New Zealand Population Review, Vol 50, 223–268.

Where Do Falls Happen? Using Fall-SAFE to Audit the Street Environment for Falls Risk among Older Adults – A Virtual Audit in Google Street View

Ko te Tikanga Hinga ai te Tangata i Hea? Te Whakamahi i Fall-SAFE ki te tātari i te Taiao Tiriti mō te Tūpono ka Hinga te Hunga Mātāpuputu – He Tātari Mariko mā te Tirohanga ā-Tiriti Google

TESSA POCOCK,* ANGELA CURL,† ALISON WATKINS,‡ VERITY TODD,§ BRIDGET DICKER,** AND SALLY KEELING††

* Tessa Pocock was an assistant research fellow at the Department of Population Health, University of Otago | Ōtākou Whakaihu Waka, Christchurch and a doctoral student at the School of Nursing, Faculty of Medical and Health Sciences, University of Auckland | Waipapa Taumata Rau when this research was completed.

† Angela Curl is a social scientist at the Department of Population Health, University of Otago | Ōtākou Whakaihu Waka, Christchurch. Corresponding author: angela.curl@otago.ac.nz

‡ Alison Watkins was an assistant research fellow at the Department of Population Health, University of Otago | Ōtākou Whakaihu Waka, Christchurch.

§ Verity Todd is a senior lecturer in the Paramedicine Department at Auckland University of Technology | Te Wānanga Aronui o Tāmaki Makau Rau and an Honorary Research Fellow at Hato Hone St John.

** Bridget Dicker Bridget is the Head of Clinical Audit and Research for Hato Hone St John, a registered paramedic, and concurrently serves as an Associate Professor at Auckland University of Technology | Te Wānanga Aronui o Tāmaki Makau Rau.

†† Dr Sally Keeling (now retired) was formerly a senior research fellow at the Department of Medicine, University of Otago | Ōtākou Whakaihu Waka, Christchurch.

Abstract

Falls are a leading cause of injury and accidental death among older adults, but little is known about the built environment and falls risk. We present a virtual audit tool, Fall-SAFE, designed to assess the street environment from a falls-risk perspective, along with interrater reliability assessment of the tool. We then use the tool to describe the diverse street environment characteristics of locations of moderate to severe falls among older adults in Aotearoa New Zealand. Fall-SAFE can aid better understanding of the environments in which falls occur and support interventions to reduce pedestrian falls.

Keywords: environment, falls, Google Street View, older adults, street audit, virtual audit

Whakarāpopotonga

He pūtake matua ngā hinganga o ngā wharanga me ngā aituā i waenga i te hunga pēperekōu, engari he iti ngā mōhiotanga ki te taiao hanga me te mōrea kei tūpono hinga te tangata. Kei te whakarato mātou i tētahi utauta tātari mariko, a Fall-SAFE, kua hoahoatia ki te aromatawai i te taiao tiriti hei whakatau i te tūponotanga ka hinga te tangata i reira, me te aromatawai i te pono i waenga kaiwhakatau o te utauta. Kātahi ka whakamahi mātou i te utauta ki te whakaahua i ngā āhuatanga taiao rerekē o te tiriti mō ngā tauwāhi i reira ngā hinganga āhua ngāwari ki ngā mea taikaha i waenga i te hunga pēperekōu i Aotearoa. Ka āwhina pea a Fall-SAFE kia mārama ake te tangata ki ngā taiao e hinga ai te tangata, ki ngā hāpaiora tautoko hoki hei whakaiti i ngā hinganga kaiwaewae.

Ngā kupu matua: taiao, ngā hinganga, Google Street View, hunga pēperekōu, tātari tiriti, tātari mariko

Regular physical activity in older age is associated with improved mental and physical health and wellbeing (Taylor et al., 2004) and is essential for positive ageing (Pocock et al., 2022). Walking in the local neighbourhood is a familiar mode of exercise and a convenient way to maintain physical activity and social connection (Gardner, 2011). Extensive research has examined environmental correlates of walking, with some research focused specifically on older adults (Grant et al., 2010; Van Cauwenberg et al., 2012; Vine et al., 2012; Ward Thompson et al., 2014). The built environment can be particularly important for older adults who are ageing in their communities, given that older adults' mobility radius tends to reduce with increasing age and frailty (Milton et al., 2015; Portegijs et al., 2016; van Hoven & Meijering, 2019). Yet, the urban environment can be unsupportive for older adults who may experience reduced physical function, highlighting the importance of quality and accessible neighbourhood environments (Curl et al., 2022; Sugiyama & Ward Thompson, 2007).

Although physical activity and walking have substantial health benefits, walking can also increase exposure to risks such as falling. Frank et al. (2019) identified two pathways connecting land use and transport to health outcomes: (1) the environment can support healthy behaviours such as walking, but (2) increased walking can result in harmful exposures, particularly among older adults. When older adults walk (behaviour) in their environment, they can be exposed to the negative impacts of poorly designed or inadequately maintained pedestrian infrastructure (exposure). These exposures may, in turn, influence older adults' behaviour through fear of falling or choosing not to walk in an unpleasant or unsafe environment. As such, perceived hazards in the built environment may deter older adults from being physically active, to the detriment of their health and wellbeing (Kerr et al., 2012).

The quality of the environment is an equity issue that may promote or inhibit the wellbeing of older adults and those with disabilities. Older adults and persons with differing mobility needs (such as wheelchair users) may be more susceptible than others to injury or loss of accessibility where pedestrian infrastructure is poor (Clarke et al., 2008; Meher et al., 2021; Spray et al., 2022). For example, Clarke et al. (2008) found that outdoor mobility among older adults with a physical impairment was reduced in areas with streets in fair or poor condition. Although substantial research has considered associations between design aspects of the built environment and behavioural outcomes such as walking, less research has considered the impacts of walking in poor quality environments (Bostock, 2001; Curl & Mason, 2019; Spray et al., 2022).

Falls are a leading cause of injury and accidental death among older adults (Injury Prevention Research Unit, 2019). Around one-third of older adults fall each year in any context (Curl et al., 2020; Li et al., 2006; Li et al., 2014), although this estimate varies between studies. One-third to one-half of all falls are pedestrian falls, defined as those occurring on the road or footpath (Curl et al., 2020; Li et al., 2006; Li et al., 2014). Falls outside the home are particularly important because falling, and a fear of falling, can prompt older individuals to restrict their activities outside the home (Hjorthol, 2013) which can further affect quality of life (Perez-Jara et al., 2010). Physical activity restriction, associated with fear of falling, can lead to social isolation and decline in mental and physical function (Todd & Skelton, 2004). While considerable research has examined individual risk factors associated with falling and falls in the home environment (Keall et al., 2017), limited research has examined falls outside the home and the associated environmental risk factors (Curl et al., 2020; Nyman et al., 2013; Watkins et al., 2021).

Street environment characteristics are a key modifiable risk factor for falls and fear of falling. Perceived accessibility and negative environmental characteristics, such as uneven walking surfaces or higher traffic speeds, are associated with fear of falling (Curl et al., 2020; Lee et al., 2018). Negative environmental characteristics are also associated with falls among those who have not previously fallen (Lee, Lee, & Ory, 2019). Although pedestrian falls have received greater research attention since Li et al. (2006) highlighted this understudied area, research in this space is still limited and lacks standardised measures to systematically assess environments.

This limited research on environmental risk factors associated with outdoor falls is, at least in part, attributed to the lack of spatial data on where falls occur. In Aotearoa New Zealand, Hato Hone St John emergency medical service (EMS) records the location of incidents attended by an ambulance (including falls outdoors), resulting in a unique spatial data set which can be used to understand environmental risk factors for outdoor falls if linked with measures of the urban environment (Watkins et al., 2021).

Street environment audit tools

Urban street environments can be measured using secondary data sets (e.g., road type, density of intersections, destination availability) or 'on-the-ground' street environment audits. Secondary data sets have been used effectively to measure the street environment for walkability (Leslie et al., 2007; Pikora et al., 2002) and falls risk (Watkins et al., 2021). However, the environmental factors associated with outdoor falls (e.g., footpath width, surface type, elevation, steps) require more detailed spatial information than is typically available using secondary data sets.

Environment audit tools are generally designed to construct a systematic and objective measure of the environment (Brownson et al., 2009) which can be used to explain variation in health behaviours or outcomes, such as walking. Many environment audit tools have been developed to assess the streetscape for pedestrian and cycling activity (e.g., Bader et al., 2017; Griew et al., 2013; Hanibuchi et al., 2019; Millstein et al., 2013; Pikora et al., 2002), but not from a falls-risk perspective. Few environment audit tools have been developed specifically for older adults (e.g., Curl et al., 2016; Michael et al., 2009).

Virtual audits utilising Google Street View (GSV) as a tool are increasing in popularity to reduce the time and resources associated with on-the-ground audits (Badland et al., 2010; Brookfield & Tilley, 2016; Gullón et al., 2015; Rzotkiewicz et al., 2018). However, virtual audits have drawbacks; for example, image quality can be poor, image data collection protocols are ambiguous, and it can be difficult to identify small or temporary features (Plascak et al., 2020; Rzotkiewicz et al., 2018). Nonetheless, cost and time savings make virtual audits an attractive option, and one that may be accessible to community groups as well as researchers. Developments in virtual audit protocols are ongoing; for example, the recent 'drop-and-spin' technique elucidated by Plascak et al. (2020). Drop-and-spin audits are conducted at a single point and have clear time and resource benefits when compared with traditional segment-based audit protocols which traverse a short length of road (Plascak et al., 2020).

In this study, we develop a detailed environment audit tool to assess the microscale street environment from a falls-risk perspective. The data collected from environmental audits could be used to understand patterns of falls in relation to environmental conditions and determine environmental risk factors for falls.

Research aim

The aim of this research is to develop and use a fall-specific virtual environment audit tool to characterise the microscale urban environments in which outdoor falls among older adults have occurred and required ambulance attendance in Aotearoa New Zealand. To address this aim, we:

1) developed a virtual environment audit tool to assess the street environment for falls risk among older adults. We call this tool Fall-SAFE (Fall-Systematic Audit oF Environment)
2) tested the functionality and interrater reliability of our virtual environment audit tool, Fall-SAFE, and
3) described the street environment characteristics of locations where moderate-to-severe falls among older adults occurred in Aotearoa New Zealand.

