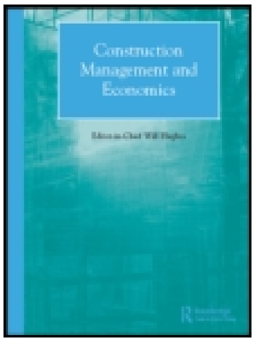

Construction Management and Economics

ISSN: 0144-6193 (Print) 1466-433X (Online) Journal homepage: https://www.tandfonline.com/loi/rcme20

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To cite this article: Kun Hu , Hazhir Rahmandad , Tonya Smith-Jackson & Woodrow Winchester (2011) Factors influencing the risk of falls in the construction industry: a review of the evidence, Construction Management and Economics, 29:4, 397-416, DOI: 10.1080/01446193.2011.558104

To link to this article: https://doi.org/10.1080/01446193.2011.558104

Construction Management and Economics (April 2011) **29**, 397–416

Factors influencing the risk of falls in the construction industry: a review of the evidence

KUN HU*[1], HAZHIR RAHMANDAD[1], TONYA SMITH-JACKSON[2] and WOODROW WINCHESTER[3]

[1]*Department of Industrial and Systems Engineering, Virginia Tech, 7054 Haycock Rd, Rm 433, Falls Church, 22043 USA*
[2]*Department of Industrial and Systems Engineering, Virginia Tech, 260 Durham Hall, Blacksburg, VA, 24061 USA*

Received 3 August 2010; accepted 22 January 2011

Falls are a significant public health risk and a leading cause of non-fatal and fatal injuries among construction workers worldwide. A more comprehensive understanding of casual factors leading to fall incidents is essential to prevent falls in the construction industry. However, an extensive overview of causal factors is missing from the literature. In this paper, 536 articles on factors contributing to the risk of falls were retrieved. One hundred and twenty-one (121) studies met the criteria for relevance and quality to be coded, and were synthesized to provide an overview. In lieu of the homogeneity needed across studies to conduct a structured meta-analysis, a literature synthesis method based on macro-variables was advanced. This method provides a flexible approach to aggregating previous findings and assessing agreement across those studies. Factors commonly associated with falls included working surfaces and platforms, workers' safety behaviours and attitudes, and construction structure and facilities. Significant differences across qualitative and quantitative studies were found in terms of focus, and areas with limited agreement in previous research were identified. The findings contribute to research on the causes of falls in construction, developing engineering controls, informing policy and intervention design to reduce the risk of falls, and improving research synthesis methods.

Keywords: Accident causes, causal map, literature synthesis methods, safety.

Introduction

The construction industry faces many occupational injuries and fatality risks, making it both unique and challenging to study. Construction is always risky because of outdoor operations (Hsiao and Simeonov, 2001; Imriyas *et al.*, 2007), working at heights (Lipscomb *et al.*, 2006), and often working in dynamic and complex environments—i.e. diverse construction methods (Hsiao and Simeonov, 2001), working conditions and materials (Chi *et al.*, 2004; Imriyas *et al.*, 2007). Equipment operation coupled with workers' attitudes, behaviours and physical characteristics relevant to safety also contribute to the relatively higher risk context in this industry (Hsiao and Simeonov, 2001; Sa *et al.*, 2009). In theory, most construction injuries can be either prevented or controlled. Unfortunately, achieving this goal has been very slow in practice (Gambatese *et al.*, 2008). Hazard prevention and control in construction is a persistent and global challenge, with construction having one of the worst safety records among diverse economic sectors, including high-risk industries such as chemical, mining, electrical and transportation (Lehtola *et al.*, 2008; Sa *et al.*, 2009; Hallowell, 2010a). The US construction industry accounts for 19% of all occupational fatalities, and despite a gradual decline, remains the highest source of fatal occupational accidents (Bureau of Labor Statistics, 2010). The construction fatality rate in the United Kingdom has risen over recent years to constitute 21.5% of total occupational fatalities (Health and Safety Executive, 2010) while reportable non-fatal injuries averaged 16 per 1000 workers between 2004 and 2009, significantly higher than the average of 10 per 1000 workers overall (Labour Force Survey, 2009). Construction

*Author for correspondence. E-mail: hukun@vt.edu

Construction Management and Economics
ISSN 0144-6193 print/ISSN 1466-433X online © 2011 Taylor & Francis
http://www.informaworld.com
DOI: 10.1080/01446193.2011.558104

incidents account for more than one-third of all industrial incidents over the last 10 years in China (Chua and Goh, 2004; Li and Wang, 2004; Tam *et al.*, 2006; Liao and Perng, 2008). In addition to the loss of life and reduction in the quality of life of construction workers, construction incidents lead to project delays (Meerding *et al.*, 2006; Gavious *et al.*, 2009), increased project costs (Lipscomb *et al.*, 2003a; Horwitz and McCall, 2004), medical burden (Lipscomb *et al.*, 2003a), and other negative consequences. The direct effect may be billions of dollars annually (Hallowell, 2010b); while indirect costs of incidents are estimated to be six times more than the direct costs (Gavious *et al.*, 2009). For example, the estimated costs related to disabling injuries in the American construction industry were estimated at $15.6 billion (The Construction Chart Book, 2008).

Falls are a primary cause of construction injuries. Despite modest overall reduction, in the US, between 1992 and 2006, falls accounted for 32% of fatal occupational injuries in general (Dong *et al.*, 2009) and 50% of fatalities in construction (2009 data; Bureau of Labor Statistics, 2010). Internationally, falls from heights in New Zealand are the leading cause of occupational injuries (Department of Labour, New Zealand, 2010). Falls account for approximately 51% of injuries in China's construction industry (Yung, 2009). In Hong Kong, falling from heights represented more than 47% of the total fatal incidents (Chan *et al.*, 2008). As a result, falls are the most costly occupational hazard in many countries (Gavious *et al.*, 2009). In the US, the annual costs of fall-related occupational injuries were approximately $6 billion in 2000 (Courtney *et al.*, 2001). The total compensation for injuries due to falls from heights reached the peak of HK$39 643 353 in 2008 in Hong Kong (Li and Poon, 2009). In the Netherlands, total health care costs due to work-related injuries were €1.15 billion in 2004, from which 44% of injuries resulted from falls (Meerding *et al.*, 2006). Overall, similar statistics across many different countries indicate that work-related falls represent an extraordinary global financial burden. Consequently, the prevention of falls is an important priority in the construction industry (Chi *et al.*, 2004; Winn *et al.*, 2004; Bentley *et al.*, 2006; Lehtola *et al.*, 2008).

