AGING AND SAFETY PERFORMANCE: A STATISTICAL ANALYSIS OF UNSAFE BEHAVIORS AMONG CONSTRUCTION WORKERS

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Aging and safety performance: a statistical analysis of unsafe behaviors among construction workers

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CERTIFICATE OF ORIGINALITY

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Abstract

Safety awareness in the construction industry has been raised substantially in the past few decades around the globe. For one thing, the hazard-prone nature of construction works demands attention to safety. For another, construction companies have realized that accident prevention, which had been advocated on moral basis, greatly benefits them in economic terms. The aging workforce problem is getting more and more severe in the construction industry. The Census and Statistics Department of Hong Kong stated that the median age of Hong Kong population increased from 36.7 in 2001 to 41.7 in 2011. And they estimated that the situation shall get worse as the projected population aged above 65 would soar from 13% in 2011 to 30% in 2041. With the growing number of older workers, the aging effect on safety performance is becoming a vital issue. In general, aging is associated with declined physical abilities and increased cognitive capabilities, which lead to a mixed effect on safety performance. Physical constrains make senior workers more vulnerable to dangers, but their experience could help them avoid dangers on site. Previous research has demonstrated the relationship between age and injury/accidents, but failed to investigate the relationship between age and unsafe behaviors. In the classic safety pyramid, unsafe behaviors are at the very bottom, which directly reflect workers' safety attitude and capabilities to comply with safety regulations. By monitoring workers' safety behaviors on site, we could reveal more information on how aging affects safety performance.

Real-time location systems (RTLS) applied on construction sites can objectively monitor workers' safety behaviors, as it provides information on how often workers enter danger zones and how they react to danger warnings. These records will demonstrate workers safety attitude and their ability to comply with safety warnings, which are direct reflections of their safety performance. In this study, to explore the relationship between aging and safety performance, a RTLS called Proactive Construction Management System (PCMS) was applied in a field study in Shanghai. The system recorded workers unsafe behaviors (entering pre-defined danger zones) and their reaction to danger warnings. The frequency of entering danger zones and the average response time were chosen as the metrics to assess safety performance for workers in different age groups. Through statistical analysis with the help of IBM SPSS, the results revealed that aging has mildly negative effects on safety performance, as in general older workers entered danger zones more frequently and had longer response time. More specifically, the findings are mostly consistent with previous findings in identifying workers in age group 31-40 have the worst safety performance. But the bad safety performance identified in older workers is more worrisome for the aging construction industry. Despite their high awareness of safety issues on site, older workers still exhibited unsatisfactory safety performance most likely due to their declined physical capabilities. As a result, more attention should be drawn to enhance the safety performance among older workers. In practice, senior workers might be better-off assigned to less dangerous jobs, and special safety warnings and protection gears will be helpful in extending their working life.

Key words: **Aging; RTLS; Safety performance.**

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Chapter 1: Introduction

1.1 Research background

1.1.1 Construction safety

Safety awareness in the construction industry has raised substantially in the past few decades around the globe. There are a number of reasons contributing to the emphasis on safety in the construction sector. For one thing, the hazard-prone nature of construction works demands attention to safety. In the past 40 years, even though the construction industry accident rate has dropped significantly, it still ranks at the top of all industries along with agriculture and manufacturing. According to the Health and Safety Executive, although the constructions sector accounts for only 5% of the employees in Britain it took up to 31% of fatal injuries to employees and 10% of reported major/specified injuries (Hse.gov.uk, 2015). The statistic is consistent across the globe as the Hong Kong Labor Department reported that despite the dropped number of accidents and accident rate in the past decade, the construction industry still recorded highest number of fatalities and accident rate among all industry sectors (*Occupational Safety and Health Statistics 2014*, 2015). Safety is still a vital issue in construction sector. Another positive turn for safety is that construction companies have realized that accident prevention, which had been advocated on moral basis, greatly benefits them in economic terms. As a fact, providing a safe and healthy working environment for construction workers is one of the most effective methods to minimize costs, which is the key to success in business (Goetsch, 2013).

1.1.2 The aging workforce

Population aging has been defined as the phenomenon that occurs when the median age of a country rises. It is a pervasive, profound and enduring tide sweeping across the globe and Hong Kong is no exception (*Third Quarter Economic Report 2013*, 2013). The Census and Statistics Department of Hong Kong (2012) stated that the median age of Hong Kong population increased from 36.7 in 2011 to 41.7 in 2011. And they estimated that the situation shall get worse as the projected population aged above 65 would soar from 13% in 2011 to 30% in 2041. Accordingly, the aging problem is especially worrisome in the labor-intense construction sector. According to the Hong Kong Construction Registration Board (2014), construction workers aged above 50 took up more than 42% total registered construction workers as shown in figure 1.1, much more than their middle-aged (defined as workers aged 40-50 in this study) colleagues. In addition, Hong Kong Construction Industry Council (2014) predicted a need of additional 30,000 to 35,000 workers by the end of 2015.

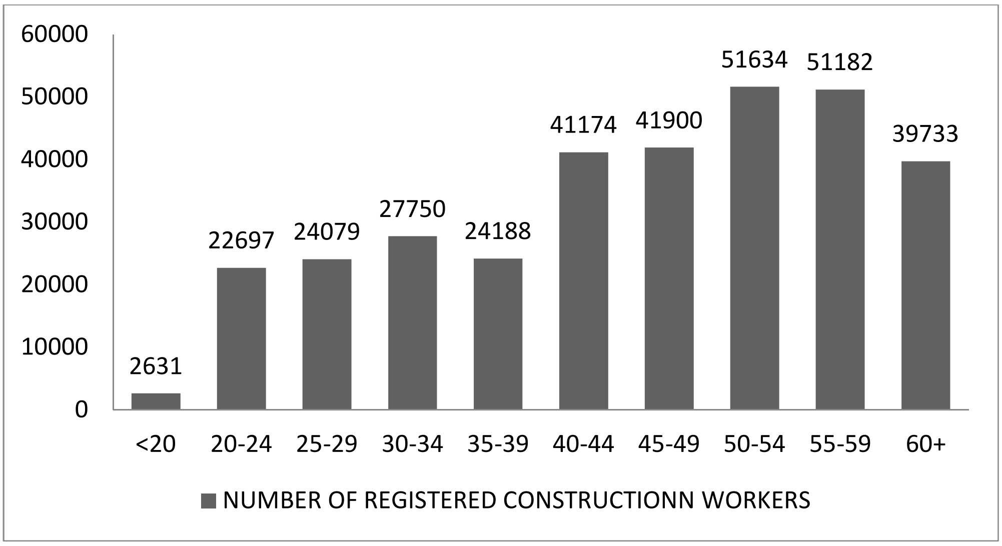

Figure 1.1: Total Number of Valid Registered Workers in Designated Trades Quarterly Update (2014)

In mainland China, the aging problem is even worse. In 2006, Chinese official reports predicted the population of citizens above age 60 would reach 400 million, taking up almost 20% of the whole world's aged population ("A prediction on the aging population in China", 2016). There is an urging need to investigate the impact of aging among construction workers.

1.2 Research problem

1.2.1 The Domino theory

A number of accident causation theories have been proposed and revised, but the Domino theory put forward by Heinrich (1959) remains a classic. As shown in Figure 1.2, the theory link personal characters and unsafe behaviors with injuries and accidents in a linear causation model. Heinrich (1959) even pointed out that 88 percent of accidents were caused by unsafe behaviors, and only 10 percent were caused by unsafe conditions. Since then, multiple revisions have been made to implement his theory, but the fact that personal traits have clear impact on safety outcome has remained unchallenged. Age, as an essential factor defining personal characters, will have a strong impact on safety outcomes as this theory suggests. The question is: what are the impacts?

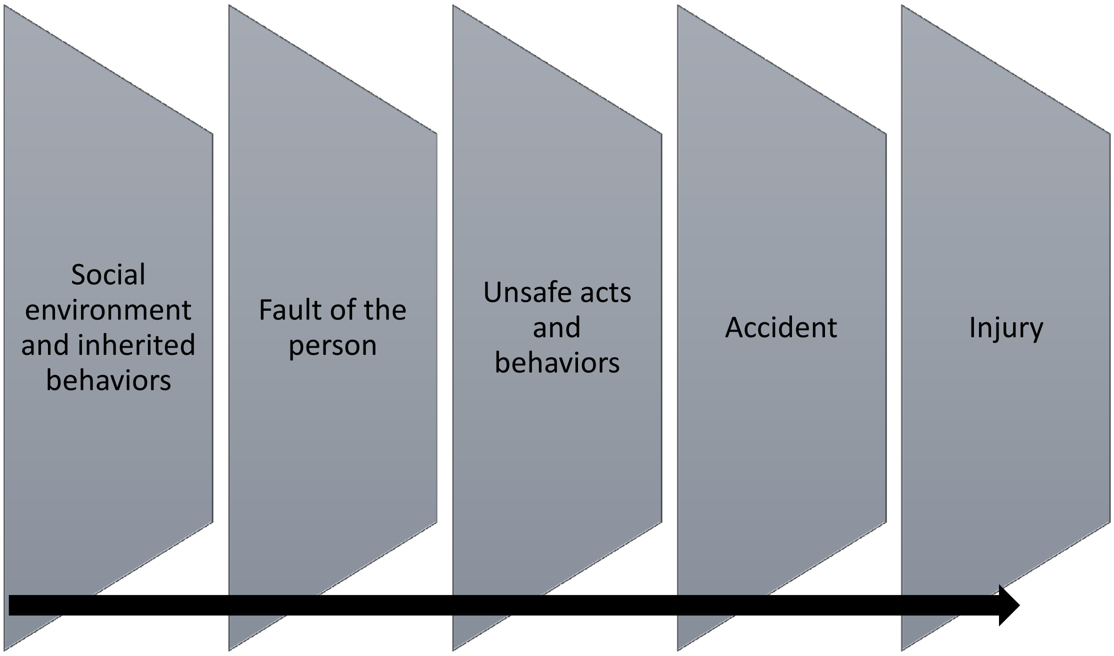

Figure 1.2: The Domino theory

1.2.2 The aging effect on physical capabilities and cognitive abilities

It is no wonder that physical capabilities mostly decline with growing age. Apart from the general declining physical capabilities, scholars argue that aging has considerable variation among individuals affected by genetic heritage and environment (Hedge et al., 2006). Correspondingly, the hazardous construction site conditions often result in the serious physical capability degeneration among construction workers. LeMasters et al., (2006) conducted cross sectional study of retirees for various occupations, and concluded that, compared to less physical demanding occupations, construction retirees suffer from physical pains for almost all body areas and enjoy a poorer quality of life. Most common problems among senior construction workers include hearing loss, reduced physical strength and flexibility. On a different note, cognitive abilities have a more complex relation with aging. Apart from perceptual speed which starts to decline around 25-32, other abilities like spatial orientation, numerical ability, and inductive reasoning actually increase moderately with age until workers reach age 46 (Hedge et al., 2006). With the complex effects of aging on physical capabilities and cognitive abilities, the overall effect of aging on job performance has raised some discussions. Surprisingly, contrary to common belief of declined job performance among senior workers, research concerning aging and job performance has found no clear correlation between them (Hedge et al., 2006). Among all the possible explanations, high degree of experience and expertise among older workers is the most common and sensible one.

1.2.3 Safety performance and performance assessment

In the safety management field, safety performance is usually assessed by key performance indicators (KPI), containing both lagging indicators and leading indicators. The lagging indicators include injuries, accidents, days lost due to injury, compensation costs, and regulatory fines. This type of indicators are observed after injury/accidents have occurred, thus called "lagging" indicators. The leading indicators are proactive measurements include, "number of audits or inspections performed, number and types of findings and observations, timeframe required to close action items, training completed, near miss incidents, timely preventive maintenance tasks performed, safety committee meetings " (Baldauf, 2010) . It is an interesting fact that no matter in the research field or in real life practice, the lagging indicators are preferred in safety performance assessment. The popularity of the lagging indicators could be attributed to the objectivity of these statistics and the easy interpretation of these indicators. These statistics are easy to obtain and have yielded fruitful results to enhance safety management. However, these indicators overlooked the fact that injuries and accidents are merely the visible outcomes of unsafe behaviors. Some unsafe behaviors probably will not result in injuries or accidents, and are ignored in safety performance adopting lagging indicators. The leading indicators implement safety performance assessment as they reflect the subjective safety awareness and objective endeavors workers dedicate in elevating safety performance. Together with lagging indicators, leading indicators can demonstrate workers' safety performance at most times. But to measure workers' performance with the leading indicators, current practice relies on subjective measurements such as questionnaire surveys. Especially when the perplex effects of aging are considered, neither lagging indicators nor leading indicators could reflect the intricate effects of such factors on safety performance. For instance, an aged worker could be active in safety training and demonstrate high level of safety awareness, but his/her degenerated working ability could easily put him/her in danger on site. Sparer et al. (2013) contrasted safety performance assessment results by the contractor safety assessment programs (CSAPs) of 68 companies with the safety climate results of the same 68 companies obtained by surveys. The results showed that safety assessment cannot accurately capture the safety climate in the construction industry due to the complex factors influencing safety performance.