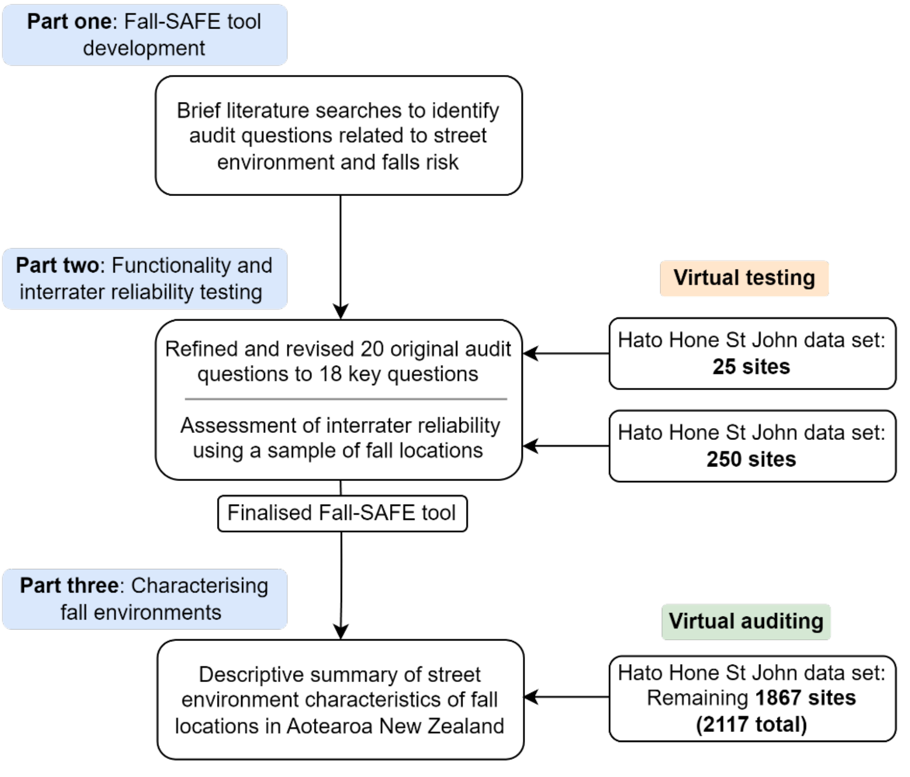
The processes of tool development and testing are presented in Figure 1.

Study context

This study is a spatial analysis of the location of falls in the urban environment of Aotearoa New Zealand.[1]

The study population includes all cases of a fall among adults aged 65+ years that occurred on the road or footpath in urban areas (Stats NZ, 2017) and was attended by an ambulance, between 1 July 2016 and 30 June 2018. Spatial information on the location of a fall is difficult to source; most previous studies have relied on participant recall or patient home address (Watkins et al., 2021). Spatial data on pedestrian falls attended by an ambulance were obtained from Hato Hone St John (the main ambulance service in New Zealand) by selecting records that included 'fall' as a presenting complaint and a fall site that included 'footpath' or 'road', as recorded by the attending clinician in the electronic patient report form. Hato Hone St John's definition of a presenting complaint of *fall* aligns with the World Health Organization's definition, "as an event which results in a person coming to rest inadvertently on the ground or floor or other lower level" (World Health Organization, 2021), although there can be differences.

Figure 1: Processes of Fall-SAFE tool development and testing



between clinical impression and presenting complaint (e.g., loss of consciousness). Records were cleaned to remove duplicates, inaccessible GPS locations, and entries where the environment was unlikely to be the primary cause of the fall.

In Aotearoa New Zealand, ambulance callout or transfer for an accident-related injury is publicly funded within 24 hours of the injury for permanent residents or citizens, those with work visas for more than two years, those from the Cook Islands, Niue and Tokelau, and for UK citizens visiting New Zealand. Records from Wellington, New Zealand were excluded from this data set as Wellington Free Ambulance provides emergency medical services in the Wellington region.

The data set includes GPS coordinates for each ambulance attendance location using ambulance vehicle location data. Accuracy of GPS coordinates can vary depending on the environment (Duncan et al., 2013), and in some cases, the ambulance attendance location may differ from the fall location. However, these data are a reasonable estimate of the location of a fall, which is difficult to obtain from other data sets. Between 1 July 2016 and 30 June 2018, there were 2117 falls attended by an emergency ambulance among adults aged 65+ years in urban areas of Aotearoa New Zealand (excluding Wellington).

Developing the Fall-SAFE virtual audit tool

We first developed an audit tool to assess the microscale street environment from a falls-risk perspective using GSV.

Identification of audit questions related to the street environment and falls risk

We conducted two brief literature searches to inform the audit tool development. The first search identified street environment features associated with falling, while the second search focused on existing audit tools that we could draw from to identify questions to assess street environment features. We undertook these two searches in April 2020.

<u>Street environment factors associated with falling</u>

We completed forward and backward citation searches on known articles (based on our previous research (Curl et al., 2016)) that identified street environment features associated with falls among older adults. We identified 18 articles meeting these criteria. We subsequently included a further two relevant articles published by the authors after the April 2020 search date (Curl et al., 2020; Watkins et al., 2021).

A summary of 28 features associated with older adults' falls in pedestrian environments are provided in Table 1. Further detail on the study and participant characteristics in these articles can be found in Supplementary Table 1.[2] These key features include wet or icy surfaces (*n* =

10 sources), uneven surfaces (n = 9), road crossings (n = 8), footpath condition (n = 7), crowded or busy areas (n = 6), intersections (n = 5), steps (n = 5), streetlights (n = 5), deprivation (n = 4), kerbs (n = 4), permanent obstructions (n = 4) and temporary obstructions (n = 3). We focused on these street environment features when searching for suitable audit questions in the wider literature on street audits to be included in our tool.

Table 1: Summary of street environment features associated with older adults' falls in pedestrian environments

	Ceccato and Willems (2019)	Chippendale and Boltz (2018)	Chippendale and Boltz (2015)	Curl et al. (2016)	Curl et al. (2020)	Elvik and Bjørnskau (2019)	Gyllencreutz et al. (2015)	Jung et al. (2018)	Lai et al. (2009)	Lai et al. (2011)	(Lamy, 2017)	Lee et al. (2018)	Lee, Lee and Rodiek (2019)	Lee, Lee and Ory (2019)	Li et al. (2006)	Li et al. (2014)	Morency et al. (2012)	Nyman et al. (2013)	Schepers et al. (2017)	Watkins et al. (2021)	**Total**
Wet and icy surfaces/ wet weather		■	■	■		■	■		■	■								■	■		**10**
Uneven surfaces			■				■		■	■				■	■			■	■		**9**
Road crossings	■		■	■					■			■						■	■		**8**
Footpath condition		■	■	■							■	■		■	■						**7**
Crowds/busy pedestrian area		■		■					■		■								■		**6**
Intersections	■								■									■	■		**5**

	Ceccato and Willems (2019)	Chippendale and Boltz (2018)	Chippendale and Boltz (2015)	Curl et al. (2016)	Curl et al. (2020)	Elvik and Bjørnskau (2019)	Gyllencreutz et al. (2015)	Jung et al. (2018)	Lai et al. (2009)	Lai et al. (2011)	(Lamy, 2017)	Lee et al. (2018)	Lee, Lee and Rodiek (2019)	Lee, Lee and Ory (2019)	Li et al. (2006)	Li et al. (2014)	Morency et al. (2012)	Nyman et al. (2013)	Schepers et al. (2017)	Watkins et al. (2021)	**Total**
Steps (presence, count, depth, handrail)				■				■		■								■	■		**5**
Street lighting			■	■								■						■	■		**5**
Deprivation										■				■		■				■	**4**
Kerbs			■	■						■									■		**4**
Permanent obstructions				■						■								■	■		**4**
Temporary obstructions				■										■					■		**3**

	Ceccato and Willems (2019)	Chippendale and Boltz (2018)	Chippendale and Boltz (2015)	Curl et al. (2016)	Curl et al. (2020)	Elvik and Bjørnskau (2019)	Gyllencreutz et al. (2015)	Jung et al. (2018)	Lai et al. (2009)	Lai et al. (2011)	(Lamy, 2017)	Lee et al. (2018)	Lee, Lee and Rodiek (2019)	Lee, Lee and Ory (2019)	Li et al. (2006)	Li et al. (2014)	Morency et al. (2012)	Nyman et al. (2013)	Schepers et al. (2017)	Watkins et al. (2021)	**Total**
Destination density																	■			■	**2**
Path material				■			■														**2**
Population density	■																■				**2**
Road width (lanes)			■	■																	**2**
Slope				■														■			**2**
Traffic speeds			■									■									**2**
Design of walkways													■								**1**

	Ceccato and Willems (2019)	Chippendale and Boltz (2018)	Chippendale and Boltz (2015)	Curl et al. (2016)	Curl et al. (2020)	Elvik and Bjørnskau (2019)	Gyllencreutz et al. (2015)	Jung et al. (2018)	Lai et al. (2009)	Lai et al. (2011)	(Lamy, 2017)	Lee et al. (2018)	Lee, Lee and Rodiek (2019)	Lee, Lee and Ory (2019)	Li et al. (2006)	Li et al. (2014)	Morency et al. (2012)	Nyman et al. (2013)	Schepers et al. (2017)	Watkins et al. (2021)	**Total**
Drainage ditches												■									1
Footpath continuity				■																	1
Footpath presence				■																	1
Neighbourhood conditions (aggregated measure)					■																1
Pedestrian signals and systems				■																	1

	Ceccato and Willems (2019)	Chippendale and Boltz (2018)	Chippendale and Boltz (2015)	Curl et al. (2016)	Curl et al. (2020)	Elvik and Bjørnskau (2019)	Gyllencreutz et al. (2015)	Jung et al. (2018)	Lai et al. (2009)	Lai et al. (2011)	(Lamy, 2017)	Lee et al. (2018)	Lee, Lee and Rodiek (2019)	Lee, Lee and Ory (2019)	Li et al. (2006)	Li et al. (2014)	Morency et al. (2012)	Nyman et al. (2013)	Schepers et al. (2017)	Watkins et al. (2021)	**Total**
Perceived accessibility					■																1
Seating													■								1
Social environment (crowded, outdoor tables, porches, passive surveillance)				■																	1
Useable width of path				■																	1

Identifying relevant street audit tools and questions

After identifying relevant street environment features that are associated with older adults' falls in pedestrian environments, we drew on existing audit tools to formulate our audit questions. We identified 19 audit tools designed for physical and virtual audits in the literature. Most audit tools were primarily intended for assessing walkability in the general population (rather than falls or the needs of older adults). Two notable exceptions were the Revised Senior Walking Environmental Assessment Tool (SWEAT-R) (Michael et al., 2009) and the falls checklist developed by Curl et al. (2016). A full list of identified audit tools is presented in Supplementary Table 2.[3]

We collated these 19 audit tools into a spreadsheet and recorded the audit questions and reliability information from each tool (to the extent possible) that were related to the key street environment features identified above. We excluded area level measures (e.g., deprivation, population density, neighbourhood walkability) that are better assessed with secondary data sets. We also excluded questions for items that are difficult to identify in GSV (e.g., icy surfaces, steps, traffic speeds, crowds) due to camera positioning, size of the feature, obstructions, temporality or distance.