Key construction stakeholders, including policy makers, owners, contractors, workers, engineers and researchers, could benefit from an overall understanding of factors contributing to falls in the construction industry. To direct safety intervention efforts, construction safety practitioners need such an overview (Arboleda and Abraham, 2004). This knowledge can support policy makers in designing and evaluating policy, construction owners and contractors in investing in safety interventions, and workers in conducting their day-to-day activities. However, many diverse factors are relevant to understanding the causes of work-related falls in the construction industry. Different types of studies including surveys, interviews, questionnaires, case studies, accident/incident records, observations and controlled laboratory experiments in various disciplines have been conducted to elaborate these factors. Given the multiplicity of factors involved, the volume of studies and the diverse methods of research used, building an overall understanding that benefits different stakeholders is challenging. Previous review articles have focused on narrower questions such as factors influencing balance (Hsiao and Simeonov, 2001) or fall prevention interventions (Rivara and Thompson, 2000). A review of this literature that captures the diversity of studies, assists with in-depth scholarly investigations, and also provides an aggregate overview of the knowledge domain for practitioners can fill an important research and practice gap.

Objective

This paper focuses on a study conducted to review and integrate existing knowledge domains relevant to factors that influence the risk of falls in the construction industry. Three specific goals distinguish the contributions of this research effort. First, in this review, a wide range of previous studies with different methods and approaches are covered. Second, we advance a causal mapping methodology to provide a comprehensive overview of casual factors related to falls for practitioners in the construction industry. Third, to make the results useful for researchers, a framework for synthesizing the causal factors is created and the raw review data are provided, which can be used for further analyses and aggregations.

Methods

To achieve the above goals, a four-step approach was followed. These steps were:

(1) Conducting a literature search to identify potentially relevant studies.
(2) Selecting studies that contributed to understanding the factors influencing falls in the construction industry and ensuring the selected studies were of acceptable scientific quality.
(3) Coding the findings of each study.
(4) Synthesizing the results of the coded data.

These steps are illustrated in Figure 1 and detailed in the subsequent sections.

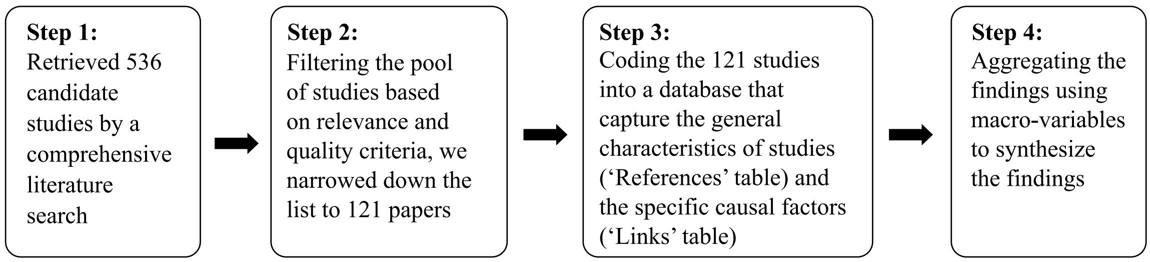

Figure 1 Process model of causal factor extraction

Step 1: Comprehensive literature search

Potentially relevant papers were first retrieved from multiple databases and literature collections of published, peer-reviewed research articles and reports. Keyword bibliographic searches were conducted in electronic databases including Web of Science (AKA: 'ISI Web of Knowledge'), MedLine, Engineering Village, ScienceDirect, PubMed and Google Scholar. We began with a few proverbial keywords related to the topic as seeds, including combinations of 'risk(s) of fall(s)', 'fall(s)', 'injury/injuries', 'risk(s)', 'fall(s) factor(s)/ factor(s) of fall(s)' and 'construction industry'. By reviewing retrieved papers in the literature, a few new keywords were obtained and the search was expanded. A few rounds of this iterative method led to additional search keywords: 'falls from heights/ladder/scaffolds/ supporters/to a lower level/into a hole', 'construction/ industrial safety', 'construction accidents/incidents', 'construction/ occupational falls', 'construction/occupational injuries', 'non-fatal/fatal falls/injuries', 'occupational accidents/incidents', 'hazard of falls', 'falls protection', 'slips', 'trips', 'construction ergonomics', 'safety climate', 'safety culture', 'high-risk group in construction' and 'fatal occupational falls' and so forth. We also contacted several scholars in a variety of related domains to track additional relevant studies including working articles that could not be found through online databases. Finally, search results were augmented through back-referencing potentially relevant citations in the identified papers.

The resulting sample includes 536 studies and reports in the literature and covers more than 50 journals and conference proceedings. The major contributing journals to this sample include *Safety Science*, *Ergonomics*, *Injury Preventions*, *Journal of Construction Engineering and Management*, *International Journal of Industrial Ergonomics*, *Applied Ergonomics*, *American Journal of Industrial Medicine*, *Accident Analysis and Prevention*, *International Journal of Occupational Safety and Ergonomics* and *Journal of Safety Research* with impact factors[1] ranging between 0.410 to 1.721 (details available in the 'Online supplement' below).

Step 2: Filtering and categorization of the sources

The identified studies were filtered and categorized in a two-step procedure by two reviewers (a doctoral student and a faculty member, both from the field of industrial and systems engineering). First, based on the abstract review, the studies were narrowed down according to the following criteria:

(1) The study was reported in English, and published no earlier than 1980.[2]
(2) The research focused on the casual factors contributing to falls in the construction industry (commercial and residential building sectors, and the roadway construction sector were included).
(3) Given our purpose, more macro factors, papers reporting medical evidence on factors inside the body relevant to falls (e.g. investigating the impact of blood pressure and the rate of heartbeat) and studies on medical impact of injuries of falls (e.g. impact of different fall-related traumas on body) were excluded.
(4) Opinion-based or anecdotal papers not supported by empirical evidence or previous literature were excluded.
(5) Editorials, commentaries, letters to the editor and news items were excluded.

The resulting pool of studies was reduced to 279 papers. In the second step, we reviewed the full papers and grouped them into different categories according to study type and quality. Then the following three categories were selected:

(1) Well-designed quantitative papers, i.e. statistical estimation of impact or probability of risk associated with one or more factors related to the risk of falls in construction industry (17 papers).
(2) Quantitative papers with the estimation of effects but lacking detailed controls to isolate different factors (40 papers).
(3) Papers discussing causes of falls based on qualitative data and quantitative papers without an

empirically strong estimation process, e.g. counts and histograms, and mathematical cost models (e.g. insurance studies) (64 papers).

This step led to a final sample of 121 studies, where most of the excluded papers in the second step lacked an empirical basis. The citations for the full sample of 121 papers are reported in Appendix A.

Step 3: Data extraction

Full papers were coded by the same doctoral student to extract direct and indirect causal factors for the risk of falls, as well as the magnitude and statistics of estimated relationships, where available. This information was recorded in a database within two tables (i.e. 'Reference' and 'Links'). The 'Reference' table includes information about each article coded and the 'Links' table includes the information about the causal relationships extracted from the articles. Data extracted from each coded paper in the 'Reference' table include: year, reference authors, and full reference, study type, sample size, sample selection method, construction sector, and geographical location of sampled population (see one sample in Table 1). In 'Links' table, the 'Initial' and 'Final' variable fields were used to denote the independent and dependent variables in each causal relationship captured; the types and units of these variables were specified in this table as well (see one sample in Table 2). Where available, the type of statistical tests, effect sizes and standard deviations were recorded in the 'Links' table as well.

