized intersections were associated with greater reductions in pedestrian-vehicle collisions, compared with the reductions at untreated sites (Zegeer et al., 2017). Similarly, Guo et al. found that parallelogram-shaped pavement markings at unsignalized mid-block pedestrian crosswalks significantly reduced both the frequency and severity of crashes at pedestrian crosswalks (Guo et al., 2016). In addition, crash models suggested that the presence of the pavement markings reduced vehicle-pedestrian crashes although rear-end crashes increased. In contrast, Rothman et al. found that PMVC rates remained unchanged at school crossing guard locations after implementation and that most PMVCs involving children occurred outside school travel times (Rothman et al., 2015).

3.3. Traffic calming

Three studies evaluated interventions aimed to slow traffic and reduce PMVCs. Nadesan-Reddy et al. examined the impact of the installation of speed humps on the number and severity of incidences of collisions and injuries using an observational interrupted time-series

study design (Nadesan-Reddy and Knight, 2013). Outcomes included serious pedestrian-vehicle collisions and fatal collisions and data were obtained from the local traffic authority. Rothman et al. also examined the effect of speed hump installation on PMVC rates (Rothman et al., 2015). They used a quasi-experimental study to examine collision counts before and after speed hump installation. The outcome was the incidence rate of PMVCs and police-reported data were obtained from the city. Finally, Karndacharuk examined the impact of implementing a shared space intervention (i.e., streetscape design that minimizes the separation between pedestrians and vehicles) on a busy road in Auckland (Karndacharuk et al., 2014). The study compared recorded crash history data from the national crash analysis data system before and after the intervention.

Results from these three studies examining traffic calming interventions were consistent in demonstrating expected reductions in PMVCs. Nadesan-Reddy et al. observed that the number of PMVCs and the severity of pedestrian injuries were reduced after the installation of speed humps (Nadesan-Reddy and Knight, 2013). Similarly, Rothman et al. also found that the incidence rate of PMVCs declined by 22% after installing speed bumps (Rothman et al., 2015). They also observed that the incidence rate of PMVCs declined more for children than for adults (43% and 20%, respectively). Finally, Karndacharuk reported a reduction in PMVCs based on crash prediction models after implementing a shared space intervention on a busy road (Karndacharuk et al., 2014).

3.4. Vision Zero countermeasures

Three studies evaluated interventions as part of Vision Zero initiatives, or comprehensive traffic safety programs that were precursors to Vision Zero, and the impacts on safety. The study by Chen et al. examined 13 safety countermeasures and street designs installed in NYC between 1990 and 2008 as part of their city-wide traffic safety model (Chen et al., 2013). A set of untreated locations were selected as the comparison group and crashes during pre- and post-treatment periods were collected for the treated and untreated groups. Crash data for all reportable crashes in the five boroughs of NYC from 1989 to 2008 were obtained from a database maintained by the New York State Department of Motor Vehicles and New York State Department of Transportation (NYSDOT).

The two other studies were reports from the grey literature by the New York City DOT (NYCDOT) and the Seattle DOT (SDOT). The report by the NYCDOT included minimal information on the study design and metrics (New York City Department of Transportation, 2012). The purpose of the report was to illustrate how different metrics, including 2 related to safety (crashes/injuries and traffic speed), can be used to evaluate street projects using a cross-section of recent street design projects. The second report by SDOT reported before and after outcomes

of street design changes aimed at improving safety within the study area (Seattle Department of Transportation, 2017). Information on speeds and collisions was obtained from SDOT's Transportation Operations Center that monitors Seattle streets and significant incidents.

Results of these studies showed that safety improvement were associated with these countermeasures. Chen et al. found PMVCs declined for the following interventions: all-pedestrian phase signal, split phase timing increased pedestrian crossing time, signal installations, left-turn phase, speed hump, and road diet (i.e., lane reduction (Chen et al., 2013). The report by the NYCDOT provided a second evaluation of NYC's Vision Zero initiatives including implementing neighborhood traffic calming, pedestrian islands, protected bicycle lanes and dedicated bus lanes, and economic expansion (i.e., new businesses that would interface with walkers and bicyclists) (New York City Department of Transportation, 2012). In one area, traffic calming successfully decreased speeding, which resulted in a 67% decrease in pedestrian crashes (evaluations of the other interventions did not provide pedestrian-specific data). As part of Seattle's Vision Zero Program, the city implemented speed limit reductions, lane reductions, transit improvements, signal timing adjustments with additional pedestrian interval, and paint and posts to enhance sight lines with the aim of reducing injury risk among various road users (Seattle Department of Transportation, 2017). The researchers reported vehicle speeds within the project area declined by 10–16% and PMVCs decreased by 9%.