We focused our attention on tools that reported a high proportion of questions or groups of questions with Kappa or Intraclass Correlation Coefficient (ICC) above 0.6, which is generally interpreted as a relatively high degree of agreement (Landis & Koch, 1977). We then selected one question for each street environment feature based on high interrater reliability, with a preference for clearer and more specific questions.

Ultimately, most of our questions were drawn from three sources: SWEAT-R (Michael et al., 2009), a tool focused on the needs of older adults; the New Zealand Systematic Pedestrian and Cycling Environment Scan (NZ-SPACES) (Badland et al., 2010), a tool which has already been adapted for use in Aotearoa New Zealand; and the tool developed by Hanibuchi et al. (2019) with very clear focused questions designed for use in virtual audits with "crowdworkers". Three questions were drawn from other sources: the Virtual Systematic Tool for Evaluating Pedestrian Streetscapes (Virtual-

STEPS) (Steinmetz-Wood et al., 2019), the Microscale Audit of Pedestrian Streetscapes (MAPS) (Cain et al., 2018; Millstein et al., 2013), and the Falls Efficacy Scale International (FES-I) (Yardley et al., 2005). Although not a street environment audit tool, the FES-I is designed to evaluate fear of falling in individuals during everyday activities (Yardley et al., 2005). Questions related to some street environment features (e.g., road crossings, streetlights) were very similar across two or more tools. In these situations, we drew from the available questions to construct a clear and specific audit question.

We also identified and selected six additional questions from the audit tools beyond the key features identified by our initial literature search (footpath buffers, tactile pavers, attractiveness, physical difficulty, fear of falling). On discussion with our advisory team, we added a question related to the social environment (adapted from SWEAT-R tool).

In total, we selected 20 questions to combine into an initial virtual audit tool and arranged these questions into five domains (footpath, obstructions, street, crossings, amenities). These questions were transferred into the online survey software Qualtrics to streamline our testing phase and minimise errors.

Testing the functionality and interrater reliability of the Fall-SAFE virtual audit tool

Identification of audit sites

GPS coordinates for each Hato Hone St John ambulance attendance location were identified (see Watkins et al., 2021, for more details). In total, 2117 records met our criteria. An initial sample of 250 sites from the data set was selected for reliability testing using a proportional stratified random sample. Stratification of the sample was used to ensure that the reliability sample contained the full spectrum of locations likely to be encountered in the final audit. The variables used to create the strata for the initial reliability sample were city (Auckland; Christchurch; one of Hamilton, Tauranga or Dunedin; other), area deprivation (higher or lower) (NZDep2013), and walkability score (higher or lower) based on dwelling density and connectivity measures used in a previous analysis of the data (Watkins et al., 2021).

Use of Google Street View

Google Street View (GSV), part of Google Maps, is a freely available online tool providing users with 360° virtual views of a location (https://www.google.com/streetview/). To conduct virtual audits, the location of each fall was searched in Google Maps using GPS coordinates from the original Hato Hone St John data set. Once each point was located, the proximity to the closest GSV track was evaluated. Sites were only audited if they were within 50 metres of a GSV track and not within a structure or other location that made viewing the actual point difficult; for example, inside a building, complex (such as a retirement village), car park with no GSV, or a natural feature. If the location was suitable, the auditor dropped into the GSV track closest to the GPS point. Once GSV was opened at the correct point, the GSV imagery date was adjusted to be as close as possible to the fall date recorded in the original data set.

We used the virtual audit approach of Plascak et al. (2020) called *drop-and-spin auditing*. Compared with segment-based audit protocols that move along the street segment, drop-and-spin auditing requires the auditor to spin 360° around a point location to complete the audit (zooming in on street environment features is encouraged). Drop-and-spin virtual audits are quicker than physical audits, but similarly reliable. Furthermore, drop-and-spin virtual audits enable assessment over large geographic areas (such as the urban environment of Aotearoa New Zealand) that are not feasible with physical audits (Plascak et al., 2020).

All audit items were assessed based on the visual presence at the point location, irrespective of objects obscuring the street environment. For example, if a large vehicle was blocking one side of the street, the other side of the street was assessed. If no items were visible anywhere on the street with the obstruction, the response option that best indicated the feature was not present was selected. (The finalised manual to support this virtual audit tool is available at https://ourarchive.otago.ac.nz/handle/10523/16373.)

Initial functionality and interrater reliability testing

As we developed this audit tool during COVID-19 lockdown restrictions in Aotearoa New Zealand, we conducted a brief auditor training exercise to familiarise ourselves with the nuances of conducting virtual audits. Four auditors (AW, TP, JG, AC) visited seven sites near their homes in person and conducted on-the-ground audits of each site; the sites were then evaluated virtually. Initial results were compared and discussed as a group to identify and correct sources of disagreement and clarify any items before commencing interrater reliability testing. This process qualitatively influenced tool design and audit processes but was not considered a formal testing exercise.

To test the functionality and interrater reliability of the 20 questions in our virtual audit tool, four auditors (AW, TP, JG, SK) conducted virtual test audits at 25 sites (results not shown here). These sites were the first 25 sites of the 250 sites identified from the full data set. The results of the initial auditing of these 25 sites were checked by the principal investigator (AC) and inconsistencies were discussed and corrected before the remainder of the reliability sample was completed (described below).

Based on the functionality and interrater reliability tests, we removed one question due to lack of visibility in GSV (whether kerb cuts were flush with the street) and combined four other questions to streamline the audit process (footpath presence/type; crossing presence/type). In addition, as interrater reliability testing indicated low agreement with the footpath condition question and trip hazards question, we modified the original questions (from SWEAT-R, NZ-SPACES, and Griew et al., 2013) into more specific questions from MAPS (Cain et al., 2018; Millstein et al., 2013).

We made several other minor changes to the final audit tool. These changes involved streamlining questions through reducing the number of response options (either by combining options, reducing the options to those most commonly identified during testing, or providing an 'other' response category) and making questions more consistent with each other.

We refined our virtual audit tool to 18 key questions (excluding initial questions identifying the auditor, site, suitability for audit and

GSV date). Table 2 includes the final set of audit questions, arranged into five domains, and indicates where we have used a question directly from existing audit tools or adapted it to better reflect the specific purpose of this virtual tool. The questions that were modified from our initial tool are also noted.

Reliability testing of initial 250 sites

Interrater reliability analysis was conducted on the sample of 250 sites (including re-auditing the 25 test sites). Each site was audited by two trained auditors (AW, TP). Both Cohen's Kappa (κ) statistic and the percentage agreement between auditors were used to demonstrate tool reliability. The Kappa (κ) statistic agreement ranges proposed by Landis and Koch (1977) were used to interpret the interrater reliability results (< 0.00 poor, 0.00–0.20 slight, 0.21–0.40 fair, 0.41–0.60 moderate, 0.61–0.80 substantial, and 0.81–1.00 almost perfect).

Results of interrater reliability testing using the Fall-SAFE virtual audit tool

Across the 500 audits completed for reliability testing, 13 sites (2.6 per cent) lacked suitable GSV imagery. The GSV imagery of the audited sites ranged in date from January 2010 to January 2020. Most sites had GSV imagery dated between 2017 and 2019 (92 per cent of the 487 reliability audits conducted).

Table 2: List of questions included in the Fall-SAFE virtual audit tool and related data sources

#	Domain	Feature	Question adaptation	Source	Audit questions and response options
1	Footpath	Footpath presence	Adapted	SWEAT-R	Are footpaths present? **Response options**: Pedestrian Street or plaza; Present on both sides; Present on one side/partial; Not present or not visible
2	Footpath	Buffer between road and footpath	Direct	SWEAT-R	Is there a buffer zone between the footpath and road? (e.g., landscaped strip, trees, benches, etc.) **Response options**: Present on both sides; Present on one side/partial; Pedestrian Street or plaza; No buffer present
3	Footpath	Width of footpath	Direct	Hanibuchi et al. (2019)	Is the footpath wide enough for two people to pass comfortably? **Response options**: Yes; No
4	Footpath	Footpath material	Direct	NZ-SPACES SWEAT-R	From what material is the path predominantly constructed? Select the one that dominates the scene: **Response options**: Bitumen/asphalt; Continuous concrete; Paving bricks; Gravel; Bark, grass, or sand; Under repair
5	Footpath	Trip hazards	Adapted	MAPS	Are there poorly maintained sections of the footpath that constitute trip hazards? (e.g., heaves, misalignment, cracks, overgrowth) **Response options**: None; One; A few; Many

#	Domain	Feature	Question adaptation	Source	Audit questions and response options
6	Footpath	Tactile paving presence	Adapted	Virtual-STEPS	Does the path include tactile paving? **Response options**: Yes; No
7	Obstructions	Obstructions	Adapted	NZ-SPACES MAPS	Are there any path obstructions? Select all that apply: **Response options**: Poles; Signs; Litter bins; Overhanging vegetation; Planters or trees; Utility boxes; Manholes, service covers, or grates; Other obstructions; None visible
8	Street	Slope	Direct	NZ-SPACES	How steep is the street or path at this location? This is usually easiest to see facing the side of the street. **Response options**: Flat or gentle slope; Moderate slope; Steep slope
9	Street	Street width	Adapted	SWEAT-R NZ-SPACES	How wide is the street? Consider the width from side to side that a pedestrian would need to cross without protection from cars, ideally at a designated crossing point. **Response options**: Pedestrian street or plaza; One to three cars wide; Four to five cars wide; Six or more cars wide

#	Domain	Feature	Question adaptation	Source	Audit questions and response options
10	Crossings	Road crossings	Adapted	SWEAT-R Hanibuchi et al. (2019) NZ-SPACES	Is there an intended crossing present? If there is an intended crossing, what type? Select all that apply: **Response options**: There is no visible crossing; Traffic signals; Zebra crossing; Median or refuge island; Kerb extensions; Kerb cuts on both sides of the road connected to the footpath; Different road surface/paving; Raised area; Other crossing feature
11	Street	Kerb type	Adapted	NZ-SPACES	What type of kerb does the street have? **Response options**: No kerb; Normal kerb (includes low and sloped kerbs); Storm drain
12	Street	Streetlights	Adapted	Hanibuchi et al. (2019) NZ-SPACES	Are there any streetlights? **Response options**: Present on both sides; Present on one side/partial or very sparse; None visible
13	Amenities	Public seat	Direct	NZ-SPACES	Are there any public seats? E.g., benches, bus stop seat. **Response options**: Yes; No
14	Amenities	Social environment	Adapted	SWEAT-R	Are there any shops, cafes or commercial properties with street-facing entrances visible? **Response options**: Yes; No
15	Street	Type of location*	New	Authors' own addition	How would you characterise this location? **Response options**: High street; Residential; Light industrial; Rural; Other