In this coding process, the same variable names were extracted and recorded, verbatim, as used in the original studies. We also included all the causal links reported rather than simply those with dependent variables related to the risk of falls. The coding system therefore covers the full causal chain of the risk of falls as discussed in the sample papers. For instance, if worker training impacts on safety behaviour and that in turn impacts on the risk of falls, two different causal links should be included in the database.

Step 4: Synthesis of data

The data extracted from the empirical studies in Step 3 include 534 variables with different names and definitions, many variable types and statistical and non-statistical metrics. One of the most common practices to aggregate results of previous research is to conduct a formal meta-analysis that pools results from multiple studies to judge the strength of different causal links. A systematic meta-analysis requires consistent variable definitions and comparable statistical methods, so that data can be pooled from different studies to inform the overall strength of one (or more) causal relationship(s). However, the lack of homogeneity in the sample of studies reviewed makes it premature to conduct a quantitative meta-analysis for most of the causal relationships identified. To address this challenge, a set of macro-variables was used to aggregate the diverse variables into more general categories. In this method, we benefited from the previous contribution of Derzon and Lipsey (1999) who applied summary categories to different variables that they identified in their review of tobacco use predictors. We extended their approach to developing qualitative causal maps, which may make the analysis more useful to future researchers by formatting the raw data to allow for alternative macro-variable definitions.

Specifically, the similar variables and concepts were merged into 21 summary categories or macro-variables

Table 1 An example record in the 'Reference' table of the database

Year	Authors	Full reference	Study type	Sample size	Sample selection method	Sample population	Construction sector
2003	Lipscomb HJ, Dement JM, Nolan J, Patterson D, Li LM, Cameron W.	Lipscomb HJ, Dement JM, Nolan J, Patterson D, Li LM, Cameron, W. Falls in residential carpentry and drywall installation: findings from active injury surveillance with union carpenters. Journal of Occupational and Environmental Medicine 2003, **45**(8): 881–90.	Onsite interview	5137 carpenters	Partnership with the Carpenters' District Council of Greater St Louis and the Homebuilders Association of Greater St Louis	St Louis, USA	Residential construction

Note: Complete 'Reference' table is publicly available online for interested readers. See the URL in 'Online supplement' section at the end.

Table 2 An example from the 'Links' table of the database

Initial variable (cause)	Final variable (effect)	Reference number	Link sign (+ or −)	Initial type	Initial unit	Final type	Final unit	Significance test	Estimated effect
Fall protection program	Falls from heights	120 (Sa *et al.*, 2009)	−*	0–1 variable	Dimensionless	0–1 variable	Dimensionless	Log-binomial regression (examines prevalence ratios (PRs))	P < 0.001

Notes: Complete 'Links' table is publicly available online for interested readers. See the URL in 'Online supplement' section at the end.
*Negative relationship between the initial and final variables means that by increasing the initial variable we expect a decrease in the final variable, and vice versa.

(see details in Appendix B). For example, 'falls from heights', 'falls from ladders', 'falls from scaffolds', 'falls', 'slips, trips and falls' and 'fatal falls', as well as a few others were merged into a single macro-variable: 'risk of falls and injuries'. Once the macro-variables were created, the causal links connecting the original variables within two macro-variables were aggregated to one causal macro-link that connects macro-variables. Through this procedure, the 866 links were synthesized in the 'Links' table into 32 macro-links. Appendix B describes macro-variables we chose and the full set of initial variables that were grouped together.

The use of macro-variables in this context helps synthesize commonalities across the diversity of definitions and the heterogeneity of disciplines from which the studies originated. In this way, the relationships captured in previous studies are demonstrated in a concise overview map of the aggregated factors (i.e. macro-variables). However, the categorization of original variables into macro-variables is both subjective and context dependent. Depending on the goals of the research, one could select more macro-variables to capture the nuances across a range of closely related concepts, e.g. separating working surface and working platform macro-variables, whereas we currently have a single macro-variable for both concepts. Researchers may also wish to restrict the review to a more homogeneous subset of the current studies, thus aggregating over fewer original variables. Moreover, different researchers may partition the original variables into somewhat different macro-variables. To overcome these limitations, we publicly and freely provide the full coded data (see the URL in 'Online supplement' section below) so that other researchers can use alternative categories of macro-variables to synthesize the data. In this review study, one set of aggregated results is provided to be consistent with the purpose of the review, which is to help create an aggregate overview of the causes of falls in the construction industry.

A further limitation of the use of macro-variables is a reduction in the conceptual sharpness of variables. By aggregating multiple variables, a macro-variable loses some precision; therefore causal relationships among macro-variables should be interpreted with caution. For example, 'PPE (personal protective equipment) and methods' have a link to 'risk of falls and injuries'. In practice, many 'PPE and methods' do not influence the 'risk of falls', but protect the worker from injuries when work-related falls happen, while others may have a direct impact on the probability of a fall. These effects are causally different, but are combined in the macro-variable synthesis.

Results

Characteristics of coded studies

Sectors of the construction industry studied

Three distinct sectors in the construction industry were identified in our data: residential building, commercial building and roadway construction. A large fraction of the coded papers (56 out of 121 papers) reported studies on risk factors based on data from the commercial building sector. Thirty-two (32) papers analysed fall-related causal factors in the residential building sector, focusing especially on residential roofing. Only two coded papers (Mungen and Gurcanli, 2005; Chau *et al.*, 2007) relied solely on data from the road and railway sector. The remaining 31 papers reported data from all sectors in the construction industry as a whole. Given the significant variations of construction tasks, practices and organizational arrangements across these sectors, additional sector-specific research especially in heavy roadway and railway construction is warranted. Detailed information on the industry is also available in the 'Reference' table (see details in Online supplement).

Geographic distribution

Data from 16 different countries and districts, covering five continents, were reported in the studies summarized in this review. The distribution of the countries in the coded sample is illustrated in Table 3. More than half of the research was based on data from the US

Table 3 Geographic distribution of data informing the coded papers (percentages represent proportions of the papers in the final sample (i.e. 121 studies) from a particular population)

Country name	Occurrence
Australia	2
Canada	3
China (Hong Kong, Taiwan)	11
Denmark	6
Finland	3
France	6
Jordan	1
N.A.	6
New Zealand	2
South Africa	1
South Korea	1
Sweden	5
Spain	1
The Netherlands	1
Turkey	2
UK	4
USA	66
Total	121

Note: N.A.: not available.

potentially due to the higher research volume in the States, better surveillance and data availability in developed countries and our focus on papers published in English. Moreover, upon a closer examination, only a handful of states, namely Washington, California and West Virginia, contributed the majority of the US data. As a result, current research may not capture all country- or state-specific factors (such as weather, terrain, industry standards, legal frameworks and workers' safety norms). This suggests that additional research with a focus on local factors (such as weather, cultural and institutional factors) may be warranted for many countries and regions around the world.