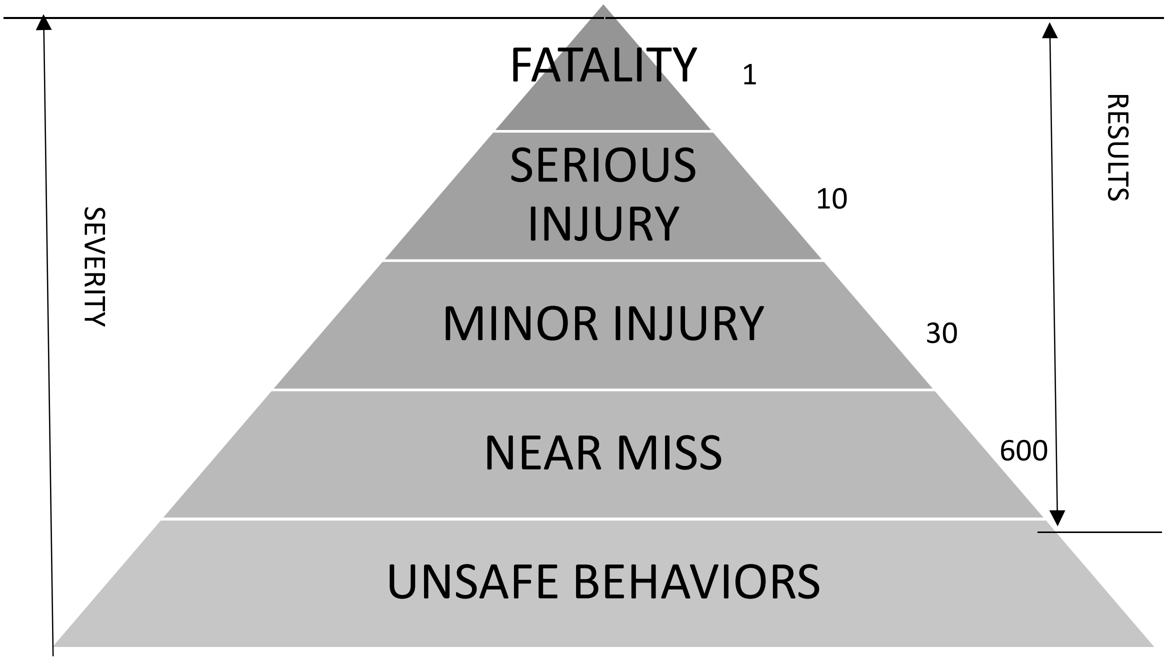

Figure 1.3: The accident triangle

In the 1930s H. W. Heinrich changed the safety management domain with his pioneering accident triangle theory. As illustrated in the figure above, the ratio of fatality to near-miss accidents is roughly 1:600. It is rational to assume that the amount of unsafe behaviors in the construction industry, which is at the base of the safety pyramid, would be immense to be causing such a high number of fatalities across the globe every year. Unfortunately, both the lagging indicators and the leading indicators fail to represent unsafe behaviors for a comprehensive safety performance assessment. To understand the effect of aging on safety performance, safety performance should be presented in an objective and comprehensive manner, which is why this study intends to introduce concrete metrics to represent worker's unsafe behaviors on site to objectively demonstrate their safety performance.

1.3 Research objectives

Objective 1: Monitor construction workers' safety performance (unsafe behaviors) on site and suggest concrete metrics for safety performance assessment.

Current studies on aging among construction workers have mainly focused on its observable results, such as age related injuries (Dong, Wang and Daw, 2011; Schwatka, Butler and Rosecrance, 2011; Holmstrom and Engholm, 2003), age related compensation cost (Schwatka, Butler and Rosecrance, 2012), etc. There are few scientific researches concerning the latent impacts of aging, such as the prolonged reaction time, the decreased productivity, etc. This phenomenon could be attributed to the methodology of previous researches. Most researches concerning age-related injuries adopted quantitative methodology where injury information were obtained from relevant databases (Schwatka, Butler and Rosecrance, 2011; Schwatka, Butler and Rosecrance, 2012). This type of retrospective research, dependent on recorded data, explored the factual relationship between aging and injury but failed to delve into the causal connections between aging and injury. Another major type of research adopted questionnaire surveys and interviews as research methods. These efforts have generated precious information about problems caused by aging from construction workers' perspective, while the results have been questioned due to the subjective nature of questionnaire survey and interview. To tackle the above mentioned problem, this study adopts a real time location monitoring system that stores danger zone location information and track workers' real-time locations. It will generate warning signals to workers in danger zones, and record their corresponding behaviors. To leave the danger area (safety compliance behavior) or keep invading the danger zone (unsafe behaviors) is a direct reflection of workers' safety awareness, safety attitude, and safety performance. This method ensures direct, in-time, and objective safety performance assessment metrics for analysis and discussion.

As stated above, this study adopts the Proactive Construction Management System (PCMS) in a real construction site in Shanghai China. General behavioral data of on-site workers will be collected from the PCMS system, such as the movement path, working hours, individual task performing time, etc. Concrete indicators for safety performance will be chosen from the obtained data.

Objective 2: Compare unsafe behaviors of workers in different age groups using statistical analysis methods

After obtaining safety behavior data of construction workers on site, the correlation of aging and safety performance will be explored using statistical analysis methods. Answers will be provided as to whether age is a significant factor affecting safety performance, and to what extent does the safety performance of workers in different age group vary.

Objective 3: Give suggestions concerning safety management of the aging workforce

Once the effect of aging on safety performance is revealed, corresponding suggestions will be made to enhance safety management. A comprehensive literature review summarizing current findings of aging on safety performance (using injuries and accidents as assessment metrics) will be presented in the following chapter. If the findings of this study contradict results in former studies, discussions will be made to interpret the differences and to investigate the possible influence on safety performance.

1.4 Research significance

First and foremost, this research will prove the feasibility of applying real-time location system in safety behavior monitoring and explore possible metrics indicating unsafe behaviors for safety performance assessment, which will complement current safety performance assessment schemes. Other than that, the following data analysis will reveal the relationship between aging and safety performance. Building on the existing knowledge of the relationship between aging and injuries/accidents, the analysis will reveal how aging affects safety behaviors, which do not only reflect workers' safety attitude and also demonstrate their physical and mental abilities to ensure safety on site. If aging does have a significantly negative effect on workers' safety performance, the result will then help devise safety management strategies for elderly workers as the aging workforce continues to grow, and it will postpone the retirement age in the construction industry and relieve the aging work force pressure in the long run.

Chapter 2: Literature review

2.1 Age and safety performance

2.1.1 Academic interests in age related construction safety

A total of 70 articles are identified in twenty-two journals concerning the age factor in construction safety. Combinations of selected keys words were used to search for target publications including age/aging/youth/senior, construction/construction worker, safety/safety performance/ safety behavior.

As shown in figure 2.1, the majority of these papers are from the *American Journal of Industrial Medicine* (AJIM), the *Journal of Occupational and Environmental Medicine* (JOEM), *Accident Analysis and Prevention* (AAP), and the *Journal of Safety Research* (JSR). AJIM ranks at the top with 27 articles, accounting for approximately 39% of all selected publications. JOEM, AAP, and JSR follow with 8 papers (11%), 7 papers (10%), and 5 papers (7%) respectively. *Applied Ergonomics* (AE), *Experimental Aging Research* (EAR), *Safety Science* (SS), *Human Factor* (HF) and *Work* each published two articles, while the rest of the chosen Journals each published one article.

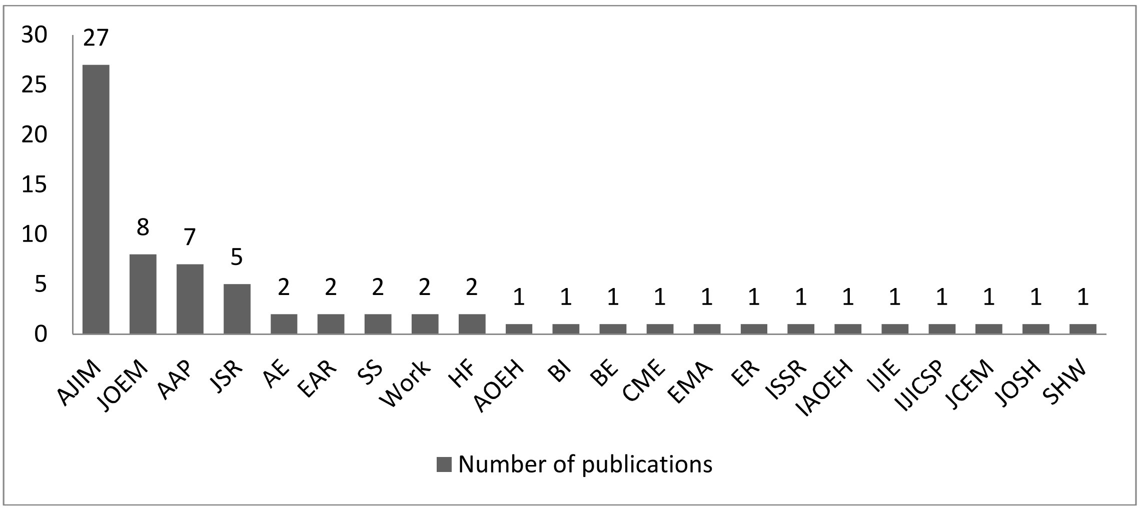

Figure 2.1: number of publications from each selected Journal

As shown in the chart below, aging in the construction industry has been a consistent topic in the safety research domain for the past two decades with a growing number of publications, which matches the increasing seriousness of workforce aging.

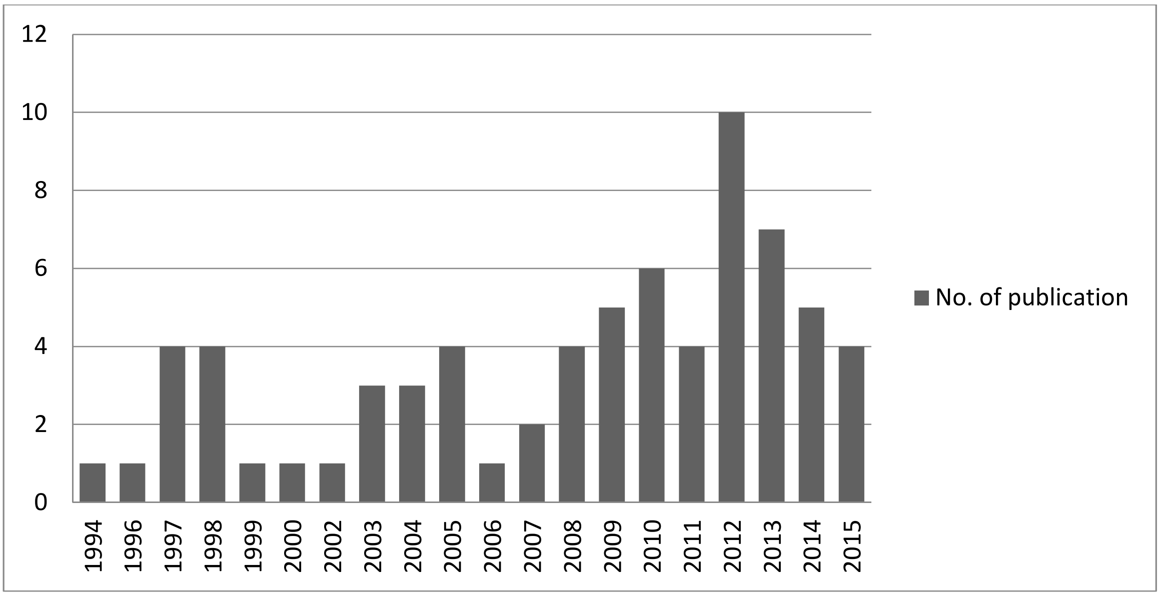

Figure 2.2: Annual number of publications on age related construction safety.

2.1.2 Current findings

As stated above, safety performance is traditionally assessed through measurement and statistical analysis of accident rate, accident frequency, severity rate, days lost due to accidents and workers' compensation costs. Thus the majority of identified literatures still adopt this traditional approach to evaluate the effect of aging on safety performance among construction workers.

An overview of identified literature suggests that,

1) current research mainly explored the visible outcomes of age related effect on

construction workers' safety behavior, i.e. injury numbers, injury rates, fatality rate, compensation costs, etc.;

2) Most studies agreed that middle aged construction workers generally had most injuries and fatalities, whereas injury rate and fatality rate were highest among younger and older workers. However, the findings are not universal as some studies have revealed challenging results. A detailed description is listed below.

Author, Year	Research scope	Main Findings
Jones et al., 2013	The study examined work-related fatalities aged 55 years and older, 2000–2009, in Australia following coronial investigation.	The percentage of fatalities was similar (around 18%) for both the 55–64 and 65–74 year age groups before dropping to 6% for the 75 + age group.
Chi et al., 2005	The study analyzed 621 case reports of work related fatal falls during 1994–1997 in Taiwan.	Fatal falls of workers aged 55 and above could have been caused by reduced sensory capability (e.g., decline of vision and hearing), reduced physical strength and flexibility. Workers younger than 24 years old are suspected to suffer fatal falls due to inexperience and carelessness.
Arquillos et al., 2012	The paper analyzed 1,163,178 accidents in	The injury severity increases with the age of the worker, which is

	the construction sector in Spain between 2003 and 2008	especially significant in groups of ages between 60 and 65 years, and between 20 and 24 years.
Huang et al., 2003	Data collected by the Occupational Safety and Health Administration (OSHA) from January 1990 through October 2001 were examined; particular emphasis was placed on fall accidents that occurred in the last 5 years of this time interval.	Age has a U shaped effect on fall accidents. The ages of those workers most frequently involved in falls are between 31 and 40, with the overall average being 38.3. "It is possible that age or experience does not significantly improve judgment where hazardous situations are concerned."
Cheng et al., 2012	This study used data mining methods to analyze a database of 1542 accident cases in Taiwan during the period 2000–2009.	The most commonly injured group was 35–44 years (31%). And workers older than 55 and younger than 24 were the most likely to be involved in fatal accidents.
Cheng et al., 2010	The data used in this study was collected from the Council of Labor Affairs of Taiwan Central Government	49% of the workers involved in the analyzed accidents were in the age range between 25 and 44. And there is the significant correlation between worker age and unsafe act

	between years 2000 and 2007.	for small construction enterprises, but not for larger construction enterprises.
Tsaur et al., 2011	Labor insurance payment data of Taiwan in 2002~2008 were used as the basis.	Aged workers have a higher accident rate, and female workers who are older than 45 years old have the highest accident rate. In addition, female construction industry workers who are older than 35 years old have unique occupational characteristics.
Rothenbacher et al., 2005	A ten Year follow-up study of 14,474 male workers.	Musculoskeletal disorders were the leading cause of disability in all age categories, having a U-shaped influence with highest relative risks among the youngest and the older age groups. And the relative risk of disability due to accidents was highest among the older age groups and smallest among the younger. Mental disorders, injury, and poisoning were important contributors to disability among young age groups mainly.