#	Domain	Feature	Question adaptation	Source	Audit questions and response options
16	Amenities	Attractiveness	Direct	NZ-SPACES	How attractive would you rate this location for walking? **Response options**: Very attractive; Attractive; Neither attractive nor unattractive; Unattractive; Very unattractive
17	Amenities	Difficulty for walking	Direct	NZ-SPACES	How physically difficult would you rate this street for walking? **Response options**: Easy; Average; Moderately difficult; Very difficult
18	Amenities	Concern about falling	Adapted	FES-I	How concerned would you be about falling in this area? **Response options**: Not at all concerned; Somewhat concerned; Fairly concerned; Very concerned
Question changes following functionality and reliability testing					
19	Footpath	Footpath presence			<u>**Combined with footpath presence (#1 above)**</u> Original question: Are footpaths present? **Response options**: Yes; No
20	Crossings	Road crossings presence			<u>**Combined with road crossing type (#10 above)**</u> Original question: Is there an intended crossing present? **Response options**: Yes; No

#	Domain	Feature	Question adaptation	Source	Audit questions and response options
21	Street	Kerb cuts			**Removed** Original question: Are kerb cuts flush with the street? **Response options**: Yes; No; None visible
22	Footpath	Footpath condition			**Replaced with question from MAPS tool (#5 above)** Original question: What is the condition of the footpath? **Response options**: Poor (many bumps, cracks, holes or weeds); Moderate (some bumps, cracks, holes or weeds); Good (very few bumps, cracks, holes or weeds); Under repair
23	Footpath	Trip hazards			**Replaced with question from NZ-SPACES and MAPS tool (#7 above)** Original question: Does the path contain any features that could pose a slip or trip hazard? Select all that apply: **Response options**: Decorative surfaces or tiles; Manhole or service covers; Grates; Uneven or poorly aligned pavers; Lichen growing on the path; None visible

Notes: 1. The questions are presented in the order they appear in the virtual falls audit tool.
2. Multiple audit tools listed for a specific feature indicates substantively similar questions across the tools.
3. * Indicates this question was added after interrater reliability assessment.

The median time taken to conduct an audit was 199.5 seconds (3.33 minutes) across the reliability sample of audits. One audit was excluded due to an obviously erroneous time (> 13 hours). A pairwise Wilcoxon Signed Rank test demonstrated a small but significant difference in overall mean audit duration by auditor (27 seconds, $p < 0.001$) in the reliability sample. Most audits in the reliability testing (90 per cent) were less than 5 minutes long. While we did not record audit time by question, the median audit time equates to an average of 9.0 seconds per question across 22 questions (including set-up questions such as site ID, whether the point was on/near a street with GSV, and GSV date).

Table 3 summarises the results of the interrater reliability assessment for the initial testing of the Fall-SAFE tool. Thirty-one items were examined for interrater reliability as each obstruction and crossing type was tested separately. Of these 31 items, 20 items (65 per cent) had a substantial level of reliability ($\kappa \geq 0.6$) or higher,and all but five items had a moderate level of reliability ($\kappa \geq 0.4$) (84 per cent). The items that did not meet the moderate reliability threshold included two that suffered from training error that affected the testing process (street width ($\kappa = 0.10$) and overhanging vegetation ($\kappa = 0.36$)). These items were not able to be retested, but the question and audit expectations were clarified in the later part of the auditing process. The remaining three items that failed to meet the threshold of at least moderate reliability were inherently subjective and expected to have poorer performance: attractiveness ($\kappa = 0.32$), concern about falling ($\kappa = 0.30$), and difficulty for walking ($\kappa = 0.24$). We chose to include these subjective outcome measures (which are commonly used in the study of street environments) to understand their relationship with objective measures of the street environment.

Following interrater reliability assessment, we added a question on location type (high street, residential, light industrial, other). This question was developed based on our knowledge and experiences and not drawn from an existing audit tool.

Table 3: Results of interrater reliability statistics for the Fall-SAFE tool

Item summary	κ	% Agreement
Footpath characteristics		
Footpath presence	0.81	97.1
Buffer between road and footpath	0.77	85.8
Width of footpath	0.61	80.0
Footpath material	0.88	94.2
Trip hazards	0.46	49.4
Tactile paving presence	0.88	95.4
Street characteristics		
Slope	0.66	81.3
Street width	0.10	37.5
Kerb type	0.73	97.9
Streetlights	0.54	76.7
Obstructions		
Poles	0.79	90.4
Signs	0.76	89.6
Litter bins	0.84	94.2
Overhanging vegetation	0.36	76.3
Planters or trees	0.85	94.6
Utility boxes	0.58	79.6
Manholes, service covers or grates	0.63	85.4
Other obstructions	0.56	78.8
Crossing features		
Traffic signals	0.91	97.5
Zebra crossing	0.82	96.3
Median/refuge island	0.76	91.3
Kerb extensions	0.60	87.1
Kerb cuts	0.53	76.3
Different road surface/paving	0.76	95.4
Raised area	0.79	96.3
Other crossing features	0.43	97.9

Item summary	κ	% Agreement
Amenities		
Public seat	0.76	89.2
Social environment	0.85	93.3
Attractiveness	0.32	61.7
Difficulty for walking	0.24	43.3
Concern about falling	0.30	60.4

Note: Interrater reliability assessment data is not available for the 'Location type' question, as this audit item was added after the interrater reliability assessment was completed.

Characterising urban environments in which outdoor falls have occurred

As the interrater reliability testing on the 250 sites indicated adequate agreement, the remaining 1867 sites were split into two groups and each audited by one of the two trained auditors (AW, TP). For the purposes of subsequent analysis, one of the two audits conducted on the interrater reliability sample was randomly selected for inclusion in the final data set (audits from AW = 132; TP = 118).

In total, 2117 unique fall sites were included in this study. Of these sites, 61 (2.8 per cent) audits were unable to be completed due to the absence of suitable GSV imagery, resulting in complete audits of 2056 sites using the Fall-SAFE tool. The GSV imagery used across all audits ranged in age from November 2009 through to June 2020. The majority of sites (1831, 86 per cent) had imagery dated 2017 or later. Imagery from 895 sites (42 per cent) reflected the period that data on pedestrian falls attended by an ambulance were available for (1 July 2016 through to 30 June 2018).

The GSV images were dated a median of 7 months after the original fall date (range: 8.4 years before the fall date to 3.5 years after the fall date). The median age of images collected before the fall date was 8 months before, while the median age of images collected after the fall date was 13 months after.

In the full audit, the median time taken to conduct a virtual audit was 185 seconds (3.08 minutes), slightly shorter than the 3.33 minutes in the interrater reliability testing. A pairwise Wilcoxon Signed Rank test demonstrated a small but significant ($p < 0.001$) difference in the duration of audits by auditor. Most audits (93 per cent) were less than 5 minutes long.

While we did not record audit time by question, the median audit time equates to an average of 8.4 seconds per question across the 22 questions.

A descriptive summary of street environment characteristics of locations where moderate-to-severe falls among older adults have occurred is presented below. Details on the full question source and response options can be found in Table 2.

Footpath characteristics

Across the audited fall locations, 87.7 per cent of sites had footpaths on both sides of the street and 10.5 per cent had partial footpaths or a footpath on one side. A small proportion of sites were pedestrian streets or plazas (0.7 per cent) or had no footpaths present (1.0 per cent) (Figure 2). The predominant footpath material was continuous concrete (45.6 per cent), followed by bitumen/asphalt (40.0 per cent) and paving bricks (14.0 per cent). Few sites were gravel (0.2 per cent) or under repair (0.2 per cent) (Figure 3). Footpaths in 55.0 per cent of sites were wide enough for two people to pass comfortably. Over one-quarter of footpaths had tactile paving present (27.3 per cent).

One-quarter of fall locations had a buffer (e.g., landscaped strip, trees, benches) between the road and footpath on both sides of the street (25.8 per cent), while a further 18.4 per cent had a partial buffer or buffer on one side of the street (Figure 4). Over half of the sites (55.3 per cent) had no buffer present.

Sixty-one per cent of fall locations had one or more poorly maintained sections of the footpath (e.g., heaves, misalignment, cracks, overgrowth) that constituted trip hazards (one trip hazard: 24.5 per cent; a few: 31.4 per cent; many: 5.1 per cent). Thirty-nine per cent of sites were audited as having no trip hazards (Figure 5).