Study types and variables

The current literature on risk factors of falls offers an array of sampling methods, variable definitions and estimation techniques. Looking at the nature of analysis informing each link in the database (see Figure 2), 506 of the 866 links were identified using qualitative methods. The quantitative analyses also included many different types of statistical tests, including mortality ratios, ANOVAs, odds ratios, among others (also see Figure 2). This diversity is partly due to different study types used to gather the data. The majority of studies used data from archival sources (most used data sources are government and research institute databases of falls). Other study types include controlled laboratory experiments, analytical models based on empirical data, onsite and telephone interviews, and questionnaires by mail or online (see Table 4 for a summary of study types).

Summary of causal factors

Figure 3 illustrates the summary of synthesis of causal factors. Following the aforementioned synthesis method, all the results in the sample of papers are captured within 21 macro-variables and 32 causal links among them in order to present an overview of the causal pathways. Given that each link in this graph represents aggregation of multiple original links in previous studies, two additional characteristics of these links are used to further elaborate on the results. First, the thickness of each link represents the number of

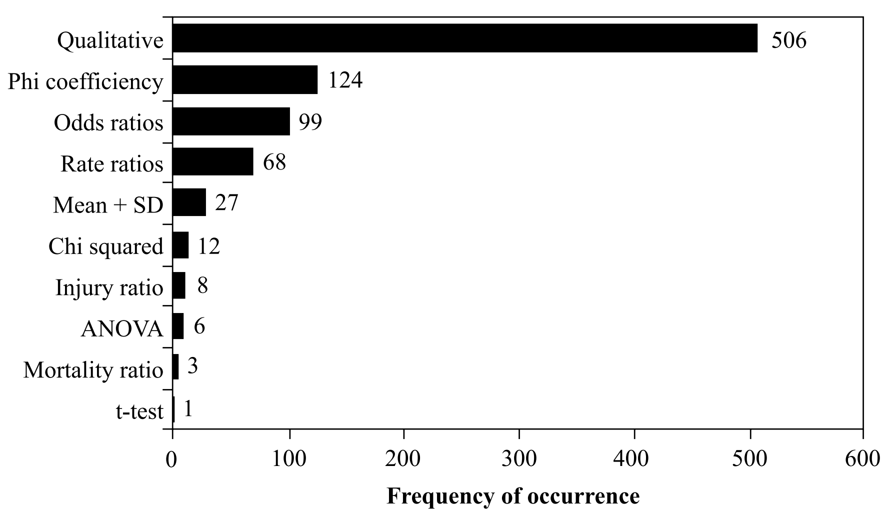

Figure 2 Frequency of the occurrence of the nature of statistical tests for causal links reported in coded studies

Table 4 Sample selection methods reported in coded papers in the literature

Study types	Occurrence
Analytical model based on empirical data	6
Archived data—doctor's first reports	2
Archived data—insurance compensation claims	12
Archived data—literature review	10
Archived data—research institutes (e.g. National Institute for Occupational Safety and Health, Occupational Safety and Health Administration and so on)	60
Controlled laboratory experiment	12
Onsite or phone interview	9
Questionnaire by mail or online	12
Total	123*

Note: *Two papers used two types of studies.

instances in the previous literature where a causal link has been identified among (the original variables defining) the macro-variables. Note that this representation does not capture the magnitude of impact for the link, rather, the emphasis in the previous literature on that link which may simply be the result of the ease of data collection for some variables. The pattern of the link (i.e. solid, dotted and dashed lines) further elaborates on the level of agreement in the previous literature on the sign of the causal link. Where the literature consistently provides a positive/negative causal link, a solid line is used. Where inconsistencies are observed in the previous findings, we use dotted or dashed lines. For example, the dotted line between 'workers' experience' and 'risk of falls and injuries' suggests that there is some agreement that as a worker's experience in a sector increases, he/she faces a reduced risk of falls (Cellier *et al.*, 1995; Hsiao and Simeonov, 2001; Lipscomb *et al.*, 2003c; Bobick, 2004; Bentley *et al.*, 2006; Choudhry and Fang, 2008; Lipscomb *et al.*, 2008). However, the literature is not unequivocal on this connection, for example Haslam *et al.* (2005) and Kaskutas *et al.* (2010) argued that experienced workers may become over confident and more likely to face fall-related risks resulting from carelessness and oversight.