McCann & Cheng, 2012	The paper studied 829 construction workers killed in dump truck-related incidents in the United states from 1992 to 2007.	Workers aged 20–34, 35–44, 45–54 and over 55—each accounted for one-quarter of the deaths. There was no appreciable difference between age groups.
Chang et al., 2015	A review of 98 studies published between 1980 and 2013was conducted to evaluate risk factors of work related traumatic brain injury.	In general, construction industry had a high risk of traumatic brain injury. Male workers, those in the youngest and oldest age groups, were more likely to sustain work related brain injury.
Dong et al., 2009	This study evaluated occupational deaths resulting from fall injuries among Hispanic construction workers using data from the Census of Fatal Occupational Injuries from 1992-2006.	Nearly half of the Hispanic fall decedents (48.5%) were under 35 years old, 10.3% of fatal falls occurred for Hispanic workers aged 55 years or older. The distribution was drastically different among white workers in that time period.
Jackson & Loomis, 2002	525 fatal injuries in the state's construction industry between 1978	The 25 to 34 age group accounted for the largest number of fatalities taking up 25.9% of all fatalities.

	and 1994 using the North Carolina Medical Examiner's system were identified and studied.	Older workers have the highest rate of fatalities.
Lin et al., 2008	This study analyzed one thousand eight hundred ninety work-related accident reports filed in the years 1996–1999.	Construction workers aged older than 55 (76.4) had the highest fatality rate, followed by age group 45-54 (35.0), and 15-24 (33.9).
Chi et al., 2014	Four hundred and eleven work-related fatalities in the Taiwanese construction industry were analyzed.	Age group 35-44 had the highest fatality rate taking up for 28.7% of all fatalities, followed by 25-34 (24.8%) and 45-55 (24.6%).
Choi et al., 2013	The study surveyed 27 companies of a total of 12,452 employees having an average of 75 years' experience in the industry.	The aging problem among the construction workforce was well aware in the industry. However, older workers were still very vulnerable to injuries.
Lipscomb et al., 2014	The study examined a total of 24,830 union carpenters in Washington State from 1989 to 2008.	Age group 30-40 had the largest number of injuries (559), whereas workers younger than 30 had the highest injury rate (2.58). The injury

		rate decreased steadily with increasing age.
Bena et al., 2011	This study targeted a cohort of 8,955 workers employed at construction sites of the high-speed Torino to Novara railway between 2003 and 2005.	The majority (492) of work-related injuries involved workers aged between 35 and 44. And the injury rate fell with age.
Chi et al., 2009	The study analyzed 255 electrical fatalities in the construction industry in Taiwan.	The fatality rate due to electric shock declined significantly with age.
Kisner & Fosbroke, 1994	Fatal (from 1980 to 1989) and nonfatal (from 1981 to 1986) injuries of 702,867 construction workers in the United States.	59% of the nonfatal injuries occurred to workers under 35 years of age. 47% of the fatalities occurred to construction workers under 35 years of age, workers 65 years and older had the highest fatality rate
Pratt et al., 1997	1,901 machinery-related deaths in the U.S. construction industry between 1980 and 1992 recorded in the National	25.9% of the fatalities were from workers aged 25-34.Workers aged 65 years and older accounted for only 121 deaths, but had the highest fatality rate (7.79).

	Traumatic Occupational Fatalities (NTOF) surveillance system were studied.	
Dement et al., 2009	An analysis of 8,976 former construction workers in nuclear sites in the United States.	Workers who started working younger than 30 years had an increased risk rate of asbestosis.
Ore & Fosbroke, 1997	2144 work-related motor vehicle fatalities among construction workers in the United States over the years 1980–92 were analyzed.	Age group 25-34 had the largest number of motor vehicle deaths (537). And the fatality rate was significantly higher than other age group for construction workers aged 65+.
Schoenfisch et al., 2010	Around 3,216,800 construction workers with fall-related nonfatal injuries treated in US emergency departments during 1998-2005 were analyzed.	The highest number of construction workers treated in emergency department was in age group 25-34 (estimated 1,040,500 cases). And rates of injury were significantly higher among workers younger than 24 and the rate declined steadily with increasing age.
Lipscomb et al., 2010	A total of 1,734,000 contact injuries treated in the US emergency	Age group 25-34 had the largest number of contact injuries. Younger workers had much higher injury

	departments between 1998 and 2005 were analyzed.	rates than other age groups, and the rate decreased steadily as age increased.
Cattledg et al., 1996	182 nonfatal fall injuries of west Virginia construction industry in 1991 were observed.	The highest number of injuries occurred to age group 30-39 (76 cases). Only one worker age 65 + was injured.
Jeong, 1998	3,028 fatal and 125,929 nonfatal injuries among construction workers in South Korea from 1991 to 1994 were analyzed.	Numbers of nonfatal injuries (34,047) and fatal injuries (1,234) were highest among workers aged 45+.
Janicak, 2008	The study analyzed 997 fatalities due to electrocutions occurred between January 1, 2003 and December 31, 2006.	Workers aged 20-24 had the highest percentage of fatalities by contact with overhead power lines, while workers aged 65+ had the highest percentage of fatalities by contact with electrical wiring, transformers, or other electrical components.
Dong & Platner, 2004	The study examined all work-related fatalities occurred in the US construction industry during 1992–2000.	Age group 25-44 had the largest number of death. And the risk index increased with growing age. And Hispanic workers had higher risk index than non-Hispanic workers in every age group.

Grzywacz et al., 2012	Data were obtained from 119 Latino residential construction workers. And 107 study participants (89.9%) attended the three month follow-up interviews.	Injury risk among Latino residential construction workers did not have significant difference in various age groups.
Lemasters et al., 1998	522 carpenters participated in questionnaire surveys for this study.	Age was a significant factor for musculoskeletal disorders in shoulders, knees, and back.
Nurminen, 1997	217 occupationally active male concrete reinforcement workers aged 25-54 participated in the study.	Generally, the risk of sciatic pain increased with growing age, but the degree depended on occupation and injury records.
Chau et al., 2004	A case-control study was conducted on 880 male workers who had had at least one occupational injury between 1 January 1995 and 31 December 1996.	Young age had a significant effect on occupational injuries.

Chau et al., 2004	The study subjects were construction workers who had worked for 5+ years and had at least one occupational accident with sick leave between 1 January 1995 and 31 December 1996.	Young workers had more occupational injuries caused by hand tools. More experienced workers had a reduced risk of injuries.
Lowery et al., 1998	The study utilized data from 769 contractors hired to complete 2,843 construction contracts in the Denver International Airport construction project.	Younger workers had more injuries, but the rate of injuries increased with age.
Zwart et al., 2000	This study applied a cross-sectional questionnaire among 637 male construction workers aged 40+.	Aging was associated with deterioration in health and work ability status. Around 33% of the senior workers were uncertain about working in the construction industry till normal retirement age.
Chau et al., 2014	The study obtained data from three-year observation of 22,952 permanently employed	Younger workers had higher injury rates across all injury types. Older workers had higher injury risk of falls. Experienced workers had

	women at the French national railway company.	more injuries related to materials/equipment/objects handling
Choi, 2009	A comprehensive literature review of U.S. publications related to aging workforce and safety.	The highest injury rates are among age group 25-34 and 35-44. But older workers sustained more severe injuries in general.
Zwart & Frings-Dresen, 1999	Analysis was performed on data collected from 44,486 employees by one Dutch regional occupational health service between 1982 and 1993.	Age was a significant factor related to safety and health in the construction industry.
Colantonio et al., 2009	This cross-sectional study utilized data of 218 traumatic brain injuries in Canada during 2004–2005.	The 25-34 age group had the highest traumatic brain injury rate. Older workers tend to suffer more from falls, while younger workers had more injuries of being struck-by/against. Workers under age 45 were more likely to be injured in the morning.

McCoy et al., 2013	The study covered 24,830 carpenters over a 20-year study period from 1989-2008.	All types of injuries had the largest number in age group 30-39. Incidence rate of struck by objects declined with growing age, while the rate of fall increased with growing age.
Cheng et al., 2010	This study analyzed 1347 accidents in the Taiwan construction industry during 2000–2007.	The age group of 30–49 years accounted for 54% of injuries related to falls or tumbles.
Ore, 1998	An analysis of 139 deaths of U.S. female construction workers during 1980–1992.	53.2% of the female fatalities occurred before the age of 35.
Santana et al., 2012	14,499 occupational injuries among workers aged 16–24 of 2006 in Brazil.	Workers aged 20-24 of both genders had much higher numbers of injuries compared to workers in the 16-20 age group.
Kachan et al., 2012	This study examined 168,671 adults with 4,768 injured subjects from 1997–2009.	The three-month injury prevalence decreased with increasing age.

Lipscomb et al., 2015	The study examined musculoskeletal disorders and injuries of the upper extremity and knee of a total of 24,830 union carpenters in Washington State from 1989 to 2008.	The injury rate of upper extremity declined with increasing age, while the rate of knee remained steady.
Friedman & Forst, 2009	An analysis of 19,734 construction workers' injuries in Illinois between 2000 and 2005.	Workers aged 25-44 accounted for more than 60% of all injuries. Age had a linear positive association with level of compensation.
Schoenfisch et al., 2013	The study examined injuries of a total of 5,073 union drywall carpenters in Washington State from 1989 to 2008.	The age related injury rate patterns differed depending on whether drywall material was considered to be a contributing factor.

Table 2.1 current findings on the aging effect on injuries/fatalities

3) Most younger workers' injuries are attributed to insufficient knowledge and cognitive abilities, while older workers suffered from declined mobility and are easier to suffer from falls.

Author, Year	Research scope	Main Findings
Dong et al., 2012	The Fatality data in this study were from the Census of Fatal Occupational Injuries of the United States from 1992 to 2008.	Older workers have a higher fatality rate from falls than young workers. Roofs and ladders are particularly risky for older construction workers.
Dong et al., 2014	This study utilized data from two large national datasets to analyze fall fatalities of residential construction between 2003 and 2010 in the United States.	25.9% of residential fall fatalities happened to workers aged 45-54. Workers aged 55 and older accounted for 26.5% of residential fall fatalities.
Dong et al., 2013	This study examined data obtained from 2 databases of fatal falls from roofs in the U.S. construction industry over an 18-year period (1992–2009), with detailed analysis for 2003–2009.	Workers younger than 20 and older than 44 had higher rate of fatalities of roof falls.

Son et al., 2014	2147 occupational injury subjects 2010in Korea from July to October were analyzed.	Older construction workers suffered the highest risk for fall-related occupational injuries.
Arcury et al., 2012	A cross-sectional survey of 119 Latino construction workers in western North Carolina.	Age had a significant positive impact on safety climate among Latino construction workers.

Table 2.2 special features of current findings on the aging effect

4) Older workers had less injuries but the compensation cost per case was much higher;

Author, Year	Research scope	Main Findings
López et al., 2008	The study analyzed 1,630,452 accidents of workers in the construction sector in Spain over the period 1990-2000.	As the age of the worker involved in the accident increases, the probable severity of the accident increases.
Waehrer et al., 2007	Statistics covered the 2002 national incidence from the Bureau of Labor in the United States.	Age group 25–34 and 35-44 had the highest costs of injury with approximately USD 50,000 per case, accounting for half of the industry’s total days away from work costs.

Lipscomb et al., 2003	The study observed a cohort of 16,215 active union carpenters, hours worked, and their workers' compensation claims for a 10-year period.	Mean costs per fall increased with age. Age was not associated with risk of falls from elevations; younger carpenters had modestly reduced rates of falls from the same level.
Schwatka et al., 2011	A review was conducted of epidemiologic literatures on the impact of age on injury among workers in the construction industry in terms of cause, type, and cost.	Older worker have higher injury costs, which are most likely due in part to the severity of the injuries.

Table2.3 current findings on aging and workers' injury/fatality compensation cost

5) Workers' physical capability weakened with age, such as heat tolerance, etc.