Figure 2: Footpath presence

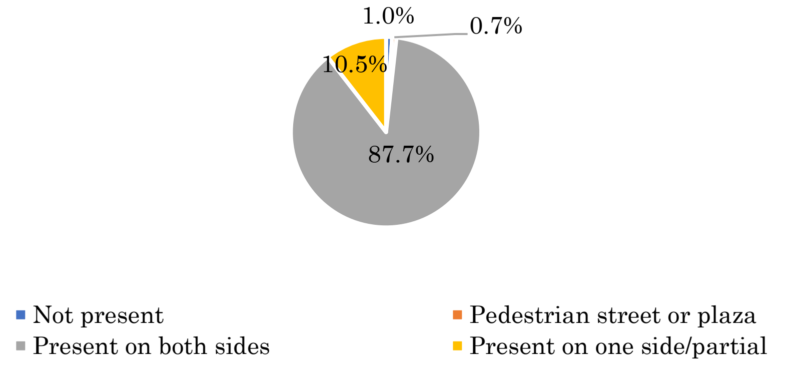


Figure 3: Footpath material

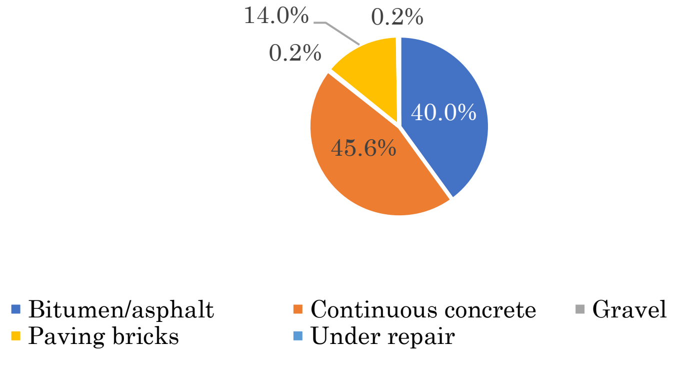


Figure 4: Buffer between road and footpath

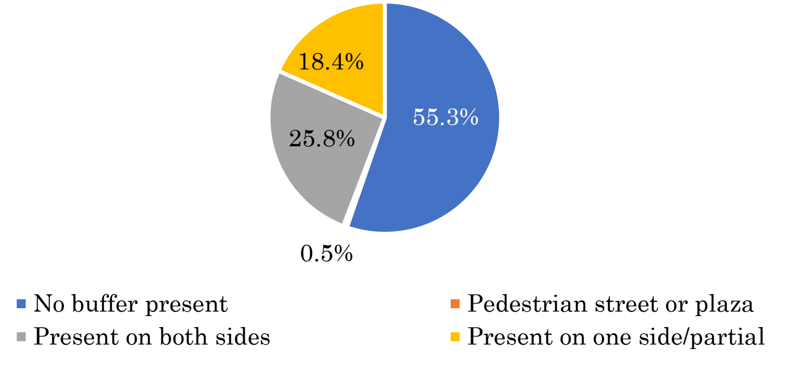
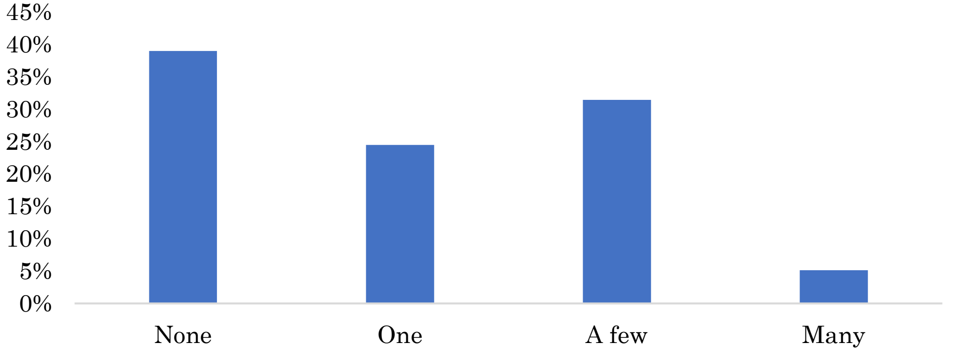


Figure 5: Number of trip hazards



Street characteristics

Half of all the falls had occurred in residential locations (49.1 per cent) and one-quarter in commercial (high street) locations (22.4 per cent) (Figure 6). A further 16.2 per cent of the falls had occurred in 'other' locations, 11.2 per cent in light industrial locations, and 1.1 per cent in rural locations.

Three-quarters of the falls had occurred in locations that had a flat or gentle slope (76.3 per cent). Only 15.5 per cent of the falls had occurred on a moderate slope, while 8.2 per cent had occurred on a steep slope (Figure 7). Half of the falls had occurred on a street that was four or five cars wide (49.1 per cent), while a further one-third of the falls had occurred on streets that were one to three car wides (31.8 per cent). Less than one-fifth of the falls had occurred on streets six or more cars wide (18.9 per cent) (Figure 8).

Most of the fall locations had normal height kerb/s (~10 cm, including low and sloped kerbs) (95.6 per cent). Few locations had no kerbs (2.3 per cent) or storm drains (2.0 per cent). Streetlights were present in most fall locations, either on one side of the street (including partial or very sparse locations) (54.8 per cent) or on both sides (44.3 per cent). Streetlights were not visible in 0.9 per cent of sites.

Figure 6: Fall location type

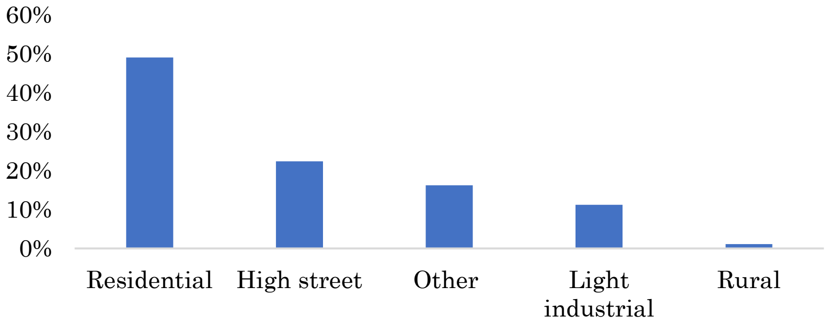


Figure 7. Slope of street

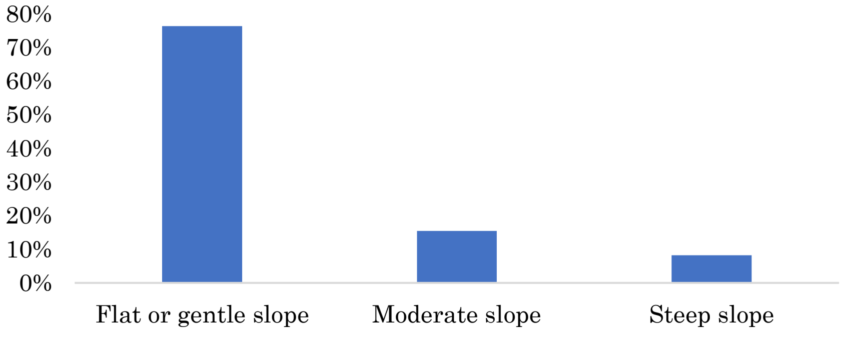
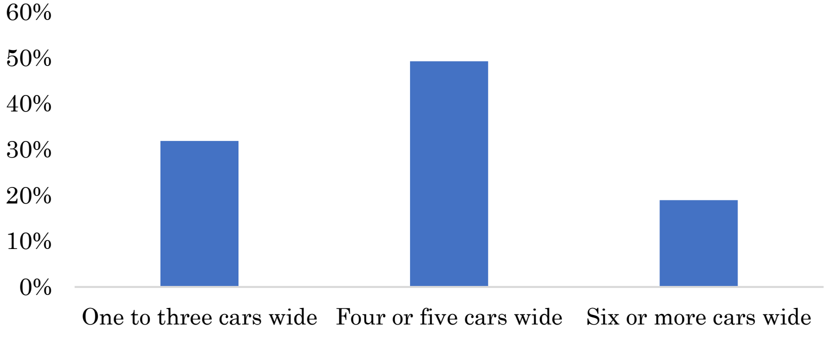


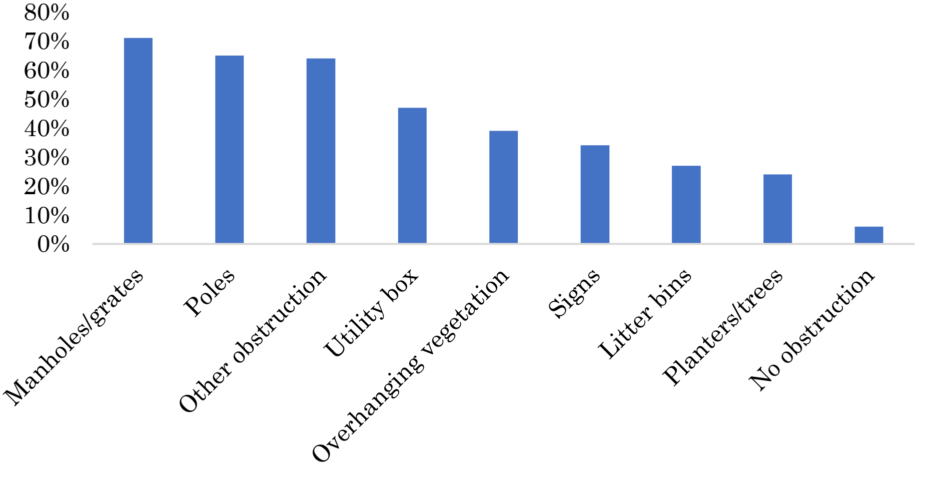
Figure 8. Street width



Obstructions

Only 5.8 per cent of the fall locations had no obstructions. The most common obstructions were manholes, service covers or grates (71.5 per cent), poles (65.4 per cent), utility boxes (46.6 per cent) and overhanging vegetation (39.5 per cent). Other obstructions were noted at 64.5 per cent of the sites (Figure 9).

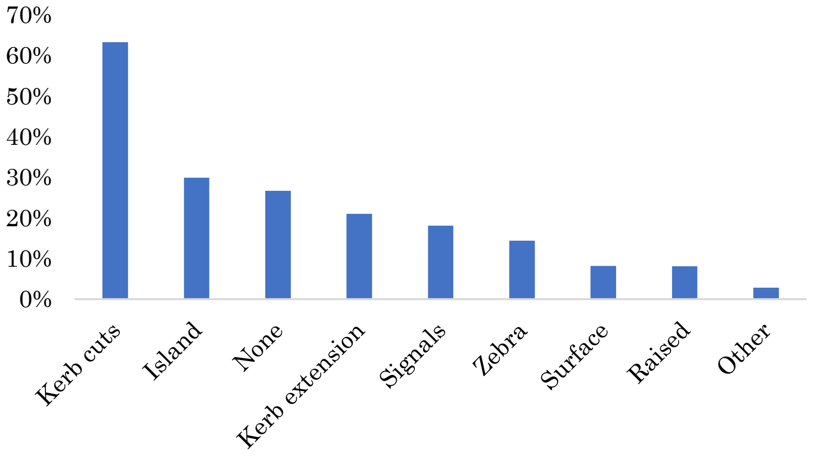
Figure 9: Obstruction types



Crossing features

One-quarter of the fall locations had no crossing amenities present (26.7 per cent). Of the remaining sites, the most common crossing features were kerb cuts (63.3 per cent), median/refuge islands (30.0 per cent) and kerb extensions (21.1 per cent). Traffic signals and zebra crossings were present at less than one-fifth of the sites (18.1 per cent and 14.5 per cent, respectively), while different road surface/paving and raised crossing areas were present at less than one-tenth of the sites (8.2 per cent and 8.1 per cent, respectively). Other crossing features were noted at 2.9 per cent of sites (Figure 10).

Figure 10: Crossing feature types



Amenities

Across the audited fall locations, 43.2 per cent of the sites had shops, cafes or commercial properties with street-facing entrances present, and 35.1 per cent of the sites had a public seat available. Assessments of attractiveness, difficulty for walking, and concern about falling are not presented here (reasons are presented in the discussion section).

Discussion

We have presented the development of a reliable virtual audit tool, Fall-SAFE, that can be used to audit street environments for falls risk among older adults. In addition, we presented an initial descriptive summary of the street environment characteristics of locations where moderate-to-severe falls among older adults occurred in Aotearoa New Zealand. Overall, our results indicate that: (1) the Fall-SAFE tool items largely showed 'moderate' to 'almost perfect' interrater reliability, (2) Fall-SAFE is a time-efficient and reliable way to assess locations using the drop-and-spin technique, and (3) the fall locations had diverse street environment characteristics. Given the present findings, we recommend the use, and continued development, of the Fall-SAFE tool to understand patterns of falls in relation to street environment conditions.