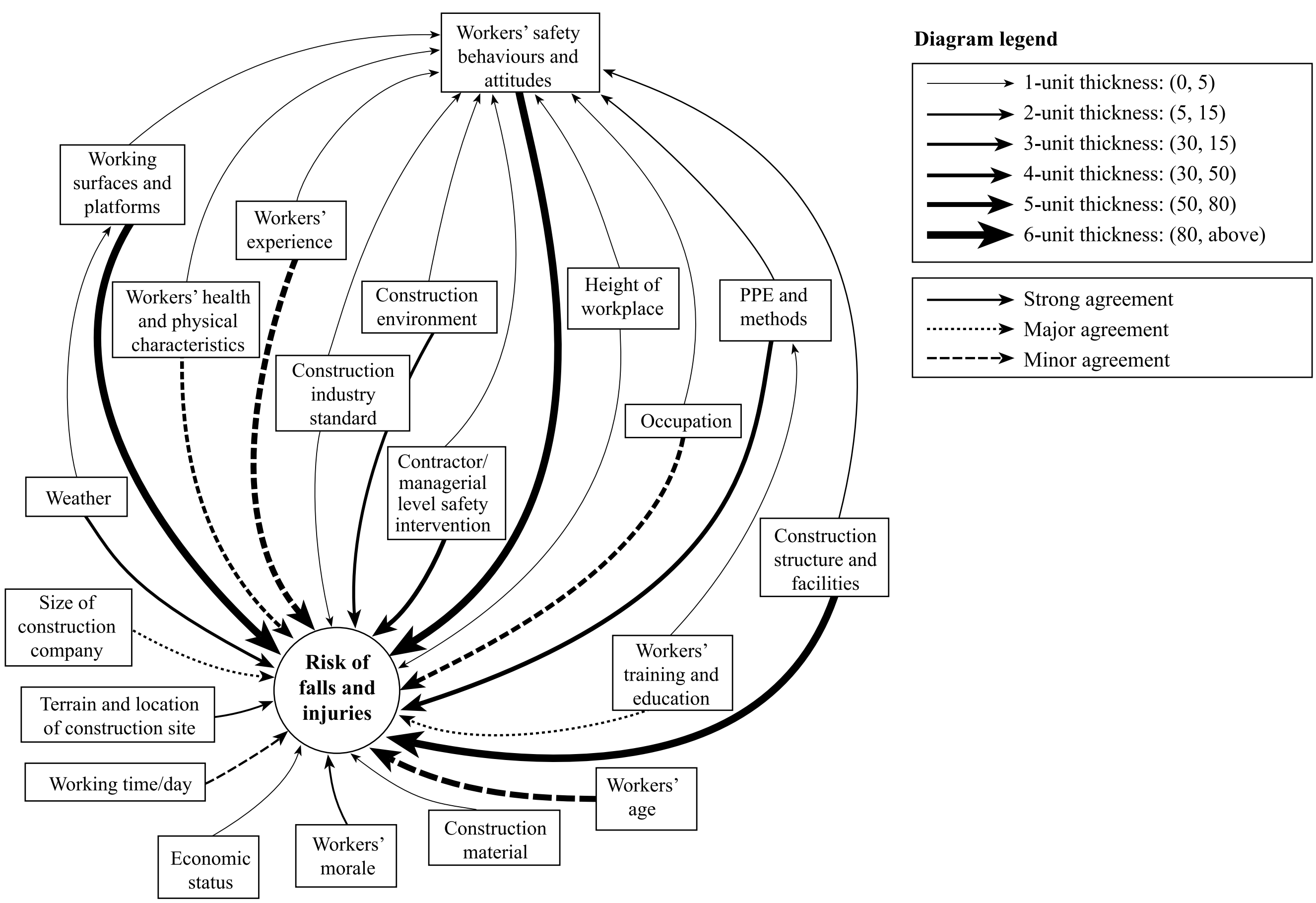

Figure 3 Causal relationships of macro-variables supported by qualitative and quantitative studies
Note: Ranges in legend represent the number of instances obtained from the literature on macro-variable relationships and consequences, and agreement consistency of causal relationships are summarized from coded studies by different line styles.

Table 5 The number of link occurrences (instances) in the literature originating from macro-variables directly influencing the 'risk of falls and injuries'

Ranking	Macro-variables of factors	Consistency of agreement	Number of link occurrences
1	Working surfaces and platforms	Strong	128
2	Workers' safe behaviours and attitudes	Strong	127
3	Construction structure and facilities	Strong	96
4	Contractors/managerial level safety intervention	Strong	55
5	Workers' age	Minor	53
6	PPE and methods	Strong	51
6	Workers' experience	Major	51
8	Workers' health and physical characteristics	Strong	50
9	Occupation	Major	45
10	Construction environment	Strong	40
11	Weather	Strong	32
12	Workers' training and education	Major	24
13	Size of construction company	Major	20
14	Workers' morale	Strong	16
15	Working time/day	Minor	10
16	Construction industry standard	Strong	9
17	Terrain and location of construction site	Minor	7
18	Height of workplace	Strong	6
19	Construction material	Strong	5
20	Economic status	Strong	4

Table 5 sorts the macro-variables directly influencing the 'risk of falls and injuries' variable in decreasing order of the number of links, and provides the consistency from the previous work. The three most mentioned causes of falls in this literature include: (1) working surfaces and platforms (e.g. slippery surfaces, improper concrete surfaces, slippery roof, use of platforms, bamboo scaffold and slip of ladder base); (2) workers' safety behaviours and attitudes (e.g. safety procedure, perceived risk, evaluation of risk, operation at unsafe speed, or horseplay while working); and (3) construction structure and facilities (e.g. the stability of the building's framework, and the reliability of the construction equipment). The agreement across these links is strong in the literature.

The other highly studied and consistently rated factors contributing to risks of falls include the safety behaviour at the contractor/managerial level, the use of personal protective equipment (PPE) and methods, the workers' health and physical characteristics, and the environment at the construction site. Factors such as age, workers' experience, and occupation of workers are also discussed frequently, but the agreement about their impact is somewhat modest. The experience effect is complicated through the direct effect of experience on improved safety and the indirect effect of experience due to over confidence, which can reduce adherence to safety procedures (Cellier *et al.*, 1995; Hsiao and Simeonov, 2001; Lipscomb *et al.*, 2003c; Bobick, 2004; Haslam *et al.*, 2005; Bentley *et al.*, 2006; Choudhry and Fang, 2008; Lipscomb *et al.*, 2008; Kaskutas *et al.*, 2010). The age effect is confounded by experience (which is correlated with age), and health characteristics which are negatively correlated with age. As a result, the overall picture of the impact of age on the risk of falls is not very clear. Two variables, work time (of day/month) and construction site terrain, show little consistency among findings across different studies. While several studies found an impact for the time of the day and the day of the month on risks of falls, the results are not consistent across different studies (Pollack *et al.*, 1996; Kines, 2002; Chan *et al.*, 2008). Similarly, the location and terrain of the construction site is mentioned as an impact factor on the risk of falls; yet there is no general agreement across the current studies on the details of this impact (Buchner *et al.*, 1997; Lipscomb *et al.*, 2003b).

'Workers' safety behaviours and attitudes' is the top influencing variable in terms of the number of studies that found a relationship between this variable and the risk of falls. Moreover, this variable is influenced by many other direct causes of risks of falls shown in Figure 3. Therefore the literature suggests many causal factors, such as 'contractor/managerial level safety intervention', 'PPE and methods', and 'workers' experience' having both a direct and an indirect effect on the risk of falls. However, most of these direct vs. indirect influence pathways come from different studies.

Therefore this finding may be partially due to different levels of aggregation in the original studies. Where the investigators have explicitly included workers' safety behaviours and attitudes, this has become a direct contributor to the risk of falls while many other variables influence this intermediate cause. In lieu of including this intermediate cause, studies found a direct impact for many of those secondary causes. A few longer causal chains are also observable in Figure 3. Specifically, 'workers' training and education' influences 'PPE and methods', while 'weather' influences 'working surface and platforms'. Both these latter variables subsequently have an impact on 'workers' safety behaviour and attitudes', which, in turn, influences 'risk of falls and injuries'.

If the same synthesis of results is repeated using only the quantitative studies with a statistical test (total of 298 links) an interesting picture emerges. Many organizational and psychological concepts such as 'workers' behaviour and attitudes' rarely appear in the quantitative studies. For example, in this alternative synthesis, there is no more than a single mention of the macro-variable 'contractor/managerial level safety intervention', even though it is the fourth most cited item in the full sample. Other factors that rarely show up in quantitative studies include 'workers' training and education', 'workers' morale', and 'construction industry standards'. This is not entirely surprising given that softer variables are harder to measure quantitatively and to trace in large-sample studies that provide a reliable statistical power.

Methodological contributions

Besides summarizing the factors contributing to the risk of falls and injuries in construction, this paper makes a methodological contribution to the review of heterogeneous bodies of literature. Specifically, by capturing the coding and synthesis results in tables of a database, this method offers the researcher the flexibility to move across different levels of aggregation, or focus on different subsets of results, without the need to rework. This additional flexibility is now feasible through the digital appendices that could be included online with published work. We freely provide the full database in the URL reported at the end of the paper (i.e. Online supplement).

Varying levels of aggregation of the data could be achieved by using different macro-variables. At one extreme, each original variable could be seen as a unique macro-variable, providing much specificity in terms of variable definition and precision, but lacking a real synthesis of previous findings. At the other extreme, by aggregating all closely related variables, a broad outline of the literature could be synthesized at the cost of reduced precision in the definition of concepts used. We selected a point towards the more aggregate part of this continuum, but the data provide other researchers with the ability to modify these macro-variables or define new ones, and rapidly generate a picture that is appropriate for their purpose. The only hard rule in creating such alternative macro-variables is that every original variable in the sample of interest should be included as part of one and only one macro-variable. The quality of the resulting synthesis also depends on the conceptual homogeneity of the variables included in each macro-variable. If those variables conceptually differ significantly, the resulting causal map (which would be parallel to Figure 3) would potentially be uninformative and confusing.