Welch et al., 2008	A cross-sectional study of U.S. construction roofers who were current union members between the ages of 40 and 59 was conducted.	Older age was associated with the presence of reduced physical functioning, which put older workers at a higher risk of disability retirement compared to younger workers with similar

		medical conditions and work limitations.
Dong et al., 2011	The study utilized six waves (1998 to 2008) of the Health and Retirement Study and studied 7200 male workers (510 in construction trades).	A higher proportion of older construction workers suffered functional limitations compared with other worker groups. There is a trend of occupational transition among aged construction workers.
Petersen & Zwerling, 1998	This study focuses on persons born between 1931 and 1941, thus the sample population ranges in age from 51 to 61years.	Older construction workers were 1.4 times more likely to have a back problem, 1.3 times more likely to have a foot or leg problem and 1.7 times more likely to have been diagnosed with an emotional problem than were other blue-collar workers.
LeMasters et al., 2006	This cross-sectional study compared the quality of life and physical health of 77 retirees from the construction industry to that of 174 retirees from less physically demanding	The results showed that, compared to less physically demanding occupations, retirees in the construction sector reported significant physical limitations for almost all body

	occupations.	areas and a poorer quality of life.
Haupt et al., 2005	Data was collected from 300 construction workers on 15 construction sites in the Western Cape and Eastern Cape provinces.	Younger workers had higher levels of acceptable knowledge about HIV and AIDS and lower levels of uncertainty than older workers.
Welch et al., 2010	This paper followed 979 roofers working with the Roofers International Union in a longitudinal study who were between the ages of 40 and 59.	Each year increase in age at the baseline interview was associated with an 18% increase in likelihood of leaving roofing.
Dong et al., 2015	This study analyzed 1988–2006 data from a national longitudinal survey covering 12,686 construction workers who were 14–22 years of age in 1979.	Blue-collar construction workers who experienced occupational injuries resulting in days away from work injuries reported significantly worse physical and mental health at age 40 compared to those who had no occupational injuries. They were almost twice as likely to report musculoskeletal problems, depression, and emotional problems compared to

		non-injured workers.
Hoonakker & Duivenboden, 2010	All employees (an average of 250,000 persons per year in the period 1993–2003) in the Dutch construction industry were studied.	"Older construction workers have fewer complaints about physically demanding work and psychosocial workload, but have more complaints about working in awkward postures. Older workers have more complaints about their health than workers in other age categories. Older construction workers have fewer injuries than younger workers."
Holmstrom & Engholm, 2003	The study is based on questionnaire survey of 85,191 male Swedish construction workers.	Musculoskeletal disorders increased steadily with age. The severity of musculoskeletal disorders corresponds with the level of physical exposure of various construction trades.
Shishlov et al., 2011	Around 555,700 nonfatal falls treated in US emergency departments, 1998–2005 were analyzed.	Workers older than 45 had much higher rates of falls than younger workers. Younger workers had more numbers of contusions/abrasions and

		sprains/strains than fractures, while the variance is smaller among worker aged 40+.
Yi & Chan, 2013	Study data were collected from field studies conducted during July-September 2010-2011in Hong Kong.	Age was one of the three most influential factors in determining construction workers' heat tolerance.
Dement et al., 2005	This study examined 3,510 construction workers of U.S. Department of Energy sites.	92.7% workers aged 65+ were reported to suffer hearing loss.

Table2.4 current findings on workers' physical ability and age

By comparing the results of these studies, we can tell that even though, in general, older workers are physically weaker than their young colleagues. Still aging does not necessarily undermine their safety performance, because aged workers are usually more experienced and mentally aware of safety issues. Thus, the aging effect on construction safety is still unclear.

More importantly, these studies are mostly result-oriented, which is a lagging assessment of safety performance. This study intends to fill the gap by utilizing a location-based surveillance system to monitor construction workers onsite activities, which provide precious insight into workers' dangerous behaviors (behaviors that are against safety protocols but do not have serious outcomes). The behavior pattern can reveal direct information as to workers' safety attitude and safety awareness.

2.2 Real-time location system (RTLS)

2.2.1 Academic interest in RTLS in the construction industry

Five prominent journals in the field of construction management and information technology were chosen for the literature review, namely the Advanced Engineering Informatics (AEI), ASCE Journal of Computing in Civil Engineering (CCE), Automation in Construction (AC), Journal of Construction Engineering and Management (CEM), and Journal of Computer-Aided Civil and Infrastructure Engineering (CACIE). Key words like real-time location system/GPS/RFID/positioning /location tracking etc. were used for literature search. A total of 75 relevant articles were chosen in this literature review. A detailed distribution of identified articles is presented in the chart below.

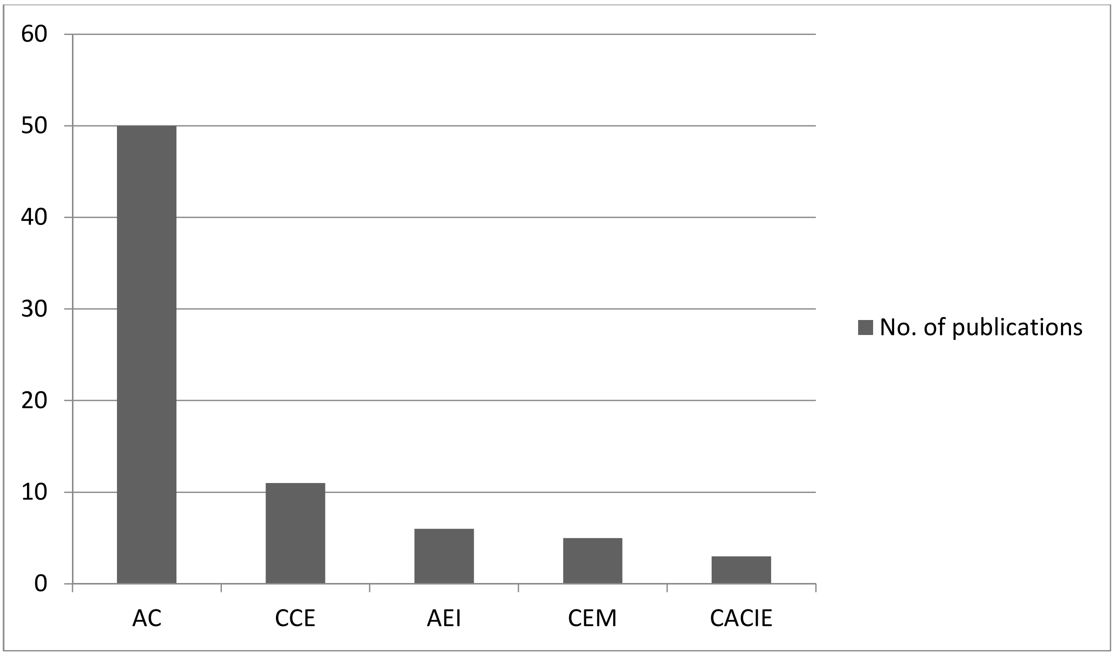

Figure 2.3: number of publications from each selected Journal

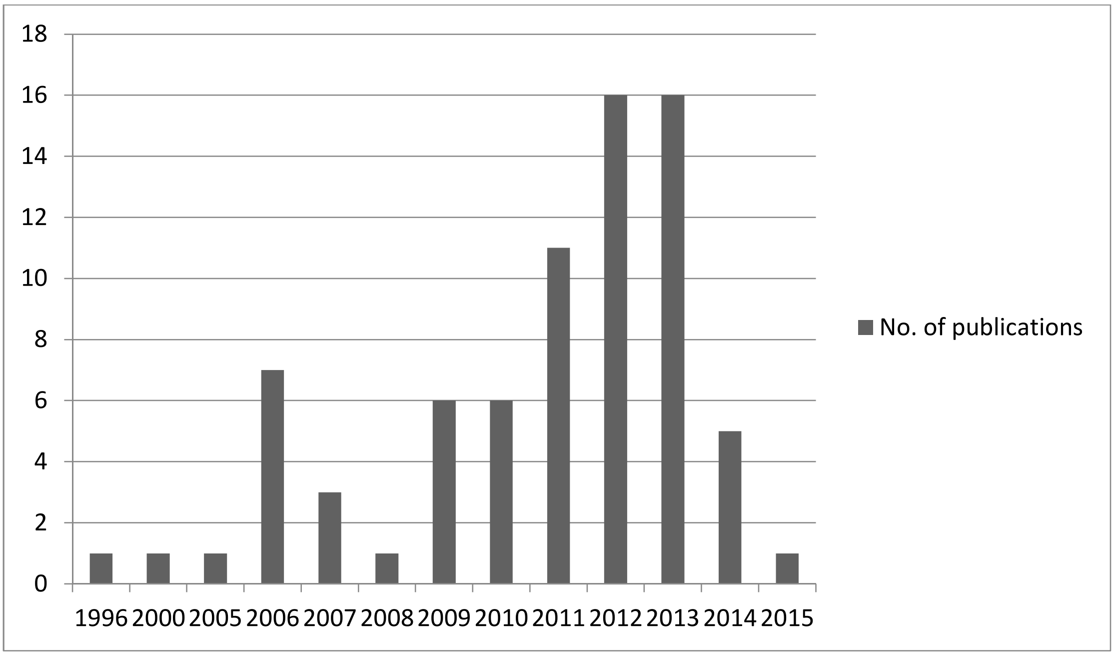

Figure 2.4: Annual number of publications on age related construction safety.

Of the 75 articles, Automation in Construction (AC) took up 66.6% with 50 relevant publications, while CCE had 11 (14.6%), AEI with 6 (8%), CEM with 5 (6.7%), and CACIE with 3 (4%) as shown in Figure 2.4. The yearly production of RTLS related articles suggests that RTLS has become increasingly popular in construction management studies. There are a growing variety of RTLSs being tested in experiments and applied in real-life construction sites. And the location data obtained from RTLS help provide insight in almost all domains of construction research, from the design stage to maintenance.

2.2.2 RTLS and its usage in the construction industry

Real-time locating systems (RTLS) are used to automatically identify and track the location of objects or people in real time. In the chosen literature, six main types of RTLSs were identified, namely Global Positioning System (GPS), Radio-Frequency Identification (RFID), wireless local area network (WLAN), ultra-wideband (UWB), vision tracking, and ultrasound. Apart from GPS, which is an outdoor position monitoring system, the other six RTLSs are mostly applied in indoor location tracking. For the past decade, the use of RTLS is quite common in the construction management domain. Out of the six RTLSs, the most frequently used is RFID, while ultrasound and infrared were only occasionally applied. The features of these RTLSs are presented below.

Global Positioning System (GPS)

GPS utilizes multiple satellites to provide location and time information in all weather conditions. The most obvious advantage of GPS is that it has the greatest coverage of all the location tracking systems. However, its accuracy has been questioned. For instance, a field trail on GPS accuracy concluded that the average position error ranged from 2 meters on an open square to 15 meters non-open areas (Modsching et al., 2006). Lu et al. made similar observations stating that the GPS positioning accuracy was around 10 m, but the error can be further improved to be within centimeters with the assistance of differential corrections and special algorithms (Lu et al., 2007). In the construction industry, GPS has been proven efficient in material tracking, equipment positioning, automobile tracking and plant control by a number of studies (Roberts et al., 1999, Peyret et al., 2000; Caldas et al., 2006; Grau et al., 2009; Razavi and Hass, 2010; William et al., 2012). However, due to its inaccuracy in indoor positioning, GPS is most commonly used in association with indoor RTLSs, mainly with RFID (Ergen et al., 2007; Song et al., 2007; Lu et al., 2007; Garu et al., 2009; Razavi and Hass, 2010; Razavi and Hass, 2012).

Radio-Frequency Identification (RFID)

RFID is the technology of using radio frequencies to transfer data wirelessly to automatically capture and transmit data (Jaselskis et al., 1995). As early as 1995, the potential use of RFID in the construction was discussed, and the prediction of RFID applying in material control (Song et al., 2006; Ergen et al., 2007), and labor and equipment control (Lu et al., 2007; Woo et al., 2011Ding et al., 2013) has become reality. The wide adoption of RFID is probably due to its ability to 1) uniquely identify construction materials; 2) store information on the component; 3) access the stored data on demand (Ergen et al., 2007). More importantly, the accuracy of RFID in indoor positioning is high. Earlier studies reported 5-9 m errors with greater than 95% confidence (Taneja et al., 2011). And more recent research echoed and found an average error of mere 1.3 m (Razavi and Moselhi, 2012). The improved accuracy could be a result of advanced technology and algorithm (Motaser and Moselhi, 2014). There are three types of RFID, passive (without battery), semi-passive (battery assisted), and active (battery powered) (Costin et al., 2012). The passive RFID is smaller, less expensive, but covers less area compared to the active RFID (Gu and Lo, 2009).

Wireless local area network (WLAN)

"A wireless local area network (WLAN) is a wireless computer network that links two or more devices using a wireless distribution method (often spread-spectrum or OFDM radio) within a limited area" (Wikipedia, 2015). WLAN has been widely adopted in a variety of professions. As to location tracking in the construction industry, there are some discrepancies as to the accuracy of WLAN. In experiment results, Taneja et al. reported an error of 1.5

m. But in a case study conducted in Guangzhou MTR, the error was 5 m (Woo et al., 2011). The difference between experiment and real-life was significant. In addition, Behzadan et al. explored the efficiency of a combination of WLAN and GPS for location tracking and reached a satisfactory accuracy (Behzadan, 2008). However, the result was obtained in an experiment, and further real-life studies need to be conducted to verify the high accurary.

Ultra-wideband (UWB)

Compared to RFID, UWB is a radio technology which is usually used at a very low energy level for short-range, high-bandwidth communications using a large portion of the radio spectrum. It is designed for mobile tracking of labor and equipment (Khoury and Kamat, 2009; Cho et al., 2010). The accuracy was proven high with an error of 50 mm in static conditions and 65 mm in dynamic conditions (Cho et al., 2010). However, Khoury and Kamat (2009) compared UWB, GPS, and WLAN in experiments and concluded that UWB, despite its high accuracy, was relatively expensive and required significant amount of time and effort to deploy. The high accuracy of UWB has made it a valuable method in construction management studies. It was applied in plants, equipments and labor tracking (Carbonari et al., 2011; Cheng et al., 2011; Yang et al., 2011; Hwang 2012). Cheng and Teizer (2013) even proposed a construction management system utilizing UWB to monitor construction sites. In addition UWB has been utilized for data collection in ergonomic analysis (Cheng et al., 2013) and safety training (Teizer et al., 2013).

Vision tracking

Vision tracking is commonly accomplished with the help of cameras, which is quite commonly seen in our daily life (e.g. traffic surveillance). When applied in the construction industry, it has the clear disadvantage of having limited coverage and less useful in dynamic environment (Gu and Lo, 2009). More recently, with advanced 3D visualization technology, the camera-based site monitoring was applied in safety management, and reached a high accuracy of 88% (Han and Lee, 2013). It has been applied in a wide range of construction domains such as personnel monitoring on construction site (Teizer and Vela, 2009), plant tracking (Brilaakis et al., 2011), and maintenance (Adhikari et al., 2014).