4. Discussion

To our knowledge, this is the first systematic review to examine methods used to measure pedestrian injuries when evaluating changes to the built environment to support walking and walkable communities. Simultaneously examining walking and pedestrian injury, with appropriate methods, is important because interventions that make communities more walkable should theoretically also promote pedestrian safety. The ability for pedestrians to safely travel is important for transportation safety and physical activity promotion, as well as for achieving health equity, which refers to the ability for every person to attain their health potential (U.S. Centers for Disease Control and Prevention, 2020). The health equity considerations are particularly important for walking because of the disproportionate impact of traffic fatalities on people of color (QuickStats, 2009), especially the documented inequities in the enforcement of traffic laws such as jaywalking for pedestrians (Mahdawi, 2020). Ensuring that people of color can walk safely is important for efforts to also reduce disparities in physical activity rates between racial and ethnic groups (U.S. Department of Health and Human Services, 2018; U.S. Department of Health and Human Services, 2015; Smart Growth America, 2019).

The articles included in this review often quantified safety as the frequency of PMVCs based on crash data from a state or local department of transportation from police reports (Pulugurtha et al., 2010; Richmond et al., 2014; Rothman et al., 2015; Nadesan-Reddy and Knight, 2013; Rothman et al., 2015; Karndacharuk et al., 2014; Chen et al., 2013; New York City Department of Transportation, 2012; Seattle Department of Transportation, 2017). Only one study that met the inclusion criteria measured injury severity and no studies in our review reported injury risk based on walking exposure (e.g., injury per mile walked). The small number of studies identified suggests a need for further research in this area that include studies that conduct thorough assessments of pedestrian injury along with the measures needed to estimate injury risk.

Because of variation in non-fatal injuries, it is important to document severity of injury for pedestrians involved in PMVCs; however, pedestrian injury severity was only reported by Richmond et al. (2014). This study included an injury severity classification based on nomenclature developed by the local police: no injury, minimal injury (no medical attention), minor injury (emergency department treatment only), major

injury (hospital admission), and fatal injury (Richmond et al., 2014). Police reports were the primary data source in the included studies, but these data underestimate total pedestrian injury because they represent crashes rather than all pedestrians involved in a crash (Sandt et al., 2020). In addition, police data do not provide data on severity (Lusk et al., 2015; Pucher and Dijkstra, 2003). Thus, while using police data may be useful due to its availability, other data sources should also be considered to link to these data to ensure comprehensiveness. For example, injury codes from the International Classification of Diseases that are included as part of medical records can be used to calculate the Abbreviated Injury Scale (AIS), which measures threat to life on an ordinal scale that ranges from 0 (no injury) to 6 (not likely to survive) (Segui-Gomez and MacKenzie, 2003). Scores for single injuries can be combined to estimate the impact of multiple injuries sustained by a given person using measures such as the Injury Severity Score or the New Injury Severity Score (Segui-Gomez and MacKenzie, 2003). Beyond metrics that can be captured in medical records, injuries may be treated outside the health system, not reported, or not treated at all, making them difficult to measure.

Despite limitations of police crash reports, localities seeking to monitor pedestrian injuries rely on police crash reports, which when linked to hospital inpatient discharge data and emergency department (ED) data would allow for the examination of crash-contributing and injury-related outcomes. Although ED data provide important information on the pedestrians' injuries, they often lack detail about the context, such as how or why the injury occurred, which supports a need for using integrated data (QuickStats, 2009).

Recommendations from a 2017 consensus report on pedestrian injury surveillance included a need for training practitioners in state and local health departments and transportation agencies, among others; and increasing collaboration across sectors to link various types of data including traffic data, police reports, and emergency room visits (Injury Surveillance Workgroup 8 (ISW8), 2017). Another recommendation from the report was the systematic inclusion of pedestrian data as part of routine transportation data. All these efforts can enhance pedestrian safety surveillance as communities promote walking, especially if the data are geocoded to better determine location specific contextual factors of the pedestrian injury.