Another point of flexibility that results from this method concerns the selection of relevant causal links. The discussions so far focus on an overview perspective where all studies identified are included. Some differences exist across different study contexts which may require a more specific set before the aggregation of results. For example, a researcher may be interested in studying only the results from quantitative studies with specific statistical tests. Other researchers may be interested in examining the impact of studies that only include the residential sector, or the commercial sector, or some other criteria. The raw data provided in the database tables include the details required for such alternative inclusion criteria. For example, consider studying the causes of falls and subsequent injuries among residential roofers. Figure 4 provides the overview of the literature based on the same macro-variables as before, but this time coding only the studies that are based on the residential roofing construction industry. Here 'contractor/managerial level safety intervention' was most frequently reported as a major cause of the risk of falls (Hsiao and Simeonov, 2001; Lipscomb *et al.*, 2003b, 2003c; Shah *et al.*, 2003; Kaskutas *et al.*, 2009, 2010; Sa *et al.*, 2009), followed by 'workers' safety behaviours and attitudes' (Hsiao and Simeonov, 2001; Lipscomb *et al.*, 2008; Sa *et al.*, 2009; Kaskutas *et al.*, 2009, 2010), 'construction structures and facilitates' (Hsiao and Simeonov, 2001; Lipscomb *et al.*, 2003c; Kaskutas *et al.*, 2009; Sa *et al.*, 2009) and 'working surfaces and platforms' (Hsiao and Simeonov, 2001; Kaskutas *et al.*, 2009, 2010; Sa *et al.*, 2009). This figure is easily generated from the data given the connection between the two tables through the reference number: once a filtering criterion is defined (e.g. only residential sector and only roofers as sample population), the subset of relevant links can be automatically retrieved and an alternative overview picture can be created using that data.

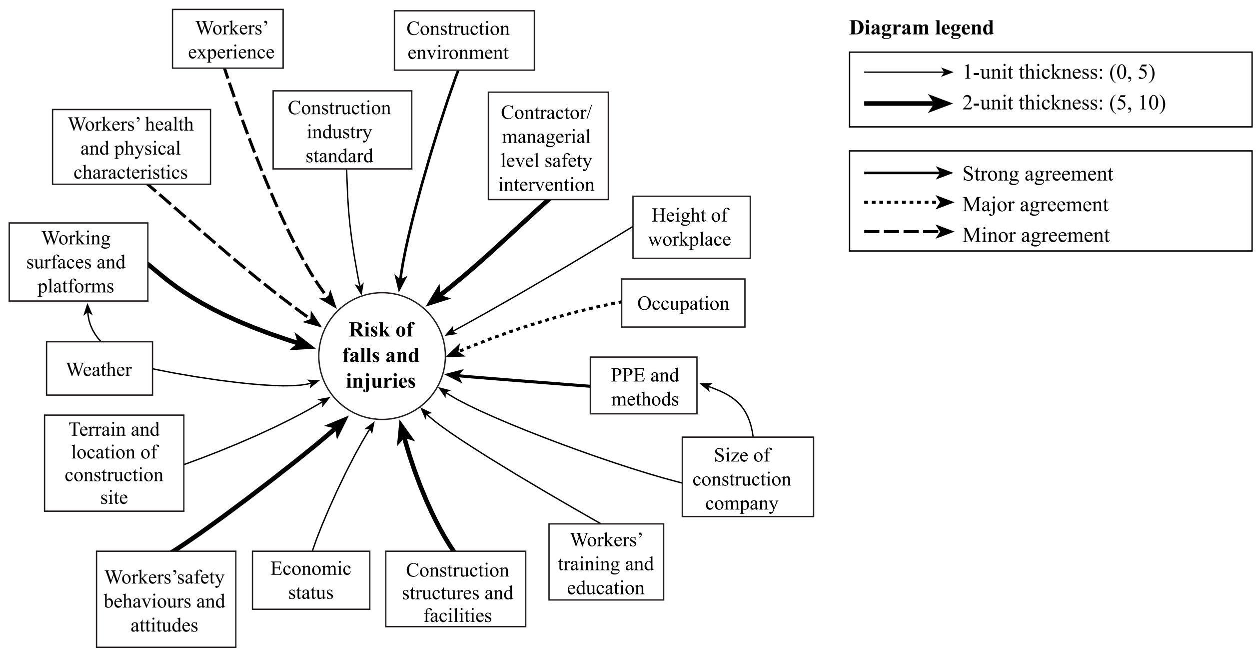

Figure 4 Subset-causal relationships of macro-variables for an instance on how to better utilize our coded online data to facilitate interested researchers in certain specific research fields—residential roofing industry

Discussion and conclusions

Our analysis makes a number of contributions to understanding the risk of falls in construction. We provided a methodical compilation of the relevant research on the causes of and contributors to construction falls. The results can assist future researchers and practitioners in doing more relevant research and in designing more effective safety interventions that can help to reduce work-related falls. For example, our study points to the gap between qualitative and quantitative research on the causes of falls, where more quantitative studies are needed to assess the ultimate impact of psychological and organizational factors and how they tie into managerial interventions. Better estimation of different pathways is needed for analysing the cost effectiveness of different managerial and engineering interventions. For instance, both 'workers' safety behaviours and attitudes' and 'working surfaces and platforms' are significant drivers of falls. Whereas 'contractor/managerial level safety intervention' is expected to influence the former, 'PPE and methods' are likely to tackle the second source. Yet the expected reduction in fall or fatality hazard from a dollar of investment in one intervention or another is not clear from the current literature. Both these observations point to fertile areas for future research.

We also proposed a systematic method for aggregating data from multiple types of studies into a coherent causal network, even in the absence of homogeneity needed for formal meta-analysis. This framework is general and can be used in research in other areas of interest. Moreover, the framework provides a flexible architecture, in that it allows researchers to define their own macro-variables (how to partition the original variables into different sets for macro-variables) and compile summaries of the literature at different levels of analysis without much rework. The detailed database is provided openly online (see Online supplement).

A fairly complex picture is found about causes of the 'risk of falls and injuries' in this review, in which different types of phenomena (e.g. weather, industry types, psychological factors) and different levels of analysis (e.g. individual, organizational, geographical and cultural) interact in determining the fall-related outcomes. While feasibility and research design concerns require researchers to break down this complex picture into smaller chunks that could be empirically assessed, these chunks should later be brought together to provide a holistic picture where one can assess the impact of different interventions, many of which cross different domains or levels of aggregation. One major challenge is in moving across these different levels of aggregation, from focused empirical studies to systematic synthesis of those results. The result indicates few previous attempts at building such holistic maps, and we anticipate this first attempt can lead to more nuanced and refined future work. Indeed, safety policy analysis for a construction firm requires simultaneous examination of different causes of injuries associated with falls as well as other types of injuries in selecting effective safety enhancing actions. We hope this method provides a blueprint that can promote the accumulation and utilization of research findings.