Ultrasound

Ultrasound positioning system was an innovation inspired by bats. It is not commonly used in the construction industry yet. Skibniewski and Jang (2009) compared the accuracy of Radio Frequency (RF) in tracking construction assets with a combined system of Radio Frequency and ultrasound (US). And the RF-US system showed enhanced accuracy in simulation.

2.2.3 RTLS in construction safety management

From the above discussed studies, it can be concluded that RTLS has been widely adopted in the construction industry in many domains such as material management, safety management, facility management, etc. A total of 15 articles concerning RTLS utilized for safety management was identified and presented in detail below.

Author, year	RTLS used	Main findings
Ding et al., 2013	RFID combined with fiber Bragg grating (FBG) sensor system	The study proposed system a RFID-FBG combined safety management system. And the system was verified in the cross passage construction site in the Yangtze Riverbed Metro Tunnel project in Wuhan, China. The system has proven to be effective in real-time monitoring and early warning of safety risks.
Cheng and Teizer, 2013	UWB	The study conducted three experiments and demonstrated that real-time construction field operations can be automatically monitored and visualized with precision. And the data obtained could increase safety awareness among workers, and better inform decision makers as to the conditions on site from a remote location.
Wu et al.,	RFID integrated with	The study proposed an

2013	Wireless sensor network (WSN)	information management system using RFID and WSN to prevent struck-by-falling-object accidents. And it further verified the efficiency of RFID in real-time tracking.
Carbonari et al., 2011	UWB	The study proposed and tested a proactive real-time safety management system in construction sites, and the results showed that the system was helpful in reinforcing safety policies and dealing with accidents.
Teizer et al., 2010	Radio Frequency	The study applied a Very-High Frequency (VHF) active Radio Frequency (RF) technology in a real-time safety alert system. And a site trial proved the system an improvement in alerting workers of close proximity to heavy equipment even in noisy surroundings.
Riaz et al.,	GPS integrated with	A safety system using GPS,

2006	Micro-Electro-Mechanical Systems (MEMS)	wireless communication, and MEMS was developed for vehicle pedestrian collision.
Lee et al., 2012	RFID	Two case studies were conducted to test a RFID based safety management system, and the results showed despite its disadvantage in steel-structured environments, the system could be applied to diverse construction sites for multiple tasks such as asset tracking and workforce management. Moreover, the accuracy was high in dynamic and busy construction sites, which would contribute to comprehensive safety management.
Teizer et al., 2013	UWB	UWB was applied in a safety training program in Atlanta. Workers showed raised safety understanding and awareness.
Han and Lee, 2013	Camera-based tracking	The study proposed a framework of behavior based

		safety management based on camera-assisted motion capture and recognition. And the framework was tested to identify predefined unsafe ladder-climbing and proven feasible.
Hwang, 2012	UWB	This study utilized UWB to prevent equipment collision, and the experiment results of this study prove that real-time collision prevention system can enhance equipment safety.
Chae and Yoshida, 2010	RFID	Active RFID were applied in a construction site, and the data obtained were useful in preventing collision accidents.
Wu et al., 2010	RFID	A network consisting of RFID sensor was developed to monitor near-miss accidents and later the network was briefly tested in a warehouse trial with satisfactory results.
Garcia et al., 2006	GPS	The safety of three interstate construction zones was

		monitored by GPS collected traffic data.
Cheng et al., 2013	UWB	UWB was integrated with physiological status monitoring technology to remotely monitor construction workers' unsafe behaviors.
Li et al., 2015	Chirp-Spread-Spectrum-based (CSS) RTLS	The study applied a proactive RTLS based on CSS in safety training and proved the system efficient during precast installation.

The above presented articles delved into all aspects of safety management such as accident analysis (Wu et al., 2010), behavior based science (Han and Lee, 2013), and even safety training (Teizer et al., 2013; Li et al., 2015). More importantly, these studies have proposed and verified several RTLS based safety management system (Ding et al., 2013; Wu et al., 2013; Li et al., 2015). These proactive real-time safety management systems provide location data of construction assets and labor autonomously, which is precious for dangerous behavior analysis. Despite issues of cost and other limitations, these systems are deemed accurate in most studies (Gu and Lo, 2009; Montaser and Moselhi). As Wu et al. (2013) stated near-miss accidents are not fully studied and they are important for accident cause analysis. More importantly, monitoring workers behavior and tracking their responses based on real-time alerts can objectively reveal their attitude and awareness towards safety. For these reasons, this study adopts a proactive safety management system to obtain safety behavior data of construction works in a real-life project in Shanghai, China.

Chapter 3: Methodology

3.1 The Proactive Construction Management System (PCMS)

The Pro-active Construction Management System (PCMS), developed by the Construction Virtual Prototyping Laboratory of the Hong Kong Polytechnic University, integrates logistics enabling technologies, with virtual construction simulation technologies to detect potential sources of danger and provide pro-active warnings to workers when they are exposed to dangerous situations. Specifically, PCMS consists of two major parts: the Real Time Location System (RTLS), which comprises tags, anchors and wireless communication devices; and the Virtual Construction Simulation system (VCS).

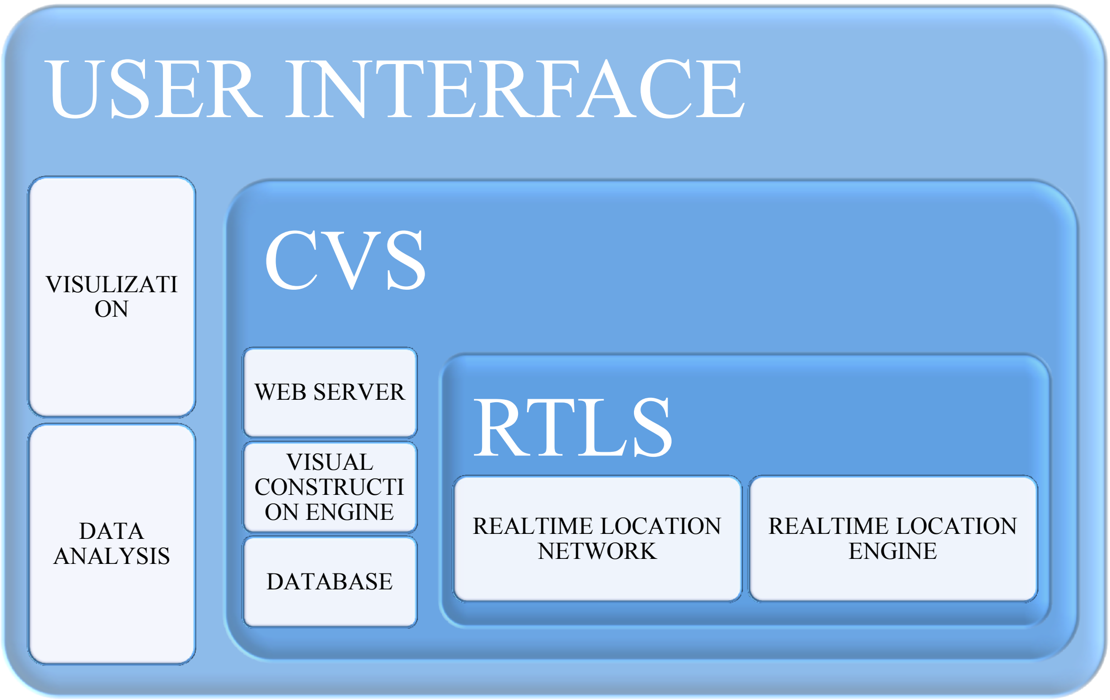

Figure 3.1: The PCMS system structure

3.1.1 Real-time location system (RTLS)

The RTLS consists of two parts, the real-time location network and the real-time location engine. This system adopts the chirp spread spectrum (CSS) method as the wireless communication technology because it is relatively accurate in a dense and cluttered construction site (Li et al., 2015). To be more specific, it adopts the Institute of Electrical and Electronics Engineers (IEEE) 802.15.4a in a wireless personal area network (WPAN) and a time of arrival (TOA) as the location method (Li et al., 2015). The location engine utilizes trilateration to locate the coordinates of the tags based on the three distance values. Tags are mounted to safety helmets and moving equipment on site; and anchors are installed in particular locations of a construction site to provide reference points for the RTLS. The calculated location data are sent to the application server through the location network.

Figure 3.2: Tags and anchors used in PCMS

3.1.2 Virtual Construction Simulation System (VCS).

The VCS utilizes the location data obtained by RTLS to simulate workers' real-time movements on construction site. It mainly consists of the Virtual

Construction Engine, a web server, and a database server, which connect the end user to the location engine. A three-dimensional model of the site and, mostly importantly, the location information of pre-defined hazardous areas are visualized in VCS. And the system can display the locations of workers, equipment, and vehicles in the virtual model in real-time. The visualization of the unsafe behavior can help enhancing safety behavior monitoring.

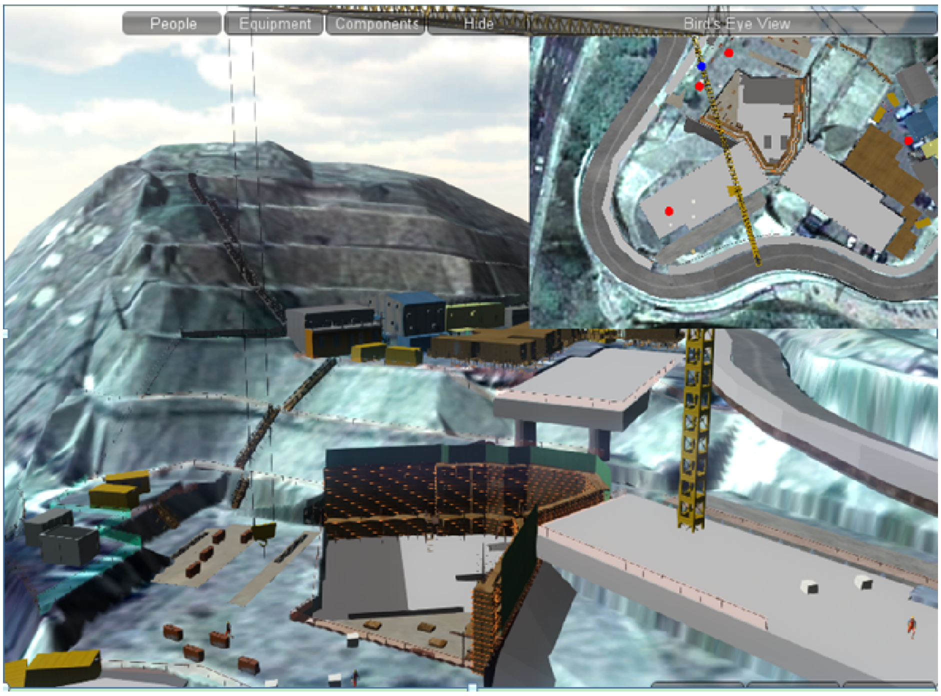

Figure 3.3: Visualization of construction sites in PCMS

3.1.3 User interface

End users of PCMS (safety mangers, workers, etc.) can access the 3D construction information and workers' location data in real time through the user interface. Information displayed includes the danger zone information (type, danger zone ID), personal information (name, work type, etc.) and time information (danger warning time).

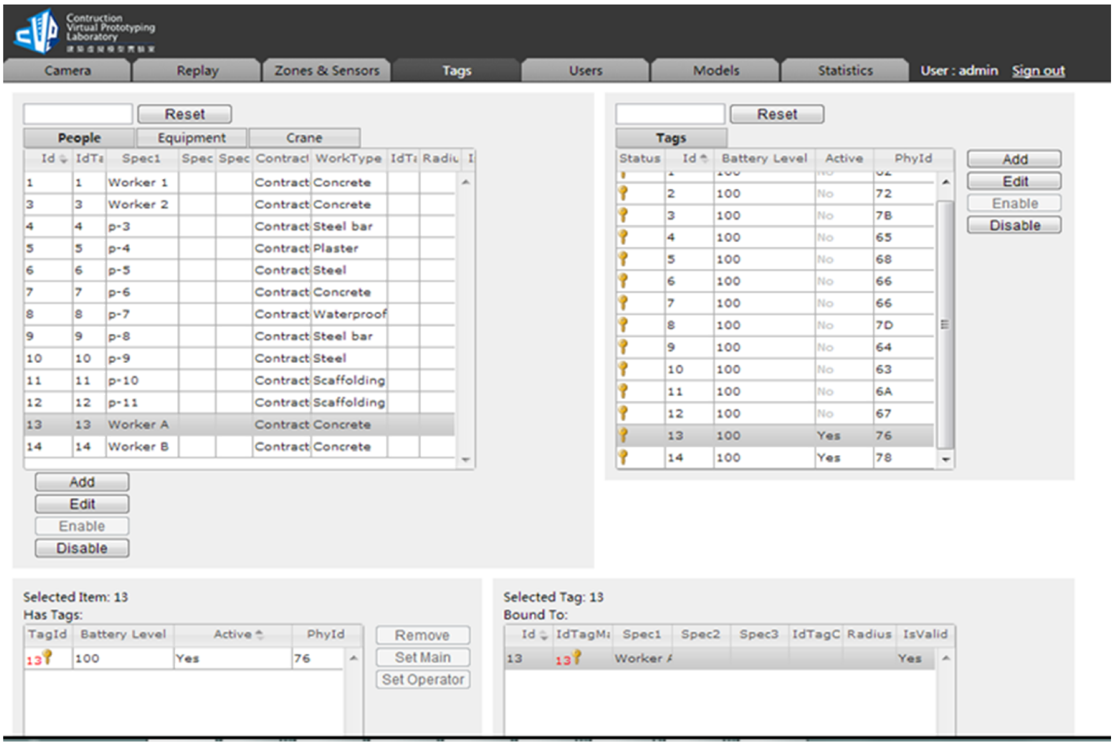

Figure 3.4: The user interface of PCMS

3.2 Functions and usage in this study

PCMS has two major functions that are crucial for this purpose, 1) it traces the tag locations which denote the tag carriers' movement on site, and 2) it transmits danger warnings (through sound and vibration) to specific tag carriers through the location network when it detects tags in pre-defined danger zones. These functions can provide essential information concerning safety performance in two aspects. Firstly, it counts every single time a worker enter a pre-defined danger zone. Moreover, by calculating the warning data, PCMS provides the time it takes for a construction worker to leave a danger zone after receiving warning signals. In this study, these two metrics are essential for the identification of workers' safety behaviors. Entering danger zones does not necessarily lead to injuries and accidents, but it is definitely unsafe behaviors, and should be included in safety performance assessment. Under normal circumstances, the more times a construction worker enters danger zones and the longer he/she stays in the zone after receiving warnings would suggest a poorer safety performance.