While the contribution of the environment to pedestrian falls has received increasing research attention, environment audit tools have continued to focus on walkability in general, rather than on features that are relevant for falls. Our initial brief literature search highlighted 28 features associated with older adults' falls in pedestrian environments. By drawing on six existing audit tools of high interrater reliability (SWEAT-R, NZ-SPACES, Hanibuchi et al. (2019), Virtual-STEPS, MAPS and FES-I), we formulated audit questions specific to street environment characteristics from a falls-risk perspective. Interrater reliability testing of the Fall-SAFE tool items were largely comparable with the original tools from which we drew the questions (to the extent that can be determined from item-level data reported in these tools; data not presented). However, the three questions derived from Hanibuchi et al. (2019) did not perform as well in testing as the clear and simple questions originally used with crowdworkers. This difference in interrater reliability (lower, although still adequate) is potentially due to our adaptation of the original questions to assess more complex characteristics of streetlights (present on one side/partial or both sides of the road) and crossing types. The advantage of asking more complex questions is that we achieve a richer understanding of the street environments in which falls occurred.

The Fall-SAFE tool items largely showed moderate to almost perfect interrater reliability. The lowest reliability was found for items on attractiveness, difficultly for walking, and concern about falling, although reliability was still in the 'fair' category. Low reliability for assessing environmental aesthetics or attractiveness is consistent with previous research (Cain et al., 2018; Pocock et al., 2020). Assessing attractiveness, difficultly for walking, and concern about falling requires more subjective judgement than other items (e.g., footpath or streetlight presence), which is likely informed by an auditor's perceptions and experiences of environmental attributes. We chose to retain these subjective measures in our tool to explore the relationship with more objective measures of the street environment at a later point. The other two low-reliability items (street width, overhanging vegetation) were an artefact of a training error, which was clarified in the later part of the reliability testing process. Thus, auditor training and reliability testing were valuable and enabled us to clarify discrepancies in our processes to enhance consistency and reliability.

Ultimately, our reliability assessment demonstrated that Fall-SAFE is a reliable virtual audit tool when used by independent observers.

The drop-and-spin technique elucidated by Plascak et al. (2020) made for time-efficient audits of a large number of fall locations across Aotearoa New Zealand (2056 unique fall sites). While we did not directly record the time taken to audit each item, drop-and-spin virtual audits are quicker than segment-based protocols and physical audits, but similarly reliable (Badland et al., 2010; Plascak et al., 2020). Researcher time and resources to complete street environment audits, especially across large geographic areas, is often a barrier to engaging in such projects. Virtual audits using the drop-and-spin technique enabled us to assess a large data set of falls across Aotearoa New Zealand, ultimately enabling us to explore environmental patterns across the data set in future analyses.

Many of the falls occurred in residential or commercial locations on flat/gentle slopes. This concurs with our previous analysis using a digital elevation model (DEM) to assess slope, which found most falls occurred on a flat (0°) or gentle (1–2°) slope (Watkins et al., 2021). Future research could compare the researcher assessments of slope with the values from the DEM. Our descriptive results also indicated that footpaths were largely present on both sides of the road and were constructed from either continuous concrete or bitumen (thought to be safer than alternative footpath materials). Most of the fall locations had one or more crossing amenities present. However, 61 per cent of the fall locations had one or more trip hazards from poorly maintained sections of the footpath and only 5.8 per cent of sites had no obstructions (e.g., manholes, poles, overhanging vegetation).

These descriptive results characterise the types of locations where pedestrian falls have occurred among older adults in Aotearoa New Zealand and required ambulance attendance. We previously found that falls happened more frequently in more-deprived locations (relative to the home location of the respondent), which we expected could be indicative of poorer-quality street environments in more-deprived areas (Watkins et al., 2021). These descriptive results suggest considerable presence of trip hazards and obstructions in locations where falls have occurred. The high proportion of sites with trip hazards/obstructions suggest that greater attention is needed from local councils towards the quality of pedestrian infrastructure, particularly in areas with older infrastructure that may have been developed prior to modern guidelines. Audit tools are valuable for highlighting deficiencies in the pedestrian environment to address upstream determinants of health.

However, we cannot know from this research how these fall locations compare with locations where falls have not occurred. In other words, we do not know that these environmental features are associated with higher prevalence of falling; we can simply describe the features of places where falls have occurred. Future investigations are required to characterise the similarities and differences between environments where moderate-to-severe falls have and have not occurred.

The researchers who undertook the audits were trained in using the tool and had expertise in research with older adults and in built environments and health. However, they are also younger in age than those most at risk of falls and for whom the tool is targeted, indicating that this subjective assessment may potentially be misaligned with the perspectives of older adults generally and those at risk of falling. It is also important to understand the perspectives of older adults themselves, alongside objective measures of the environment. An additional aspect of this larger project was to work with older adults to undertake participatory audits of fall locations using GSV. We will report on these results in future publications. Future research could also consider use of machine learning to categorise the fall environment in GSV (Ki et al., 2022)

Limitations

Previous authors have highlighted limitations of virtual audits, including image quality and update frequency (Badland et al., 2010; Griew et al., 2013; Hanibuchi et al., 2019), obstructions or features that are difficult to view such as kerb cuts blocked by parked cars (Griew et al., 2013; Steinmetz-Wood et al., 2019), lack of non-visual information such as sound or smell (Plascak et al., 2020; Steinmetz-Wood et al., 2019), and absent information on the image collection day and time (Griew et al., 2013; Hanibuchi et al., 2019; Plascak et al., 2020).

Some of these limitations made our audits difficult. For example, images that appeared to have been taken later in the day during winter months in southern (higher latitude) parts of Aotearoa tended to have poor light and high glare, making it difficult to see some street features (also described by Griew et al., 2013). In addition, considerable differences between the date of available GSV imagery and the date of the fall (range: 8.4 years before the fall date to 3.5 years after the fall date) means that the imagery assessed may show different environmental features to the time the fall occurred. This is particularly an issue in Christchurch, New Zealand where the urban environment has changed considerably in the post-earthquake period (after 2010/11) (Curl et al., 2022).

Another consideration is the temporal nature of the environment, often related to obstructions from fallen leaves, kerbside rubbish-bin collection, or the number of cars parked on the side of the road. While some of these are regular occurrences, their appearance in GSV imagery is unpredictable and their impact varies, making them difficult to assess when not visible. However, the literature suggests that these temporary obstructions present a considerable challenge from a falls-risk perspective.

The availability of detailed spatial information on the location of a fall is a strength of the Hato Hone St John data, relative to other administrative data sets on falls. The fall locations obtained from Hato Hone St John are based on the location attended by an ambulance, however, and may not directly correspond to where a moderate-to-severe fall actually occurred. Furthermore, the GPS location can 'drift' and the accuracy may vary in different environments (Duncan et al., 2013). Nonetheless, these locations are still broadly reflective of the wider environments in which moderate-to-severe falls have occurred.

Exclusion of minor/non-injury related falls is a limitation of all administrative data sets on falls. The rate of falls in this data set is 200 per 100,000 adults aged 15+ years (Watkins et al., 2021), whereas survey research with older adults suggests that approximately a third have experienced a fall in the past year (Curl et al., 2020; Li et al., 2014; Todd & Skelton, 2004; Wijlhuizen et al., 2007). Future research could seek to understand the location of minor falls.

This analysis has not included characteristics of fall locations among older adults who did not require ambulance attendance or characteristics of environments where falls have not occurred. Thus, we do not know which environmental features are associated with higher prevalence of falling. Current and future analyses will advance knowledge in the spatial understanding of fall environments.

Conclusion

The Fall-SAFE tool is a reliable virtual audit tool developed specifically to assess the street environment from a falls-risk perspective. Although we tested the tool in environments where moderate-severe falls occurred, it is suitable for use in any environment, as it was developed based on literature on falls risk. Our tool draws on established walkability and environment audit tools, has a reasonable level of reliability, and is suitable for use with virtual environment tools, such as GSV. The use of GSV and the short time required to conduct a Fall-SAFE audit is likely to make this tool accessible both to researchers and community groups who may be concerned about falls in their local area. A standardised tool could also be used by community groups or advocates to demonstrate to local government a need for improved pedestrian infrastructure.

Notes

1 The study was approved by the University of Otago Human Ethics Committee (Approval number H19/143) and by the Hato Hone St John Locality Assessment procedures.

2 'Table S1: Study and participant characteristics of identified articles' is in the supplementary notes, which are available at https://hdl.handle.net/10523/41952

3 'Table S2: Identified audit tools' is in the supplementary notes, which are available at https://hdl.handle.net/10523/41952.

Acknowledgements

We thank Jak Gilden for assistance in developing and testing the audit tool during his Public Health Elective placement, and Hato Hone | St John Clinical Audit and Research Team for providing fall location data.

This research was funded through a University of Otago | Te Whare Wānanga o Ōtākou Research Grant.

References

Bader, M. D. M., Mooney, S. J., Bennett, B., & Rundle, A. G. (2017). The promise, practicalities, and perils of virtually auditing neighborhoods using Google Street View. *The ANNALS of the American Academy of Political and Social Science*, *669*, 18–40. https://doi.org/10.1177/0002716216681488

Badland, H. M., Opit, S., Witten, K., Kearns, R. A., & Mavoa, S. (2010). Can virtual streetscape audits reliably replace physical streetscape audits? *Journal of Urban Health*, *87*(6), 1007–1016. https://doi.org/10.1007/s11524-010-9505-x

Bostock, L. (2001). Pathways of disadvantage? Walking as a mode of transport among low-income mothers. *Health and Social Care in the Community*, *9*(1), 11–18. https://doi.org/10.1046/j.1365-2524.2001.00275.x

Brookfield, K., & Tilley, S. (2016). Using virtual street audits to understand the walkability of older adults' route choices by gender and age. *International Journal of Environmental Research and Public Health*, *13*(11), Article 1061. https://doi.org/10.3390/ijerph13111061

Brownson, R. C., Hoehner, C. M., Day, K., Forsyth, A., & Sallis, J. F. (2009). Measuring the built environment for physical activity: State of the science. *American Journal of Preventive Medicine*, *36*(4S), S99–S123. https://doi.org/10.1016/j.amepre.2009.01.005

Cain, K. L., Geremia, C. M., Conway, T. L., Frank, L. D., Chapman, J. E., Fox, E. H., Timperio, A., Veitch, J., Van Dyck, D., Verhoeven, H., Reis, R., Augusto, A., Cerin, E., Mellecker, R. R., Queralt, A., Molina-García, J., & Sallis, J. F. (2018). Development and reliability of a streetscape observation instrument for international use: MAPS-global. *International Journal of Behavioral Nutrition and Physical Activity*, *15,* Article 19. https://doi.org/10.1186/s12966-018-0650-z