This literature review can inform the development of simulation models to predict fall injuries and inform prevention initiatives. The data gathered from this review could serve as input to a simulation model of incident causation for risks of falls. Such a simulation model will provide feedback to construction stakeholders to aid in the prevention of injuries and for efficient planning of safety initiatives. A holistic systems model can help with the direction for follow-up research in many fields such as ergonomics (e.g. optimizing the design of safety training and its implementation, creating safe workplaces or systems), biomedicine (e.g. improving fall arresting/protection methods), materials science (e.g. creating new materials of shoes to prevent slipping), and medical science (e.g. to conduct quantitative experiments on influencing the specific factors).

The methods used and the results of our analyses can assist consensus among standards committees. For instance, standards committees often need to understand trends in larger bodies of research to ensure standards revisions are timely in addressing prevention and control practices. We have provided a process that can be replicated at minimal costs and used by individuals and groups who need to examine trends in the knowledge domain. This method and results can impact on the effectiveness of policy setting as well. One should be cautious in drawing policy conclusions from this paper however, because the wide range of methods and variables did not allow a quantitative assessment of the magnitude of the impact of different causal factors. Therefore, the fact that one variable or the other is associated with the risk of falls and injuries in many studies does not necessarily mean the impact of that factor is great in magnitude. With this caveat in mind, it is still useful to summarize the major policy levers that are seen to have an impact on reducing the risk of falls and injuries based on this review. These levers include: (1) focusing on proper working platforms/surfaces: ladders, scaffolds, and working platforms and surfaces should be dry and stabilized; (2) sufficient and timely safety training along with close supervision and guidance, e.g. through safety consultants, safety checking, focusing on reducing the anxiety and rush to unsafe working speed; (3) a proper fall arresting system and other PPEs can reduce the injuries due to falls significantly; (4) targeting the safety culture in construction companies as well as the safety climate in the whole industry could provide additional leverage; (5) ergonomics of the worksite, from e.g. comfortable temperature, modest humidity, enough but not too much lighting/luminance level, low level of noise, are all expected to help with reducing falls or their impact.

Governments and labour organizations within various countries use data to determine allocations of funds in occupational safety and health. The systematic method applied in this study could be used in a variety of different occupations to produce information about trends in a specific occupational setting. This information will, in turn, help agencies evaluate budgets and impact measures over time. Researchers and funding agencies that set research agendas can employ our systematic method to identify gaps in research in occupational safety and health in terms of specific research topics and gaps in research within and between nations.

Moreover, as means by which information and communication technologies could address onsite safety challenges emerged and are more actively sought, the insight offered by the presented synthesis of causal factors, for example, could spur more innovative design and research explorations. The causal chain depicted in Figure 3 illustrates this notion. As 'workers' training and education' influences 'PPE and methods' with latter implications on 'workers' safety behaviour and attitudes' and thus 'risk of falls and injuries', investigations of the role of smartphones, often ubiquitous onsite, and other mobile technologies (e.g. tablet computers such as the iPad) as delivery platforms in providing in situ, possibly tailored, training are availed. These types of efforts could offer new directions in intervention design in impacting the incidences of falls.

Finally, the database designed can be standardized and used as a repository of current knowledge for other fields of study focusing on different safety risks. It can be made open to the research community for editing through a wiki-like technological platform. This democratization of accumulated knowledge could have a significant effect on the speed and efficiency of research reviews and intervention design implementations.

Online supplement

The full coded data are available in online tables from: http://spreadsheets.google.com/pub?key=t4oRPwkps6BeqIkyUQhJQrQ&output=html.

Notes

1. Based on 2010 Journal Citation Reports by Thomson Reuters's ISI Web of Science.
2. A cut-off date was chosen for consistency in construction practices and research methods. However the sample is not sensitive to the 1980 date, e.g. only two of the papers in the final sample are published in the 1980s.

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Appendix A

Complete list of coded papers

We report here the full list of 121 papers that were selected in Step 2 and coded during Step 3 (refer to Figure 1).

(1) Abdelhamid, T.S. and Everett, J.G. (2000) Identifying root causes of construction accidents. *ASCE Journal of Construction Engineering and Management*, **126**, 52–60.

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Appendix B

Table of macro-variables and their original variable mappings

Macro-variable	Original variable in 'Links' table in the database
Risk of falls and injuries	'falls from heights', 'falls', 'slips, trips and falls', 'falls on the level', 'fall from ladder', 'slip on footstep of the ladder', 'falls to a lower-level', 'falls from loading platforms or into shafts', 'falls through structures', 'falls from scaffolds', 'fall and slip injuries', 'fatal falls', 'falls risk', 'falls and trips risk', 'slips and falls injuries', 'fatality death', 'fatal injuries', 'non-fatal injuries', 'accident in construction industry', 'construction injuries', 'construction accident', 'construction incident', 'injury occurrence', 'STF (slip, trip and falls) accidents', 'male construction worker lost-time-injury elevation falls', 'ladder-related injuries', 'occupational fatal accidents', 'construction falls accident', 'falls from extension ladders', 'fatal occupational injuries', 'falls from roofs', 'falls into holes in ground', 'falls from moveable platforms'.
Working surfaces and platforms	'grass/wet', 'slippery underfoot condition', 'uneven and damaged paving', 'obstacles on the walking surface', 'opening/holes', 'heavy construction/improper surface', 'improper plumbing and heating surface', 'improper painting surface', 'improper carpentry surface', 'improper concrete surface', 'floor condition bad', 'work area condition—slippery surface', 'serve surface condition of working place, such slippery surface and so on', 'slippery roof', 'slip of ladder base', 'good roof surface condition', 'good type of surface', 'slippery underfoot condition', 'place of falls—ladder', 'place of falls—scaffolds', 'place of falls—bamboo scaffold', 'strong cover', 'platform', 'strength of roof', 'connection of platform', 'fixation of platform', 'steps and stairways'.
Workers' safe behaviours and attitudes	'failure to use safety equipment', 'safety procedure', 'perceived risk', 'evaluation of risk', 'attention/vigilance', 'limiting injury seriousness', 'lack of orderliness at the workplace or unsecure climbing devices', 'fainting-fit, loss of balance', 'stability of balance', 'tipping of ladder top', 'correct placement and protection of ladder', 'stability of user on the scaffolds', 'stability of user on the roof', 'stability of user near a hole in ground', 'movement control', 'failed to secure and warn', 'horseplay', 'operated equipment without authority', 'operated at unsafe speed', 'remove safety device', 'took unsafe position or posture', 'safe behaviour', 'taking risks (taking hazardous short cuts and entering hazardous areas)', 'diverted attention', 'satisfactory safety level', 'construction safety', 'condition of vestibular system'.
Construction structure and facilities	'the utilization of the design for construction safety concept', 'construction structure factors', 'shortcomings with equipment', 'poor structure', 'good construction design and processes', 'collapse of scaffolding', 'collapse of structure', 'quality and availability of equipment', 'equipment fails', 'good condition of equipment, such as good shape, structural weakness, ladders, scaffolds and vehicles', 'ladder structure failure', 'strength of ladder', 'stability of ladder', 'strength of scaffolds', 'stability of scaffolds', 'anchoring of scaffolds on buildings or structures', 'foundation base structure', 'scaffold floor condition', 'strength of support', 'machinery/hoisting', 'stability of support machinery', 'condition of lift/support/hoisting', 'foundation'.
Contractor/ managerial level safety intervention	'relevance to both researchers and industry practitioners', 'management's support, involvement and commitment in safety', 'occupational organizations—activity', 'originating influences—inadequacies with risk management', 'good project management', 'good risk management', 'adjustment strategies to confront the risk of falling or balance disturbance in occupational situation', 'requirements for contractors', 'limited choice offered to workers', 'PPE availability', 'assigning blame', 'responsibility of employer demands', 'ineffective communication styles', 'poor access to resource', 'poor compensation/pay', 'high demand of pace of work', 'not responding to injury', 'size of company', 'construction trade: general contractor', 'accepted hazardous work conditions by management level person', 'safety monitors', 'availability of safety professions'.
Workers' Age	'age: 15–24', 'age: 45–54', 'age: < 30 years', 'age: < 30 years', 'younger than 35', 'age_35 years and older', 'age>30', 'age < 30', 'age', 'age > 45', 'age group: <16', 'age group: 16–19', 'age group: 20–24', 'age group: 25–29', 'age group: 30–34', 'age group: 35–39', 'age group: 40–44', 'age group: 45–49', 'age group: 50–54', 'age group: 55–59', 'age group: >59', 'age: 16–24', 'age: 25–34', 'age: 35–44', 'age: 45–54', 'age: 55–64', 'age: 65–79'.