PCMS is designed to warn workers of three types of dangers for construction workers including fall from heights, struck by equipment (i.e. crane), and struck by moving vehicles. The developers argue these are the three main types of dangers on construction sites and usually lead to the most serious outcomes (Li et al., 2015).

However, in this study, to include more danger types into safety behaviour assessment, I put forward the idea of using PCMS to detect all types of location based danger sources including hazardous area, high voltage area, etc. The rationale behind the new development is the same as the previous version of PCMS, using anchors to define the center location of danger zone and lay out the danger zone border using tags. Still the limitation of PCMS is that it can only be used to observe location-based unsafe behaviors. Dangerous behaviors such as misuse of tools or violating safety protocols cannot be observed by PCMS. However, these danger behaviors usually do not have as serious outcomes as the danger types covered in PCMS, so they are not included in this study. Future research will be conducted to investigate these behaviors.

3.3 Validity and accuracy

Four trial studies have been conducted in Hong Kong to test the validity and accuracy of PCMS, including the Ngau Tau Kok Slope Reinforcement project, the Public Rental Housing Development at Tung Tau Estate, the Hung Shui Kiu Bus Station Construction, and the MTR Express Station Construction at Nam Cheong (web). These trial studies have proven PCMS quite useful in detecting hazard zones and give pro-active warnings. And the average location accuracy is around 1 meter, which is acceptable compared to previous studies (Modsching et al., 2006; Razavi and Moselhi, 2012).

3.4 Field study

A real life project in Shanghai was chosen as the field study site. The detailed description of the site is attached in Appendix 1. Three criterions are considered for choosing this site. First and foremost, this site covers a large area of lands containing a variety of danger zones, which makes it perfect for danger behavior monitoring. Secondly, this project lasts for an ample period of time for this study to collect large sets of information for data analysis to ensure the objectivity and validity of this study. Moreover, to think practically, multiple construction workers working in this project were previously trained on the usage of PCMS, and it is convenient to choose them as study subjects.

3.4.1 Preparation and equipment deployment

Site condition was input into PCMS with the help of AutoCAD, Revit and Google Earth. The information help generate a comprehensive 3D model of the study field. Safety managers and supervisors were trained on how to properly use PCMS beforehand. During the study period, danger zones were identified by safety mangers and experienced workers before work started every day to ensure most detectable danger sources were included. This step is crucial for the validity of the study. As these danger zones are acknowledged by professionals as dangerous areas. And as the sits is huge, the main working area and the weather conditions varied in different testing days, the correct identification of danger zones are the foundation of success in the study. To lay out the boundaries of each danger zone, PCMS equipment (anchors) was attached to defined danger zones, so the danger zone information could be visualized in PCMS. And safety managers will double-check the danger zone information in the PCMS interface.

3.4.2 Randomized sample selection

A total of 64 construction workers, aged from 24 to 60, were randomly selected to participate in this experiment. The majority (60) of the participants are male, only four of the participants are female. The participants were divided into four groups according to their age, as illustrated in Figure 3.5.

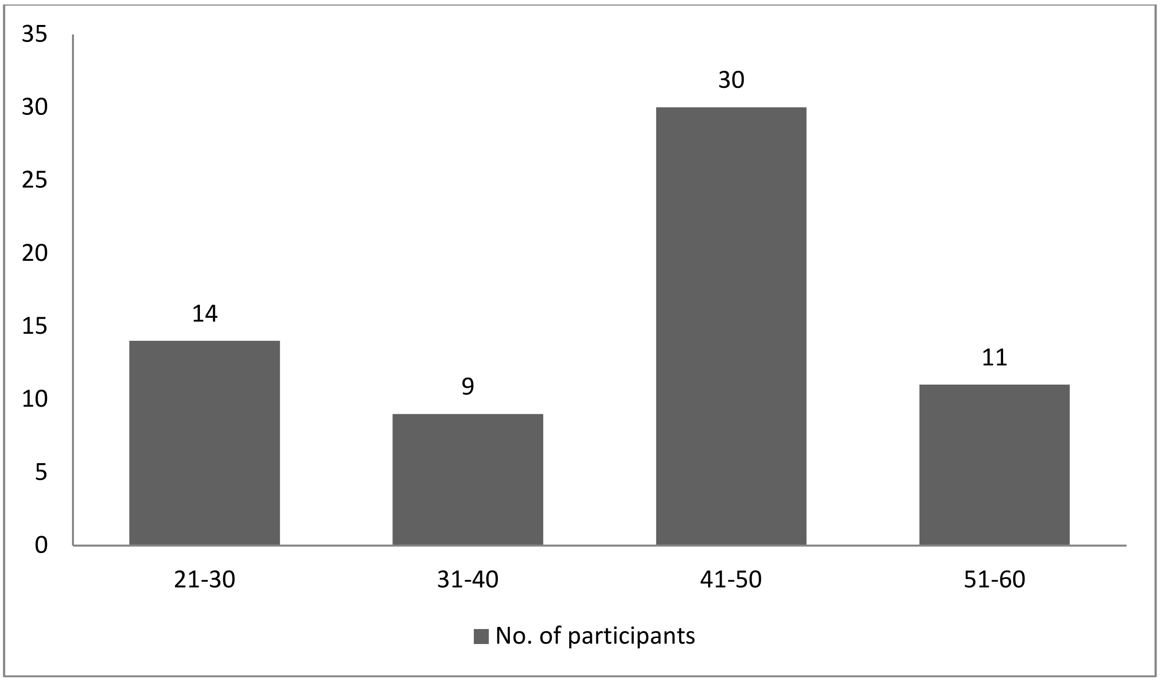

Figure 3.5: Distribution of participants according to age

This distribution of workers according to age and gender in this study is consistent with the general distribution in construction sits stated in the introduction part of the study, as male workers are the majority and workers aged 41-50 take the largest portion of the total number of workers. This result further enhanced the validity of the randomized sample selection.

3.4.3 Field study conditions

The field study was conducted on thirteen working days from January 12th 2015 to April 17th in a real construction site in Shanghai. The average temperature ranged from 3°C to 19°C. The total valid testing period was approximately 198 hours, with an average of around 3 hours for each participant. For a detailed description, please refer to Appendix 2.

3.5 Data summary

PCMS obtained 483,560 location records of the participants. Of all the records, 74,124 were warning records which denoted participants were in danger zones. Warning records constituted approximately 15% of the total location records.

3.6 Data filtering

These auto-collected records needed to be filtered for further analysis, because there were special cases to be considered. For one thing, due to their nature of work, certain types of workers were permitted to enter corresponding danger zones. For instance, rebar workers were allowed to enter certain "stumble-prone areas" for those were their main working areas. However, the current PCMS cannot identify different types of workers, so the auto-collected records included the permitted entries. As a result, the permitted records needed to be filtered manually. For the information concerning permitted entry of participants, please refer to Appendix 3.

3.7 Metric selection

To measure the safety performance of the participants, PCMS provide two types information, 1) the entry into danger zone times, and 2) the time spent in the danger zones. For the former type of information, merely using entry times as safety performance assessment metric will not comprehensively reflect the safety behavior, for the total working hours need to be considered. Therefore, this study chooses to calculate the entry frequency per hour for each participant as the first safety performance assessment metric. And for the time spent in danger zones, because workers mostly entered danger zones multiple times and each time they spent different amount of time to response to danger warnings, an average of all the recorded response time to danger warnings is calculated for each participant as their second safety performance assessment metric. The detailed calculation steps are explained in the following part. In general, lower entry frequency and shorter response time would suggest a better safety performance.

3.8 Entry frequency calculation

To calculate workers' frequency of entry into danger zones, the following equation was applied

$$F = ToE \div W$$

where F stands for frequency of entry into danger zones, ToE is the total entry times of a construction worker during his recorded working hours, and W is the working hours recorded by PCMS in hours.

To calculate workers' entry times into danger zones, all the warning records were examined, of which the successive warning records of the same danger zone were considered as one entry (Example 1). However, single warning record, mostly suggesting workers were near danger zones but did not actually enter the danger zone, was interpreted as near-entry and was not included in the times of entry calculation (Example 2). Another special scenario was when multiple danger zones overlapped, and the entrance of such overlapped area were considered as multiple entry times (Example 3).

王清贺		1/12/2015 2:03:44 PM
王清贺	焊接区域	1/12/2015 2:03:46 PM
王清贺	焊接区域	1/12/2015 2:03:47 PM
王清贺	焊接区域	1/12/2015 2:03:49 PM
王清贺	焊接区域	1/12/2015 2:03:49 PM
王清贺	焊接区域	1/12/2015 2:03:50 PM
王清贺	焊接区域	1/12/2015 2:03:52 PM
王清贺	焊接区域	1/12/2015 2:03:53 PM
王清贺		1/12/2015 2:03:54 PM

One entry

Example 1: successive warning records as one entry

王清贺		1/12/2015 2:10:08 PM
王清贺		1/12/2015 2:10:10 PM
王清贺		1/12/2015 2:10:11 PM
王清贺	焊接区域	1/12/2015 2:10:13 PM
王清贺		1/12/2015 2:10:15 PM
王清贺		1/12/2015 2:10:16 PM
王清贺		1/12/2015 2:10:17 PM

Near-entry

Example 2: single warning records as near-entry

毛利	临边区域;危险品区域	2/6/2015 1:30:26 PM
毛利	临边区域;危险品区域	2/6/2015 1:30:26 PM
毛利	临边区域;危险品区域	2/6/2015 1:30:27 PM
毛利	临边区域;危险品区域	2/6/2015 1:30:29 PM
毛利	临边区域;危险品区域	2/6/2015 1:30:30 PM
毛利	临边区域;危险品区域	2/6/2015 1:30:30 PM
毛利	临边区域;危险品区域	2/6/2015 1:30:33 PM
毛利	临边区域;危险品区域	2/6/2015 1:30:33 PM
毛利	临边区域;危险品区域	2/6/2015 1:30:38 PM
毛利	临边区域;危险品区域	2/6/2015 1:30:39 PM
毛利	临边区域;危险品区域	2/6/2015 1:30:41 PM
毛利	临边区域;危险品区域	2/6/2015 1:30:43 PM
毛利	临边区域;危险品区域	2/6/2015 1:30:46 PM

Multiple entries
(Twice in this case)
()

Example 3: warning records of multiple danger zones at the same time as multiple entries.

3.9 Response time calculation

To calculate workers' response time to danger warnings, the following equation was applied

$$R = Tex - Ten$$

where R stands for response time, Tex is the time of the last warning record of successive warning records recorded by PCMS, and Ten is the time of the first warning record of successive warning records recorded by PCMS (Example 4). And response time was measured in seconds. Note that, single warning entry, mostly suggesting workers were near danger zones but did not actually enter the danger zone, was interpreted as near-entry and was not included in response time calculation (as in Example 2). Whereas in situations where successive warning records had the same time (when $Tex = Ten$), R was considered as one second (Example 5). For each participant, the average response time was calculated for further analysis.

王清贺		1/12/2015 2:03:44 PM	
王清贺	焊接区域	1/12/2015 2:03:46 PM	$\rightarrow T_{en}$
王清贺	焊接区域	1/12/2015 2:03:47 PM	
王清贺	焊接区域	1/12/2015 2:03:49 PM	
王清贺	焊接区域	1/12/2015 2:03:49 PM	
王清贺	焊接区域	1/12/2015 2:03:50 PM	
王清贺	焊接区域	1/12/2015 2:03:52 PM	
王清贺	焊接区域	1/12/2015 2:03:53 PM	$\rightarrow T_{ex}$
王清贺		1/12/2015 2:03:54 PM	

Example 4: successive warning records. In this instance, R = 7.

毛利		2/6/2015 1:36:07 PM	
毛利	危险品区域	2/6/2015 1:36:08 PM	$\rightarrow T_{en}$
毛利	危险品区域	2/6/2015 1:36:08 PM	$\rightarrow T_{ex}$
毛利		2/6/2015 1:36:09 PM	

Example 5: one entry with same time. In this instance, R = 1.

3.10 Data analysis

After collecting and filtering all the location records, statistical analysis were conducted using IBM SPSS. Due to the non-normality of the data, the Kendall's tau-b correlation test was conducted to test the correlation between age and frequency and between age and response time. Nonparametric variance tests (the Kruskal-Wallis test) were then conducted to test if safety performance varies in different age groups. Pairwise comparisons were made to detect detailed variance of safety performance among the four age groups.

Chapter 4: Results

4.1 Data description

The calculated average response time (R) and entry frequency (F) of each participant are presented in the table below.