Ceccato, V., & Willems, O. (2019). Temporal and spatial dynamics of falls among older pedestrians in Sweden. *Applied Geography*, *103*, 122–133. https://doi.org/10.1016/j.apgeog.2018.12.007

Chippendale, T., & Boltz, M. (2015). The neighborhood environment: Perceived fall risk, resources, and strategies for fall prevention. *Gerontologist*, *55*(4), 575–583. https://doi.org/10.1093/geront/gnu019

——— (2018). Outdoor fall experiences: An exploratory study of urban and suburban dwelling older adults. *Physical and Occupational Therapy in Geriatrics*, *36*(2–3), 234–244. https://doi.org/10.1080/02703181.2018.1495677

Clarke, P., Ailshire, J. A., Bader, M., Morenoff, J. D., & House, J. S. (2008). Mobility disability and the urban built environment. *American Journal of Epidemiology*, *168*(5), 506–513. https://doi.org/10.1093/aje/kwn185

Curl, A., Annear, M., Keeling, S., & Hackett, G. (2022). Building back better: Do post-earthquake neighborhoods promote active aging? A long-term audit analysis in Christchurch, New Zealand. *Journal of Aging and Environment*, *37*(3), 255–276. https://doi.org/10.1080/26892618.2022.2071373

Curl, A., Fitt, H., & Tomintz, M. (2020). Experiences of the built environment, falls and fear of falling outdoors among older adults: An exploratory study and future directions. *International Journal of Environmental Research and Public Health*, *17*(4), Article 1224. https://doi.org/https://doi.org/10.3390/ijerph17041224

Curl, A., & Mason, P. (2019). Neighbourhood perceptions and older adults' wellbeing: Does walking explain the relationship in deprived urban communities? *Transportation Research Part A: Policy and Practice*, *123*, 119–129. https://doi.org/10.1016/j.tra.2018.11.008

Curl, A., Ward Thompson, C., Aspinall, P., & Ormerod, M. (2016). Developing an audit checklist to assess outdoor falls risk. *Proceedings of the Institution of Civil Engineers – Urban Design and Planning*, *169*(3), 138–153. https://doi.org/10.1680/udap.14.00056

Duncan, S., Stewart, T. I., Oliver, M., Mavoa, S., MacRae, D., Badland, H. M., & Duncan, M. J. (2013). Portable Global Positioning System receivers: Static validity and environmental conditions. *American Journal of Preventive Medicine*, *44*(2), e19–e29. https://doi.org/10.1016/j.amepre.2012.10.013

Elvik, R., & Bjørnskau, T. (2019). Risk of pedestrian falls in Oslo, Norway: Relation to age, gender and walking surface condition. *Journal of Transport and Health*, *12*, 359–370. https://doi.org/10.1016/j.jth.2018.12.006

Emery, J., Crump, C., & Bors, P. (2003). Reliability and validity of two instruments designed to assess the walking and bicycling suitability of sidewalks and roads. *American Journal of Health Promotion*, *18*(1), 38–46. https://doi.org/10.4278/0890-1171-18.1.38

Ewing, R., Handy, S., Brownson, R. C., Clemente, O., & Winston, E. (2006). Identifying and measuring urban design qualities related to walkability. *Journal of Physical Activity and Health*, *3*(s1), S223–S240. https://doi.org/10.1123/jpah.3.s1.s223

Frank, L. D., Iroz-Elardo, N., MacLeod, K. E., & Hong, A. (2019). Pathways from built environment to health: A conceptual framework linking behavior and exposure-based impacts. *Journal of Transport & Health*, *12*, 319–335. https://doi.org/https://doi.org/10.1016/j.jth.2018.11.008

Gardner, P. J. (2011). Natural neighborhood networks – Important social networks in the lives of older adults aging in place. *Journal of Aging Studies*, *25*, 263–271. https://doi.org/10.1016/j.jaging.2011.03.007

Grant, T. L., Edwards, N., Sveistrup, H., Andrew, C., & Egan, M. (2010). Neighborhood walkability: Older people's perspectives from four neighborhoods in Ottawa, Canada. *Journal of Aging and Physical Activity*, *18*(3), 293–312. https://www.ncbi.nlm.nih.gov/pubmed/20651416

Griew, P., Hillsdon, M., Foster, C., Coombes, E., Jones, A., & Wilkinson, P. (2013). Developing and testing a street audit tool using Google Street View to measure environmental supportiveness for physical activity. *International Journal of Behavioral Nutrition and Physical Activity*, *10*(1), Article 103. https://doi.org/10.1186/1479-5868-10-103

Gullón, P., Badland, H. M., Alfayate, S., Bilal, U., Escobar, F., Cebrecos, A., Diez, J., & Franco, M. (2015). Assessing walking and cycling environments in the streets of Madrid: Comparing on-field and virtual audits. *Journal of Urban Health*, *92*(5), 923–939. https://doi.org/10.1007/s11524-015-9982-z

Gyllencreutz, L., Björnstig, J., Rolfsman, E., & Saveman, B.-I. (2015). Outdoor pedestrian fall-related injuries among Swedish senior citizens – injuries and preventive strategies. *Scandinavian Journal of Caring Sciences*, *29*(2), 225–233. https://doi.org/https://doi.org/10.1111/scs.12153

Hanibuchi, T., Nakaya, T., & Inoue, S. (2019). Virtual audits of streetscapes by crowdworkers. *Health and Place*, *59*, Article 102203. https://doi.org/10.1016/j.healthplace.2019.102203

Hjorthol, R. (2013). Winter weather – an obstacle to older people's activities? *Journal of Transport Geography*, *28*, 186–191. https://doi.org/10.1016/j.jtrangeo.2012.09.003

Hoehner, C. M., Ivy, A., Ramirez, L. K. B., Handy, S., & Brownson, R. C. (2007). Active neighborhood checklist: A user-friendly and reliable tool for assessing activity friendliness. *American Journal of Health Promotion*, *21*(6), 534–537. https://doi.org/10.4278/0890-1171-21.6.534

Injury Prevention Research Unit. (2019). *NZ Injury Query System (NIQS)*. Department of Preventive and Social Medicine, University of Otago. https://psm-dm.otago.ac.nz/niqs

Isola, P. D., Bogert, J. N., Chapple, K. M., Israr, S., Gillespie, T. L., & Weinberg, J. A. (2019). Google Street View assessment of environmental safety features at the scene of pedestrian automobile injury. *Journal of Trauma and Acute Care Surgery*, *87*(1), 82–86. https://doi.org/10.1097/ta.0000000000002338

Jung, H. Y., Kim, S. H., Lee, S. C., Kim, S., Cho, G. C., Kim, M. J., Lee, J. S., & Han, C. (2018). Relating factors to severe injury from outdoor falls in older people. *Geriatrics and Gerontology International*, *18*(1), 80–87. https://doi.org/10.1111/ggi.13144

Keall, M. D., Pierse, N., Howden-Chapman, P., Guria, J., Cunningham, C. W., & Baker, M. G. (2017). Cost-benefit analysis of fall injuries prevented by a programme of home modifications: A cluster randomised controlled trial. *Injury Prevention*, *23*(1), Article 22. https://doi.org/10.1136/injuryprev-2015-041947

Kerr, J., Rosenberg, D., & Frank, L. (2012). The role of the built environment in healthy aging: Community design, physical activity, and health among older adults. *Journal of Planning Literature*, *27*(1), 43–60. https://doi.org/10.1177/0885412211415283

Ki, D., Lieu, S., Chen, Z., & Lee, S. (2022). A novel walkability index using Google Street View and deep learning. *SSRN*. https://doi.org/10.2139/ssrn.4097441

Lai, P. C., Low, C. T., Wong, M., Wong, W. C., & Chan, M. H. (2009). Spatial analysis of falls in an urban community of Hong Kong. *International Journal of Health Geographics*, *8*, Article 14. https://doi.org/10.1186/1476-072X-8-14

Lai, P. C., Wong, W. C., Low, C. T., Wong, M., & Chan, M. H. (2011). A small-area study of environmental risk assessment of outdoor falls. *Journal of Medical Systems, 35*(6), 1543–1552. https://doi.org/10.1007/s10916-010-9431-1

Lakhotia, S., Rao, K. R., & Tiwari, G. (2019). Accessibility of bus stops for pedestrians in Delhi. *Journal of Urban Planning and Development*, *145*(4), 11, Article 05019015. https://doi.org/10.1061/(asce)up.1943-5444.0000525

Lamy, E. (2017). *Supporting independent living through the prediction and prevention of falls*. Urban Big Data Centre. https://www.ubdc.ac.uk/media/1632/supporting-independent-living-report-etaine-lamy-231017.pdf

Landis, J. R., & Koch, G. G. (1977). The measurement of observer agreement for categorical data. *Biometrics*, *33*(1), 159–174. https://doi.org/10.2307/2529310

Lee, S., Lee, C., & Ory, G. M. (2019). Association between recent falls and changes in outdoor environments near community-dwelling older adults' homes over time: Findings from the NHATS Study. *International Journal of Environmental Research and Public Health*, *16*(18), Article 3320. https://doi.org/10.3390/ijerph16183230

Lee, S., Lee, C., Ory, M. G., Won, J., Towne, S. D., Wang, S., & Forjuoh, S. N. (2018). Fear of outdoor falling among community-dwelling middle-aged and older adults: The role of neighborhood environments. *Gerontologist*, *58*(6), 1065–1074. https://doi.org/10.1093/geront/gnx123

Lee, S., Lee, C., & Rodiek, S. (2019). Outdoor exposure and perceived outdoor environments correlated to fear of outdoor falling among assisted living residents. *Aging and Mental Health, 24*(12), 1968–1976. https://doi.org/10.1080/13607863.2019.1647139

Leslie, E., Coffee, N., Frank, L., Owen, N., Bauman, A., & Hugo, G. (2007). Walkability of local communities: Using geographic information systems to objectively assess relevant environmental attributes. *Health & Place*, *13*(1), 111–122. https://doi.org/10.1016/j.healthplace.2005.11.001

Li, W., Keegan, T. H. M., Sternfeld, B., Sidney, S., Quesenberry, C. P., & Kelsey, J. L. (2006). Outdoor falls among middle-aged and older adults: A neglected public health problem. *American Journal of Public Health*, *96*, 1192–1200. https://doi.org/10.2105/AJPH.2005.083055

Li, W., Procter-Gray, E., Lipsitz, L. A., Leveille, S. G., Hackman, H., Biondolillo, M., & Hannan, M. T. (2014). Utilitarian walking, neighborhood environment, and risk of outdoor falls among older adults. *American Journal of Public Health*, *104*(9), e30–e37. https://doi.org/10.2105/AJPH.2014.302104