While knowing the absolute number of PMVCs is important, using such a relatively crude measure hinders the ability to fully understand the risks to pedestrians. For example, studies have documented the challenge of relying on the frequency of pedestrian injuries as a measure of safety, especially as communities become more walkable (U.S. Department of Health and Human Services, 2015). Increases in the number of pedestrian injuries have been documented in areas where the number of people walking has increased; however, when considering exposure, the risk of being injured is low. Research has also shown that PMVCs are less likely to occur as the number of people walking increases (Jacobsen, 2003). Thus, assessing pedestrian injury rates per population would not fully capture the story without assessing the level of exposure. Exposure could include measuring the miles or minutes walked; however, determining how to precisely capture these data is important. Mindell and colleagues converted distance traveled to time spent traveling and showed the value of accounting for time when calculating exposure and determining risks for pedestrians and cyclists (Mindell et al., 2012). Future research is needed that account for exposure is determining risks to pedestrians.

Prior research has noted the limitations of existing data sources in measuring pedestrian injuries. Stutts and Huner published a seminal article in 1996 that documented under-reporting of pedestrian injuries by police (Stutts et al., 1996). Subsequent studies have noted strengths and limitations of secondary data, issues with data linkages, and a need for data integration from police, emergency departments, and hospitalizations to fully understand pedestrian injuries (Injury Surveillance Workgroup 8 (ISW8), 2017). These methods could help capture more severe injuries, which would not necessarily be captured by local police

data that tends to record specifics about the crash without information on injuries.

Limitations to this study include the search strategy and publication bias. This review only included studies through 2018, so some studies could have been missed. This is especially likely with the increased attention to Safe Streets and Complete Streets initiatives in response to the COVID-19 pandemic (Smart Growth America. Complete Streets + COVID-19; Berigan et al., 2019). An ad hoc search of the databases used in this study did not find any relevant studies published between January 1, 2019 and July 31, 2020, so the influence of this bias is likely minimal albeit a limitation, nonetheless. Because of the focus of this review on data sources and measures, we opted not to rate the overall quality of the included papers and instead we critically appraised the measures. This process is limited by the subjectivity of the appraisal and although one member of the team took the lead on this aspect of the project may have led to bias. We excluded papers not published in English, so we may have missed other salient publications, although an ad hoc exploration of the published literature did not identify papers that were omitted and would have met the inclusion criteria. In addition, while crime has been explored as a measure of safety, this study narrowly focused on quantifying pedestrian injury. The decision to limit the included papers to pedestrian injury as a measure of safety was in recognition of the significant global burden of crashes and growing proportion of road traffic deaths that involve pedestrians (World Health Organization, 2021). Finally, while the scope of this review was limited, we think that the conclusions about data and measures are relevant for various jurisdictions and countries, with appropriate contextual considerations. For example, some of the limitations of police data that are present in the U.S. may be nonexistent or different in other areas of the world.

Our review also had several strengths. Despite the narrow inclusion criteria, we considered over 2,000 documents for this review. We reported high inter-rater reliability between the reviewers and the lead author confirmed all studies. Finally, this is the first review to examine how pedestrian injury has been quantified when evaluating built environment interventions that promote walking and walkable communities; the information summarized can support practitioners as they work to promote safe and walkable communities.

5. Conclusions

Our review revealed that few studies have quantified pedestrian injury in relation to built environment interventions to support walkable communities. Additional research that estimate injury risk could help clarify the additional safety benefits of walkable communities and refine methods to quantify safety. Important to additional research is a closer collaboration between physical activity promotion and injury prevention professionals, which could bolster use of valid and reliable injury measures and support consistency in measurement to strengthen the evidence on additional benefits of walkability. Bourgeoning strategies in the U.S. such as the Safe System approach, which have been popular globally for decades, have expanded the range of transportation and physical activity professionals who address safety issues (International Transport Forum, 2016; Safe System Consortium, 2021). Walkability and safety are key elements of these strategies, and as their uptake expands across the U.S. and around the world, there is an opportunity to increase the use of valid and reliable measures to monitor and ensure pedestrian safety.

CRedit authorship contribution statement

Keshia M. Pollack Porter: Conceptualization, Methodology, Writing – original draft. **John D. Omura:** Conceptualization, Validation, Writing – review & editing. **Rachel Ballard:** Conceptualization, Validation, Writing – review & editing. **Erin L. Peterson:** Writing – review & editing. **Susan A. Carlson:** Conceptualization, Validation, Writing –

review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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