NAME	AGE	R	F
Li Song	24	7.5	1.344914542
Yang Q	24	5.5	2.032367332
Li Q	25	4.333333333	2.120349465
Mu S	25	85.45454545	6.287710384
Li P	26	6	3.058334907
Shui X	27	7.571428571	2.338313074
Yang T	27	11.6	1.940491591
Yang X	27	12.08333333	4.109589041
Gao X	29	0	0
Niu F	29	2	1.70212766
He L	30	1.833333333	2.068965517
Huang S	30	6	0.354121582
Mao L	30	30.61016949	18.59569252
Wang J	30	0	0
Luo M	34	12.60714286	8.425275827
Yang H	35	13.48717949	30.8707124
Feng Z	38	20.28571429	10.94106154
Li Y	38	10.97619048	14.09001957
Luo C	38	46.80745342	42.62705008

Bian L	39	2.636363636	3.352239059
Deng M	40	35.18072289	43.99617169
Wang B	40	13.18181818	2.972749794
Zhang H	40	15.61538462	5.102485826
Cao H	41	61.796875	25.34374656
Wang X	41	17.44444444	3.064989121
Xian D	41	0	0
Hu D	42	19.81027668	73.66548043
Wang C	42	27.38586957	72.93547677
Wang M	42	0	0
Wang Q	42	8.4375	7.984474633
Xie J	42	0	0
Lu D	43	9.475409836	22.05262101
Zhang Z	43	44	1.026030781
Han J	44	36.59036145	44.10006642
Wei Y	44	13.12686567	47.90942497
Zhou J	44	25.14225941	63.07917889
Chen G	45	21.74285714	18.70685176
Li C	45	15.56179775	24
Hou R	46	15.66666667	1.854395604
Wang X	46	12.375	2.712630687
Yin H	46	0	0
Lv G	47	10.2	3.454231434
Lan Z	48	0	0
Li P	48	0	0
Li X	48	46.5483871	9.21780788
Li X	48	5.714285714	4.555314534

Liu P	48	0	0
Ma J	48	0	0
Weng Z	48	20.9375	9.958506224
Xi J	48	18.40425532	13.95579017
Dai W	50	33.28099174	35.89912642
Fan J	50	0	0
Pu Y	50	0	0
Bao T	52	70.8627451	15.14476615
Gao Y	52	6	0.678925035
Li C	52	19.85294118	10.10568032
Rao X	52	11.4047619	13.69937483
Wang J	52	103.1666667	7.415672474
Wang G	53	23.02912621	59.90306947
Xia S	56	4.457943925	32.38063215
Li R	58	42.60714286	8.31408776
Xiang C	59	60.15	10.72705602
Chen Z	60	50.45714286	13.69118766
Er L	60	4.178571429	9.456797073

Table 4.1: the average response time (R) and entry frequency (F) of each participant

Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation
R in sec	64	.00	103.17	18.9230	21.87645
F per hour	64	.00	73.67	13.6769	18.72339

Table 4.2: Descriptive analysis of the filtered data

Test of Homogeneity of Variances

	Levene Statistic	df1	df2	Sig.
R	3.865	3	60	.014
F	5.855	3	60	.001

Table 4.3: Results of the homogeneity test on R and F

The experiment showed the average frequency of entry was roughly 14 times for all the participants, and there were rather large differences of entry frequency among workers (Table 4.3). The average response time for all participants was just under 19 seconds and the rather big differences of average response time among workers were evident (Table 4.3). Moreover, the Levene's test (Table 4.4) showed the data of F and R were nonparametric (P < .5) in nature. As a consequence, this study has chosen Kendell's Tau-b correlation coefficient to test the correlation of age and safety performance among construction workers.

Correlations

			AGEGROUP
Kendall's tau_b	R	Correlation Coefficient	.196*
		Sig. (2-tailed)	.045
		N	64
	F	Correlation Coefficient	.192*
		Sig. (2-tailed)	.049
		N	64

*. Correlation is significant at the 0.05 level (2-tailed).

Table 4.4: The Kendall's tau-b test of age and R, and of age and F

The correlation test revealed positive correlation between age and R, and between age and F. Moreover, the correlation between R and age ($\tau b = .196$, $p = .045$).was significant, and the correlation between F and age was significant ($\tau b = .192$, $p = .049$) as well. However, note that τb in both cases are relatively small, thus the correlation is moderate. In other words, when age increased, worker's frequency of entry and the average response time slightly increased.

To further analyze the relationship between age and safety performance, participants were divided into four age groups. The Kruskal-Wallis test was conducted to compare construction workers' safety performance among different age groups.

4.2 Frequency of entry into danger zone (F) in different age groups

The null hypothesis (H_0) was that the frequency of entry was consistent among different age groups. The result of the Kruskal-Wallis test is shown in Table 4.5. It indicates there is a significant difference in the medians, x^2 (3, N=64) =10.23, p = .017. Thus the null hypothesis was rejected. Frequency of entry into danger zones varied in different age groups. To detect the specific differences, pairwise comparison among different groups were conducted.

Ranks

	AGE GROUP	N	Mean Rank
F	21-30	14	21.57
	31-40	9	42.33
	41-50	30	31.27
	51-60	11	41.73
	Total	64	

Test Statistics

	F
Chi-Square	10.234
df	3
Asymp. Sig.	.017

Grouping Variable: AGE

Table 4.5: The results of the Kruskal-Wallis analysis

As Keselman et al. (1979) proved that when conducting pairwise comparison among four or less groups, there is no need to adjust the alpha for type I error. Tutzauer (2003) further explained that “alpha adjustment should be applied only in the narrowly circumscribed instance when the researcher wants to make a strong claim that there is no Type I error in a specific collection of tests.” As this study only attempts to explore the effect of aging on safety performance, the alpha was not adjusted in the pairwise comparisons.

Six pairwise comparisons between the four different age groups were conducted, and only the comparison between age group 21-30 and 31-40, and the comparison between age group 21-30 and 51-60 are significant. The results of the pairwise comparison are shown in Figure 4.1.

	21-30 and 31-40	**21-30 and 41-50**	**21- 30 and 51-60**	**31-40 and 41-50**	**31-40 and 51-60**	**41-50 and 51-60**
Mann-Whitney U	12	166	19	97	49	122
Wilcoxon W	117	271	124	562	94	587
Z	-3.213	-1.12	-3.176	-1.277	-0.038	-1.274
Asymp. Sig. (2-tailed)	0.001	0.263	0.001	0.201	0.97	0.203
Exact Sig. [2*(1-tailed Sig.)]	.001		.001	.215	1.000	.215

Figure 4.1: The results of the pairwise comparison between all age groups.

As shown in Figure 4.1, all the median frequency of entry (F) in the four age groups were under 20. The median F of the under 30 age group is significantly smaller than age group 31-40 and age group 51-60, while it is not significantly smaller than the median F in age group 41-50. The median frequency of age group 31-40 was almost equal to the median of age group 51-60.

In addition, the under 30 age group had the narrowest spread of data, while age group 41-50 had the widest spread of data and largest number of outliers. Age group 31-40 had wide spread of data as well, and age group 51-60 had moderate spread of data.

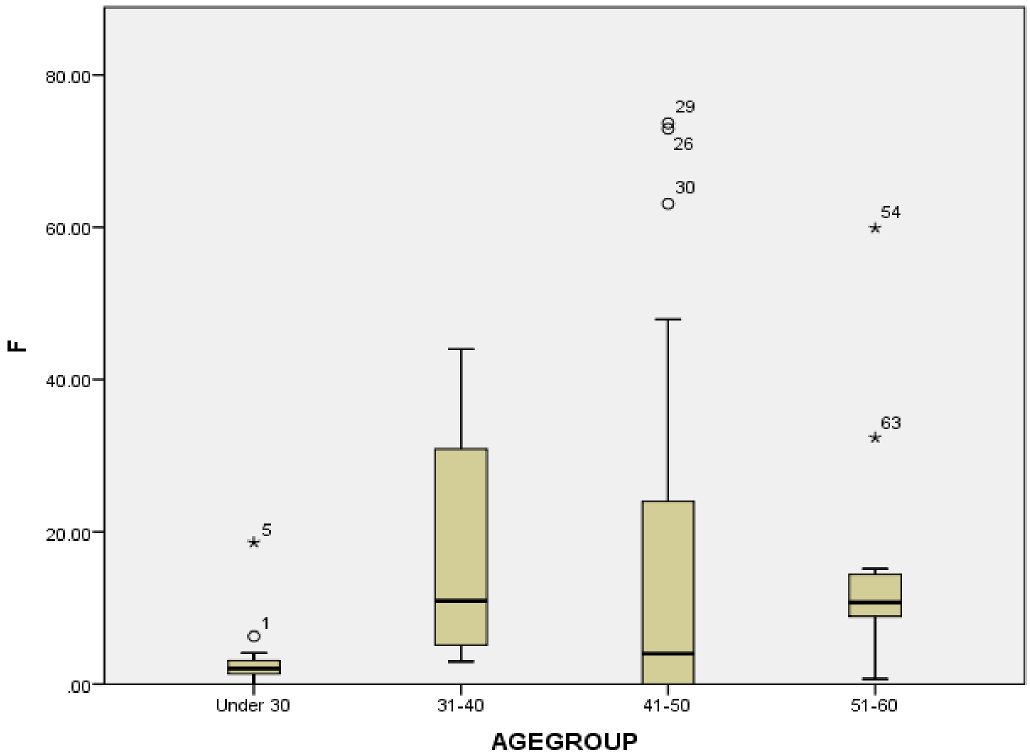

Figure 4.2: The distribution of F for four age groups

4.3 Average response time (R) in different age groups

The results of the Kruskal-Wallis test are shown in Table 4.6. It indicates that there is no significant difference in the medians, x^2 (3, N=64) =7.63, p = .054. In other words, there was no strong evidence indicating workers in different age groups had significantly different response time.

Ranks

	AGEGROUP	N	Mean Rank
R	21- 30	14	24.71
	31-40	9	38.44
	41-50	30	30.33
	51-60	11	43.45
	Total	64	

Test Statistics

	R
Chi-Square	7.630
df	3
Asymp. Sig.	.054

Table 4.6: The result of the Kruskal-Wallis test on R in the four age groups

Even though there was no significant difference among all age groups in terms of average response time, Figure 4.3 demonstrated age group 51-60 had the widest range in average response time, and its median is slightly larger than the medians of other age groups.

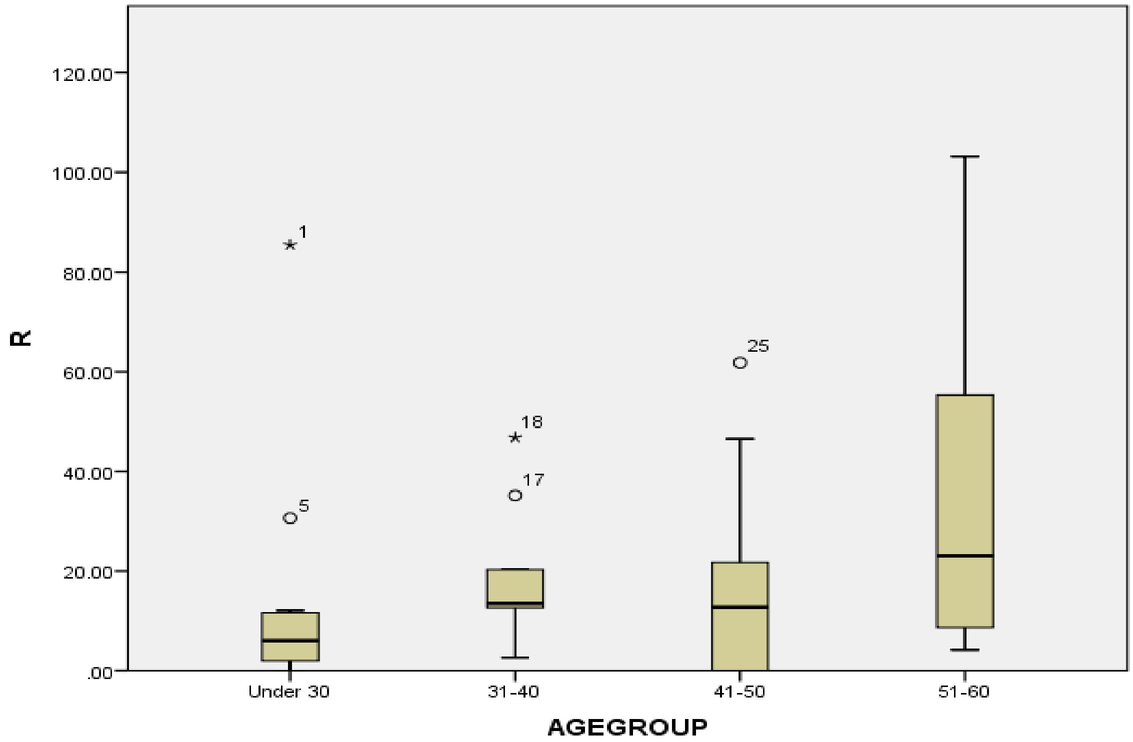

Figure 4.3: The distribution of R for four age groups

Chapter 5: Discussion

5.1 An overview of the findings

This study intends to investigate the effect of aging among construction workers on their safety performance. And the results demonstrate that aging has mildly negative effects on workers' safety performance.

For one thing, in terms of frequency of entry into danger zones, age has an overall positive impact (Table 4.4), which suggests, in general, aged construction workers will probably enter danger zones more frequently. More detailed pairwise comparisons between age groups suggest that the frequency of entering danger zones was the lowest among workers in the 21-30 age group. The frequency then surged to the highest in age group 31- 40 and dropped a little in age group 41-50 before it increased again among workers in age group 51-60. In a word, workers in age group 31-40 and age group 51-60 entered danger zones much more frequently than younger workers. The findings of aging on frequency of entry in this study are somewhat consistent with previous research findings. To be more specific, several studies have reported most number of injuries and fatalities occurred to workers aged 31-40, which explained the high frequency of entry into danger zones in age group 31-40. For instance, Huang et al. (2003) stated that workers in age group 31-40 were most frequently involved in fall accidents. Cheng et al. (2010) pointed out that most commonly injured workers were from age group 35-44. Jackson and Loomis (2002) also identified that age group 25-34 accounted for the largest number of fatalities. It is rational to assume that the number of injury and the frequency of entering danger zones have a positive correlation, thus explaining the high frequency in age group 31-40 for this study.