Meher, M., Spray, J., Wiles, J., Anderson, A., Willing, E., Witten, K., Ofanoa, M., Ameratunga, S., & Inclusive Streetscapes Project Team. (2021). Locating transport sector responsibilities for the wellbeing of mobility-challenged people in Aotearoa New Zealand. *Wellbeing, Space and Society*, *2*, Article 100034. https://doi.org/10.1016/j.wss.2021.100034

Michael, Y. L., Keast, E. M., Chaudhury, H., Day, K., Mahmood, A., & Sarte, A. F. (2009). Revising the senior walking environmental assessment tool. *Preventive Medicine*, *48*(3), 247–249. https://doi.org/10.1016/j.ypmed.2008.12.008

Millstein, R. A., Cain, K. L., Sallis, J. F., Conway, T. L., Geremia, C., Frank, L. D., Chapman, J., Van Dyck, D., Dipzinski, L. R., Kerr, J., Glanz, K., & Saelens, B. E. (2013). Development, scoring, and reliability of the Microscale Audit of Pedestrian Streetscapes (MAPS). *BMC Public Health*, *13*(1), Article 403. https://doi.org/10.1186/1471-2458-13-403

Milton, S., Pliakas, T., Hawkesworth, S., Nanchahal, K., Grundy, C., Amuzu, A., Casas, J.-P., & Lock, K. (2015). A qualitative geographical information systems approach to explore how older people over 70 years interact with and define their neighbourhood environment. *Health & Place*, *36*, 127–133. https://doi.org/10.1016/j.healthplace.2015.10.002

Mooney, S. J., DiMaggio, C. J., Lovasi, G. S., Neckerman, K. M., Bader, M. D., Teitler, J. O., Sheehan, D. M., Jack, D. W., & Rundle, A. G. (2016). Use of Google Street View to assess environmental contributions to pedestrian injury. *American Journal of Public Health*, *106*(3), 462–469. https://doi.org/10.2105/AJPH.2015.302978

Morency, P., Voyer, C., Burrows, S., & Goudreau, S. (2012). Outdoor falls in an urban context: Winter weather impacts and geographical variations. *Canadian Journal of Public Health*, *103*(3), 218–222. http://dx.doi.org/10.1007/BF03403816

Nesoff, E. D., Milam, A. J., Pollack, K. M., Curriero, F. C., Bowie, J. V., Gielen, A. C., & Furr-Holden, D. M. (2018). Novel methods for environmental assessment of pedestrian injury: Creation and validation of the Inventory for Pedestrian Safety Infrastructure. *Journal of Urban Health*, *95*(2), 208–221. https://doi.org/10.1007/s11524-017-0226-2

Nyman, S. R., Ballinger, C., Phillips, J. E., & Newton, R. (2013). Characteristics of outdoor falls among older people: A qualitative study. *BMC Geriatrics*, *13*, Article 125. https://doi.org/10.1186/1471-2318-13-125

Perez-Jara, J., Walker, D., Heslop, P., & Robinson, S. (2010). Measuring fear of falling and its effect on quality of life and activity. *Reviews in Clinical Gerontology*, *20*, 277–287. http://dx.doi.org/10.1017/S0959259810000237

Pikora, T., Bull, F., Jamrozik, K., Knuiman, M., Giles-Corti, B., & Donovan, R. (2002). Developing a reliable audit instrument to measure the physical environment for physical activity. *American Journal of Preventive Medicine*, *23*(3), 187–194. http://dx.doi.org/10.1016/S0749-3797(02)00498-1

Plascak, J. J., Rundle, A. G., Babel, R. A., Llanos, A. A., LaBelle, C. M., Stroup, A. M., & Mooney, S. J. (2020). Drop-and-spin virtual neighborhood auditing: Assessing built environment for linkage to health studies. *American Journal of Preventive Medicine*, *58*(1), 152–160. https://doi.org/10.1016/j.amepre.2019.08.032

Pliakas, T., Hawkesworth, S., Silverwood, R. J., Nanchahal, K., Grundy, C., Armstrong, B., Casas, J. P., Morris, R. W., Wilkinson, P., & Lock, K. (2017). Optimising measurement of health-related characteristics of the built environment: Comparing data collected by foot-based street audits, virtual street audits and routine secondary data sources. *Health & Place*, *43*, 75–84. https://doi.org/https://doi.org/10.1016/j.healthplace.2016.10.001

Pocock, T., Moore, A., Molina-García, J., Queralt, A., & Mandic, S. (2020). School neighbourhood built environment assessment for adolescents' active transport to school: Modification of an environmental audit tool and protocol (MAPS Global-SN). *International Journal of Environmental Research and Public Health*, *17*, Article 2194. https://doi.org/10.3390/ijerph17072194

Pocock, T., Woodward, A., Wiles, J., Raphael, D., & Smith, M. (2022). Diverse approaches to conceptualising positive ageing: A scoping review. *Kotuitui: New Zealand Journal of Social Sciences Online*. https://doi.org/10.1080/1177083X.2022.2090968

Portegijs, E., Rantakokko, M., Viljanen, A., Sipilä, S., & Rantanen, T. (2016). Is frailty associated with life-space mobility and perceived autonomy in participation outdoors? A longitudinal study. *Age and Ageing*, *45*, 550–553. https://doi.org/10.1093/ageing/afw072

Rzotkiewicz, A., Pearson, A. L., Dougherty, B. V., Shortridge, A., & Wilson, N. (2018). Systematic review of the use of Google Street View in health research: Major themes, strengths, weaknesses and possibilities for future research. *Health Place*, *52*, 240–246. https://doi.org/10.1016/j.healthplace.2018.07.001

Schepers, P., den Brinker, B., Methorst, R., & Helbich, M. (2017). Pedestrian falls: A review of the literature and future research directions. *Journal of Safety Research*, *62*, 227–234. https://doi.org/10.1016/j.jsr.2017.06.020

Spivock, M., Gauvin, L., & Brodeur, J.-M. (2007). Neighborhood-level active living buoys for individuals with physical disabilities. *American Journal of Preventive Medicine*, *32*(3), 224–230. https://doi.org/10.1016/j.amepre.2006.11.006

Spray, J., Witten, K., Wiles, J., Anderson, A., Paul, D., Wade, J., & Ameratunga, S. (2022). Inequitable mobilities: Intersections of diversity with urban infrastructure influence mobility, health and wellbeing. *Cities & Health*, *6*(4), 711–725. https://doi.org/10.1080/23748834.2020.1827881

Stats NZ. (2017). *Urban rural 2018 (generalised)*. https://datafinder.stats.govt.nz/layer/92218-urban-rural-2018-generalised/

Steinmetz-Wood, M., Velauthapillai, K., O'Brien, G., & Ross, N. A. (2019). Assessing the micro-scale environment using Google Street View: The Virtual Systematic Tool for Evaluating Pedestrian Streetscapes (Virtual-STEPS). *BMC Public Health*, *19*(1), Article 1246. https://doi.org/10.1186/s12889-019-7460-3

Sugiyama, T., & Ward Thompson, C. (2007). Older people's health, outdoor activity and supportiveness of neighbourhood environments. *Landscape and Urban Planning*, *83*, 168–175. https://doi.org/10.1016/j.landurbplan.2007.04.002

Suminski, R. R., Heinrich, K. M., Poston, W. S., Hyder, M., & Pyle, S. (2008). Characteristics of urban sidewalks/streets and objectively measured physical activity. *Journal of Urban Health*, *85*(2), 178–190. https://doi.org/10.1007/s11524-007-9251-x

Taylor, A. H., Cable, N. T., Faulkner, G., Hillsdon, M., Narici, M., & van Der Bij, A. K. (2004). Physical activity and older adults: A review of health benefits and the effectiveness of interventions. *Journal of Sports Sciences*, *22*(8), 703–725. https://doi.org/10.1080/02640410410001712421

Todd, C. & Skelton, D. (2004). *What are the main risk factors for falls amongst older people and what are the most effective interventions to prevent these falls?* (A Health Evidence Network report). World Health Organization Regional Office for Europe. http://www.euro.who.int/__data/assets/pdf_file/0018/74700/E82552.pdf

Van Cauwenberg, J., Van Holle, V., Simons, D., Deridder, R., Clarys, P., Goubert, L., Nasar, J., Salmon, J., De Bourdeaudhuij, I., & Deforche, B. (2012). Environmental factors influencing older adults' walking for transportation: a study using walk-along interviews. *International Journal of Behavioral Nutrition and Physical Activity*, *9*, Article 85. https://doi.org/10.1186/1479-5868-9-85

van Hoven, B., & Meijering, L. (2019). Mundane mobilities in later life – Exploring experiences of everyday tripmaking by older adults in a Dutch urban neighbourhood. *Research in Transportation Business & Management*, *30*, Article 100375. https://doi.org/10.1016/j.rtbm.2019.100375

Vine, D., Buys, L., & Aird, R. (2012). Experiences of neighbourhood walkability among older Australians living in high density inner-city areas. *Planning Theory & Practice*, *13*(3), 421–444. https://doi.org/10.1080/14649357.2012.696675

Ward Thompson, C., Curl, A., Aspinall, P., Alves, S., & Zuin, A. (2014). Do changes to the local street environment alter behaviour and quality of life of older adults? The 'DIY Streets' intervention. *British Journal of Sports Medicine*, *48*(13), 1059–1065. https://doi.org/10.1136/bjsports-2012-091718

Watkins, A., Curl, A., Mavoa, S., Tomintz, M., Todd, V., & Dicker, B. (2021). A socio-spatial analysis of pedestrian falls in Aotearoa New Zealand. *Social Science & Medicine*, Article 113212. https://doi.org/10.1016/j.socscimed.2020.113212

Wijlhuizen, G. J., de Jong, R., & Hopman-Rock, M. (2007). Older persons afraid of falling reduce physical activity to prevent outdoor falls. *Preventive Medicine*, *44*(3), 260–264. https://doi.org/https://doi.org/10.1016/j.ypmed.2006.11.003

Williams, J. E., Evans, M., Kirtland, K. A., Cavnar, M. M., Sharpe, P. A., Neet, M. J., & Cook, A. (2005). Development and use of a tool for assessing sidewalk maintenance as an environmental support of physical activity. *Health Promotion Practice*, *6*(1), 81–88. https://doi.org/10.1177/1524839903260595

World Health Organization. (2021). *Falls*. Retrieved 21/11/2023 from https://www.who.int/news-room/fact-sheets/detail/falls#:~:text=A%20fall%20is%20defined%20as,though%20most%20are%20non-fatal

Yardley, L., Beyer, N., Hauer, K., Kempen, G., Piot-Ziegler, C., & Todd, C. (2005). Development and initial validation of the Falls Efficacy Scale-International (FES-I). *Age and Ageing*, *34*(6), 614–619. https://doi.org/10.1093/ageing/afi196