Appendix B (*Continued*)

Macro-variable	Original variable in ‘Links’ table in the database
PPE and methods	‘use of passive personal fall protective equipment’, ‘fall prevention equipment/personal’, ‘fall arresting systems’, ‘preventing balance disturbance’, ‘slip resistant shape’, ‘fall protection’, ‘edge protection to the scaffold worker’, ‘personal fall injury protection’, ‘concrete/damaged fall protection’, ‘fall protection not attached’, ‘personal fall arrest systems’, ‘scaffold object protection’, ‘good falling project protection’, ‘hole-edge protection’, ‘edge protection to platform worker’, ‘personal protective methods’, ‘safety nets’, ‘warning line’, ‘guardrails’, ‘slides guard’, ‘personal fall arrest’.
Workers’ experience	‘less than 10 years work experience’, ‘experience’, ‘worker and work-team capabilities factors’, ‘work experience’, ‘inexperience’, ‘experienced worker’, ‘good ability of user to stay on ladder’, ‘user ability to stay on scaffold’, ‘user ability to stay on roof’, ‘user ability’, ‘apprentice carpenters’.
Worker’s health & physical characteristics	‘hearing disorders’, ‘sleep disorder’, ‘current smoker’, ‘no sporting activity’, ‘chronic or acute pathologies’, ‘alcohol (intrinsic factors)’, ‘drugs (intrinsic factors)’, ‘physical status (intrinsic factors)’, ‘weakness (intrinsic factors)’, ‘fatigue (intrinsic factors)’, ‘heart rate’, ‘trauma’, ‘fracture’, ‘fractures sustained’, ‘male’, ‘female’.
Occupation	‘mason’, ‘carpenters’, ‘roofers’, ‘plumber’, ‘electricians’, ‘civil-engineering workers’, ‘other employees’, ‘construction trade: carpentry’, ‘construction trade: electrical work’, ‘construction trade: plumbing’, ‘construction trade: masonry’, ‘construction trade: painting’, ‘construction trade: insulating’, ‘construction trade: glazier work’, ‘construction trade: scaffolding’, ‘roofers’, ‘framing workers’.
Construction environment	‘inadequate lighting’, ‘skylights’, ‘good working environment’, ‘environment—too bright or insufficient lighting’, ‘surrounding activities, such as falling objects, heavy equipment traffic’, ‘work area condition/poor lighting’, ‘objects struck against’, ‘falling load’, ‘bad work situation (such as work surface, time)’, ‘external condition’, ‘source of injury—environment’, ‘environment/ slope sharp’, ‘environment/ non-terrain slippery’.
Weather	‘temperature (50 F)’, ‘temperature (32 to 50 F)’, ‘temperature (32 F and under)’, ‘ice/snow’, ‘temperature – < 32 F (< 0 C) to > 50 F (> 10 C)’, ‘temperature –> 10 C (50 F)’, ‘temperature – > 0–10 C (32–50 F)’, ‘temperature – 0 C (32 F) and under’, ‘weather conditions’, ‘weather bad’, ‘Winter’, ‘summer—hot’, ‘raining/snowing’.
Workers’ training and education	‘job security and education’, ‘language and cultural problem’, ‘job-specific formal safety orientation and training’, ‘safety education and training’, ‘proper preparation and training’, ‘effect of experience and training’, ‘work technology’, ‘employers are aware of fall protection standard’.
Size of construction company	‘firm size/employees : 0’, ‘firm size/employees : 1–4’, ‘firm size/employees : 5–9’, ‘firm size/ employees : 10–19’, ‘firm size/employees : 20–49’, ‘firm size/employees : 50–99’, ‘firm size/ employees : 100+’, ‘company size <30’, ‘company size 30–100’, ‘company size >100’, ‘company with less than 10 employees’, ‘site size 10 or more workers’, ‘union workers company’, ‘nonunion workers company’.
Workers’ morale	‘psychological feature (feel comfortable with supervisors who care for their safety)’, ‘self-esteem’, ‘performance pressure’, ‘feeling invulnerable’, ‘good relationship with ‘boss’, ‘being treated fairly’, ‘non-material incentives’, ‘material incentive’.
Working time/day	‘time of injury—afternoon’, ‘date of accident/ 21 to 25 days of a month’, ‘data of accident—Friday’, ‘time of accident—14:01–16:00’, ‘afternoon working time’.
Construction industry standard	‘change in the fall standard for the construction industry’, ‘effectiveness/enforcement of safety fall protection standard’, ‘regulation in construction industries’, ‘poor regulatory and legal issues/ ladder regulations’, ‘poor regulatory and legal issues/ worker protection standard’, ‘poor regulatory and legal issues/ immigration law’.
Terrain and location of construction site	‘bad condition of the terrain’, ‘face to south’, ‘face to north’, ‘southern hemisphere’.
Height of workplace	‘heights of fall’, ‘height’, ‘height of fall—below 15 m of height’, ‘elevation’, ‘height of falling’, ‘less than 6 feet’, ‘7 to 10 feet’, ‘11 to 20 feet’, ‘21 to 25 feet’.
Construction materials	‘construction material’, ‘poison materials’, ‘dangerous construction materials’.
Economic status	‘economic influences’, ‘economic feature’.