For another, in terms of response time to danger warnings, age has a moderate positive effect as well. That is to say, older construction workers have slightly longer response time to danger warnings than their younger colleagues. Further comparison revealed that workers in those four age groups had similar performance pattern concerning response time to danger warnings compared to the performance pattern on the frequency of entry into danger zones. Young workers (under 30) had the shortest average response time, and middle aged (41-50) workers had relatively shorter response time than workers in the other two age groups. However, the differences concerning response time were not evident. The increased response time associated with aging echoed the findings that senior workers suffer from reduced physical agility. Welch et al. (2005) associated older age with decreased physical functioning. Dement et al. (2005) pointed out large portions of senior construction workers suffered from hearing loss. Yi et al. (2013) also found out that age influenced workers' heat tolerance. The impaired hearing will mostly probably increase response time to warnings as the warning signal was transmitted to workers by audio and vibration. The decreased agility could possibly prolong the response time to a certain degree as well. And the low temperature in the experiment might have an effect.

5.2 Discussion of new findings

However, the high frequency and prolonged response time among older workers are worth noticing. Most studies have reported decreased number of injuries and accidents and elevated safety attitude and safety climate among older workers. For instance, Lipscomb et al. (2010) concluded that younger workers had much higher injuries and the injury rate decreased steadily with increasing age. Cattledg et al. (1996) studied 182 injury cases and found older workers had much less injuries. Arcury et al. (2012) conducted questionnaire survey among 119 construction workers and concluded that age had a positive impact on safety climate. By the traditional safety performance metric (accidents and injuries), one would assume better safety performance among older workers. But the findings in this study suggest otherwise. Note how these previous findings are either result-oriented or subjective, while this study provides objective observations for it reflects the actual on site safety performance among construction workers. The results actually suggest that despite the better safety attitude and decreased injuries, older construction workers have weakened on site safety performance. The theory could be useful in rationing discrepancies among previous safety related studies. For instance, as I have mentioned the Arcury et al. study (2012), in which 119 construction workers were surveyed and concluded that age had a positive impact on safety climate, Grzywacz et al. (2012) actually studied the same group of construction workers in three month follow-up interviews and stated the injury risk among these workers were not significantly different among different age groups. The results obtained from the same group of people pose a question as to why better safety climate does not contribute to lowered injury risk. We could attempt to use the findings in this study to answer this question. That is, the effect of improved safety climate could have been neutralized by the effect of weaker safety performance among older construction workers. The answer is not absolute and needs to be solidified with more evidence, but it does provide some insight into the workers' safety performance. The weakened safety performance among older construction workers could be supported by studies suggesting older workers have the highest injury rate of fall-related accidents. McCoy et al. (2013) observed that despite the largest number of injuries in age group 30-39, the injury rate of fall increased with growing age. Son et al. (2014) reported the highest risk for fall-related injuries among older construction workers. Choi (2015) attributed most of the injuries among older construction workers to falling from a higher level. Most fall-related accidents happen at near edge areas (fall from heights accidents) and stumble – prone areas (fall on the same level accidents), which could be easily identified. In this experiment study, multiple fall-related danger zones were identified in the experiment including fall-prone area (fall from heights) and stumble –prone area (fall on the same level), taking up large portions of the tagged danger zones. The high frequency of older workers into danger zones could be attributed to their frequent entrance into fall-prone area and stumble-prone area. However, more data need to be obtained to reach a more concrete explanation.

5.3 Implications

Considering that older workers have similar safety performance as middle aged workers, it would suggest that aging does not have a severe negative effect on safety performance. As long as safety management strategies and policies take the aging effect into consideration, the mildly negative effect can be managed. Suggestions are made as follows.

Firstly, for younger workers who had satisfactory safety performance but high injury rates, safety education targeting younger workers shall put the emphasis on how to minimize damages when accidents occur. For middle aged workers, who showed the worst safety performance on site, comprehensive safety education is necessary to raise safety awareness among them. As for senior workers, whose number is growing, a more rational work assignment of less dangerous works shall be made. Safety warnings shall be signaled to senior workers earlier and in more alerting forms.

This finding is important for construction safety management. Firstly, it implements the current result-oriented safety performance assessment. Even though the traditional assessment adopts concrete performance indicators (injuries and accidents), it is not a direct reflection of workers' safety behavior. The location data obtained in this study depict a much more precise picture of workers' behaviors on site. To include the behavior observation in future safety performance assessment can provide more accurate and comprehensive results. Secondly, this finding calls for special attention to older workers in safety management. Despite their sufficient knowledge (awareness) of safety and accumulated experience, older workers' degenerated physical functioning could impair their safety performance. Safety managers should remind senor workers of their declined ability to avoid danger, and provide more prevention measures for them. Another crucial impact of this study is that it validates the feasibility of using real-time location system in safety behavior analysis. Little research has utilized real-time location system in assessing construction workers' safety behavior. Compared to traditional research methods, which mainly rely on subjective observation/questionnaire and lagged consequences, this study provides much more direct and objective evidence concerning construction workers' on site safety behaviors. Moreover, this method could be utilized in analyzing a number of other factors affecting safety performance such as weather, gender, work type, etc. It is an unparalleled tool in workers' behavior analysis, and could shed some light on the injury causation and accident mechanism.

5.4 Limitations and future direction

The major limitation of this study is that safety behavior analysis was based on location data, and there are a number of unsafe behaviors that do not relate to workers' locations were not examined in this analysis. More advanced monitoring system is required for such analysis, and it will implement the findings in this study. And another major weakness of this research is that the number of participants for the statistical analysis is relatively small. With a larger data set, the statistical analysis would yield more convincing results. However, the experiment was conducted in a real construction project, the results obtained would better reflect the candid safety performance than in experimental environment. It was not easy to gather such data from construction workers, for participants had to wear extra equipment on job. And even though the number of data obtained is relatively small, there are other studies that came to solid conclusions with even smaller sample sizes. I intend to further explore the relationship of aging and safety behavior with more data in the near future.

For future research, more metrics could be included in safety behavior analysis, such as the distance of entry into danger zones. Video surveillance or more advanced surveillance system could be utilized to capture workers' behaviors, which could yield information as to workers' behavior outside of danger zones and workers' safety behavior involving hand tools, etc. More importantly, with more information concerning safety behavior, a comprehensive safety performance assessment scheme could be devised for practical safety management and research purposes.

Chapter 6: Conclusion

Aging has been a dire issue facing the entire world. The situation is quite serious in Hong Kong and mainland China. Previous studies have investigated the effect of aging on physical abilities and mental abilities. But in the construction sector, little research has been done to explore the effect of aging on safety performance. This study intends to investigate the effect of aging on safety performance using analytical tools with data obtained by RTLS. And a field study demonstrated the overall slightly negative effect of aging on safety performance.

The negative effect is much less severe than anticipated, and could be neutralized with proper safety management strategies. For younger workers who demonstrated satisfactory safety performance, safety trainings aiming to enhance their abilities in dealing with dangers are needed to reduce the injury rate and fatality rate. As they grow older and gain more experience, safety education should be enforced to raise their safety awareness. As for older workers, who already realized the importance of safety but hindered by their physical constrains to avoid unsafe behaviors, they should be assigned to safer jobs and equipped with better safety protection measures.

Age has been a determining factor in recruitment, as older workers have been considered less competent. However, as the aging problem progresses in the construction industry, there are bound to be more and more aged construction workers working in construction sites. This study objectively reflects how older worker performs according to safety regulations in a real construction site, and it seems that older workers are just as competent as their younger colleagues in safety compliance.

The usage of RTLS to enhance safety performance assessment has been proved effective by this study, which could potentially replace the current subjective safety assessment methods. In my future research, I intend to use this system to explore more personal elements on safety performance, such as gender, education, etc. From a practical standpoint, with a few updates, the system used in this study could be widely adopted for construction companies in their routine safety performance assessment. The massive usage of this system has the potential to dramatically lower the fatality rate and injury rate in the construction industry.

Note that this study is exploratory in nature. It is only the first step to looking into factors affecting safety performance. More behavior data shall be monitored in future studies to solidify the conclusion reached in this study, and more unsafe behaviors shall be studied in future research.

Appendix 1: The detailed description of the field study site

The Shanghai Middele Ring Pudong section starts form Jungong Road Tunnel in the north to Gaoke Middle Road in the south as highlighted in the red line in the above map. The whole length is around 9.44km.

Appendix 2: Detailed description of study participants

NO.	Name	Age	Gender	Date	Weather	Valid Test Period
1	Wang Q	42	M	12/01/2015	3	2:00:14
2	Yang H	35	M	19/01/2015		2:31:36
3	Cao H	41	M	19/01/2015	8.5	2:31:31
4	Wang C	42	M	19/01/2015		2:31:22
5	Mu S	25	M	21/01/2015		3:29:56
6	Deng M	40	M	21/01/2015		3:46:23
7	Luo C	38	M	21/01/2015		3:46:37
8	Chen G	45	M	21/01/2015		3:44:31
9	Han J	44	M	21/01/2015	8.5	3:45:51
10	Hu D	42	M	21/01/2015		3:26:04
11	Zhou J	44	M	21/01/2015		3:47:20
12	Wang G	53	M	21/01/2015		3:26:20
13	Wang J	52	M	21/01/2015		3:14:11
14	Xiang C	59	M	21/01/2015		3:43:44
15	Mao L	30	M	06/02/2015		3:10:22
16	Wang B	40	M	06/02/2015		3:42:01
17	Li C	45	M	06/02/2015		3:42:30
18	Dai W	50	M	06/02/2015	4.5	3:22:14
19	Li X	48	M	06/02/2015		3:21:47
20	Xi J	48	M	06/02/2015		3:22:04
21	Bao T	52	M	06/02/2015		3:22:03

22	Li C	52	M	06/02/2015		3:21:52
23	Li R	58	M	06/02/2015		3:22:04
24	Yang T	27	M	17/03/2015	8	2:34:36
25	Feng Z	38	M	17/03/2015		2:33:33
26	Zhang H	40	M	17/03/2015		2:32:52
27	Chen Z	60	M	17/03/2015		2:33:23
28	Luo M	34	M	18/03/2015	17.5	3:19:24
29	Xian D	41	M	18/03/2015		3:14:42
30	Hou R	46	M	18/03/2015		3:14:08
31	Weng Z	48	M	18/03/2015		3:12:48
32	Yang X	27	M	19/03/2015	13.5	2:55:12
33	Bian L	39	M	19/03/2015		3:16:53
34	Lv G	47	M	19/03/2015		2:53:42
35	Gao X	29	M	25/03/2015	12.5	3:19:09
36	Wang M	42	M	25/03/2015		3:01:12
37	Xie J	42	M	25/03/2015		3:16:58
38	Fan J	50	M	25/03/2015		3:19:08
39	Lan Z	48	F	25/03/2015		3:00:57
40	Liu P	48	M	25/03/2015		3:01:50
41	Pu Y	50	M	25/03/2015		3:01:35
42	Yin H	46	M	25/03/2015		2:59:11
43	Huang S	30	M	03/04/2015	14.5	2:49:26
44	Wang J	30	M	03/04/2015		2:45:28
45	Lu D	43	M	03/04/2015		2:45:58

46	Wei Y	44	M	03/04/2015		2:47:49
47	Li P	48	M	03/04/2015		2:42:46
48	Ma J	48	M	03/04/2015		2:32:22
49	Li X	48	M	08/04/2015		3:04:24
50	Rao X	52	F	08/04/2015	12	3:03:57
51	Xia S	56	M	08/04/2015		3:18:16
52	Li Q	25	M	10/04/2015		2:49:47
53	He L	30	M	10/04/2015		2:54:00
54	Niu F	29	F	10/04/2015	13.5	2:56:15
55	Li Y	38	M	10/04/2015		2:58:51
56	Er L	60	M	10/04/2015		2:57:39
57	Li P	26	M	15/04/2015		2:56:34
58	Zhang Z	43	M	15/04/2015	19	2:55:26
59	Wang X	46	M	15/04/2015		2:56:57
60	Gao Y	52	M	15/04/2015		2:56:45
61	Li S	24	M	17/04/2015		2:58:27
62	Yang Q	24	M	17/04/2015	17.5	2:57:08
63	Shui X	27	M	17/04/2015		2:59:37
64	Wang X	41	F	17/04/2015		2:56:11
Total						197:57:52
Average						3:05:35

Appendix 3: Entry permission into danger zones

NAME	Bar setting area	Electricity box	Falling-prone area	Fire-forbidden area	Hole area	Joint area	Lifting area	Material placing area	Stumble-prone area	Welding area
Li S		*			*					
Yang Q		*			*					
Li Q		*	*	*						
Mu S			*							*
Li P		*			*					*
Shui X		*			*					
Yang T			*	*						
Yang X		*		*						
Gao X										
Niu F		*	*	*	*					

He L		*	*	*	*					
Huang S				*						
Mao L			*	*						
Wang J				*						
Luo M		*		*						*
Yang H			*							*
Feng Z			*	*						
Li Y		*	*	*						
Luo C			*							*
Bian L		*	*	*						*
Deng M			*							*
Wang B		*	*	*						*
Zhang H			*	*						
Cao H			*							*

Wang X		*			*					
Xian D		*			*					*
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